

CRANFIELD UNIVERSITY

PHILIPPE JAMES BRIDGEMAN

INVESTIGATION OF PLASMA TRANSFERRED ARC DYNAMIC
EFFECTS IN WIRE + ARC ADDITIVE MANUFACTURING

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING

PhD Thesis
Academic Year: 2020 – 2021

Supervisor: Professor Stewart Williams
Associate Supervisor: Dr Jialuo Ding
January 2021

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Abstract

This investigation focuses on the effect of plasma transferred arc (PTA) parameters and torch geometry on arc pressure to characterise the soft plasma process and the avoidance of keyhole defect formation. A measured arc pressure comparison with gas tungsten arc (GTA) was also undertaken. The objective being to minimise arc pressure, reducing any depression of the melt-pool and thereby its effects on bead geometry. Both are essential for the wire + arc additive manufacture (WAAM) process. The research approach includes experimental measurement of arc pressure for combinations of torch nozzle and electrode geometries and process variables to determine the process sensitivities and their effect on the arc pressure, and to determine reduction methods. A novel concept of an arc interaction time, relating to gas conditioning, arc characteristics and the strength of the arc pressure, is proposed. A relationship between arc voltage and peak arc pressure is identified and proposed as a potential method of real-time pressure monitoring during WAAM operations. An empirical statistic process model was developed, which relates arc pressure to process conditions and torch design, allowing the selection of process variables while maintaining a minimum arc pressure in PTA WAAM, thus enabling higher currents and larger deposition rates while minimising keyhole defect risk. Arc pressure keyhole defect transition thresholds are identified for both stainless-steel and titanium. Arc pressure is determined as the predominant factor for initiating sharp keyhole defect transitions for a set of thermal conditions – a balance between thermal melt-pool fluid flow and arc pressure-induced hole size. A study of PTA electrodes was additionally undertaken to reduce arc pressure, improve arc starting, investigate wear and increase the longevity of electrodes and tip shape retention to optimise WAAM operations.

Keywords: Arc Pressure, Keyhole Defects, Plasma Transferred Arc (PTA), Experimental Measurement, Additive Manufacture, Wire + Arc Additive Manufacture (WAAM), Empirical Process Model, Electrode Wear.

Dedicated to my wife, Jennifer Bridgeman
and sister, Alexandra Eddy.

‘Adventure awaits, go make it happen.’

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List of Abbreviations

A	Amps
AC	Alternating Current
AI	Arc Current
AL	Arc Length
ALH	Average Layer Height
AM	Additive Manufacture
ANOVA	Analysis of Variance
APW	Arc Power
AP	Arc Pressure
APP	Arc Peak Pressure
Ar	Argon
AV	Arc Voltage
BCM	Beaded Cylinder Morphology
BTF	Buy-to-fly
CAD	Computer Aided Design
Ch.	Chapter
CNC	Computer Numerical Control
CTWD	Contact Tip Work-piece Distance
DA	Diffuser Angle
DC	Direct Current

DCEN	DC Electrode Negative
DCEP	DC Electrode Positive
DED	Directed Energy Deposition
DL	Diffuser Length
DOE	Design of Experiments
EANR	Effective Arc Nozzle Restriction
EBM	Electron Beam Melting
EDS	Energy Dispersive X-ray Spectrometry
E_{NEBD}	Effective Nozzle Exit Bore Diameter
EPSRC	Engineering and Physical Sciences Research Council
ESB	Electrode Setback
FWHM	Full Width at Half Maximum
GMAW	Gas Metal Arc Welding
GRM	Gouging Region Morphology
GTA	Gas Tungsten Arc
H	Hydrogen
HAZ	Heat Affected Zone
He	Helium
HF	High Frequency
HI	Heat Input
HSE	Health and Safety Executive

ISS	International Space Station
L	Interaction Length
KHD	Keyhole Depth
LH	Layer Height
LMD	Laser Metal Deposition
MAG	Metal Active Gas
MIG	Metal Inert Gas
min	Minute
MP	Melt-Pool
MPD	Melt-Pool Depth
NASA	National Aeronautics and Space Administration
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NEWAM	New Wire Additive Manufacturing
PBF	Powder-bed Fusion
PGFR	Plasma Gas Flow-rate
ppm	Parts Per Million
PTA	Plasma Transferred Arc
PWP	PWP Industrial (company name)
RA	Robotic Arm
SEM	Scanning Electron Microscope

SG	Shielding Gas
SLM	Selective Laser Melting
SMD-EBF	Shaped Metal Deposition – Electron Beam Free Form Fabrication
TEAR	Tungsten Electrode Arc Ring
TIG	Tungsten Inert Gas
TS	Travel Speed
V	Voltage
WAAM	Wire + Arc Additive Manufacture
WAAMsoft	WAAM Control Software
WELPC	Welding Engineering and Laser Processing Centre
WFS	Wire-feed Speed
WNOA	Wire Not Obscuring the Arc
wt.	Weight
WOA	Wire Obscuring the Arc
WW	Wall Width

List of Symbols

A	Amps	(A)
A₀	Richardson Constant	(A/cm ² /k ²)
A_E	Arc Energy	(kJ/mm)
A_F	Arc Force	(N)
A_L	Arc Length	(mm or m as indicated)
A_{PW}	Arc Power	(W: Watts)
AP	Arc Pressure	(N/m ² : Newton per Square Metre)
A_{PP}	Arc Peak Pressure	(N/m ² : Newton per Square Metre)
A_V	Arc Voltage	(Volts)
C	Charge	(C - Coulomb)
C_D	Torch Nozzle to Work-piece Distance	(mm)
C_p	Specific Heat at Constant Pressure	(kJ kg ⁻¹)
C_v	Specific Heat at Constant Volume	(kJ kg ⁻¹ k ⁻¹)
D	Distance	(mm)
D_A	Diffuser Angle	(Deg: Degrees)
D_L	Diffuser Length	(mm)
E	Energy	(J)
E_{Arc + Electrode}	Energy Generated by PTA	
E_{BM}	Energy Lost to the Base Metal	
E_D	Electrode Diameter	(mm)
E_{FZ}	Energy to the Fusion Zone	
E_L	Electrode Length	(mm)
E_{LΔ}	Change in Electrode Length	(mm)
E_{LOSSES}	Energy Lost to the Environment	
E_{NEBD}	Effective Nozzle Exit Bore Diameter	(mm)
E_{NL}	Effective Nozzle Length	(mm)
E_{SB}	Electrode Setback	(mm)
E_{TA}	Electrode Tip Angle	(Deg: Degrees)
E_{TD}	Electrode Tip Diameter	(mm)
E_W	Electrode Weight	(g)
E_{WΔ}	Change in Electrode Weight	(g)
E_{WRL}	Electrode Wear-rate (Length)	(mm /min)
E_{WRW}	Electrode Wear-rate (Weight)	(g /min)
eV	Electron Volt	(eV)
G_{BP}	Glovebox Pressure	(N/m ² : Newton per Square Metre)
H_I	Heat Input	(kJ/mm)
I	Current	(Amps)
I_E	Interaction Energy	(J)
J_s	Emission Current Density	(A/cm ²),
k	Thermal Conductivity	(W/(m·K))
k_{BC}	Boltzmann Constant	
kg	Kilogram	(kg)
K_{HD}	Keyhole Depth	(mm)
L_H	Layer Height	(mm)

m	Mass	(Kg)
M	Molecular Weight	(M)
M_{AP}	Measured Arc Pressure	(N/m ²)
M_{PD}	Melt-pool Depth	(mm)
N_D	Nozzle Diameter	(mm or m as indicated)
N_{SL}	Nozzle Straight Length	(mm or m as indicated)
P_D	Power Density	(W/m ² or w/mm ² as indicated)
P_{DY}	Dynamic Pressure	(N/m ² : Newton per Square Metre)
P_{GFR}	Plasma Gas Flow-rate	(l/min: Litre per Minute or m ³ /sec as indicated)
P_I	Impact Pressure	(N/m ² : Newton per Square Metre)
pm	Picometer	(pm)
P_S	Static Pressure	(N/m ² : Newton per Square Metre)
r	Radius	(mm or as indicated)
r_{Arc}	Arc Radius	(mm)
Ra	Surface Roughness	(µm)
R_P	Recoil Pressure	(N/m ² : Newton per Square Metre)
T	Time	(Sec.)
T_{DIFF}	Thermal Diffusivity	(m ² /s)
T_K	Temperature	(Kelvin)
T_S	Travel Speed	(m/min: Metre per Minute or mm/sec: millimetre per second)
T_w	Deposition Duration/Time	(Minutes)
V	Velocity	(m/s)
V	Voltage	(Volts)
V_O	Volume	(Litre)
V_P	Vapour Pressure	(N/m ² : Newton per Square Metre)
W_D	Wire Diameter	(mm: Millimetre)
WFS	Wire-feed Speed	(m/min: Meter per Minute)
W_w	Wall Width	(mm)
γ	Surface Tension	(N/m)
η	Process Efficiency	(%)
η_A	Arc Efficiency	
η_m	Melting Efficiency	
ρ	Density	(kg/m ³)
Φ_S	Work Function	(Joules)
+ve	Positive	
-ve	Negative	

Formula Sheet

Equation 1	Arc pressure	$AP = M_{AP} - G_{BP}$	AP = Arc Pressure (N/m ²) M_{AP} = Measured Arc Pressure (N/m ²) G_{BP} = Glovebox Pressure (N/m ²)
Equation 2	Arc Length	$A_L = E_{SB} + C_D$	A_L = Arc Length (mm) E_{SB} = Electrode Setback (mm) C_D = Torch Copper Nozzle To Work-piece Distance (mm)
Equation 3	Thermal Diffusivity	$T_{DIFF} = \frac{k}{\rho \times C_p} = \frac{\text{Heat Conducted}}{\text{Heat Stored}}$	T_{DIFF} = Thermal Diffusivity k = Thermal Conductivity ρ = Density C_p = Heat Capacity
Equation 4	Impact Pressure	$P_I = P_S + P_{DY}$	P_I = Impact Pressure P_S = Static Pressure P_{DY} = Dynamic Pressure
Equation 5	Dynamic Pressure	$P_{DY} = \rho \times \left(\frac{V^2}{2}\right)$	P_{DY} = Dynamic Pressure ρ = Density V = Velocity
Equation 6	Density	$\rho = m/V_0$	ρ = Density, m = Mass, and V₀ = Volume
Equation 7	140 A three-hole nozzle Arc Pressure Trend Equation	See Page 170	See Page 170
Equation 8	200 A three-hole nozzle Arc Pressure Trend Equation	See Page 171	See Page 171
Equation 9	Interaction Energy	$I_E = I \times V \times T$	I_E = Interaction Energy I = Arc Current V = Arc Voltage T = Time
Equation 10	Charge	$C = I \times T$	C = Charge I = Arc Current T = Time
Equation 11	Energy	$E = V \times C$	E = Energy V = Arc Voltage C = Charge

Equation 12	Empirical Model Arc Pressure	See Page 222	See Page 222
Equation 13	Arc Energy	$A_E = \frac{60 \times V \times I}{1000 \times T_s}$	A_E = Arc Energy (kJ/mm) V = Voltage (Volts) I = Current (Amps) T_s = Travel Speed (mm per minute)
Equation 14	Heat Input	$H_I = \eta \times A_E$	H_I = Heat Input (kJ/mm) η = Process Efficiency (0.6 for PTA process) A_E = Arc Energy (kJ/mm)
Equation 15	Electrode Wear (change in length)	$E_{L\Delta} = EL \text{ Initial} - EL \text{ Final}$	E_L = Electrode Length (mm) $E_{L\Delta}$ = Change in Electrode Length (mm)
Equation 16	Electrode Wear (change in weight)	$E_{W\Delta} = EW \text{ Initial} - EW \text{ Final}$	E_W = Electrode Weight (g) $E_{W\Delta}$ = Change in Electrode Weight (g)
Equation 17	Electrode Wear-rate (Weight)	$E_{WRW} = \frac{E_W \text{ Initial} - E_W \text{ Final}}{T_W}$	E_{WRW} = Electrode Wear-rate – Weight (g /Min) E_W = Electrode Weight (g) T_W = Deposition Duration (Minutes)
Equation 18	Electrode Wear-rate (Length)	$(E_{WRL}) = \frac{E_L \text{ Initial} - E_L \text{ Final}}{T_W}$	E_{WRL} = Electrode Wear-rate – Length (mm/min) E_L = Electrode Length (mm), T_W = Deposition Duration (Minutes)
Equation 19	Richardson Dushman Equation for Thermo-emission	$J_s = A_0 \times T^2 \times \exp (-\Phi_s / k T)$	J_s = Emission current density (A/cm ²) A_0 = Richardson Constant (A/cm ² /k ²) Φ_s = Work Function (Joules) k_{BC} = Boltzmann Constant T_K = Temperature (Kelvin)

List of Publications

Journals

Xingwang Bai, Paul Colegrove, Jialuo Ding, Xiangman Zhou, Chenglei Diao, **Philippe Bridgeman**, Janroman Hönnige, Haiou Zhang, and Stewart Williams, (2018) ‘*Numerical analysis of heat transfer and fluid flow in multilayer deposition of PAW-based wire and arc additive manufacturing*’, International Journal of Heat and Mass Transfer. Elsevier Ltd, 124, pp. 504–516. Doi: 10.1016/j.ijheatmasstransfer.2018.03.085.

Conference Papers and Extended Abstracts

Philippe Bridgeman, Jialuo Ding, and Stewart Williams (2019) ‘*Plasma transferred arc electrode material longevity and wear investigation*’, Proceedings of International Forum on Intelligent Manufacturing Technology for Graduate Students, July 2019, Beihang University, Beijing China, pp. 47–49.

I. Bitharas, A. McAndrew, S. Rios, **P. Bridgeman**, J. Ding, S. Williams, and A.J. Moore, (2018) ‘*Visualisation and MHD modelling of shielding gas flow and coverage in WAAM*’, International Solid Freeform Fabrication (SFF) Symposium, August 13–15 2018, Austin Texas, USA.

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Chapter 1

Thesis Introduction

With public attention increasingly turning to environmental matters, and the critical need to reduce, reuse and recycle becoming acute, the current reliance on traditional subtractive manufacturing from long lead forged material, with its subsequent elevated cost and high material/energy wastage, is gaining unfavourable attention. In light of this, the beginnings of a focus shift have taken place in recent years towards additive manufacturing (AM).

Wire + arc additive manufacture (WAAM) is an additive manufacturing (AM) process pioneered at the Welding Engineering and Laser Processing Centre (WELPC) at Cranfield University, which is at the forefront of the cutting-edge technology through equipment and software (WAAMsoft) development. As part of the WAAMMat programme, a research collaboration has also emerged between academic and industry partners to realise WAAM technology and build strategies, more recently incorporating the Engineering and Physical Sciences Research Council (EPSRC)-funded New Wire Additive Manufacturing (NEWAM) consortium research programme.

WAAM uses an arc-based heat source and six-axis robotic or computer numerical control (CNC) motion equipment to deposit metal in a layered manner onto a substrate. The technology can be used to manufacture medium-to-large moderately complex near net shape parts with a reduced production cost, high deposition rate, short lead-time, and material savings (Bai et al., 2018; Williams et al., 2015).

Plasma transferred arc (PTA) is well suited for WAAM when evaluated against other arc processes such as gas tungsten arc (GTA) and gas metal arc (GMA). PTA, compared with GTA, allows a much longer standoff distance, resulting in a higher tolerance to variations in layer height, and a much-reduced risk of the introduction of tungsten inclusions. Compared with GMA, it allows much higher levels of process control, which are needed for building complex structures because of the independence of heat input and material feed rate. GMA of titanium material also suffers from arc wandering and consequent

increases in surface roughness (Williams et al., 2015) and machining. Moreover, there is no PTA requirement for a complex metal transfer process and associated current waveforms. Simple DC negative mode can be used (except for aluminium where AC is required). PTA WAAM also avoids introduction of the wire into the core part of the arc where volatile elements can be lost, and which can also form predominantly reactive oxides.

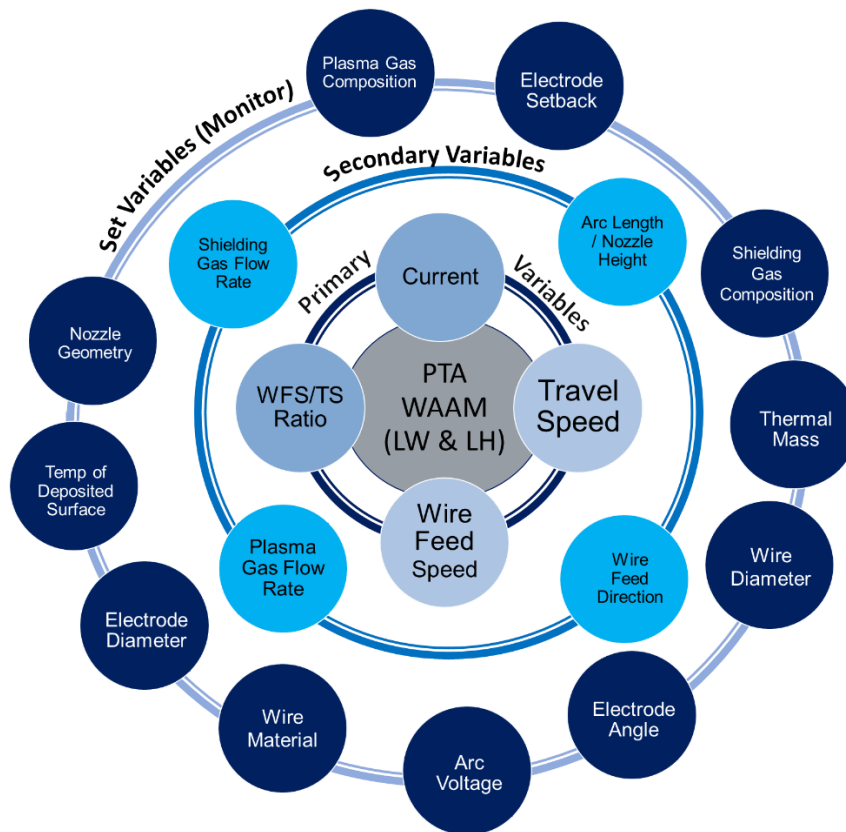


Figure 1 WAAM PTA process variables: primary variables – of chief importance and able to be modified during operation, secondary variables – of reduced importance and customarily set before operation – and set variables – typically fixed and monitored.

The PTA process is not new, but its use in industry for welding has been limited because of the complexity of the equipment, the high number of variables to be controlled, shown in Figure 1, and its limited manual operation capabilities. For mechanised WAAM, though, the independent thermal and material feed rate, and the concentrated directional arc, which allows a long standoff distance and a simple operation for a wide range of materials and repeatable results, make PTA ideal.

Increasing arc pressure can cause a depression in the melt-pool, eventually leading to a deep keyhole and a potential defect if the flowing metal is unable to refill the depression. Melt-pool depression variations also cause problems with wire-feeding, metal transfer mode and suitability of the wire-feeding method because of changes in the distance between the melt-pool and the end of the wire. For the necessary deposited bead geometry, a stable and repeatable arc pressure is therefore required. To prevent keyhole defects, meanwhile, arc pressure should be minimised.

Increases to deposition rate and speed of WAAM part building, while maintaining superior quality, are of utmost importance to the process. However, this will necessitate increases of current, which increase arc pressure and associated concerns with potential keyhole defects.

Some research has been carried out on the generation of a PTA keyhole and, to a limited extent, its relationship to PTA arc pressure. However, this has been directed towards PTA keyhole welding and cutting, which operates using a very different process regime to that involved when using PTA in WAAM. In welding and cutting, high currents and plasma gas flow-rates (PGFR) are used in order to generate deep keyhole. In WAAM, much lower currents and PGFR are used to minimise the likelihood of keyhole defects forming. In this operational regime, no studies have taken place of the relationships between arc pressures, melt-pool depression, keyhole formation and the likelihood of keyhole defects occurring. An urgent need exists to understand the effect of arc pressure on keyhole formation and the likelihood of a defect forming in the WAAM operational regime for the range of thermal conditions that could be encountered.

A further limitation in the use of PTA in the WAAM process involves the failure of the electrode, which requires the process and part building to be stopped while it is changed. A requirement therefore exists to optimise the length of time between these electrode failures. Many studies have been undertaken into electrode details for DC arcs, but these have focused on short-term operation. For WAAM, the process can run continuously for many hours, and it is necessary to study the effects of this for various electrode details and operational conditions.

1.1 Research Gap, Aims and Objectives

Research Gap and Hypothesis

A research gap existed for the study of arc pressure effects on melt-pool depression and subsequent keyhole defect generation for the operation regime of the PTA energy source in the WAAM process. A research gap also exists in the study of electrode behaviour for various electrode materials and design for the operational conditions used in the WAAM process.

Within these research gaps, the following research hypotheses were made:

1. Process conditions could be identified to further reduce arc pressure in PTA WAAM so that higher currents, and therefore larger deposition rates, can be used without the risk of keyhole defects occurring.
2. Arc pressure could be used to characterise the PTA process in terms of keyhole defect formation, and a model could be developed to relate the arc pressure to process conditions and torch design.
3. There is a specific threshold arc pressure at which keyhole defects occur, and this threshold will depend on material type and thermal conditions.
4. Electrodes can be improved to minimise arc pressure, optimise WAAM operations, and maximise equipment availability.

Aim

This study aims to investigate the relationships between arc pressure and keyhole defect formation for a variety of thermal conditions found when using PTA for the energy source in WAAM. An additional aim is to investigate factors affecting electrode lifespan when using PTA as the energy source in WAAM.

Objectives

The study has the following objectives:

1. Establish a reliable method for arc pressure measurement.
2. Establish the factors that control or affect the arc pressure in PTA and develop an empirical model to represent the relationships between them.

3. Ascertain whether peak arc pressure is solely responsible for keyhole generation independent of how it is generated.
4. Determine if there are specific thresholds for keyhole defect generation in terms of arc pressure and how these vary with thermal conditions and material type.
5. Investigate electrode lifespan effects under WAAM operational conditions and see if these can be improved.

1.2 Thesis Structure

Chapter 2 sets out a critical literature review, laying the foundation for this research study and covering the following topics:

- Additive manufacturing
 - PTA WAAM
- PTA
- Non-consumable electrodes
- Keyhole
- Bead humping
- Gas composition
- Arc pressure and measurement.

The thesis structure is outlined in Figure 2, incorporating four main chapters, each with introduction, methodology, results, discussion, and conclusion sections.

Chapter 3 outlines the full and detailed methodology used to measure arc pressure for both GTA and PTA and includes the parameters of the study and details of equipment description and setup, measurement techniques and the approach taken.

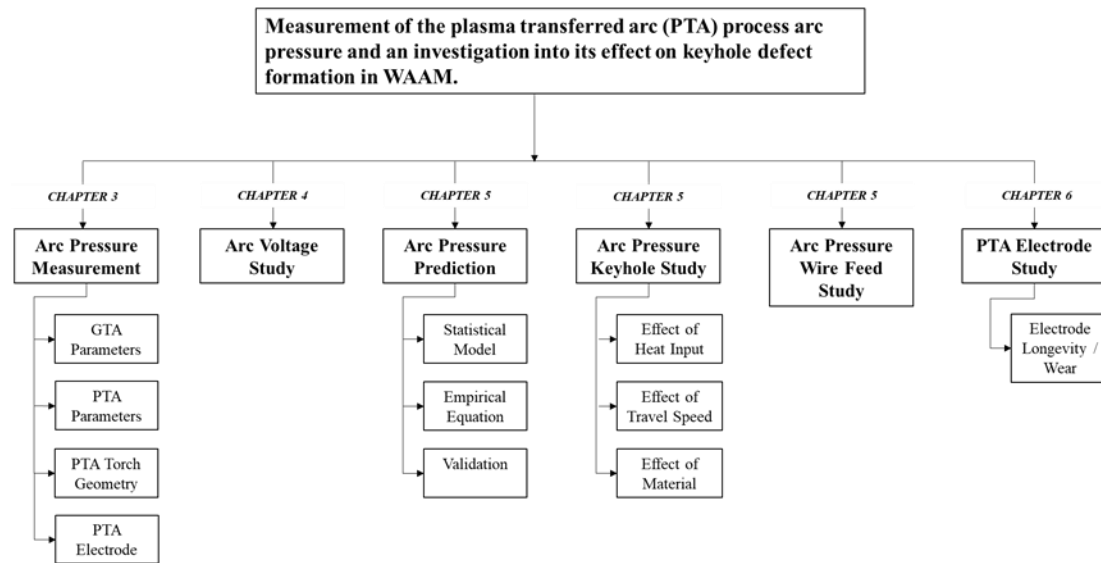


Figure 2 Thesis structure and research strategy

Within Chapter 3, the significant effects of GTA and PTA parameters, PTA torch and electrode geometry on arc pressure are measured, and the results of the two processes compared. Additionally, Chapter 3 contains a PTA electrode study that examines the effect of electrode material and its wear with use on the arc pressure of the process.

Chapter 4 is a short chapter outlining the variations in arc voltage identified coincidentally during the arc pressure study in Chapter 3.

Utilising the measurement results of Chapter 3, a statistical empirical model was produced to allow arc pressure prediction. The model outputs and validation are detailed within Chapter 5.

With the aid of the developed arc pressure forecasting tools, a keyhole defect study was undertaken to establish the influence of arc pressure on the development of keyhole defect formation, and Chapter 5 sets out the outcomes of this investigation, including the implications of travel speed, heat input and wire-feeding on keyhole defect formation.

Chapter 6 is a study of electrodes and examines the mechanisms and behaviours of PTA electrode wear and the effect of PTA electrode material and geometry on their longevity and wear to increase the availability of equipment and investigate alternative electrode materials, wear-rates, wear mechanisms and arc starting.

The conclusions of each chapter are combined within Chapter 7, and an outline of potential future work is detailed in Chapter 8.

Appendix A contains additional extended graphs from the main text, where full information was omitted for clarity.

Appendix B contains additional arc pressure distributions, where full information was omitted from the main text for clarity.

Appendix C outlines the identified measurement difficulties and errors in addition to mitigation strategies adopted.

Chapter 2

Literature Review

2.1 Introduction

This literature review aims to identify, examine, analyse, gain an understanding of and acknowledge relevant existing research relating to AM processes, specifically PTA, WAAM and the influence of arc pressure. The review undertaken helps define a research gap and support the research focus for this study and rationale for the methodology used.

This chapter also outlines the underlying information essential to fully understand the research focus of each of the technical chapters.

2.2 Additive Manufacture

Has traditional subtractive machining had its day? Traditionally, industry purchases long lead raw material of the required grade in as small a size as is available. Unfortunately, raw materials customarily come in set sizes and thicknesses. The layout of the items to be cut from the material is optimised to ensure minimal wastage. The cut material is then machined and processed to the required component final net shape – subtractive machining. The left-over material, if not reused, is wastage, as is all machining swarf. Titanium wastage/scrap is usually non-uniform and contaminated. When recycled, it is therefore typically downgraded to a ferrotitanium classification (Rotmann, Lochbichler and Friedrich, 2011).

Figure 3 illustrates an example, showing plasma cutting circles from a rectangle steel plate – though the layout has been optimised to minimise wastage a significant amount of plate is wasted through the traditional manufacturing route.



Figure 3 Plasma cutting steel plate and material wastage. Image courtesy of AncoferWaldram steel plates B.V.

On average, up to 60% (Agrawal and Khare, 2013) of metal is wastage in the subtractive machining process. However, some examples, such as that set out below, have percentages as high as 90% (Royal Academy of Engineering, 2013).

Rolls-Royce¹ outlines an example of their subtractive machining wastage during the manufacture of a Trent 1000 turbofan aircraft engine within the BBC documentary entitled, ‘How to build series 1:2 a Jumbo Jet Engine – Rolls-Royce Trent 1000 Jet Engines’ (2010). The most significant module of the engine is the titanium protective fan blade casing, which is manufactured from a five-metric tonne forging with a 24 month lead-time over 90 hours, via subtractive machining and processing. The final component is 500kg – only 10% of the original titanium forging. The 4,500kg of titanium removed is recycled to a lower grade of material.

In addition to material wastage, the process also consumes electrical power/energy, personnel hours, consumables such as cutting fluids – which, as hazardous waste, must be responsibly disposed of – and worn cutting tooling (Yilmaz and Ugla, 2016). Transportation of the oversized materials is also wasteful and results in non-environmentally friendly CO₂ emissions. Traditional processing of materials is therefore not sustainable.

¹ Mark Reid, manufacturing manager of the Rolls-Royce Ansty Warwickshire facility.

If the number of production steps can be reduced along with the number of personnel hours, consumables and material wastage, the productivity can be increased, and processing cost can be reduced. Moving away from traditional long lead forgings will also inevitably accelerate supply chains and vastly improve project delivery dates and lead to speedy resolution of critical component replacements: e.g. valve replacement on a waiting oil and gas platform, pending start-up.

The aircraft industry uses the term ‘Buy-to-fly’ (BTF) ratio, which is the ratio of the weight of raw material used to manufacture a component and the end weight of the finished component, to indicate material waste. For forgings, the BTF depends on the closeness of the forging geometry to the final component shape (Martina, 2015). Parts with BTF ratios of 10 or 20 are not uncommon (Williams et al., 2015), and can even be as high as 30 (Martina et al., 2015). The above Rolls-Royce example has a BTF ratio of 10, requiring high raw material and machining costs.

‘Because of the buy-to-fly business case and the inefficiencies of tooling, which wastes valuable materials, we have a business case for AM.’

(Royal Academy of Engineering, 2013)

Figure 4 illustrates the wastage and consequently the high BTF ratio for a finished part constructed by means of traditional subtractive manufacture/machining.

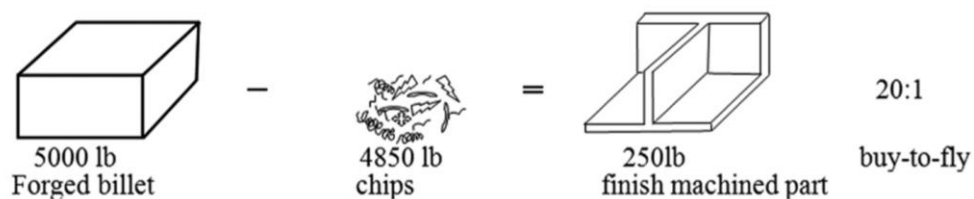


Figure 4 Example of subtractive manufacture BTF ratio. (Yilmaz and Ugla, 2016)

In recent years, 3D printing has come into the public eye mostly through the media, as a result of low-end price and capability devices. The premise of taking a digital file containing geometrical and process requirements and producing a three-dimensional solid component is therefore not unprecedented. The relatively new AM concept has led to

standards being created – like the process, they are in their infancy. However, in the last two years, great strides have been made, with several AM standards produced, which will, in time, be revised and refined.

BS EN ISO/ASTM 52900:2017 outlines AM as follows: ‘a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies’ (BSI, 2017).

Powder-bed fusion (PBF) is a form of AM that is becoming well known and prominent (buzzword), and other types of AM do exist, including WAAM, which is the focus of this study. WAAM, unlike PBF, is a welding process that can build sizeable near net shape engineered metallic parts of medium complexity in a welded layer-by-layer approach.

AM is a potential solution for costly materials where minimising material wastage is critical or where the material is challenging to process, such as titanium (Martina et al., 2012).

The aerospace industry, in the form of, for example, Airbus sponsoring this project, and the other key stakeholders Boeing, Lockheed Martin and NASA, are optimistic for the AM process and accordingly investing heavily in development of the technologies (Gisario et al., 2019). This is as a possible means to minimise raw material lead-times and wastage, reduce component BTF ratios and simplify manufacturing and the cost of parts from their current traditional subtractive manufacturing.

Figure 5 illustrates the material savings for a finished part constructed by AM when compared with the same finished part as in Figure 4, thus showing a lower BTF ratio.

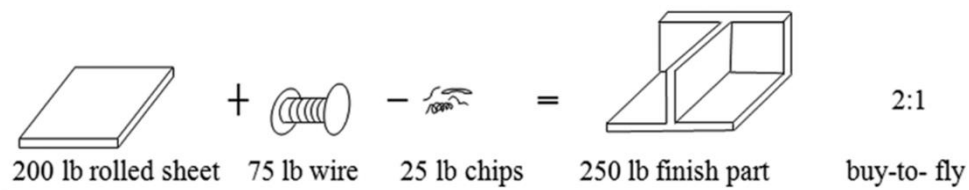


Figure 5 Example of AM manufacture BTF ratio, for the same end part as outlined in Figure 4. (Yilmaz and Uglu, 2016)

The high price of titanium and its machining for aerospace is a principal driver behind the development of titanium WAAM technologies (Martina et al., 2015). As aircraft design moves towards carbon fibre – e.g. wings – to reduce weight and fuel consumption, the demand for titanium increases. Carbon fibre induces galvanic corrosion in connected aircraft aluminium components, meaning that an intermediate non-reactive/compatible high-strength material with a high strength to weight ratio is required – titanium. However, because of titanium’s high cost, long lead-times and difficulties associated with processing it from wrought form, aircraft manufacturers are now evaluating AM as a way forward, and as a means of substantially reducing titanium part cost (Szost et al., 2016; Davis et al., 2019).

AM has been described as a ‘disruptive technology’ with the potential to disrupt the existing manufacturing market (including source material manufacture, logistics and equipment) and current supply chains (Zhang et al., 2014). International market-leading manufacturing companies could become unsettled through the superseding of traditional, well-established manufacturing technologies. Despite this, the advantages of AM could make it an ‘enabling technology’, resulting in new products, supply chains and, consequently, new businesses (Royal Academy of Engineering, 2013).

An ageing workforce, skilled workers leaving manufacturing and a reduced number taking up skilled jobs in, for example, manufacturing, manual machining and welding is resulting in a decreasing skills pool available for manufacture. AM could play a major part in resolving this issue by replacing/combining tasks previously undertaken by several discrete traditional skilled trades into one process, requiring a minimal number of skilled operators. AM also has potential to redistribute global manufacturing locations currently based around a low-paid, low-skilled workforce in, for example, China and India. AM,

combined with current manufacturing, has been cited as the next industrial revolution (Zhang et al., 2016; Royal Academy of Engineering , 2013).

A novel use of AM involves the digital storage of spare parts – an alternative to the expensive purchase and storage of critical spares in dedicated storage facilities. A catalogue of digital files could be stored and parts manufactured through a just-in-time AM system close to the location of requirement, minimising storage costs and transportation durations, such as the International Space Station (ISS) (Gisario et al., 2019).

To fully develop emerging AM technology and to instigate a move from current manufacturing processes in the future, a drive to further inform the public and educate manufacturers is required. This will lead to acceptance of the technology and enable leading manufacturing companies to embrace AM, re-tasking it for their specific needs.

In 2013 the UK government undertook an unprecedented step in launching a pilot scheme to 21 schools to promote AM technology to the younger generation, specifically involving 3D printers as part of the design and technology syllabus. This has since become part of the UK National Curriculum (UK Government Department for Education, 2013; Royal Academy of Engineering, 2013). AM is the industry terminology for 3D printing.

2.3 Background to AM

One of the first documented references to a process akin to AM is within Mr R. Bakers' 1925 approved patent (Baker, 1920). The process outlined is for the making of decorative articles using an arc welding process to form a rustic final shape with the weld deposit. Rapid prototyping of plastic components followed in the late 1980s and early 1990s, producing accurate components or scale models for quicker product development.

Cranfield University coined the now widely used term WAAM as an abbreviation of wire + arc additive manufacture in the 1990s (Williams et al., 2015). The university's Welding Engineering and Laser Processing Research Centre, with its wide range of state-of-the-art AM equipment, including many modern arc welding systems, robots and CNC gantry systems, has an international reputation for WAAM research. Using WAAM, they have

successfully built several large parts for industrial partners. Examples are shown in Figure 6.

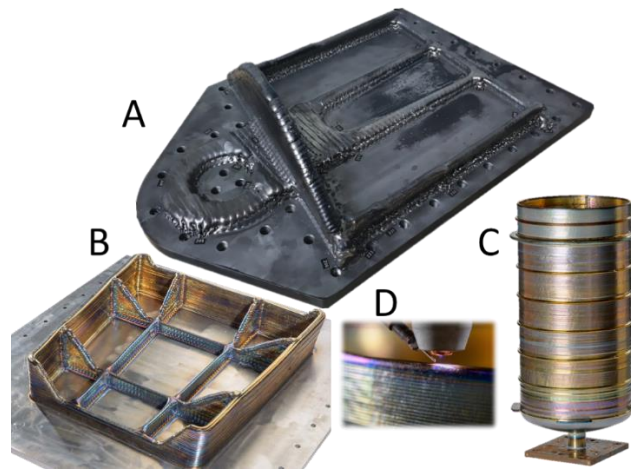


Figure 6 Example WAAM parts. A] A320 pylon bracket, B] Landing gear rib, C] Pressure vessel for space exploration, D] PTA WAAM deposition. Images courtesy of Cranfield University.

Figure 7 outlines the AM timeline and indicates the expanding use of the technology against time, as well as future predictions for AM.

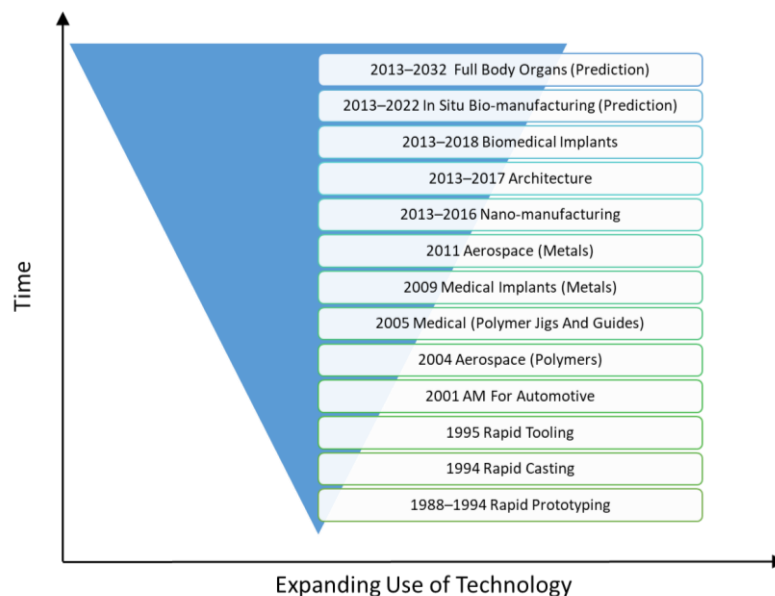


Figure 7 Timeline and future predictions for AM. Data courtesy of Royal Academy of Engineering, (2013) and Zhang et al. (2014).

In the 2000s, the Bloodhound SSC race car utilised AM technologies during its manufacture of the titanium nose cone, because of the cost savings of AM, and parts of

the cockpit, because of possible customisation through AM (Royal Academy of Engineering, 2013).

The primary industries benefiting from AM currently are aerospace, automotive and electronics (Zhang et al., 2014), with GE aviation now one of the largest AM manufactures (Royal Academy of Engineering, 2013) .

AM is relatively new to industry, with limited infiltration but a ‘promising future’. Requests for modelling and prototyping through AM are fast becoming requests for full manufacturing using the AM process. The cost of materials and equipment, as well as the production process, represents an important obstacle for the future success of AM (Zhang et al., 2014; Royal Academy of Engineering , 2013). However, the AM compound annual growth rate since the early 1990s stands at 26%, with a continued increase predicted (Zhang et al., 2014).

2.4 Metal AM Processes

AM technologies can be categorised by their heat source and material feeding approach, primarily laser, electron beam and electric arc. Material feed methods include powder-bed, blown powder and wire approaches. Examples of some of the main AM processes are outlined in Table 1.

Table 1 Classification of AM processes. (Yilmaz and Ugla, 2016)

Heat Source	Material Feed Method	Process
Laser	Powder-bed	Selective laser melting (SLM)
	Blown powder	Laser metal deposition (LMD)
Electron Beam	Powder-bed	Electron beam selective melting (EBM)
	Wire-feed	Shaped metal deposition–electron beam free form fabrication (SMD-EBF)
Arc	Wire-feed	WAAM

An efficient process requires a reduced amount of heat input to achieve the same fusion and result in a stronger joint. For intense heat sources such as laser, electron beam and keyhole PTA the required dwell at a point is correspondingly short, with the heat affected zone (HAZ) and distortion small and the travel speed rapid, meaning that automation is

required (Mendez and Eagar, 2001). The capital cost of automated laser, electron beam and keyhole PTA systems is high – proportional to the heat intensity of the process (Mendez and Eagar, 2001).

For the aviation industry for welding applications, components are produced in relatively low volumes at high unit costs and are required to be exceptionally reliable in extreme service (fatigue and temperature) and repeatable with novel designs in materials such as titanium (Kazanas et al., 2012). This has resulted in increased use of laser and electron beam systems for crucial parts – for example, titanium structural components of the Eurofighter produced by electron beam systems (Mendez and Eagar, 2001).

Arc powder processes experience issues such as powder contamination through the recycling of unused powder and low deposition rates compared with wire, and component size is restricted to the powder-bed dimensions (Martina et al., 2012).

Blown powder systems, also known as laser cladding and Laser metal deposition (LMD), operate by a controlled stream of metal powder within an inert carrier gas, directed via a coaxial or off-axis processing head into the laser beam melt-pool where the particles are melted and metallurgical bond with the substrate or component. Higher deposition rates and part sizes are possible with this process. Blown powder is unlike powder-bed, where the powder is supplied layer by layer and subsequently melted. (Lorenz et al., 2015)

Traditionally, blown powder has been used as laser cladding - surface repairs of worn components or surface coatings. Fusion of the powder deposited layer to the substrate with minimal substrate melting resulting in minimal distortion and dilution, but high bond strength - high-quality overlay. (Yellup, 1995)

Powder-based systems have been shown, because of their high equipment cost and low deposition rate, to be more costly than traditional machining of raw materials/forgings (Martina, 2015).

Wire-based systems surmount these issues, with all the wire entering the weld pool, reducing contamination and providing a higher deposition rate. The component size is limited to the setup – manipulator/rail size, type of motion system and means of local shielding (Martina et al., 2012) – resulting in the capability of large components.

WAAM fabrication of titanium Ti-6Al-4V, utilising PTA as the heat source, is state of the art, owing to the possibility of independently setting the wire-feed rate and arc power. However, increases in arc power to enable further increases in deposition and, consequently, improvements in WAAM performance, are hindered by the onset of keyhole defects (Ríos, 2017).

The three processes referred to in this review are laser, electron beam and arc-based.

2.4.1 Laser and Electron Beam AM

Both the laser and electron beam approaches are used for precision welding applications and can be utilised as heat sources for AM. Using electromagnetic lenses and optical lenses, the electron and laser beams are focused, respectively, to form a narrow beam diameter, tens of micrometres in size, with a high-power density. This enables high precision welding and deep penetration, but with minimal distortion. The deep penetrations are termed keyhole penetrations and are sustained by means of metal vaporisation (Lancaster, 1984). Compared with traditional subtractive manufacturing, AM utilising laser and electron beam enables design freedom, net part production, high resolution, minimal wastage and alleviation of dependence on costly and long lead forgings (Addison et al., 2015). However, there are also some disadvantages (Park and Hirata, 2017).

Laser AM

Lasers are used as an intense heat source for AM, typically as a powder-based system, with high accuracy. They are capable of creating accurate net shape parts with high complexity, containing lattice structures and narrow melt-pools down to 0.3 mm for SLM (Gisario et al., 2019), enabling small features/details, with little or no post-machining required (Bai et al., 2018). To avoid oxidation, a closed chamber filled with inert gas is utilised (Gisario et al., 2019). The deposited layer heights for powder-bed (SLM) are between 10 and 100 μm , but are typically around 30 μm to allow higher part resolution (Gisario et al., 2019). Laser equipment has a high capital cost and is also associated with laser reflectivity issues when processing metals, very low thermal efficiency, and low energy efficiencies – typically from 2% to 5% (Ding et al., 2015a), as well as low

conversion of electrical to light energy (Park and Hirata, 2017). The part surface finish is also poor, with inconsistent mechanical properties, while the parts produced are not fully dense and suffer from defects, and the deposition rate for powder-bed (SLM) is low, typically 9–120 g/h (Martina et al., 2012). The working envelope of the equipment also constrains the components – typically, components of 300 mm x 350 mm x 30 mm or larger are problematic to produce (Martina et al., 2012). An advantage of SLM is the ability to create multiple components simultaneously. However, the number is constrained by the chamber volume. This type of AM is therefore most applicable to applications requiring small but accurate complex parts (Williams et al., 2015).

The blown powder (LMD) process is capable of high deposition rates and large parts (Szost B, 2016). However, the part size is still restricted by the chamber or build table size. Rodríguez et al., (2013) sets out the build rate as between that of powder bed and WAAM – approximately 117.5 to 1000 g/h.

However, the ratio of powder supplied to that incorporated in the part for the blown powder (LMD) process is less than 100% and can be a lot lower; the surplus powder – overspray, is an environmental and financial issue of the process. Contamination concerns hinder the capture and reuse of the overspray powder, which reduces, for large scale parts, the cost-effectiveness of the process. Reactive powders such as aluminium and titanium are also potential fire hazards. (Lorenz et al., 2015)

Electron Beam AM

Electron beam can be used as a surface heat source similar to SLM. However, the ability to perform deep penetrations – keyhole penetrations – is what makes the process beneficial. In this mode, awkward materials and alloys can be welded, distortion avoided and complex joint arrangements tackled (Lancaster, 1984). Electron beam can be utilised for AM typically as a powder-based system. The parts produced, typically for aerospace, are fully dense, up to 98% (Gisario et al., 2019) and with good properties and high chemical purity Bai et al., 2018). The melt-pool is slightly larger than SLM enabling part features of around 1 mm (Gisario et al., 2019). However, the equipment has a high capital cost, low energy efficiencies, typically 15–20% (Ding et al., 2015a), and the deposition rate is low, typically 120–600 g/h (Ding et al., 2015a). Additionally, it requires a vacuum

chamber, which necessitates a time-consuming vacuum pump-out and atmospheric re-pressurisation and part removal for every cycle, while the chamber restricts the manufactured part size (Park and Hirata, 2017; Lancaster, 1984).

2.4.2 Arc-based Directed-energy Deposition (DED)

An arc-based AM system consists of a motion system, industrial six-axis robotic arm or CNC system, a torch and power supply as a heat source and a raw material supply of powder or wire (Williams et al., 2015). Arc-based AM is of interest to industry because of the high deposition rates, typically 3000–7800 g/h (Ding et al., 2015a), ability to build sizeable components, and the relatively low equipment cost (Gu et al., 2015). This approach is ideally targeted at specific applications requiring low volume production runs (Ermakova, Mehmanparast and Ganguly, 2019).

Fronius cold metal transfer (CMT) equipment has several advantages for AM, including a high deposition rate and efficiency, resulting in rapid build rates and lower heat input. It is therefore an ideal process for aluminium and steel (Williams et al., 2015), with a large proportion of current research based around it. However, for titanium, because of issues of surface roughness as a consequence of arc wandering with CMT, alternative processes are best utilised, including GTA and PTA (Williams et al., 2015).

A further benefit of PTA with an automated wire-feed is its ability to allow the independent control of current, voltage, PGFR and wire-feed speed, enabling additional control over the AM process.

PTA is a precision process that is simpler and more efficient than both laser and electron beam (Park and Hirata, 2017). It is also low-cost in comparison and can produce a high energy density that allows a keyhole mode of operation (Wu et al., 2002). The power density of PTA keyhole is significantly lower than the electron beam, with the keyhole sustained by arc pressure and not by metal vaporisation, as with laser and electron beam (Lancaster, 1984). Nevertheless, the keyhole mode is detrimental to AM.

WAAM

The WAAM process utilises an arc-based heat source and direct metallic wire-feed. It can be used with several materials, including steel, aluminium, nickel-based and titanium

alloys (Ding, Martina and Williams, 2015). WAAM parts are built on a substrate from layer upon layer of deposited beads until the near net shape is reached. The process has several distinct advantages. It utilises existing low-cost welding and motion equipment (industrial robot arms or CNC), requires minimal operator involvement, and has short setup times, low material costs and high deposition rates – up to ten times higher than powder-based systems, reducing the deposition cost (Martina et al., 2012), and reducing fabrication durations by 40–60%, as well as decreasing machining periods by up to 15–20% (Wu et al., 2018). The process also has high energy efficiency – approximately 70% (Davis et al., 2019) – and reduced material wastage compared with traditional manufacturing from solid wrought material – for example, 78% for an aircraft landing gear rib (Wu et al., 2018) – as well as fully dense parts greater than 99.99% for defect-free titanium (Biswal et al., 2019), low material costs and relatively low equipment costs, without the need for expensive tooling, leading to cost savings of up to 69% over traditional manufacturing methods, reducing traditionally manufactured component lead-times. This therefore creates leaner supply chains (Gisario et al., 2019) and theoretically leads to an unlimited component build envelope (Rodríguez et al., 2013; Martina, 2015). Titanium and nickel alloy components are uneconomical to produce via traditional manufacturing (Ding et al., 2015b). Large WAAM parts have been produced several metres in geometry (Davis et al., 2019). This enables design freedom, potential weight savings of flying components, control of mechanical properties and customisation of the finished part that is not constrained in volume by equipment in the way of laser and electron beam AM systems. Multiple robots can be combined to increase the working envelope of the WAAM system (Dahat et al., 2020; Ding, Martina and Williams, 2015; Williams et al., 2015; Martina et al., 2016; Marinelli et al., 2019; Gisario et al., 2019).

Utilising wire in place of powder mitigates powder-handling difficulties and operator exposure to a hazardous powder environment. It is also cleaner and more environmentally friendly. For titanium, WAAM, compared to powder-based processes, is gas pore free (Biswal et al., 2019). The process efficiency is also higher than powder, as a high percentage, up to 100%, of the wire is incorporated into the deposit. The price of metallic

powders is also greater than of shelf wire, making the wire-feed process cost-effective (Ding et al., 2015a; Davis et al., 2019).

Ancillary processes, such as interpass cold rolling, mechanical peening, NDT and machining, have also been successfully included into automated WAAM – an example of this is the European LASIMM project (Ding, Martina and Williams, 2015).

Drawbacks of this include distortion and residual stresses, which, through building strategies and axillary processing – e.g. rolling/mechanical peening – can be minimised. The produced component is of near net shape with a surface waviness that requires post-deposit machining to the final required geometry (Rodríguez et al., 2013; Dahat et al., 2020).

Several processes can be used in WAAM. Figure 8 identifies these.

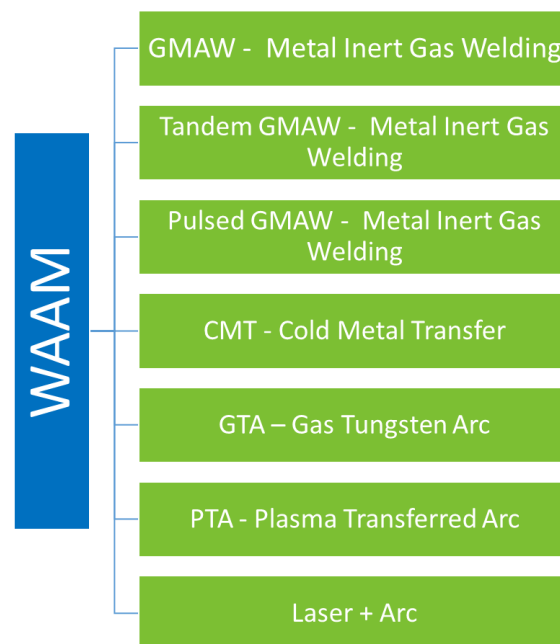


Figure 8 Processes that fit within the WAAM classification.

Each has its advantages and specialisations, using either powder or wire as their build material, and some processes are more easily adapted to automation.

WAAM part geometries are controlled by the deposited layer height and effective wall width, which in turn are determined by the process parameters and their effect on the melt-pool (Ríos et al., 2018).

PTA WAAM for titanium (Ti-6Al-4V) has a maximum deposition rate of 1.8 kg/h at an average deposition efficiency of 93%. Experiments have shown a 12% increase in strength over the substrate, making it an ideal WAAM process for sizeable aerospace components (Martina et al., 2012), and the focus of this project. High deposition rates are possible with WAAM. However, if too high a rate is used, surface waviness, residual stresses, distortion, and component repeatability can become problematic. PTA WAAM exhibits a high energy density and increased deposition rate, with a reduced surface roughness (Bai et al., 2018). Final machining requirements may increase, along with the BTF ratio, increasing component cost. It is therefore recommended that deposition rates are kept at a maximum of 1 kg/h as there is no significant economic benefit of exceeding this rate, irrespective of the BTF ratio (Martina, 2015).

If the WAAM process was applied to the previous Rolls-Royce example, the feedstock material – titanium wire – is available off the shelf. At a deposition rate of 1 kg/h, the as-deposited material would therefore be available within around 500 hours – approximately 56 days – a saving of 674 days. The parts are near net shape – with an additional 0.5–1.5 mm on each surface to account for surface waviness/roughness (Addison et al., 2015), the machining time would be significantly less, as would consumption of electrical power/energy, material and consumable waste. Transportation would also be restricted to only the feed-wire spools, drastically reducing shipping CO₂. Given that the final material properties from a part produced by WAAM are equal or better than a forged part, the case for WAAM as a more sustainable manufacturing method is evident. Industry support is also apparent, with the spinoff company WAAM3D start-up supplying the equipment and consumable wire in 2020.

Though a lot of WAAM research has been undertaken, with notable success in the process development, auxiliary processes, metallurgy and moderately complex parts generated, several process issues remain to be fully understood and overcome, representing the focus

of this study. Once addressed, this will allow the straightforward repeatability of WAAM generated parts – an industry requirement.

A relatively small body of literature considers the issues associated with arc pressure and WAAM. Han et al. (2019) for example asserts that an increased current, required to rise GTA WAAM deposition, results in arc pressure-induced defects, and, without investigation into or measurement of arc pressure, developed a twin electrode GTA torch to mitigate the defects. Dahat et al. (2020) note that arc pressure of gas metal arc AM should be minimised to prevent ‘pool lateral sag’, but also does not examine arc pressure in any further detail. Most studies are unsatisfactory as they have not investigated arc pressure-induced defects or included variables related to arc pressure in WAAM.

2.5 PTA

PTA is a highly stable process and a focused heat source, which makes deep penetration – keyhole – possible with a relatively low heat input and minimal distortion. The process, with its high energy density, enthalpy and efficiency, is comparatively inexpensive compared with laser systems, and readily automated (Kobayashi, 1990; Camacho, 1988). PTA is advantageous in situations where high energy input is required – i.e. thick plate or deep penetration, or where high energy is necessary to enable quicker system motion (Langford, 2018). To fully understand the PTA process, it is necessary to understand its history, development, design and operation, as well as its namesake – plasma.

The Oxford dictionary defines plasma as follows:

‘An ionized gas consisting of positive ions and free electrons in proportions resulting in more or less no overall electric charge, typically at low pressures or at very high temperatures – e.g. the current passed through a column of plasma.’

(Oxford Dictionary)

In terms of PTA, a plasma, or gaseous mixture of positive ions and electrons, is generated by heating the plasma/orifice gas, normally argon, increasing its activity through thermal agitation, to the point of ionisation and increased electrical conductivity. The plasma dynamics are sensitive to voltage and electromagnetic fields, which influence the ions

and, to a greater extent, the lighter electrons. Plasma is quasi-neutral because of the free electric charge and positive and negative charge balance (Kobayashi, 1990; Camacho, 1988).

The plasma torch or PTA is a misnomer as other welding torches also generate a plasma arc through which they pass current to the work-piece. However, the use of this name has, since the 1950s, become commonly associated with the process (Gage, 1960).

The processes inventor Robert M. Gage (1960) refers to the PTA process as follows:

‘...the plasma arc can be considered either as a superior and economical flame source of heat or as a stable high-velocity arc. It will make its mark as such, where either or both of these characteristics are needed.’

(Gage, 1960)

The National Aeronautics and Space Administration (NASA) arguably concurred with Gage in the 1960s:

‘...plasma technology will make it on its own technical and economic merits.’

(Camacho, 1988)

2.5.1 History of PTA

The PTA process is often referred to as the ‘latest technology’, and a ‘new welding and cutting process’. However, this is not the case, and these perceptions are likely a result of the relatively recent acceptance of the process and use by industry.

Robert M. Gage is accredited with its invention in the 1950s with a patent entitled ‘Arc torch and process’ issued in 1957 (Gage, 1957). However, the origins of the theory behind the invention are much earlier.

Devices utilising plasma are referred to as far back as the beginning of the 1900s and include:

- a. Schonher’s (1909) device, which used gas vortexes, caused by tangentially fed gas into an arc discharge tube to stabilise the plasma arc (Dimitrova and Tabakova, 2012; O’Brien, 1991).

- b. Ezra A. Mathers' (1911) patent entitled '*Electric-arc furnace heater*', which utilised a restricted plasma arc as a furnace heat source (Mathers, 1911).
- c. Gerdien and Lotz's (1922) device, which utilised a water vortex caused by tangentially injecting water into the centre of the arc discharge tube to stabilise and concentrate the plasma arc and increase current density (Dimitrova and Tabakova, 2012; O'Brien, 1991).
- d. Introduction of the term '*thermal plasma*' (1927) by American physicist Irving Langmuir following his work with gas ionisation.

Despite these developments, only limited, short, laboratory experiments were undertaken because of the rapid consumption of the carbon electrodes and water vapour within the plasma arc (O'Brien, 1991).

The lack of refractory metals, a means of increasing the longevity of the restriction, and insufficient interest in a high-temperature process, precluded further investigation at that time but set the groundwork for future study.

In the 1950s, with the development of new equipment for space exploration with heat-resistant material requirements, along with the development of refractory metals, there was a renewed interest in the high-temperature process (PWP Engineering & Welding Supplies).

During the early 1950s, Robert M. Gage, while employed by Linde research laboratories in Tonawanda, USA, now known as Union Carbide, worked on a project to melt titanium material with an electrical arc. During this project, the concept of improved control and implementation of extreme heat and arc velocity through a small diameter nozzle arose – a restricted arc with a higher arc temperature than GTA – PTA. Further validation work resulted in the patent, with commercially available PTA welding equipment for industrial use becoming available in 1963 (Almqvist, 2003; O'Brien, 1991).

The NASA space programme of the 1960s steered research into the plasma torch away from industrial use towards use in space capsule heat shield simulation research. During this time NASA made several developments and advancements with the technology. By

the conclusion of the space race, plasma, technology-driven research again returned to industrial applications (Camacho, 1988).

Two further patents have since been issued for transferred arc torch designs, incorporating hollow electrodes that enable a second inert gas to pass through:

- e. Gordon et al. (1989) obtained a patent entitled '*Hollow electrode and arc initiation method*' for a GTA torch incorporating a hollow channel through the electrode, through which an inert gas can transition. The novel tip design includes a moveable plunger within the electrode that enables arc initiation between the electrode and plunger inside the electrode, without producing electromagnetic interference and without the concern of electrode contamination of the work-piece. The electrode and plunger control gas flow, arc starting and emitting a controlled and stable arc and enhancing welding performance and the cooling rate of the melt-pool, as well as the direction of thermal gradients of the melt-pool and orientation of the grains produced – an increased number of columnar grains (Gordon, Dyer and Flanigan, 1989).
- f. McGee et al. (1995) obtained a patent entitled '*Ternary gas plasma welding torch*' for a PTA torch device, which includes a third inert gas introduced to the arc through a hollow bore electrode. The secondary inert plasma gas transitioning through the electrode is thought to supply a 'stiffer arc' that is less susceptible to becoming distorted/skewed, reducing issues associated with asymmetrical arcs. The stiffer and more controllable arc should also minimise defects and improve productivity through increased travel speeds (McGee, Rybicki and Waldron, 1995).

Only minimal further research and implementation of hollow electrodes has taken place since patent issue, except for NASA, which participated in the 1995 patent (Nishikawa et al., 2001).

Plasma arc cutting developed alongside, with both manual and automated cutting initially developed for aluminium plate in the mid-1950s. However, Linde quickly extended this in 1958 for the cutting of stainless steel. From that time plasma cutting equipment has been further developed to cut a range of materials, including carbon and high alloy steels,

copper and copper alloys, utilising plasma gases such as nitrogen, oxygen and compressed air (Almqvist, 2003).

2.5.2 PTA Torch

There are distinct advantages over the constricted PTA compared with the GTA's open arc, and there are numerous applications for PTA in industry settings. However, its use is obstructed because of the incorrect impression that PTA is overly complicated, as a result of its high number of process parameters including PGFR, current, arc length, travel speed and nozzle diameter. Inability to directly transfer parameters between different manufacturers of PTA systems because of differences in torch design, nozzle and electrode geometries is also an impediment to PTA use. Parameters and settings cannot be shared and must be derived through trials for each system, and involve adjusting the PTA process and its parameters to a specific production task and material (Schnick, 2016; Bashenko and Sosnin, 1988; Short et al., 2011).

GTA is the precursor to PTA – both are arc processes utilising a non-consumable tungsten electrode and inert shielding gas. For the PTA, with a separate plasma gas, the heat of the restricted plasma arc between the work-piece and tungsten electrode enables fusion – the resistive heating of the current passing through the plasma maintains the temperature. Chen et al.'s (2015) results indicate that PTA has a 30% increase in arc heat compared with GTA – arc constriction increases arc heat. The heat is carried by the arc plasma and not the electron flow – the arc plasma differentiates the free arc of the GTA from the constrained arc of the PTA. The arc plasma temperature reduces with travel speed (Chen et al., 2015).

For PTA the plasma gas passes into a plenum chamber between the nozzle and electrode, where it is superheated (ohmic), becoming highly conductive ionised gas, containing an increased number of charged particles (Kobayashi, 1990). The electricity is converted to heat energy that increases the internal energy/enthalpy of the plasma gas – conditioning of the plasma gas is a primary role of the PTA torch (Camacho, 1988). When the ionised gas contacts the electrode tip, it forms the plasma arc (Lancaster, 1984), a conductor of ionised plasma gas through which current can flow. A current-induced magnetic field

circumferentially around the arc radially restricts the arc through an electromagnetic pinch force – Lorentz force, close to the electrode tip, which is balanced by the radial arc pressure gradient in the reverse direction (Adonyi, Richardson and Baeslack, 1992; Lin and Eagar, 1986), into a cylindrical plasma arc column, with a diameter smaller than the nozzle restriction (Venkatramani, 2002). The flow-rate of the plasma gas is a key parameter that affects the stability of the arc column and determines the arc voltage characteristic of the PTA torch (Camacho, 1988). The plasma column then passes through the water-cooled nozzle, designed to stabilise the plasma and direct the arc plasma through an orifice at the tip, further constricting the arc, which determines the torch power density. On exiting the nozzle, the column diameter increases slightly and reduces in velocity and temperature (Venkatramani, 2002). The result is a stiff, almost straight, plasma arc column, more tolerant to changes in arc length, which conducts the arc current from the electrode to the work-piece, converting electrical energy to heat (Wang et al., 2017). Figure 9 illustrates the main components of the PTA torch.

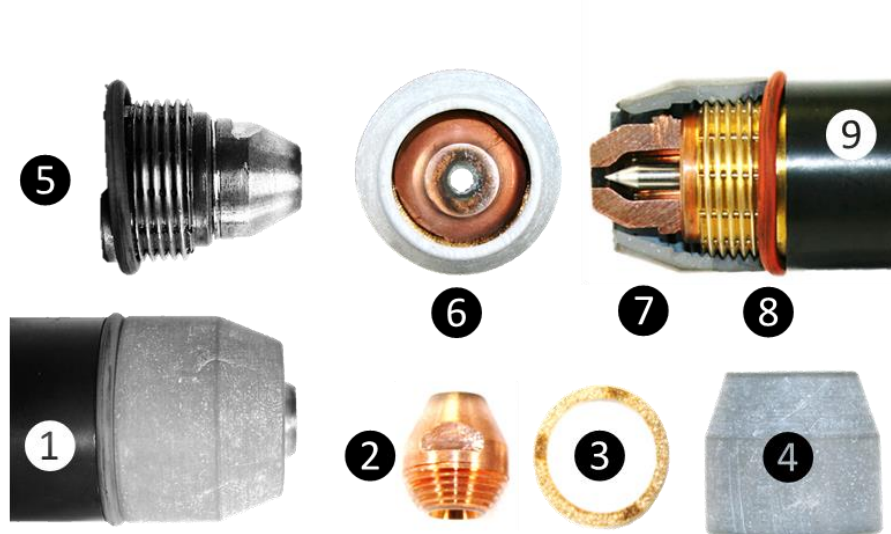


Figure 9 PWP Viper PTA torch, assembly and main components: 1] Fully assembled torch side on, 2] Water-cooled copper restriction nozzle, 3] Gas diffuser ring (not shown on cutaway for clarity), 4] Shielding gas nozzle/cup, 5] Partially assembled torch, 6] Fully assembled torch end on, 7] Fully assembled torch cross-section, 8] Shielding gas sealing ‘O’ ring, 9] Torch body.

As can be seen in Figure 9, and in more detail in Figure 10, the main body of the PTA torch has a ceramic shielding gas nozzle attached via a threaded connection and ‘O’ ring seal. Shielding gas, normally argon, passes from within a torch body channel and out

within the thread grooves and through a diffuser ring, which straightens and evenly distributes the gas within the nozzle. The shielding gas then flows within the shielding gas nozzle until it reaches and exits through the shielding gas nozzle orifice, between the copper nozzle and the shielding nozzle tip. The shielding gas then flows towards the work-piece, protecting the arc and melt-pool from oxygen and atmosphere contamination.

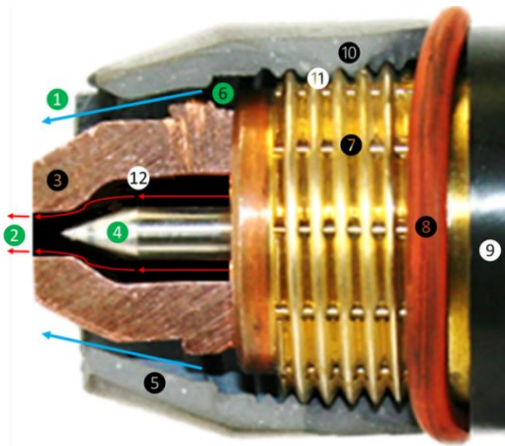


Figure 10 Enlargement of PTA torch cross-section with the following components:
 1] Shielding gas flow, 2] Plasma gas flow, 3] Water-cooled copper restriction nozzle, 4] Thoriated tungsten electrode, 5] Shielding gas nozzle/cup, 6] Gas diffuser ring location (removed for clarity), 7] Shielding gas grooves, 8] Shielding gas sealing 'O' ring, 9] Torch body, 10] Internal mail threads of shielding gas nozzle/cup, 11] Torch body external female threads, 12] Nozzle plenum chamber.

A tungsten electrode, typically 2% thoriated, is centrally mounted into the end of the torch body, within the copper nozzle. The electrode threaded fitting also supplies its electrical connection to the supply through the torch body.

If the extreme temperatures involved in PTA are not addressed in the torch design, this will result in equipment failure – the high PTA heat flux being a principal constraint of the torch design. An internally circulating water coolant supply is therefore incorporated within the torch body to reduce the temperature of the tungsten electrode and restriction nozzle (Wu et al., 2002).

The water-cooled copper restriction nozzle is coupled to the torch body by a threaded connection. The nozzle is cooled via the copper's high thermal conductivity when in contact (via the threaded fitting) with the coolant supply within the torch body. Counterbalancing the intense arc radiation and high heat flux inflicted on the nozzle bore,

the arc column does not, in reality, come into contact with the nozzle through which it passes – the nozzle is cold in relation to the adjacent arc (Gage, 1960). The nozzle cooling water return temperature for the PWP Viper MC torch used in this study was typically found to be 40° C.

From experience gained with plasma cutting, PTA torch design has adopted gas swirl to maximise torch life (Wu et al., 2002). The PTA torch nozzle internal shape and an inner swirl ring induce a slight twist/swirling of the plasma gas. This compels the colder denser gas, through centrifugal force, to the outside of the stream. With its steep radial thermal gradient, it acts as an annular, axially symmetrical, protective boundary layer of electrical and thermal insulation between the arc and the nozzle wall, increasing the longevity of the copper nozzle and centralising/stabilising the arc (Gage, 1960). At low PGFRs, typically 0.6–0.8 l/min, a small amount of the boundary layer heat is dissipated into the water-cooled nozzle. However, at higher gas flow-rates, the heat is expelled from the torch before it can interact with the nozzle. At high plasma gas pressures the velocity is increased and the gas ionisation poor, resulting in a thicker boundary layer with a low electrical conductivity that electrically insulates the restriction nozzle from double-arcing (Prevosto, Kelly and Mancinelli, 2011). The electrode life is also extended because of the cathode spot arc root location on the electrode being forced to move around the electrode tip, more evenly distributing the arc heat and electrode deterioration.

Historically, when the PTA torch was first invented, it was set aside because of the durability of the electrode and restriction. The introduction of refractory metals for electrodes and combining a material with high thermal conductivity and water cooling for the restriction nozzles allowed the realisation of the PTA torch and an understanding of thermal pinch on the arc. If the arc column, passing through the water-cooled nozzle restriction, is cooled adequately, the arc shrinks away from the internal nozzle walls, decreasing the arc diameter. This results in a decrease in gas ionisation as the plasma gas temperature reduces, and consequently a reduction in thermal and electrical conductivity of the gas close to the internal nozzle walls. When thermal pinch occurs, the current concentrates in the arc centre where the arc column is hotter, leading to more conductivity

and increased gas ionisation and current/energy density (Wu et al., 2014; PWP Welding Basics – Plasma Welding Basics 2; Shohet, 2017).

The plasma gas passes from within the torch body and out into the chamber between the copper nozzle and electrode, increasing with velocity within the nozzle as the size decreases. On contact with the current-carrying electrode tip, the gas becomes ionised, forming a plasma. Plasma gas within the torch is close to laminar flow, turning to turbulent flow on exiting the torch nozzle (Colombo et al., 2007; Pan et al., 2002).

The arc produced from the ionised plasma gas is straightened and concentrated by the nozzle restriction through which the arc and hot gas pass. The arc within the nozzle expands to fill a majority of the nozzle restriction volume, compelling the plasma gas to pass through or in close proximity to the arc. The relatively small restriction compared with the unrestricted arc of GTA produces a higher temperature at the interface with the work-piece (Gage, 1960).

Chen et al. (2015) measured for parameters within the keyhole region and the heat of the plasma arc and determined that:

- Arc constriction affects the plasma arc heating and substrate processing but not the heat from the electron flow.
- The PGFR and arc length both affect the heat provided by the plasma arc and electron flow, but to a lesser extent than arc current.
- The heat supplied to the substrate by the plasma arc is higher than that from the electron flow and increases with increased arc current.

The PTA arc, with its nozzle restriction, has benefits, which are enhanced where the nozzle diameter is minimised (Gage, 1960):

- The arc path traverses in the direction the torch is targeted – arc stability.
- Increased power density – required for cutting or keyhole welding – is a consequence of the arc squeeze effect by the restriction nozzle, resulting in higher temperature and arc voltages.

- Concentrated momentum – necessary for surface coating, cutting or keyhole welding.
- Plasma gas heating is increased, as it is forced to pass close to or through the arc.

The electrode is also recessed and enclosed within the nozzle, which, along with the inert plasma gas, protects it to an extent from contamination with the work-piece, metal vapours and oxidation (Camacho, 1988; Tseng, Hsieh and Tseng, 2003).

PTA can be used for autogenous welding or, in the case of WAAM, with separate filler wire, as shown along with the main elements of PTA equipment in Figure 11.

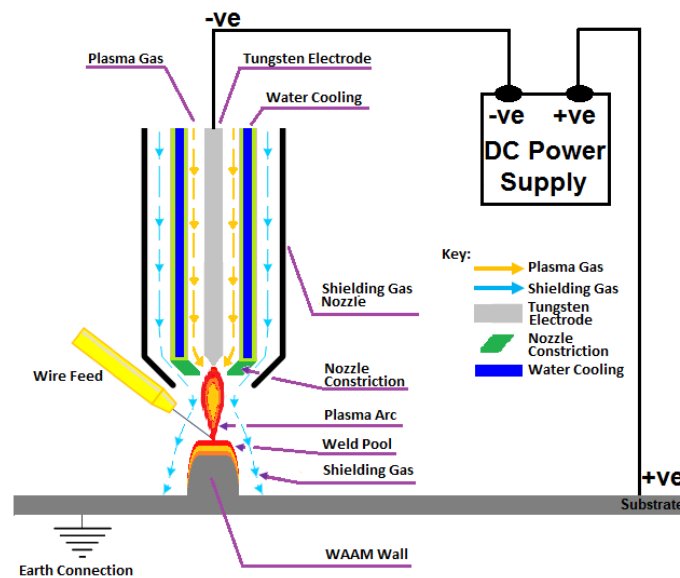


Figure 11 PTA torch elements and auxiliaries.

The PTA process has several advantages, including (O'Brien, 1991):

- High arc temperature.
- Concentrated heat profile.
- High deposition rate.
- Possibility of higher travel speeds.
- Enclosing the tungsten inhibits its inclusion in the melt-pool.
- Reduced heat-affected zone (HAZ) because of the arc concentration.
- High arc voltage.
- Arc stability.
- Less susceptibility to changes in arc length.
- Controllability of the heat input by the concentration of the arc.
- Possibility of deep penetration in keyhole mode.
- Improved process control.

- Independent wire-feeding.
- The plasma arc can be separated from the shielding gas envelope.
- Does not emit electromagnetic interference during arc ignition, which can result in measurement and control equipment interference.
- Higher current/power density.
- Reduced risk of electrode (tungsten) work-piece contamination.

However, there are also disadvantages to the process (O'Brien, 1991):

- High equipment cost.
- Copper restriction nozzle requires regular replacement.
- Requires automation and is not efficiently utilised as a manual operated process.
- Higher rate of inert gas consumption (shielding and plasma gas), intensified further if a local shielding device is utilised.
- Higher control complexity.
- Potential for keyhole defects.
- Unlike GTA, electrode cannot be re-sharpened.

PTA has two modes of operation – the non-transferred arc, where the heat is produced by the arc between the tungsten electrode and the nozzle constriction opening, and the transferred arc.

2.5.3 PTA Transferred and Non-transferred Arc

PTA arc initiation, which is similar in some ways to lightning, is a two-part process: pilot arc followed by main arc ignition. Positively charged items have a concentration of charge on edges and raised points: e.g. the nozzle tip corner illustrated in Figure 12 'A'. Before pilot arc initiation, the electrode is negatively (-ve) charged and the nozzle positively (+ve) charged because of induction, as in Figure 12. The higher concentrated positive charge of the nozzle edge and its higher conductivity than argon gas attracts the arc like a lightning conductor.

Once the high voltage, low current, high frequency (HF)-induced microsecond spark is initiated, the negative electrons on the negative electrode are attracted to the positive

charge of the nozzle edge. If the force of attraction is strong enough, the electrons will jump across the gap, neutralising the charge separation and allowing a sudden flow of electrical current to flow from the electrode to the nozzle: pilot arc. The arc takes the easiest route and winds through the gas because of differences in temperature and density.

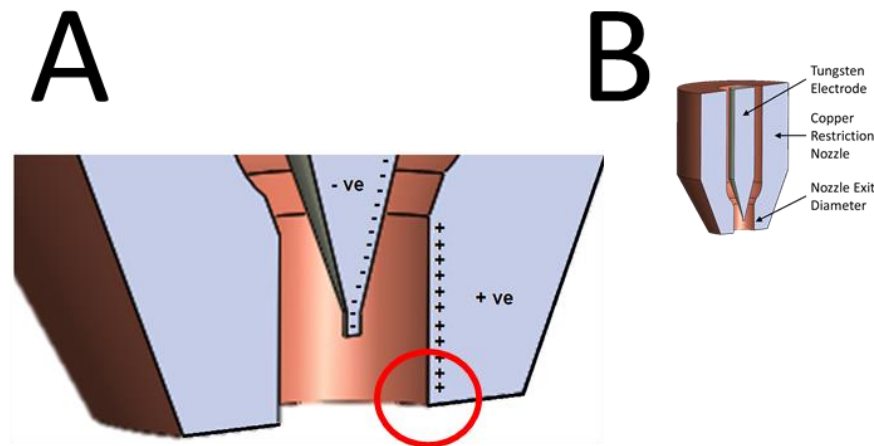


Figure 12 Charge on nozzle and electrode arrangement. A] Enlargement of electrode tip and nozzle exit – nozzle tip corner indicated, B] Annotated 3D model of nozzle cross-section.

HF and an increased operator set pilot current (normally 24 A, reducing to a pilot operational 7–11 A once the pilot is ignited) are utilised to initiate the pilot arc between the electrode and nozzle within the body of the torch: non-transferred arc. Once initiated, the pilot arc can remain ignited during inactive equipment intervals or torch movements and maintain a hot electrode tip ready for primary arc ignition. Limiting the HF to pilot ignition also mitigates potential electrical interference to measurement equipment. For non-transferred arc operations, the plasma gas transfers the heat to the work-piece (Lincoln Electric Company, 1973). On exiting the restriction nozzle orifice, unlike the transferred arc, only the hot gas stream proceeds to the work-piece (Gage, 1960).

Figure 13 'A' illustrates a schematic of the non-transferred arc. With the electrode, DC negative, and following the convention of electric current direction '+ve' towards '-ve', the current is supplied to the electrode via the main electrode cable. It creates an arc across the short distance from the electrode tip to the nozzle, favouring edges/angles. The current returns via the pilot cable, completing the circuit to the power supply.

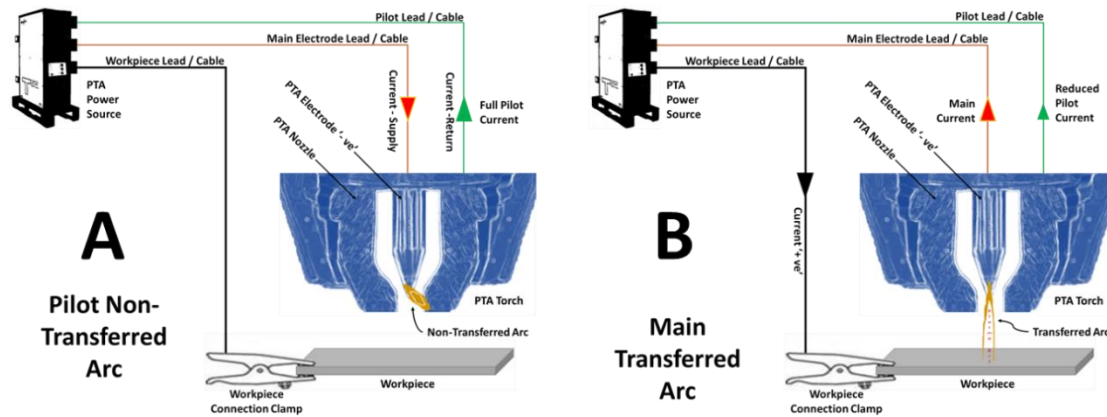


Figure 13 PTA equipment schematics. A] PTA non-transferred (pilot) arc, B] PTA transferred (main) arc.

Once the PTA torch is positioned in relation to the work-piece, the main arc can be initiated by transferring the pilot arc from the electrode, at the thermionic cathode spot on the electrode tip (Lancaster, 1984), to the work-piece with a higher current, arc voltage and energy density through the pilot arc, initially ionised gas, through which the main arc is established: transferred arc. The PTA nozzle constricts the arc into a directional arc column (Tseng, Hsieh and Tseng, 2003). On exiting the restriction nozzle orifice, both the arc and gas stream proceed to the work-piece (Gage, 1960). The PTA arc between the electrode tip, cathode and substrate anode is attracted by the potential gradient, which is more robust for PTA than for GTA, which can be more affected by electromagnetic and draft effects (Gage, 1957). Figure 13 'B' shows a schematic of the transferred arc, with current, supplied to the work-piece via the work-piece lead transferred to the negative electrode, and returning to the power supply via the main electrode cable. The visible bright arc is the highly heated ionised plasma gas.

The arc column is at a high temperature, with sufficient gas ionisation to allow current conduction. The flow velocity of the column towards the substrate is also high (Lancaster, 1984).

Measurements undertaken as part of this study show a small reduction in the returned voltage because of cable and heat losses, and as part of the deposition process and current. Additionally, a reduced current, less than the pilot operational value, is returned via the pilot cable – the sum of both returned currents equalling that supplied. This suggests that

the PTA transferred main arc for the power supplies used by this study is a combined transferred/non-transferred arc, which is not standard in other power supplies. Typically, the nozzle is electrically separated from the system once the main arc is initiated, with no current to the nozzle (Nemchinsky, 2009). However, what is experienced is not double-arcing as no nozzles are damaged, and the PTA power supply manufacturer, EWM, also confirmed, for the equipment used in this study, that this is a characteristic of the unit.

Both the transferred and non-transferred arc require plasma gas to ignite. However, a large proportion of the transferred arc plasma gas reaches a sufficient temperature to enable ionisation. For the non-transferred arc with relatively high PGFRs, the centre of the pilot arc is forced by the gas flow to protrude outside the torch nozzle (Gage, 1960).

PTA arc initiation via this method is reliable and reduces HF and potential for tungsten inclusions of the work-piece.

Although, for some applications, the low energy density PTA non-transferred arc can be utilised – e.g. plasma spray coatings – for WAAM, only the more efficient and higher energy density PTA transferred arc is used.

2.5.4 Double-arcing

Double-arcing is a phenomenon experienced in PTA cutting, spraying and welding, and results in restriction nozzle damage, in some cases instantly, preventing the extremely constricted plasma arc, capable with PTA (Nemchinsky, 2009). High thermal stresses and currents produce erosion and catastrophic damage to the restriction nozzle through double-arcing (Ramakrishnan et al., 1997). This occurs during the transferred arc mode of operation when the nozzle is incorporated within the current path: Figure 14 ‘A’. In double-arcing, the current of the transferred arc finds the shorter electrical path (Marantz et al., 1995). Instead of crossing the main arc between the electrode tip and workpiece, the current crosses to the restriction nozzle and from the nozzle to the work-piece, as shown in Figure 14 ‘B’, forming two arcs. The anode and cathode spots on the nozzle result in nozzle damage (O’Brien, 1991), and double-arcing is also detrimental to the PTA torch.

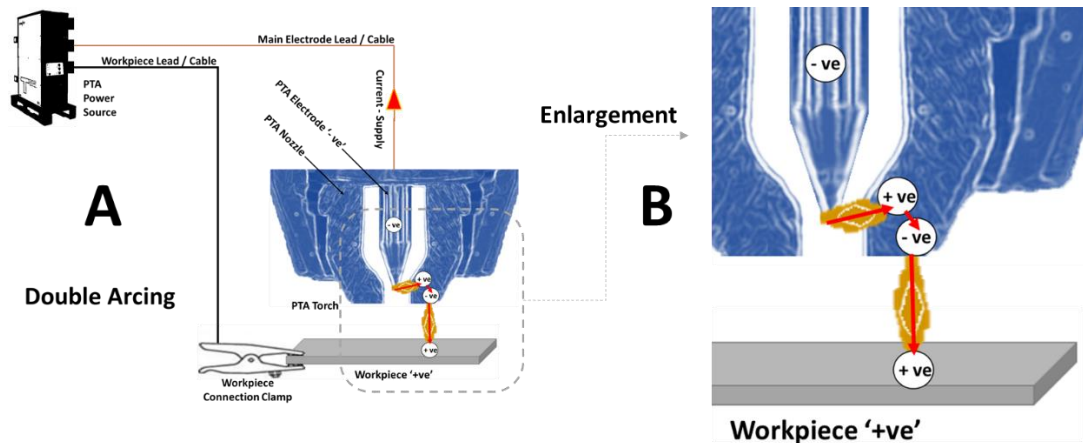


Figure 14 A] PTA equipment schematics of double-arcing, B] Enlargement of highlighted section.

As the selected nozzle diameter is reduced, the maximum current that can be applied before double-arcing takes place decreases (Short et al., 2011).

Variable polarity PTA, with its blunter electrode, is more susceptible to double-arcing and requires a broader nozzle diameter and more frequent electrode replacement (Zarnick, 1986).

Double-arcing typically occurs when one or more of the following circumstances are present (Prevosto, Kelly and Mancinelli, 2011):

- Insufficient PGFR.
- Restriction nozzle bore diameter too small.
- Restriction nozzle length too long.
- Too high arc current.
- Restriction nozzle bore diameter too large.
- Insufficient gas swirl – torch design.

In addition to the above conditions, when the arc current is high or the nozzle diameter is large the arc voltage drop within the nozzle is high (Prevosto, Kelly and Mancinelli, 2011).

Double-arcing is therefore of interest and relevance to this study, which manipulates these variables, especially given the limits to mitigate double-arcing, which limit the increasing capabilities of the PTA process.

The accepted cause of double-arcing is a high voltage drop of the plasma whilst inside the nozzle (Nemchinsky, 2009), and a breakdown and elimination of the protection boundary layer of colder, dense, non-ionised, quasi-neutral gas, which insulates the restriction nozzle from the arc (Short et al., 2011).

However, the mechanism causing the phenomenon is less understood. Nemchinsky (2009) investigated the triggers of double-arcing and proposed that dielectric films deposited within the nozzle orifice play a critical role, with a Townsend avalanche, where accelerated free electrons collide and free secondary electrons allowing electrical conduction are responsible for the breakdown of the boundary layer.

Conversely, Leandro Prevosto et al. (2011) concluded that, in addition to the Townsend avalanche, the local electric field strength at the nozzle wall, close to the nozzle exit, could have sufficient strength to initiate the breakdown.

2.5.5 Arc Restrictions

The arc produced by PTA is restricted by four means:

- 1) Lorentz force – an electromagnetic pinch force acting towards the centre of the plasma stream, induced by the magnetic field resulting from the current flow, shown in Figure 15. The force is greatest close to the electrode – the cathode spot prior to the nozzle (Fan and Shi, 1996). The radial arc pressure, acting in the reverse direction, counteracts and offsets the restricting Lorentz force (Lin and Eagar, 1986). The current density is higher at the cathode (electrode) than at the anode (work-piece) (Lin and Eagar, 1986), resulting in a downward force (Fan and Shi, 1996). The arc rigidity is a product of the pinch force, and the Lorentz force principal effect is on the pinch force (Wang et al., 2017).

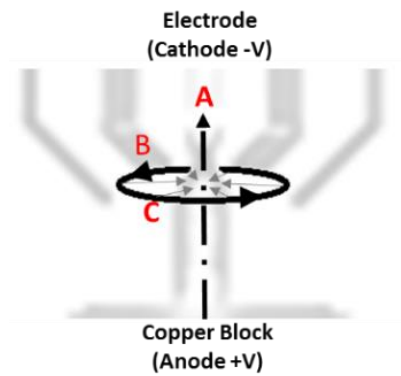


Figure 15 Magnetic forces, generated by the arc current, acting on the arc, shown overlaid onto PTA torch and arc. ‘A’ – current density and direction, ‘B’ – azimuth magnetic field and direction, ‘C’ – direction of Lorentz force ($C = A \times B$) towards the centre. Based on a sketch from Lin and Eagar (1986).

- 2) PGFR – as the PGFR is increased the additional ionised gas must pass through the same nozzle restriction, further restricting the plasma stream prior to the nozzle and through the nozzle (Venkatramani, 2002). The nozzle-induced vortex also has a restriction effect (Venkatramani, 2002). Chen, Yan and Jiang, (2019) observed that the PTA arc started to diverge when free from the confining plasma gas.
- 3) Nozzle – as the plasma stream passes through the nozzle’s narrowest point it is further restricted. This is only effective if the nozzle diameter is narrower than the plasma stream.
- 4) Shielding gas – unlike GTA, where the shielding gas is the plasma gas, in PTA the separate shielding gas, once it has passed the nozzle, impinges somewhat on the plasma stream.

These restrictions result in a concentrated, straighter, more stable arc column, and increased current density and consequently arc pressure, with less arc divergence than the GTA inverted cone. PTA is therefore more tolerant to changes in arc length.

2.5.6 Restriction Nozzle Design

The distance between the arc plasma and the inner wall of the restriction nozzle decreases as the nozzle bore diameter is reduced. Consequently, the radial thermal gradient increases. The extent of this is dictated by the nozzle shape. If the temperature is too high

and the water cooling insufficient, nozzle damage can occur. Double-arcing can also arise if copper vapour from the nozzle is generated, allowing an alternative current path and an arc split. The PTA restriction nozzle constricts the upper part of the current path between the cathode electrode and the anode substrate, resulting in a narrow beam, unlike GTA (Park and Hirata, 2017).

Park and Hirata (2017) found that, for PTA micro-plasma, as the restriction nozzle is reduced, current density and arc voltage increase. Accordingly, the power density increases. In addition, the dynamic plasma pressure on the melt-spot increases. They established that, for tiny nozzle diameters, the melt-spot width equated to the nozzle diameter.

Xiaoxia (2015) undertook an analysis of four PTA nozzle diameters and found that the arc temperature increased with a decreasing nozzle diameter – i.e. a 2.8 mm PTA nozzle reached a maximum temperature of 25843 K whereas a 4 mm nozzle reached 23385 K. They also established that current density also significantly increases with a decreasing nozzle diameter, shown in Figure 16 'A' to 'C'. The maximum velocity along the plasma arc axis is shown in Figure 16 'D' to increase with decreasing nozzle diameter. Figure 16 'D' also shows that, for all nozzle diameters, velocity decreases with arc axis distance (Jian, 2015).

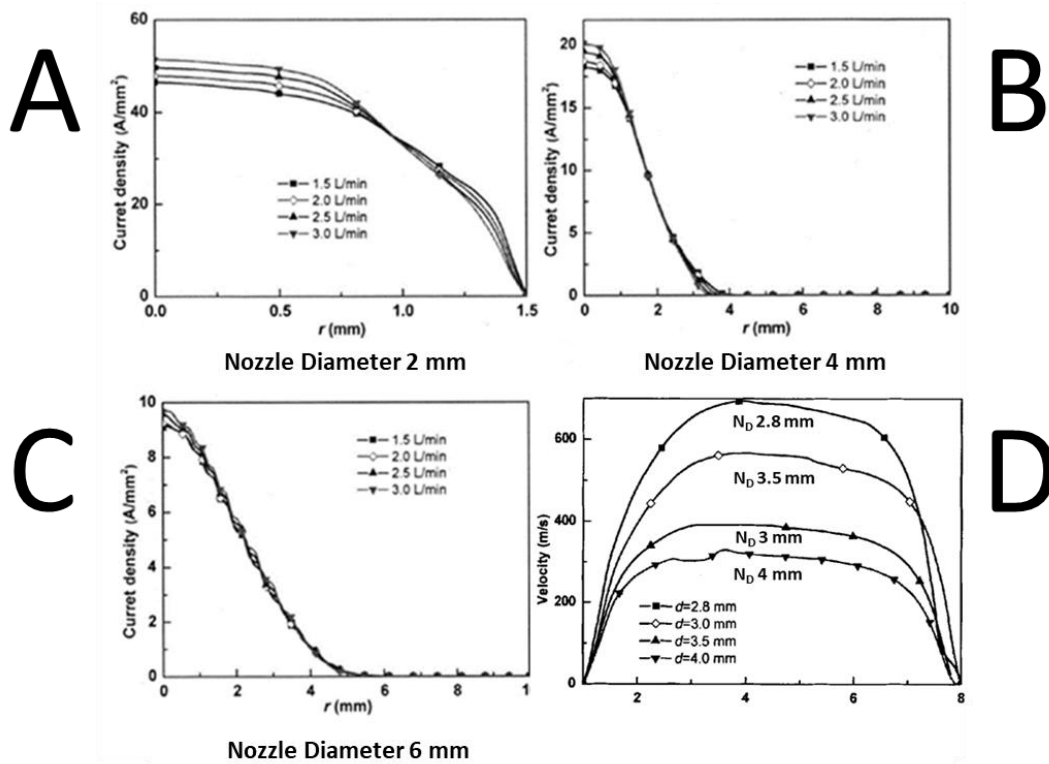


Figure 16 A] to C] Radial distribution of current density with nozzle diameter. D] Distribution of velocity along the plasma arc axis with nozzle diameter (N_D). (Jian, 2015)

Teker and Özdemir (2013), in their investigation into the effect of PTA nozzle diameter on keyhole size, penetration and mechanical properties, found that higher energy input and smaller nozzle diameter results in a narrow and more intense arc column with increased keyhole depth. Conversely, a larger diameter was found to reduce the keyhole shape and penetration depth. They also established that the deeper penetration and higher heat input from the smaller nozzle increased the maximum strength values and notch impact of the material.

Alternative nozzle materials, i.e. ceramic, as used by Park and Hirata (2017), were considered to allow the nozzle diameter to be substantially reduced while preventing double-arcing. However, this would prevent PTA arc ignition via the non-transferred arc so was conceded.

Prevosto and Risso (2009) investigated the effect of PTA nozzle length on the arc for plasma cutting. They found that a shorter nozzle resulted in a hotter and thinner arc than

a more extended nozzle, and arc voltage increased with nozzle length. This association is attributed to a ‘clogging effect’ of the plasma gas, which inhibits the PGFR. Lower PGFR reduces the cooling, pinch effect on the arc column peripheral boundary, resulting in a decrease in power density and arc temperature. As a result of the relationship of electrical conductivity with temperature, the reduction in arc temperature results in a broader PTA arc.

Qianhong et al. (2008) also examined the influence of the PTA nozzle length on the plasma cutting arc. They established that nozzle pressure increased with more extended nozzles because of ‘choking’, and that long nozzles result in a high-velocity arc with a high heat flux. They concur with Prevosto and Risso (2009) that arc voltage increases with nozzle length, increasing arc power, and that at higher PGFRs, as a result of the pinch effect inside the torch, there is a narrower arc and an increase in velocity, heat flux and temperature. For high PGFR, the pressure within the nozzle increases, which in turn raises the electrical conductivity and ohmic heating of the gas. The axis temperature is therefore higher for a higher PGFR. At low PGFRs, the arc voltage and heat flux increases with PGFR. Decreasing the nozzle diameter constricts the arc and increases energy density and arc momentum, enabling a high-quality plasma cut and increased productivity. The velocity was found to fall for all nozzle lengths as the nozzle diameter increased. The risk of double-arcing was found to increase with more extended nozzles but it can be mitigated by higher PGFRs.

Zhang et al. (2013) developed a water-cooled PTA three-hole nozzle design, shown in Figure 17 ‘A’ and ‘D’, to produce a soft plasma arc that improved keyhole stability, and reduced PTA arc pressure for welding. Figure 17 ‘C’ illustrates the dramatic reduction in arc pressure, validating the concept (Zhang et al., 2014).

The nozzle creator conceded that the same reduction in arc pressure could be achieved by lowering PGFR, but also noted that there was no adequate interval during operation to make the adjustment (Zhang et al. 2014), presumably mitigating against operator error for welding. The unique three-hole nozzle results in a lower plasma gas velocity and consequently a decrease in dynamic arc pressure. Additionally, the reduction in water-

cooled nozzle mass reduces to an extent the thermal constriction and thermal pinch, of the arc, again reducing the arc pressure (Zhang et al., 2014).

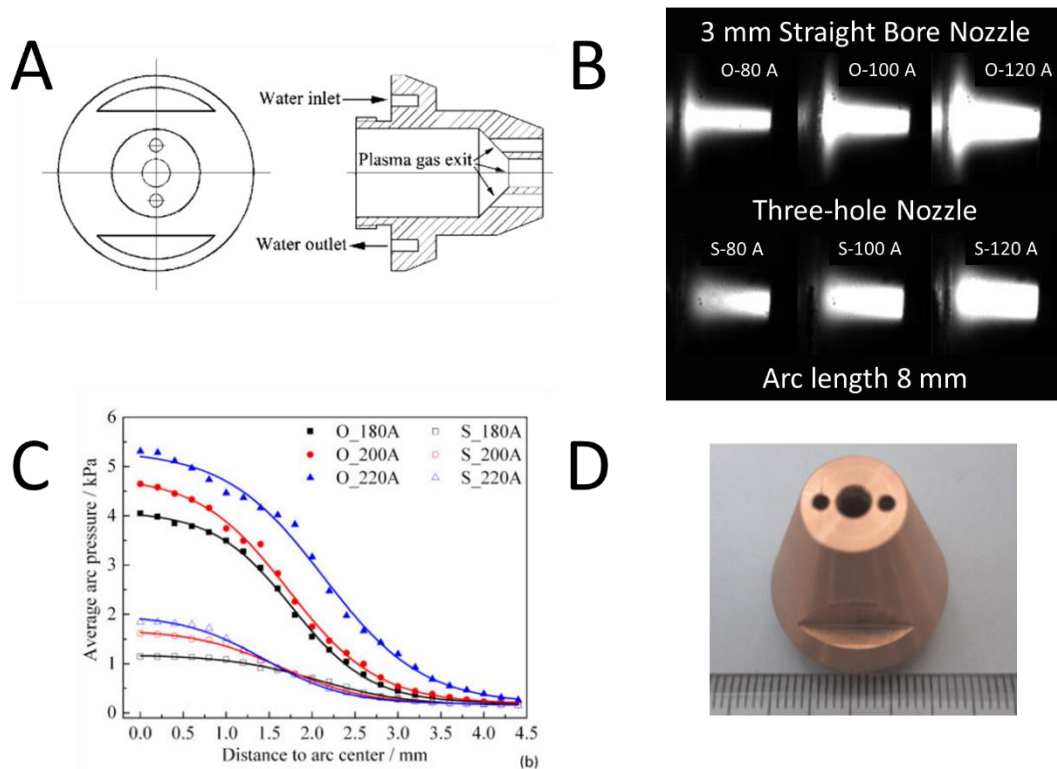


Figure 17 Three-hole nozzle. A] Nozzle design, B] PTA arc column diameter changes with current, C] DCEN arc pressure comparison between ordinary ‘O’ nozzle and three-hole nozzle/soft ‘S’ plasma, D] Photograph of nozzle. (Zhang et al., 2014)

Zhang et al. (2014) determined, using a high-speed camera, a relationship between current and PTA arc column diameter for a straight-bore nozzle – diameter substantially increasing with arc current, as shown in Figure 17‘B’ top row. A similar increase was found for their three-hole nozzle, shown in Figure 17 ‘B’ bottom row. However, the broader arc columns were less divergent in shape at the substrate.

Zhang et al. (2015) propose that the size of the PTA arc at the substrate signifies the magnitude of the PTA arc impact. The higher the arc pressure and consequently the impact, the more extensive the base of the arc column. Using this perspective, the reduction in arc pressure and arc momentum between a straight-bore nozzle and three-hole nozzle is visible in Figure 17 ‘B’ and the heat field images of Figure 18. They also identified that the base of the arc column is circular for a straight-bore nozzle, as in Figure

18 ‘A’, but elliptical for the three-hole nozzle shown in Figure 18 ‘B’ and ‘C’ because of the reduction in diameter in the direction of travel.

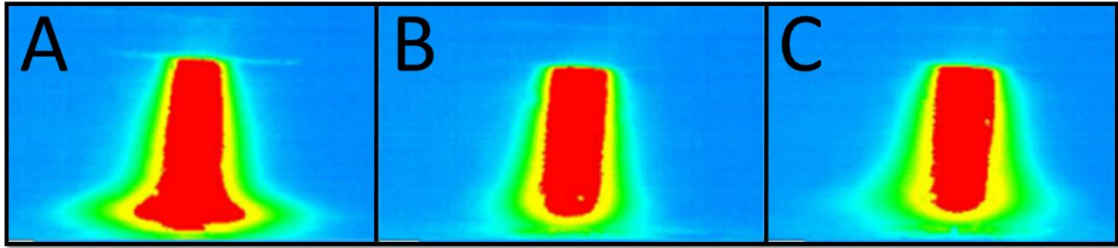


Figure 18 PTA DCEN heat field. A] Ordinary PTA 3.2 mm nozzle, B] Three-hole nozzle along direction of travel, C] Three-hole nozzle perpendicular to the direction of travel. (Zhang et al., 2015)

To achieve similar results to a straight-bore nozzle, the three-hole nozzle requires a reduced arc length and an increased PGFR, suggesting that the penetration capability of the three-hole nozzle is lower (Zhang et al., 2015).

Demars et al. (1973) investigated several converging and converging–diverging PTA nozzles with varying electrode setbacks (ESBs), shown in Figure 19. Demars et al. (1973) found that, for the converging–diverging nozzle, where there is no straight nozzle length, the arc is restricted by the plasma gas flow. The electrode and consequently arc position, stand proud of the throat, Figure 19 ‘C’, enabled arc ignition via the throat edge but also minimised nozzle erosion, increasing nozzle longevity. In addition, converging nozzles, shown in Figure 19 ‘A’ and ‘B’, were found to severely erode at the nozzle tip where there is minimal material.

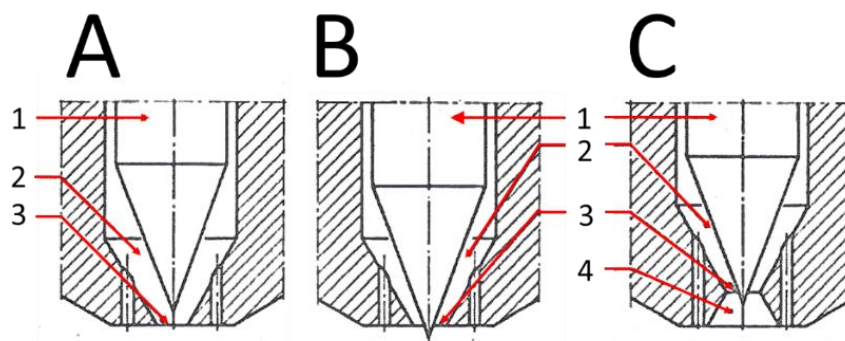


Figure 19 Demars converging and converging–diverging PTA nozzle cross-sections. 1) Electrode, 2) Convergence, 3) Throat, 4) Divergence. A] Converging nozzle with retracted electrode, B] Converging nozzle with electrode standing proud of throat, C] Converging–diverging nozzle with electrode standing proud of throat. (Demars et al. 1973)

The onset of PTA keyhole hampers increases in arc power to enable further improvements to the rate of WAAM deposition. Sergio Eduardo Ríos (2017) investigated diverging nozzle design, shown in Figure 20, in an attempt to mitigate the issue. He found that the WAAM operating region was strongly affected by the nozzle design, but the deposited material geometry was less sensitive for a region of current and PGFR values if the nozzle geometry included a diverging outlet. Also, the angle of nozzle divergence has minimal effect on the geometry of the deposited material. While the diffuser length did have an effect, this was less than for current and PGFR. By diminishing the arc restriction effect using a diverging nozzle, shown in Figure 20, Sergio Eduardo Ríos (2017) was able to show that the operation envelope could be increased to allow higher current and PGFR to increase WAAM productivity potential. The investigation established that a longer diffuser length, 2.4 mm, and narrow 36.8-degree diffuser nozzle produced the best deposit geometries. Diverging nozzles also have similar benefits to a larger diameter nozzle, but allow ease of arc ignition (Ríos, 2017).

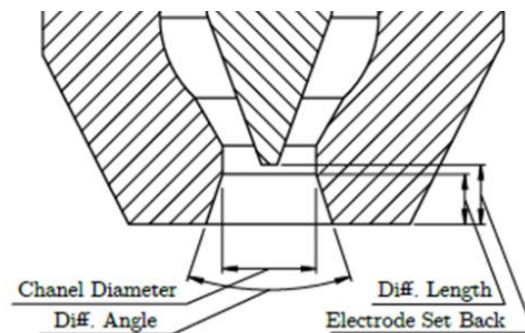


Figure 20 Diverging nozzle design features. (Ríos, 2017)

For diverging nozzles, the arc power delivered is significantly influenced by the PGFR because of the pneumatic arc constriction. Sergio Eduardo Ríos' (2017) results show that it is possible to produce similar deposited material geometry with a diverging nozzle by counteracting reductions in current with increases in PGFR. Figure 21 shows a comparison between a lower arc power and higher PGFR 'A', and a higher current and lower PGFR 'B'. It is clear for the two sets of parameters that the melt-pool is more significant for the higher arc power and the melt-pool depression is more significant for the higher PGFR. Both produced similar layer heights and deposit widths, but the melt-pool depressions are quite different. The higher current, shown in Figure 21 'B', results

in a small depression surrounded by a large melt-pool, and the increased PGFR, shown in Figure 21 'A', has a more pronounced depression at the front of the melt-pool, similar to the circumstances of bead hump formation (Ríos, 2017).

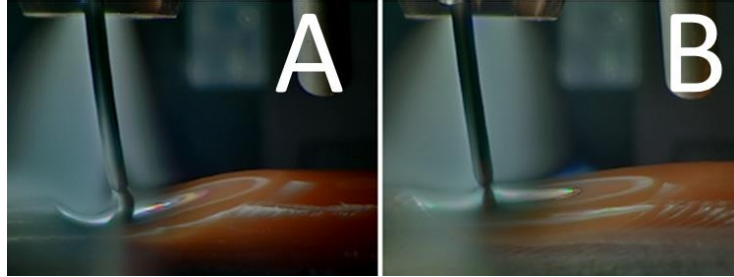


Figure 21 Comparison of the effect of current and PGFR on the melt-pool. A] Lower current and higher PGFR (120 A, 5 l/min PGFR), B] Higher current and lower PGFR (167 A, 0.8 l/min PGFR). (Ríos, 2017)

Though combinations of current and PGFR have been shown to produce similar deposit geometries, the melt-pool depressions affect wire-feeding. The melt-pool concavity, as a result of high PGFR momentum, shown in Figure 21 'A', increases the wire-feed height, which changes the mode of metal transfer and process stability. An increase in current is therefore preferable to a rise in PGFR (Ríos, 2017). No consideration was given to arc pressure or its effects as a potential explanation during this study.

G.J. Langford developed a specialist nozzle incorporating additional nozzle holes and a focusing gas, shown in Figure 22. The two extra holes are 0.045 inches/1.143 mm diameter and angled towards the arc. The impingement of the focusing gas on the arc contracts the arc and results in an increase in PTA penetration, presumably through a decrease in arc diameter and a corresponding rise in arc power density and arc pressure. The separate focusing gas stream is also effective at mitigating double-arcing and the resulting nozzle damage (Vredeveltdt, 2014).

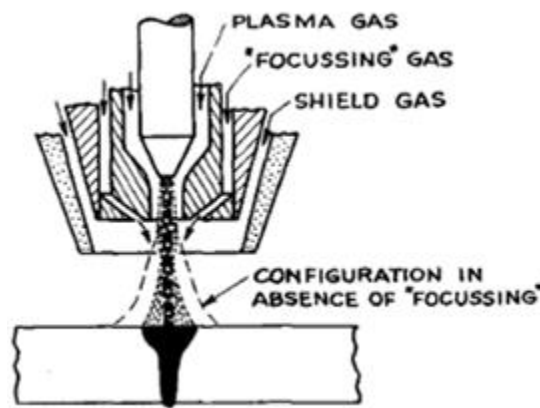


Figure 22 Specialist PTA torch including a third focusing gas. Dotted line indicates the arc geometry before contraction. (Langford, 2018)

2.6 Non-consumable Electrodes

Both GTA and PTA rely on a refractory metal non-consumable electrode commonly referred to as the tungsten to endure the high operating temperatures of the process. As the process development has shown, realisation of the process was only possible once advances in refractory metals had been made.

With the development of computer numerical control (CNC) and industrial robot arm integrated systems with increased arc-initiated duty cycles, as well as equipment availability – e.g. for WAAM part building – the need for specially selected PTA electrodes is vital. For economic and productivity reasons, the plasma system must be capable of running continuously for many hours without interruption – e.g. no need to change a failing electrode (Camacho, 1988). A suitable electrode must have the following characteristics: easy arc ignition, continued operation, restarting, extended service life/longevity, excellent tip retention to prevent melt-pool contamination, maintain electrode tip geometry, low material consumption/wear, excellent arc stability and required melt-pool geometry (Ushio, Sadek and Matsuda, 1991; Matsuda et al., 1986).

Historically, research investigating factors associated with non-consumable electrodes has focused almost exclusively on GTA electrodes and excluded the electrode needs of the hotter constrained PTA arc. A majority of this part of the literature review is therefore from GTA studies unless PTA is explicitly mentioned. There is also only a small amount

of scientific research into oxide transition within tungsten – a majority of the information found was revealed through industrial research by manufacturers.

2.6.1 Tungsten Material, Manufacture and Oxides

The PTA electrode is predominantly fabricated from refractory metal, tungsten or tungsten alloy material to endure the high temperatures essential for welding operations with minimal melting or erosion. Tungsten has a high heat conductivity, low thermal expansion, and the highest melting temperature of all metals: 3410–3420°C (Callister, 2010; Savage, Nippes and Agusa, 1979; Paschen, 1996).

Electrodes are manufactured through powder metallurgy of tungsten and oxides and through sintering. Once formed, the end shape is created through extrusion and machining. As a result of the manufacturing process, the material is porous, and due to the extrusion exhibits an elongated grain structure (Callister, 2010).

The tungsten and oxide powdered material are mixed thoroughly into a uniform consistency before being poured into a mould and compacted. The material is then sintered into blanks and the metal oxide reduced by means of chemical reactions (Paschen, 1996). The result is a fine microstructure with a homogeneous distribution, ready to be formed through drawing/extrusion and rounding into a practical shape and size before machining into the final electrodes (Wolfram Industrie, 2019).

The molecular structure of the tungsten and oxide is a fine grain polycrystalline with concentrated oxide within the grain boundaries. The polycrystalline structure maximises the number of grain boundaries and dislocations through which the oxide can migrate. It is more difficult for the oxide to move through the crystallised tungsten grains, as the oxides do not dissolve in tungsten. The finer the grains and the more homogenous the distribution of the oxide, the higher the quality of the tungsten electrode material, and the easier for the oxide to migrate. The rate of migration for oxides is attributed to each oxide and oxide reaction compounds' melting temperatures, but increases with temperature gradient (Ushio, Sadek and Matsuda, 1991; Nemchinsky, 2014; Paschen, 1996; Matsuda and Ushio, 1988).

Dispersal of the dopant and its grain size also affects the electrode properties of creep and resistance to thermal shock, in addition to machinability (Paschen, 1996).

Oxides within the tungsten electrode (Costa, 2014; Nemchinsky, 2014):

- Act as tungsten grain growth inhibitors.
- Reduce the work function of the electrode to aid electron emission.
- Increase the melting point temperature.
- Reduce electrode wear and consequently increase electrode life.
- Increase arc stability.
- Improve electrode current-carrying capability.
- Reduce melt-pool contamination risk.
- Improve thermal conductivity.

Tungsten electrodes containing a dopant are also referred to as binary cathodes. Generally, as the percentage oxide/dopant is increased, arc ignition is easier for GTA and PTA, when compared with pure tungsten electrodes. The selection of tungsten oxide alloy electrodes for each application is best determined through trials, though manufacturers may be able to supply limited high-level guidance. This study's PTA electrode material supplier, for example, recommended thoriated tungsten electrodes as very good for PTA, specifically for use with titanium substrate, while ceriated and lanthanated are only deemed good for PTA applications (Wolfram Industrie, 2019).

During PTA operation, the tungsten grains, because of the high temperatures involved, coalesce to form larger grains – grain growth. However, if the oxide is uniformly distributed and continually moves through the grain boundaries, it can pin the tungsten grains and inhibit their growth. This pinning can aid in maintaining the grain boundaries, allowing further oxide migration and oxide particle coalescence through the tungsten from the colder areas towards the hotter electrode tip – the migration rate increasing with the temperature gradient (Ushio, Sadek and Matsuda, 1991; Paschen, 1996) and tungsten and oxytungstate melting point temperatures, shown in Table 3 (Sadek, Ushio and Matsuda, 1990). The coarse grain structure of pure tungsten risks grain boundaries sliding – with the addition of dopants, the coarse grain structure becomes stabilised, minimising

sliding (Wolfram Industrie, 2019). As the oxide particles traverse up the temperature gradient, they grow in size and accelerate (Sadek, Ushio and Matsuda, 1990).

Tungsten oxide electrodes are volatile compounds that oxidise at temperatures above 400⁰ C, and shielding gases are therefore required for GTA and PTA applications (Wolfram Industrie, 2019; Nemchinsky, 2014).

For rare earth oxide additions the reaction with tungsten at temperature in GTA forms tungstate and oxytungsten. As a result of their lower melting points, these melt and migrate from the relatively low temperature zone of the electrode towards the higher temperature zone of the tip via longitudinal grain boundaries. Thorium oxide reacts with the tungsten to form pure thorium (Sadek, Ushio and Matsuda, 1990; Matsuda and Ushio, 1988).

Where the distribution of oxide is not uniform or the oxide becomes depleted in an area because of evaporation rates from the tip being higher than migration rates, the uninhibited tungsten increases in grain growth. This reduces the number of grain boundaries and consequently the number of paths available for the oxide to travel towards the tip, blocking concentrations of oxides higher up the electrode from migrating to the tip. A reduction in the oxide at the electrode tip results in poor electrode operation, limiting electrode service life and producing a localised increase in work function. This can in turn result in a repeating cycle of an increase in electrode temperature, further evaporation and, consequently, oxide reduction, further increasing the work function, restarting the cycle until electrode failure (Nemchinsky, 2014).

On termination of a PTA arc, the polycrystalline tungsten grains can re-crystallise. The larger tungsten grain size constrains oxide diffusion. The number of arc terminations can therefore reduce electrode longevity (Nemchinsky, 2014).

The electrode work function is the minimum amount of energy required to enable an electron to be emitted from the metal surface and is measured in electron volts (eV). The lower the work function of an electrode, the easier it is to emit electrons (Paschen, 1996), the lower the voltage required and the easier arc ignition is. The addition of oxides with low eV values into the tungsten grain structure reduces the overall work function of the

electrode and allows thermionic emission at a lower temperature but the required current density – e.g. the thermionic emission of thoriated tungsten – takes place below its melting temperature and maintains tip geometry and consequently a more stable arc (Lancaster, 1984). A low eV value at the electrode tip reduces the tip temperature, which in turn impedes tungsten grain growth and enables replenishment of oxide to the electrode tip, increasing electrode longevity and assisting in arc ignition. Typical work function values for common electrode materials are listed within Table 2 – pure tungsten has the highest value.

Work function values, shown in Table 2, vary greatly. In the literature, the values assigned to different electrode materials and tungsten alloys are broad even for the same percentage oxide. The electrode material manufacturer, Wolfram Industrie, advised that the difficulty of determining exact values of the work function of solid electrode materials is that the work function depends on different parameters including:

- Composition.
- Microstructure.
- Geometry (e.g. Ø).
- Surface properties.
- Temperature (diffusion effects within the material at higher temperatures).
- Atmosphere (composition/humidity/thermal conductivity).

Table 2 Typical work function values for electrode materials.

(Diamond-Group, 2002 and Mandal, 2002)

Material	Oxide % Weight	Work function (eV)
Pure Tungsten (W)	N/A	4.5
Thoriated Tungsten (W-ThO ₂)	2	3.4
Ceriated Tungsten (W-CeO ₂)	2	2.6
Lanthanated Tungsten (W-La ₂ O ₃)	2	3.3
Zirconiated Tungsten (W-ZrO ₂)	0.8	4.2

Work function increases with arc current, the relationship is thought to be as a result of the increase in oxide depletion with increased temperature, which is reduced at the lower temperature associated with the lower current (Nemchinsky, 2014).

Sadek et al. (1990) found a relationship between low work functions and minimal arc voltage required to initiate a GTA arc with a high frequency spark. For several tungsten oxide electrodes, the best-considered electrode required the lowest arc voltage. All materials started and maintained their arc for high arc voltages. However, lanthanated materials required the lowest arc voltages to initiate and sustain the arc and enabled the highest number of arc starts.

Lowke et al. (1997) experimentally found that the electrode/cathode surface temperature dropped with axial distance along the electrode from the tip and that the temperatures were significantly higher for pure tungsten than 2% thoriated tungsten for the same parameters. The sole difference was the electrode material work function value, shown in Table 2. Lowke et al. (1997) attribute the higher pure tungsten surface temperature to the increased arc conducted heat to the electrode, a result of the larger surface contact area of the plasma arc with pure tungsten as a consequence of the lower current density at the surface, compared with 2% thoriated tungsten.

Ideally, the evaporation rate of the oxide from the electrode tip is in balance with the pace of migration of the oxide, ensuring that sufficient dopant is available at the tip to serve as a good emitter. If the evaporation rate of the oxide, with its lower melting temperature from the electrode tip, is higher than the migration rate, an oxide deficit at the tip will occur, resulting in a reduced arc consistency and reduced electrode properties as the oxide electrode becomes pure tungsten with its higher work function and wear-rate (Sadek, Ushio and Matsuda, 1990; Paschen, 1996; Zhou, Ding and Heberlein, 1996).

Thorium is a radioactive element that emits alpha (α), beta (β) and gamma (γ) particles. Alpha particles make up the most significant majority, while thorium also has a relatively long half-life (Costa, 2014). Typically, small amounts of thorium oxide, usually 2% by mass, are added to tungsten electrodes. However, for safety concerns during welding and grinding of the radioactive substance, the use of other oxides was developed, including lanthanum, cerium, zirconium and yttrium.

Pure tungsten (W) is tungsten with no oxide elements, with a minimum purity of 99.95%. As a result of its very high work function, 4.5 eV, arc ignition is difficult, and arc instability issues exist in DCEN. The current-carrying capacity is lower than for alloyed electrodes (Diamond-Group, 2002). Lowke et al. (1997) experimentally demonstrated that the temperature of pure tungsten electrode tip is higher than that of thoriated tungsten, marginally because of ion heating but predominantly as a result of conducted arc heat. The pure tungsten electrode high tip temperature and structure re-crystallisation result from the high work function (Wolfram Industrie, 2019), as the arc contact area on the pure tungsten electrode is more significant than that of thoriated tungsten (Lowke, Morrow and Haidar, 1997). The high temperature at the tip also results in higher wear-rates, as well as melting and rounding of the tip (Lowke, Morrow and Haidar, 1997), and consequently short electrode longevity. Pure tungsten electrodes are typically used for AC applications of aluminium and magnesium alloys (Wolfram Industrie, 2019). Better alternative electrodes are available (Diamond-Group, 2002; O'Brien, 1991; Ushio, Sadek and Matsuda, 1991).

Thorium oxide – tungsten (W-ThO₂) – the oxide is usually up to 3.2% by mass of the tungsten alloy. For this study, 2% thorium has been used. The addition of the oxide to the tungsten electrode increases the current-carrying capacity by 20%, improved arc starting, greater tip geometry retention and increased service life, compared with pure tungsten. However, it sustains a high erosion rate. The vaporisation rate for GTA was also found to be higher than the migration rate, resulting in oxide depletion at the tip and the need to function as a pure tungsten electrode. The lower migration rate is a result of the high melting point of thorium oxide, shown in Table 3, and the even more elevated temperature of the pure tungsten produced by the reaction impeding diffusion (Ushio, Sadek and Matsuda, 1991; Sadek, Ushio and Matsuda, 1990).

Matsuda et al. (1986) experimentally established for GTA that the electrode temperature decreased with axial distance from the tip, and that the radiation energy and electrode temperatures measured for thoriated tungsten electrodes were higher than that of lanthanated electrodes by 290⁰ K and by 110⁰ K for Yttrium oxide tungsten under the same process conditions. There is, unfortunately, no explanation or conjecture for the cause given.

The slightly radioactive thorium oxide can be harmful if ingested or inhaled where it can become carcinogenic. Industry experts have therefore advised that thoriated tungsten electrode use ends at the earliest opportunity and that alternative electrode materials are utilised. In the interim, protective measures should be put in place and relevant personnel made aware and asked to acknowledge potential risks (Savage, Nippes and Agusa, 1979; Costa, 2014). However, the risk of cancer because of exposure is deemed by the Health and Safety Executive (HSE) to be low, although safeguards should be put in place. The production of thoriated tungsten is regulated by the Ionising Radiations Regulations (1999) and is starting to be prohibited. Recycling and disposal are also becoming increasingly difficult, and its use discouraged as alternatives are now readily available (Diamond-Group, 2002; Paschen, 1996; O'Brien, 1991).

Cerium oxide – tungsten (W-CeO₂) is the first available alternative to thorium oxide, and the oxide is usually up to 2.2% by mass of the tungsten alloy. Its high migration rate ensures oxide at the electrode tip for arc ignition. However, the electrode becomes depleted of oxide with time, resulting in tungsten grain growth and harder arc starting with use. Cerium has a low melting point temperature, Table 3, for both oxide and tungstate, resulting in a high consumption rate (Diamond-Group, 2002; O'Brien, 1991; Sadek, Ushio and Matsuda, 1990).

This study's electrode supplier, Wolfram Industrie (2019) states that ceriated electrodes are likely to become the market leader from thoriated electrodes for GTA and PTA, remarking that its arc ignition properties are superior to thoriated electrodes.

Ushio et al. (1991) found the migration and vaporisation rate for GTA of cerium oxide, with the lowest oxide and tungstate melting point, to be the highest of all the oxides. However, the vaporisation and burn-off rate are still lower than pure tungsten, as shown in Table 3.

The arc starts well at low currents, making it a good option for low current and small part applications, and exhibits increased longevity at the lower amperage than the 2% thoriated equivalent. Still, alternative oxides are better suited for higher currents, but ceriated electrodes are ideal for DC applications and shorter operations (Diamond-Group, 2002; O'Brien, 1991)

Lanthanum oxide – tungsten (W-La₂O₃) – generally the oxide is up to 2.2% by mass of the tungsten alloy. This is a popular alternative to 2% thoriated tungsten with one of the lowest work functions of the oxide additions, enabling ease of arc ignition at a lower voltage, increased longevity increasing equipment availability, and reduced tungsten grain growth. However, the vaporisation rate for GTA was found to be higher than the migration rate (Ushio, Sadek and Matsuda, 1991). It is commonly used for DC applications but just as suitable for AC use (Diamond-Group, 2002; O'Brien, 1991). Sadek et al.'s (1990) study into the effects of rare earth metal oxide additions to tungsten electrodes found that lanthanated tungsten exhibited the best properties for GTA compared with the other available oxides, including arc starting with a lower voltage. High stability is attributed to the melting point of the oxide element and more elevated temperature of its tungstate and oxytungstate, shown in Table 3 (Ushio, Sadek and Matsuda, 1991; Sadek, Ushio and Matsuda, 1990).

This study's electrode supplier, Wolfram Industrie (2019), states that lanthanated electrodes are Europe's most popular replacement for thoriated electrodes.

Zirconium oxide – tungsten (W-ZrO₂) – generally the oxide is up to 0.9% by mass of the tungsten alloy. Zirconiated tungsten is more stable than pure tungsten although it does not exhibit as good properties as the other non-radioactive oxides available, with a lack of arc stability and high erosion rate (Ushio, Sadek and Matsuda, 1991). It is commonly used for AC applications as the tip generates a ball quickly (Diamond-Group, 2002; O'Brien, 1991).

Zirconiated tungsten is typically only used for GTA, and applications where avoidance of melt-pool contamination is critical. Risk is mitigated by the very low oxide percentage (Wolfram Industrie, 2019).

Oxide reactions with tungsten at temperature

Table 3 outlines the melting points, reactions with temperature and behaviour of the oxide materials observed by Ushio et al. (1991) during their experiments. They established that the rare earth oxides reacted with tungsten at temperature to form compounds of tungstate and oxytungsten, except thoriated tungsten, which produced pure tungsten and pure

thorium. The melting points of both tungstate and oxytungsten are lower than both the initial tungsten and oxides: see Table 3 (Ushio, Sadek and Matsuda, 1991).

Table 3 Oxide behaviour summary. (Ushio, Sadek and Matsuda, 1991; Sadek, Ushio and Matsuda, 1990; Matsuda and Ushio, 1988)

Oxide	Thorium oxide (W-ThO ₂)	Lanthanum oxide (W-La ₂ O ₃)	Cerium oxide (W-CeO ₂)
Melting Point of Oxide (°C)	3049.85	2216.85	2599.85
Melting Point of Element (°C)	1754.85 (Th)	919.85 (La)	797.85 (Ce)
Boiling Point of Oxide (°C)	4400	4200	-
Heat of Decomposition (kJ)	1227.6	1244.7	523.4
Reaction with Temperature	Reduction of thorium oxide by tungsten occurs forming pure tungsten and pure thorium	Forms tungstate (with a melting point of 1799.85°C) and oxytungstate (melting point greater than 1499.85°C)	Forms a tungstate (with a melting point of 1089.85°C)
Oxide Behaviour	- Diffusion of thorium atoms to the electrode surface. - Vaporisation of the thorium from the electrode surface.	- Migration of lanthanum oxide occurs from the centre to the electrode tip. - Vaporisation of lanthanum oxide from the electrode surface.	- Migration rate through the electrode edge is higher than for the centre to the electrode tip. - Vaporisation of cerium oxide from the electrode surface.
Stability of Oxide	Low stability	Higher stability	Reasonable stability

For this study, the typical non-consumable tungsten electrode utilised with the PWP Viper MC torch is a 2% thoriated tungsten, with the raw material supplied by Wolfram Industrie. Material composition and test data are shown in Table 4.

Table 4 Wolfram Industrie thoriated tungsten electrode material data.

Chemical Composition			
Material Name	Thorium Oxide (ThO ₂) %	Impurities %	Tungsten %
Thoriated Tungsten (WTh 20)	1.8 to 2.2	≤ 0.2	Balance (Approx. 97%)
Test Results			
Material Name	Density (g/cm ³)	Hardness (HV 20)	
Thoriated Tungsten (WTh 20)	≥ 18.7	≥ 420	
Manufactured fully in accordance with EN ISO 6848:2004.			

The arc voltage study by Sadek et al. (1990) found a negligible effect of the oxide tungsten materials on the arc voltage current characteristic, with only a marginal change between the materials. Pure tungsten had a notable increase in arc voltage for the same parameters. Sadek et al. (1990) conjectured that the marginal change is a result of the shift in cathode potential drop as a result of electrode tip geometry change because of the effects of the different oxides.

2.6.2 Electrode Polarity

For PTA operations, DCEN is usually selected. However, PTA electrodes can be operated in three different polarities:

- Direct current electrode negative (-) (DCEN).
- Direct current electrode positive (+) (DCEP).
- Alternating current (AC).

Each has its distinct characteristics, advantages and disadvantages. The arc behaviour is also affected.

PTA DCEN, also known as straight polarity, where the electrode is connected to the power supply negative terminal, is typical for PTA when used with stainless steel, nickel-based alloys and titanium and its alloys, and is the polarity used for this study. The heat balance is 30% at the electrode and 70% at the workpiece. The current-carrying capacity is high, and penetration at the work-piece is deep and the melt-pool narrow, greater than both DCEP and AC (O'Brien, 1991).

PTA DCEP, where the electrode is connected to the power supply positive terminal, is normal for PTA when used with aluminium and its alloys and magnesium and its alloys where oxide cleaning is beneficial. The current-carrying capacity is approximately 10% of DCEN. The heat output at the electrode is higher, with a heat balance of 70% electrode and 30% work-piece, limiting the electrode current rating – see Table 47 – and reducing penetration at the work-piece, resulting in a shallow and wide melt-pool compared with DCEN and AC. DCEP polarity is not conventionally selected for PTA because of the intense heat the electrode is subjected to and the reduced current-carrying capability (O'Brien, 1991).

PTA AC, where the current changes direction each half-cycle – i.e. electrode alternating between positive and negative polarity – is commonly used with aluminium and its alloys and magnesium and its alloys, but can also be used for bronze, nickel-based alloys and titanium and its alloys, where work-piece surface oxide cleaning is desirable. Heat output is moderate, with a heat balance of 50% at the electrode and 50% at the work-piece. The current-carrying capacity is good, and penetration at the work-piece and the melt-pool width are both moderate, in between that of DCEN and DCEP (O'Brien, 1991). This study does not cover PTA AC.

2.6.3 Thermionic Emission

British physicist Owen W. Richardson won a Nobel Prize in Physics in the 1920s for his work on thermionic emission building on the discovery of the first sub-atomic particle, the electron, by British physicist J.J. Thomson, some 20 years earlier. In his Nobel lecture, he outlined the findings of his thermionic emission investigation, first demonstrating experimentally through his platinum experiment that electrons were discharged from the material and that by increasing the temperature the number of released electrons significantly increased. The freely moving electrons within the hot material moved to the surface and, where their energy was sufficient to overcome the materials' work function, were released – thermionic emission. O.W. Richardson also demonstrated (Richardson, 1929):

- The relationship between the differences of work function value for different materials, equal to their contact potential differences.
- Electrons emitted from a hot body by heat energy overcoming the work function of the material cooling the body in a similar way to water cooling by evaporation.
- It is possible to control negative emitted electrons by an external electric field.
- Initially, when a material is heated, there is a significant emission of positive ions, which declines with time – this is because of surface impurities. Once complete, more consistent emission of the actual material takes place.

In an investigation into metal oxides, A.R.B. Wehnelt found the same phenomena: low work functions, and very efficient emitters of electrodes (Richardson, 1929).

The PTA tungsten electrodes are alloyed with oxides to encourage thermionic emission from the cathode electrode when connected as a negative cathode. If sufficient electrons are thermionically emitted with sufficient intensity, the welding process can be affected – thermionic emission allows arc ignition. The higher the temperature, the greater the current density achieved by the thermionic emission (da Cruz and Scotti, 2016).

When a metal material such as PTA tungsten electrode is heated until its thermal energy is higher than its work function, charged particles and thermions overcome the material work function because of their increase in kinetic energy, and are emitted from the material surface – thermionic emission (da Cruz and Scotti, 2016). Once the electrode has reached temperature, current transfer by thermionic emission is possible, and, once the energy transfer at the surface exceeds a limit, surface evaporation takes place. At low electrode temperatures, transfer by thermionic emission is no longer likely (Jüttner et al. 1997). However, at low temperatures, thermionic emission is still feasible as a material thermionically emits a small amount based on the area of the material and its temperature and type of material – i.e. with a large area the same emission is possible at lower temperatures (Richardson, 1929). However, for small areas, once the electrode is cold, current transfer via thermionic emission is no longer possible (Lancaster, 1984). Electrode heating occurs either at short circuit pilot arc, where a set low current of around 7–11 A is enough to heat the electrode tip and initiate thermionic emission, and at the ignition of the transferred arc, the main arc, with a higher current, which ionises the environment between the electrode and work-piece (da Cruz and Scotti, 2016). Cheng (1970) outlines the potential heat sources that heat the electrode and enable thermal emission:

- Arc electrode coupling, increasing with arc current.
- Joule effect – electric current and impinging plasma particles flowing through a resistance electrode, generating heat, which increases with arc current.
- Arc-radiated heat.
- Exothermic reaction – chemical reaction on the electrode surface that releases heat energy.
- Kinetic and thermal energy – generated by the collision of ions against the electrode cathode.

The electrode temperature losses as a result of conduction and radiation are balanced by the ohmic heating. However, losses do increase as a function of current increases (Lancaster, 1984).

Typically, the arc origin on the electrode tip does not encompass the whole surface area and adheres to a small circular point on the cathode – thermionic cathode spot (Lancaster, 1984). Jüttner et al. (1997) defines the cathode spot as ‘...*an ensemble of heated surface and metal vapour plasma*’. The small, concentrated cathode spot has a particularly high temperature. At high current densities, the cathode spot has been found to move location or divide into several more minor moving spots, towards lower current density locations. The hot surface discharges electrons and evaporated material. The extent of the hot surface establishes the diameter of the cathode spot (Jüttner et al., 1997). The arc column from the cathode spot increases in diameter, reaching a maximum at the work-piece/anode. The column stream entrains the colder denser gas encircling the column, which cools the column boundary, constricting the column and cathode spot diameters (Cheng, 1970; Jüttner et al., 1997).

When the arc is emitted from the electrode/cathode surface, to form the main arc and the required current density, the electrode must reach an increase in temperature at the surface and achieve the necessary energy to sustain the arc emission. If the initial heat lost from the electrode surface is too high, the arc will not be maintained, and the surface temperature will decline back to ambient – thermionic emission will terminate. As electrodes are typically cold prior to arc ignition, the temperature gradient, from ambient to arc temperature, is very steep (Cheng, 1970).

The oxide additions not only reduce the tungsten electrode work function but also affect cathode current attachment, which in turn affects the plasma arc column through the Lorentz force at the cathode. Current attachment is dependent on Owen W. Richardson’s constant melting temperature and work function of the cathode electrode. The temperature of the arc close to the electrode tip is affected by the electrode oxide. This is a result of the current attachment, on the electrode tip, being restricted to the limited liquid area of the tip, dictated by the melting point of the material. For example, thoriated tungsten is at a higher temperature than other tungsten oxides because of its higher

melting temperature. The tungsten material still contributes, only a small quantity because of its high work function, to the amount of material emitted from the oxide-enriched electrode (Kentaro, Shinichi and Manabu, 2009). This explains why an oxide-depleted electrode continues to maintain an arc but struggles to establish a new arc.

The emission of the negatively charged thermion temporarily changes the polarity of the cathode surface to positive, which, through electrostatic attraction, pulls the negative thermions back to the cathode surface.

The electrode tip, heated by ohmic resistance, is cooled on the surface as a result of thermionic emission (Lowke, Morrow and Haidar, 1997) and the electrode boiling-off effect, which helps to reduce tip melting and total loss of tip geometry. In comparison to the electrode shaft, the tip is cooler (O'Brien, 1991). Electrode heating by self-absorption of arc radiation is negligible (Lowke, Morrow and Haidar, 1997).

A higher number of particles are emitted from a material through thermionic emission when:

- The material attraction force, specific to types of material, is lower – i.e. lower surface work function.
- There is a larger surface area to aid particle emission – surface area is proportional to the rate of thermionic emission.
- The material surface is at a higher temperature – i.e. more heat energy to assist in particle emission.
- The surface is coated, as in the case of metal oxides – thoriated tungsten.

The ideal thermionic emitter therefore requires a low work function, large surface area and high melting point.

2.6.4 Electrode Design and Tip Geometry

The design and shape of the PTA electrode tip have become critical for enabling arc stability during welding operations. By shaping the electrode tip into a cone, the area of electrode emission has been controlled – i.e. grinding of GTA electrodes. The electrode diameter, electrode tip angle, flat tip diameter and surface finish of the electrode taper are

all critical factors of the electrode geometry, which can affect an electrodes ability to arc start, arc penetration, melt-pool geometry and electrode longevity (Diamond-Group, 2002). Larger electrode diameters last longer and endure higher currents. However, narrower electrodes are more readily arc started (Diamond-Group, 2002). The geometry of the cone is usually unique to the torch manufacturer, but a concentric smooth form is critical. The electrode, while fitted within the torch, must be central – precisely in the centre of the PTA nozzle (O'Brien, 1991). A non-centred electrode will result in deposit inconsistencies and nozzle damage. Electrode cone geometry incorporates a blunt or sharp tip (Gordon, Dyer and Flanigan, 1989), or, in the case of the PWP Viper MC (water-cooled) torch electrode, used in this study, a parallel length with a 0.36 mm diameter flat tip, shown in Figure 43 'A'.

By sharpening the conical electrode tip, the electrode tip angle angle, for a fixed diameter, is also modified. Sharper electrode tips result in higher electrode temperatures when the current density at the tip is elevated – i.e. when the tip radius is reduced (Lowke, Morrow and Haidar, 1997). Reducing the electrode tip angle of the conical electrode tip – i.e. from this study standard 40° to 20° – affects the location of the maximum temperature of the electrode. At high currents the electrode temperature is increased, with a maximum at a site raised above the small electrode tip angle, electrode cathode tip, resulting in melting above the tip. In GTA this may result in tip detachment and melt-pool contamination – tungsten inclusion (Lowke, Morrow and Haidar, 1997).

Lowke et al. (1997) postulated that the combination of electrical resistance heating is more significant for the smaller angle electrode. This is because of its increased current density, arc heat conduction and thermionic cooling, which results in the maximum electrode temperature being above the tip location for small electrode angles. The effect is different for larger electrode tip angles because of the difference in surface to volume ratios (Lowke, Morrow and Haidar, 1997).

Lowke et al. (1997) determined that larger current densities at the electrode tip result from electrode tip sharpness and that the arc column temperature, arc voltage and current density are lower for pure tungsten than a 2% thoriated tungsten electrode.

Zhou, Ding and Heberlein (1996) identified that the thoriated tungsten electrode tip geometry has minimal effect with regards to the temperature of the tip, but, along with Zhou and Heberlein (1998), they note a significant effect on tip erosion. This is in contrast to Haidar and Farmer's (1994) findings that the geometry has a more significant effect on electrode temperature, with a 60° tip angle found to have the highest temperature. The temperature is highest at the tip, reducing with distance along the electrode.

The sharp, cone-shaped electrode tip cuts through the elongated electrode grain structure, exposing oxide grains and tungsten grain boundaries. Through capillary force, this enables further oxide grains to reach the electrode bevel surface – leading to a surface concentration of tungsten oxide (Ushio, Sadek and Matsuda, 1991).

Electrode diameter is usually chosen based on the required endurance – a wider electrode will last longer – and required current rating is outlined in codes and standards. A too high current for a small diameter electrode results in excessive melting, possible tip detachment and melt-pool contamination. In contrast, a too low current results in arc instability (Diamond-Group, 2002). The electrode diameter for this study's PWP Viper MC torch is fixed at 4 mm.

A reduced electrode tip angle influences the GTA arc length by increasing it for a fixed contact tip work-piece distance (CTWD), resulting in broader and shallower welds for sharper electrodes (Savage, Nippes and Agusa, 1979).

If too large, the electrode flat tip diameter will create arc wander and arc ignition issues. However, if the optimal diameter is established, maximising the flat tip diameter while preventing arc wander and ignition issues, the arc penetration and electrode life are optimised (Diamond-Group, 2002). A general rule is that the electrode flat tip diameter should be around 10% of the electrode diameter (Wolfram Industrie, 2019). The electrode diameter flat tip for this study's PWP Viper MC torch is fixed at 0.36 mm – 9% of the electrodes 4 mm diameter.

Key (1980) established that there is no optimal configuration of shielding gas composition and electrode tip geometry for GTA. Weld penetration increases with tip angle and percentage helium. The relationship between the shape of the GTA arc and electrode

angle was also established, with a larger arc with a bell shape formed with a smaller electrode tip angle, and a smaller, more concentrated, arc formed with a larger electrode tip angle. With the arc concentration comes narrower, deeper melt-pool penetration. The effect of percentage helium for GTA was examined, and helium was found to be less effective for blunt electrodes. However, for sharpened electrodes, the melt-pool fusion zones increased in depth and decreased in width as the percentage of helium increased (Key, 1980; O'Brien, 1991).

Small electrode angles behave as a line heat source, providing a high temperature following the axis, but, because of the small distribution, only a low outer temperature. Alternatively, increased electrode angles act as a large heat source with a more significant temperature distribution and, consequently, deeper melt-pool penetration. Helium percentage was found, because of its thermal conductivity, to generate a more uniform heat source irrespective of the electrode angle, and aid in transferring heat to the work-piece as a result of the gases' specific heat and thermal conductivity. With sharp GTA electrodes, helium can increase melt-pool penetration (Key, 1980).

Key (1980) found that GTA electrodes with a small electrode tip angle and a small flat tip created the most stable GTA arc. Electrode tip geometry is optimal if the arc produced is stable, and sharp GTA electrodes with an electrode tip angle of between 30 and 60 degrees are preferential.

Campbell, Galloway and McPherson (2013) established a relationship between GTA electrode tip angle and peak arc pressure – arc pressure increasing for higher angled electrodes. Fan and Shi (1996) also investigated the GTA electrode angle effect on arc pressure and found, for angles of 60° , 90° and 120° , that peak pressure increased with raised electrode angles, reaffirming this relationship. Fan et al. (1986) examined the effect of truncated GTA electrodes and found that arc pressure reduced with increased truncation diameter.

2.6.5 Electrode Tip Sharpening

For GTA and PTA, the electrode is critical for conducting current. It is therefore crucial that sharpening of the electrode is undertaken correctly, especially as incorrect preparation can lead to arc instability, arc wandering, deposit inconsistencies and defects.

To maintain GTA electrode tip sharpness, grinding is typically undertaken. PTA electrode tips require less resharping. During this operation, the operator is exposed to the associated risks and hazards of thorium oxide particles (Costa, 2014).

On the whole, little academic evidence justifies electrode tip sharpening, and the concept has developed through many years of industrial experience. However, an exception is da Cruz et al. (2016), who investigated the effect of electrode sharpening against thermionic emission for both oxide-doped and non-doped electrodes. They found that, by sharpening the electrode, the surface area for thermionic emission changed and correspondingly reduced the required electrode diameter for emission. They also concluded that sharp GTA electrodes enable easier arc ignition because of higher resistive heating and reduced thermal conduction tip loss, giving a more stable arc during operation and a reduction in gas flow disturbance. However, these effects lessen with electrode use. Doped electrodes have increased current density, therefore enabling a reduced electrode diameter to be used, compared with pure tungsten (da Cruz and Scotti, 2016).

Figure 23 shows two directions possible while grinding electrodes. ‘A’ illustrates the industry-accepted direction, parallel to the electrode length, achieved with a diamond wheel. As this is the direction of the tungsten grain structure, it is thought that there is less current restriction. The arc is straighter, more concentrated and stable, and has increased longevity. Figure 23 ‘B’ shows the grinding direction across the grain structure and is therefore thought to restrict current and lead to coarse arc wandering, readier overheating, increased wear and risk of inclusions in the melt-pool (Diamond-Group, 2002).

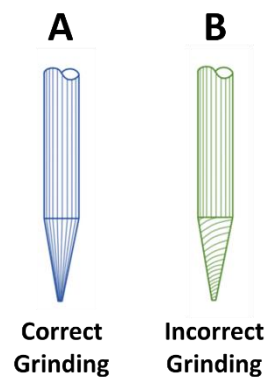


Figure 23 Tip grinding direction. A] Longitudinal (electrode tip lengthwise), B] across/clockwise (around electrode tip).

An alternative method of electrode tip sharpening is chemical, dipping a hot electrode tip into an eroding solution of sodium nitrate. The chemical reaction removes electrode material uniformly on each application, and the process is repeated until the desired tip geometry is achieved (O'Brien, 1991).

During electrode sharpening and handling, the risk of electrode contamination is highest. The risk of contaminating the melt-pool with tungsten through contact is mitigated in PTA by the electrode location within the copper restriction nozzle.

Over sharpening of GTA electrodes may initially improve arc starting but could also result in poor performance and increase the risk of tip detachment.

The PTA electrode material supplier for this study, Wolfram Industrie (2019), recommends longitudinal grinding of electrodes as it produces a more stable arc with improved penetration. Radial grinding has the potential to allow small electrode fragments from melting and detaching from the electrode, resulting in melt-pool contamination and increased tungsten erosion. Grinding of electrode tips must ensure a central tip, as a non-centralised tip could result in an unstable or asymmetrical arc, or failure of arc ignition (Wolfram Industrie, 2019).

Figure 24 illustrates the microstructure of a tungsten electrode after use. By removing two thirds of the electrode's bevelled length, the affected material is eliminated before resharpener, fully rejuvenating the electrode.

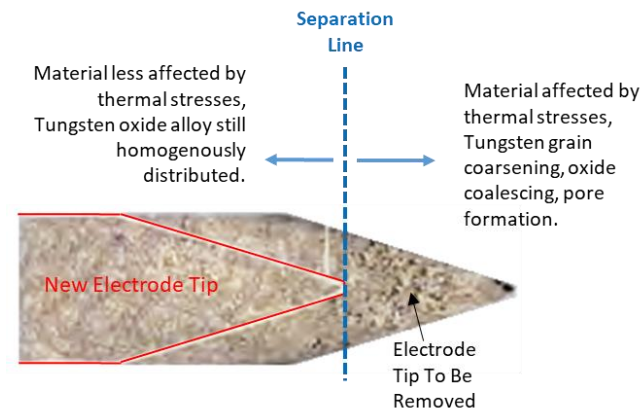


Figure 24 Microstructure of tungsten oxide electrode before and after sharpening. Modified from Wolfram Industrie (2019).

The PWP Viper MC torch electrodes are supplied machined with a tip that cannot be re-sharpened. However, as new electrodes were used and the quality control of the electrode tip was not down to the operator, the electrode geometry was repeatable for the experiments in this study. For example, change in arc voltage from one electrode to another because of geometry differences was not an issue. Additionally, the lathe machining surface marks are perpendicular to the electrode length.

2.6.6 Electrode Wear

Understanding the erosion rate of different tungsten oxide alloys leads to an increase in electrode service life and equipment availability. Once new oxides or electrode designs are developed, electrode erosion rates will diminish (Ushio, Sadek and Matsuda, 1991).

If a too high current – i.e. higher than recommended in the code and standards – is used for a narrow electrode, the material will break down and erode at a higher rate, resulting in melt-pool contamination (Diamond-Group, 2002).

Casado et al. (2001) confirmed the relationship between low current and reduced electrode erosion. However, they also identified for thoriated tungsten that a critical current is associated with maximum electrode erosion: i.e. there is not an increasing linear rate of erosion with rising current, but an intermediate peak.

Ushio et al. (1991) also noted that the evaporated material from the high-temperature GTA electrode tip accumulates at a lower temperature area where the evaporation rate is lower than the migration rate.

Matsuda et al. (1986) investigated the effect for GTA DCEN of electrode consumption by weight with the current after five minutes of initiated arc for various electrode materials, finding that, even for this short duration, pure tungsten electrodes suffer significantly, followed by thoriated tungsten at a much-reduced rate, shown in Figure 25. The investigation also examined the effect of oxygen contamination of the GTA shielding gas on electrode consumption over a 60-second arc ignition. The study showed that, for even very low percentages of O_2 , 0.1 to 5%, resulted in considerable electrode consumption for pure tungsten and a reduced but still very significant amount for thoriated and ceriated tungsten. Nitrogen contamination was found to have minimal effect.

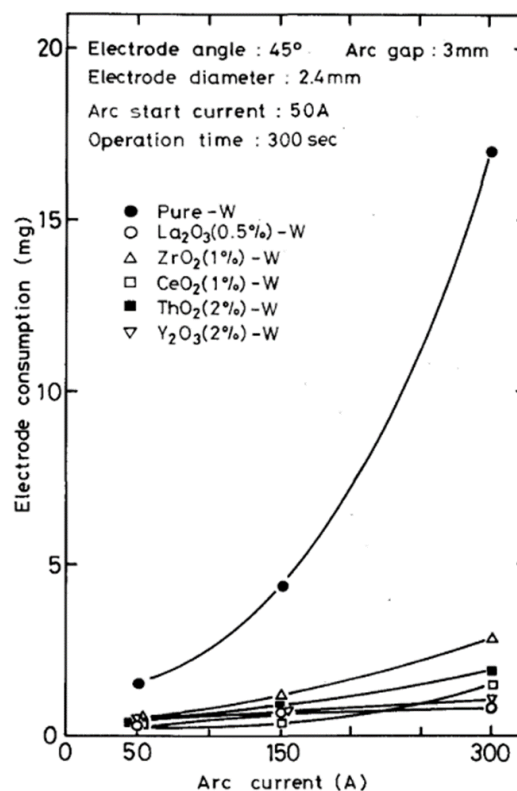


Figure 25 GTA electrode wear versus current for various electrode materials.
(Matsuda et al.1986)

Matsuda et al. (1986) refers to a GTA 'rim' at the cathode boundary and attributes this to dendritic tungsten build-up in oxygen contaminated shielding gas. The material is thought to migrate from the electrode surface through oxidation. The investigation found that the build-up caused arc instability, affecting arc pressure and voltage as a result of its impediment to plasma gas flow close to the cathode (Matsuda et al. 1986).

Sadek et al. (1990) identified and analysed GTA arc photographs of three zones on the electrode, shown in Figure 26: an emitting zone where the arc was brightest, a smooth zone behind and a rough zone above the arc. Their study found that the rough surface zone, 'rim', caused arc stability issues, suggesting that this zone dictates the longevity of the electrode. Their analysis found the rim to comprise of tungsten dendrite and considered it to originate from tungsten oxidation, migrated tungsten and broken-down unstable oxide. Higher up the electrode, the composition is unaffected, and there are concentrations of the oxide on the electrode surface. However, at locations closer to the tip, the concentration of oxide increases, and, at the tip where the temperature is highest, shown in Figure 26, the 'arc emitting zone', oxide evaporation occurs, and the material melting point temperature dictates the evaporation rate for different electrode compositions. At the 'rough surface zone', shown in Figure 26, the temperature is sufficiently reduced to prevent evaporation, and the oxide migration rate is therefore higher than the evaporation rate (Sadek, Ushio and Matsuda, 1990).

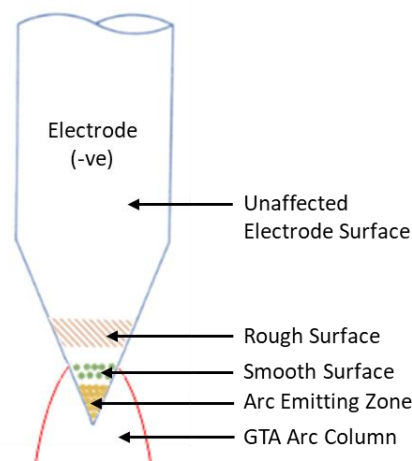


Figure 26 GTA electrode surface during arc burning. Modified from Sadek et al. (1990).

Nemchinsky (2014) refers to the formation of two rings on thoriated tungsten PTA cutting electrodes, and thorough analysis with a scanning electron microscope (SEM) found the first to be tungsten crystals and the second thorium crystals.

Sillero et al. (2010) investigated 2% thoriated PTA electrodes at arc currents between 30 and 200 A for 10 minutes of initiated arc and experienced, in this short time, erosion of the cathode as a result of the high surface temperature. They observed the formation of four distinct bands, shown in Figure 27, which occurred at all arc currents, through the zone widths, shown in Figure 27 'd' enlarged with increasing current. Figure 27 zones are as follows: I) cathode spot zone, II) thorium-depleted zone, III) unchanged zone, and IV) thorium enriched zone.

The cathode spot (Zone I), through energy dispersive X-ray spectrometry (EDS), exhibited porosity as a result of the high temperature and complete thorium depletion after just 10 minutes of initiated arc. The thorium-depleted zone (Zone II) indicated, through EDS, thorium loss via evaporation, which intensified with proximity to the cathode spot, and increases to temperature with increased arc currents. The start of surface tungsten crystal formations was also observed via an SEM. At the unchanged zone (Zone III), the percentage thorium was found to be similar to a new cathode. The thorium surface enriched zone (Zone IV), as a result of surface thorium crystal formations, was observed via SEM. The weight percentage of thorium was found, via EDS, to be significantly high, a factor of ten higher in Zone IV than the original cathode (Sillero et al. 2010).

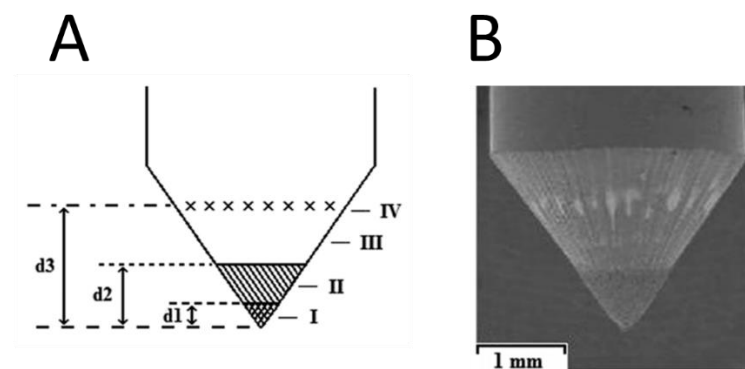


Figure 27 Cathode zones after 10 minutes of PTA arc. A] Illustration of zone location, B] SEM micrograph after 10 minutes at 100 A. (Sillero et al. 2010).

Sillero et al. (2010) also determined that the cathode spot temperature and current density increase with arc current that the work function also increases with cathode spot temperature and arc current, plateauing at approximately 200 A.

All thermionic cathode electrodes erode. Operating the PTA process should therefore be adapted to tolerate it. Manual GTA, for example, can endure electrode erosion if melt-pool contamination is avoided, by accounting for periodic electrode sharpening or replacement in the task duration estimate. Erosion encountered during plasma cutting is less tolerable as it restricts current, travel speed, plate thickness and electrode life (Nemchinsky, 2014).

Nemchinsky (2014) outlines two forms of PTA cutting electrode erosion, reducing electrode longevity:

- Constant current erosion as a result of electrode tip evaporation. Thought to be the principal method of erosion.
- Cycling erosion during arc ignition and arc termination, which could result in erosion.

Erosion by molten electrode tip droplet discharge should also not be discounted and is the likely cause of pure tungsten's high erosion rate. This may result in melt-pool contamination. Nemchinsky (2014) attributes the large droplet discharge erosion to the pinch effect and drag force of the plasma gas on the molten electrode pool.

During PTA activities, with the arc operating the hot electrode, tip material evaporates. However, the lost material returns to the electrode, resulting in a higher evaporation rate than the constant current erosion rate (Nemchinsky, 2014).

Nemchinsky (2014) showed experimentally and via modelling that the electrode tip geometry and the plasma gas flow around the electrode tip are significant, with a flat electrode tip reducing erosion but increasing arc instability. Gas swirl, incorporated in the torch design to improve restriction nozzle longevity, increases the erosion rate of the electrode.

An electrode with a lower work function can thermionically emit electrons at a reduced temperature and consequently at a decreased rate of erosion, making the work function a critical characteristic for electrode selection for increased PTA duty cycles – i.e. WAAM part building (Nemchinsky, 2014).

Wear of GTA electrodes is considered to result from high-temperature melting of the electrode and contamination of shielding gas oxidising the electrode; and using a too high current then is recommended for the electrode diameter, and material vaporisation. The concept of an electrode growth is proposed but little understood. Studies have also shown, for GTA, that lanthanated and ceriated electrodes outperform pure tungsten and thoriated tungsten. However, very little is considered in the literature for PTA, especially where different electrode materials are less readily available, and the arc conditions are more extreme. The durations of initiated arc utilised by Matsuda et al. (1986) to investigate electrode consumption are too short, in single-digit minutes to be definitive.

The high temperatures encountered at the electrode/plasma gas boundary are in excess of the melting point of the tungsten alloy. Erosion at this site is therefore inevitable. The rate of electrode erosion regulates the longevity of the electrode and consequently the availability of the PTA torch (Camacho, 1988).

Thoriated tungsten electrodes ‘emit’ at a lower temperature than its melting point, shown in Table 3. da Cruz et al. (2016) postulates that emissions of pure tungsten electrodes take place at the required current via the thermionic process at temperatures higher than its melting point. In contrast, thorium doped electrodes have an increased emission temperature, but below its melting point and its corresponding electrode wear, leading to loss of tip sharpness and reducing GTA electrode tip melting of doped electrodes compared with pure tungsten.

With use, oxide tungsten electrode surfaces become pitted and porous. This is thought to be because of material evaporation (Nemchinsky, 2014).

Nemchinsky (2014) has experimentally established for PTA cutting electrodes that the erosion rate is initially high and reduces with time for fixed parameters.

In some PTA torch designs, the electrode is adjustable/extendable to allow for electrode erosion (Camacho, 1988). However, this is unfortunately not a feature of this study's PTA torch, PWP Viper MC.

The impact and cause of electrode surface growth in PTA are also yet to be examined.

2.6.7 Effect on Arc Pressure

Kentaro et al. (2009) measured the arc pressure values of three tungsten oxide electrode materials for GTA, shown in Figure 28. They found that arc pressure diminishes with distance from the arc and that ceriated and lanthanated materials had equal distributions. Thoriated tungsten had a similar distribution but a lower peak pressure. No indication of the arc pressure measurement method was recorded.

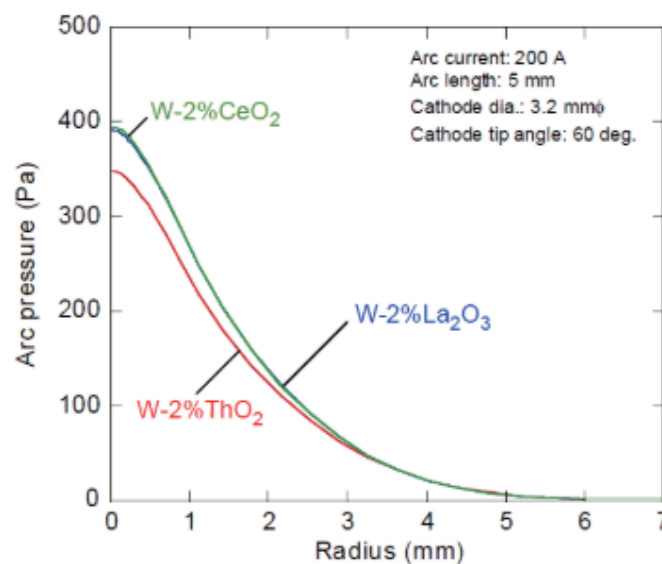


Figure 28 GTA arc pressure distributions for ceriated, lanthanated and thoriated electrodes. (Kentaro, Shinichi and Manabu, 2009)

Matsuda et al. (1986) established, via a water-cooled copper anode and semi-conductor transducer, the arc pressure values for six tungsten oxide electrode materials for GTA. The results are shown in Figure 29. The distributions indicate that Yttrium oxide-alloyed tungsten electrodes have the maximum arc pressure value, with thoriated tungsten at a significantly reduced value, and pure tungsten electrodes have the least measured arc pressure.

The two sets of values use different GTA torches, arc lengths, electrode diameters, electrode flat tip diameters and electrode tip angles, which may explain the difference in measured values. However, the order of tungsten alloy arc pressure values does correspond.

Sadek et al. (1990) conjectured that the high GTA arc pressure values of ceriated, lanthanated and yttriated tungsten, shown in Figure 29 'A', are a result of their small electrode tip deformation. In contrast, thoriated and pure tungsten, which suffered the worst tip deformation, have the lowest arc pressures.

Matsuda et al.'s (1986) results are shown in Figure 29 'B' and 'C'.

Figure 29 'B' implies that, as the GTA electrode tip diameter increases, the measured peak arc pressure decreases. The author concluded that the truncation of the electrode tips impedes the flow of plasma gas and affects the electrode thermal state, resulting in reduction in peak arc pressure (Matsuda et al. 1986).

Figure 29 'C' indicates that, for GTA, the peak arc pressures increase with the current for all materials, but at a reduced rate for thoriated tungsten and at a significantly lower rate for pure tungsten. The results are attributed by the authors to the change in tip geometry of the thoriated and pure tungsten electrodes as a consequence of tip melting affecting the electrodes' thermal state and increasing opposition to the flow of plasma gas. The other tungsten alloys are less affected by a change to their tip geometry (Matsuda, Fukuhisa, Ushio, Masao and Kumagai, 1986).

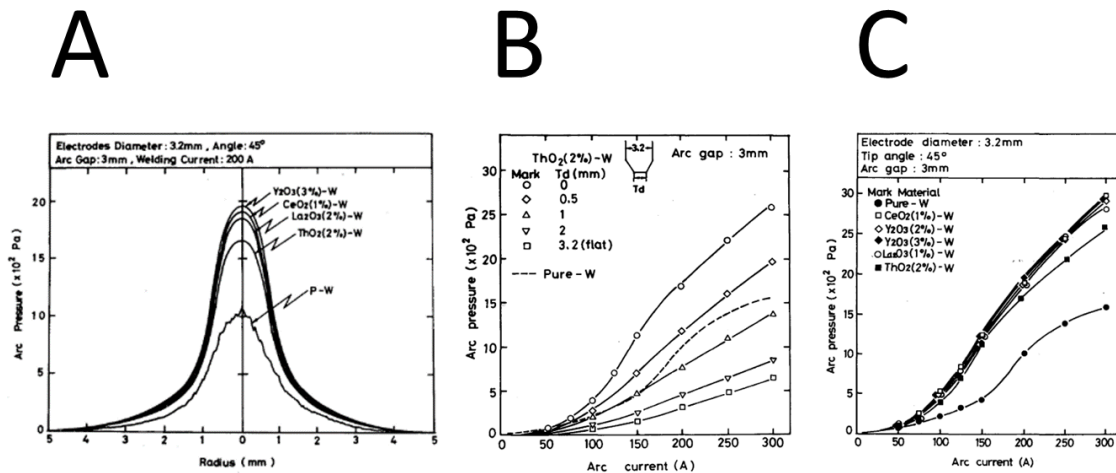


Figure 29 GTA arc pressure distributions. A] Arc pressure distributions with distance for various electrode materials, B] Arc pressure peak values vs current for electrode flat tip diameters, C] Arc pressure peak values vs current for different electrode materials. (Matsuda et al. 1986; Sadek, Ushio and Matsuda, 1990)

2.7 Keyhole

2.7.1.1 Power Density Comparison of Welding Processes

Figure 30 illustrates the power density range of various welding processes. Other arc processes refer to GTA and shielded metal arc (SMAW). The plot is split into four regions:

A) Above 10^{13} W/mm² welding is not possible and vaporisation is dominant, with minimal radial heat conduction. At these or higher power densities, a small, focused hole will penetrate through the material, with minimal heat transferred to the work-piece: e.g. high-powered pulsed lasers (Lancaster, 1984).

B) Within the range of 10^{10} to 10^{13} W/mm² vaporisation (keyhole formation), heat conduction and melting (fusion) take place – keyhole. The power and heat source size is critical and enables deep or full penetration. Processes include high power PTA, laser and electron beam (Lancaster, 1984).

C) Below 10^{10} , radial conduction dominates with heating, melting and fusion of the material, with minimal vaporisation taking place. Within this region, typical welding processes take place: e.g. GTA, SMAW and low power PTA (Lancaster, 1984).

D) Below approximately 3×10^6 W/mm², welding is not possible because of significant conduction of heat limiting/preventing material melting and fusion (Lancaster, 1984).

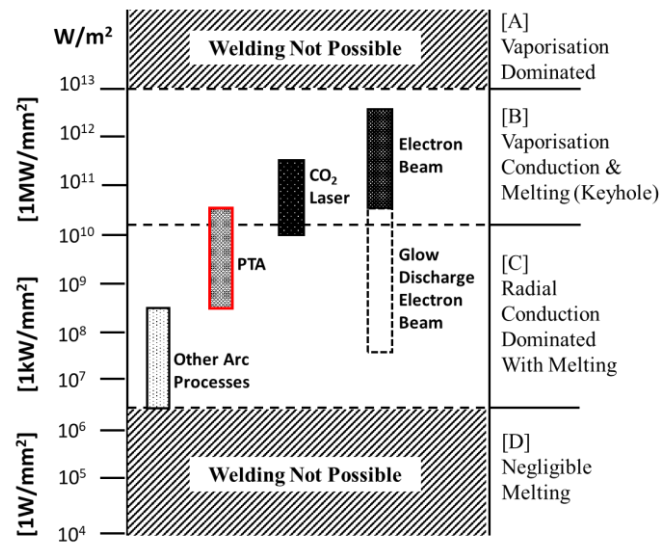


Figure 30 Comparison of power density for various welding processes. PTA highlighted in red. Adapted from a figure within ‘The Physics of Welding’ (Lancaster, 1984).

PTA exhibits a significantly higher energy density, increased gas velocity and momentum as a result of the constrained arc when compared with the unrestricted GTA arc. As stated above, PTA like laser and electron beams can develop keyhole, but at a reduced cost. This is only achievable at its high end of operational capability – i.e. once it obtains a high energy density, as shown in Figure 30. However, by producing a keyhole, deep single-pass seam welds, either autogenous or with filler wire, but with minimal thermal distortion, and without the need for weld preparations, can be generated. The PTA keyhole is not as intense as both laser and electron beam, meaning that the keyholes produced are broader (Metcalf and Quigley, 1975; Martikainen and Moisio, 1993). PTA keyhole is also predominantly formed and maintained by arc pressure, contrary to the metal evaporation recoil pressure employed by laser and electron beams (Fan and Kovacevic, 1999). To raise PTA power density, either the current and voltage must be increased or the cross-section of the thermal arc plasma decreased by means of changes to the restriction nozzle diameter through physical constraint and thermal pinch from the orifice gas (Park and Hirata, 2017).

2.7.1.2 Keyhole Mode of Operation

PTA, unlike GTA, can produce a higher arc power density, as high as $3 \times 10^{10} \text{ W/m}^2$, enabling a keyhole process mode (Martikainen and Moisio, 1993). A schematic of PTA keyhole mode is illustrated in Figure 31 'A'. Both PTA and GTA can join relatively thick titanium. However, only PTA in keyhole mode can achieve this in one pass, and, with much higher depth to width ratios, better direction control, without filler wire, from a single side, with enhanced quality, and at an increased rate, even for difficult materials like titanium, compared with other traditional welding methods such as GTA (Langford, 2018).

PTA keyhole mode can be used to generate parts with reduced distortion and increased joint strength compared with GTA and gas metal arc welding (GMAW), at a lower cost than electron beam, whilst avoiding the vacuum chamber restrictions. This is, however, at the expense of travel speed (Langford, 2018).

The substrate temperature is established by the total of the heat input from the PTA heat source and the heat lost by heat conduction into the surroundings. Phase transition, from solid to liquid and liquid to gas, arises when energy per unit volume to the substrate is enough. Once the thermal flow into the substrate is sufficient and the power density is elevated, material melting and vaporisation can take place (Park and Hirata, 2017).

In PTA keyhole mode, the plasma streams intense, concentrated heat and focused impinging arc pressure, produced by the arc current, restriction nozzle and PGFR (Short et al., 2011), penetrating by creating a hole or going partially through the substrate metal, similar to electron beam or laser welding (TWI, 2016a; Mendez and Eagar, 2001). Narrow weld beads, minimal thermal distortion and a minimal heat-affected zone (HAZ) are achievable with keyhole (Martikainen and Moisio, 1993). Joining relatively thick material butted together without edge preparations is possible in a single pass with keyhole. PTA keyhole is also more tolerant of edge misalignments than electron beam and laser keyhole but has a broader keyhole because of its reduced energy density (Tekere and Özdemir, 2013). The molten metal is transferred to the surface of the bead by the penetrating plasma stream. It flows around to the back of the penetration under the forces of surface tension (TWI, 2016) and electromagnetic and buoyancy forces (Fan and Kovacevic, 1999) as the

PTA torch transitions along the substrate material, shown in Figure 31 'B', solidifying and creating the characteristic keyhole shape and deposit bead (Martikainen and Moisio, 1993; O'Brien, 1991). PTA keyhole is a balance between fusion/conduction welding with minimal penetration and PTA cutting with full penetration, where the molten metal is ejected by the arc, rather than being transitioned to the back of the penetration to solidify as the bead. The weld quality of PTA keyhole relies on the stability of the keyhole, which in turn depends on a reasonably small range of parameters. The temperature profile of the melt-pool and around the keyhole is also critical for keyhole stability (Tekere and Özdemir, 2013). On initiating the PTA arc, it is customary to allow the arc to establish before moving the torch position. If this intermission is too long, an unstable melt-pool can be produced and can collapse, causing an initial hole at the beginning of the bead (Metcalf and Quigley, 1975; Zhang et al., 2014; Liu, Wu and Chen, 2012).

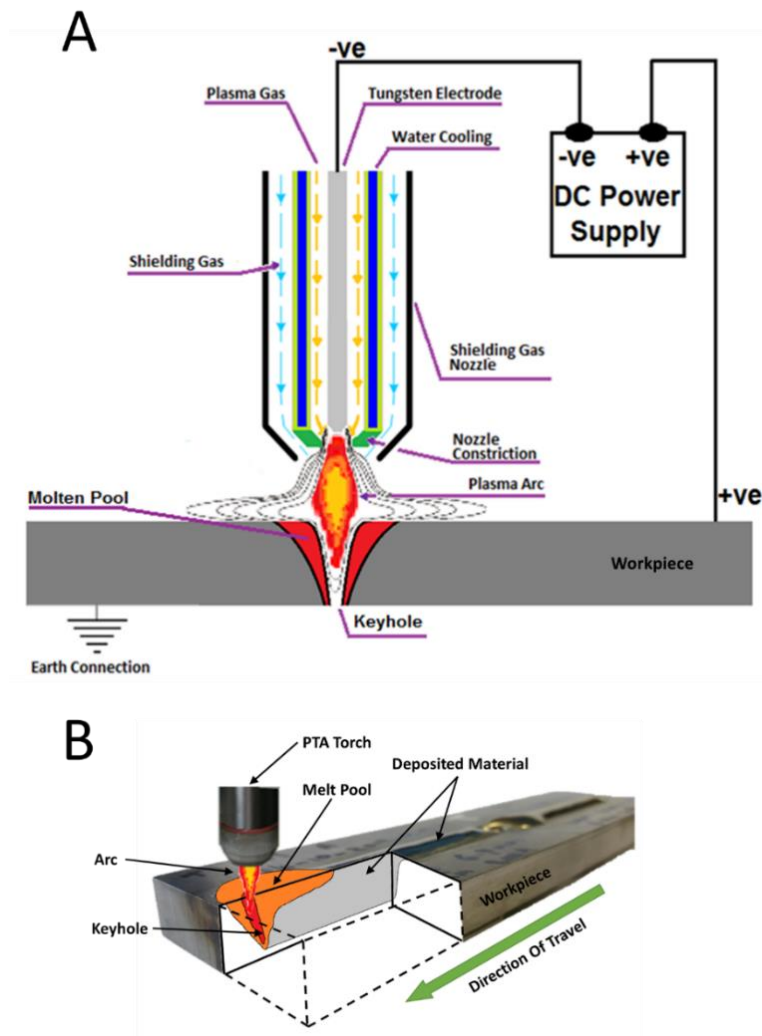


Figure 31 PTA keyhole operation mode. A] Annotated schematic of keyhole mode of operation, B] Isometric view of keyhole in operation sketch.

Displacement of the melt-pool is a reflection of the force distribution and can influence the shape of the deposit through induced melt-pool liquid motion (Lin and Eagar, 1986). This transfer is beneficial to penetration in welding (Traidia et al., 2011), through the development of a keyhole. Also, Zhang et al. (2015) concluded that arc pressure has an advantage in offsetting the effects of gravity in positional welding. However, in WAAM, a depression in the melt-pool can lead to changes in layer geometry and, eventually, defects. Keyhole defects are also detrimental to the process, requiring time-consuming repairs.

The keyhole volume and penetration depth are dictated by the equilibrium of the PTA arc current, ionised gas nozzle exit velocity and the melt-pool surface tension, shown in Figure 32 'B'. Too high current and gas velocity transitions PTA keyhole to plasma cutting, shown in Figure 32 'A', where the high-velocity gas overcomes the melt-pool surface tension and expels the molten material through the substrate material (O'Brien, 1991). To enable a stable keyhole, the diameter of the keyhole must be smaller than the melt-pool diameter. If the keyhole diameter is larger, then keyhole is no longer possible (Metcalf and Quigley, 1975). Figure 32 'A' illustrates a situation where the thickness of the material is less than the width of the keyhole. In this circumstance, the molten metal is drawn by surface tension, which minimises the surface area and energy (Fan and Kovacevic, 1999) back to the work-piece, overwhelming the forces attempting to close the keyhole and resulting in PTA plasma cutting. Figure 32 'B' shows partial penetration, with a high depth to width ratio. In this case, the hydrostatic head and surface tension counteracts and balances the arc pressure, vapour pressure and recoil pressure (Lancaster, 1986).

The parameters controlling the quality of the keyhole mode are current, travel speed, shielding gas flow-rate, and, particularly, the PGFR (Martikainen and Moisio, 1993; Short et al., 2011). A keyhole melt-pool forms because of the arc pressure and heat distribution and as a result of the nozzle restriction and PGFR (Short et al., 2011).

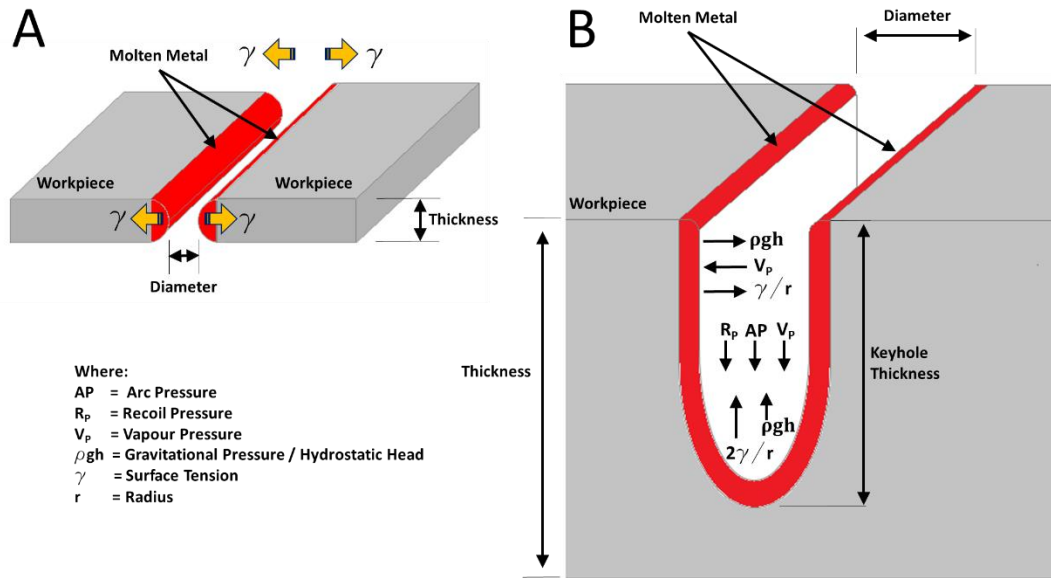


Figure 32 Forces that create and sustain keyhole. A] Full penetration keyhole of thin material, B] Partial penetration keyhole of thicker material. Based on images from Lancaster (1986).

Travel speed affects heat input and the duration the plasma stream has to act on the substrate. At decreased speeds, more heat is imparted to the substrate, resulting in a large melt-pool and large keyhole within. However, at increased speeds, the heat input is reduced, and the corresponding keyhole is shorter and narrower, with a reduction of area (Liu, Wu and Chen, 2012).

Short et al. (2011) found it challenging to achieve full penetration for large PTA restriction nozzles on thin substrates but observed that, when the nozzle geometry is selected in relation to the substrate thickness, the transition from partial to full penetration keyhole occurs with gradual increases to PGFR, arc current or reductions to travel speed. The significance of nozzle geometry is understandable given its influence on the arc pressure distribution. Decreasing the nozzle diameter concentrates arc pressure and increases the current density and arc momentum, which increases the penetration while maintaining fixed values of current and PGFR (Short et al., 2011). Langford, (2018) asserted the importance of PGFR in PTA penetration and keyhole.

PTA keyhole mode is attributed to a high arc pressure. The stability of the keyhole therefore relies on the traits of the PTA arc force and arc energy. Zhang et al. (2015) postulate that, for a straight-bore nozzle, if the arc force is maintained, the heat input will

become inadequate. However, if the heat input is maintained, the arc force will become too substantial to maintain a stable keyhole. This is explained by the arc pressure being proportional to the square of the current. Zhang et al. (2015) propose their novel three-hole nozzle design as the solution, as lower arc pressures can be achieved at high arc currents, enabling stable PTA keyhole.

Increases to arc current increase the heat input and arc pressure, resulting in keyhole growth (Liu, Wu and Chen, 2012). The PTA arc force and thermal conditions also affect the hydrodynamic processes within the melt-pool and are therefore of significance to the PTA keyhole mode of operation (Bashenko and Sosnin, 1988). The arc pressure is significant in PTA as it influences the melt-pool geometry (Zhang et al., 2014). Arc pressure and heat input/arc energy, either singularly or together, can be used to control the melt-pool. A high current maintains fluid flow within the melt-pool, where as a small arc pressure balances the melt-pool forces. High arc pressure is accredited with keyhole initiation and stability (Zhang et al., 2015). The PTA arc force can be significantly high to result in full penetration keyhole of a thin plate (Bai et al., 2018). The substrate material influences PTA keyhole through its characteristics of surface tension, thermal conductivity and viscosity, which affect the parameters required to establish and maintain a stable keyhole (Martikainen and Moisio, 1993).

This operating mode is detrimental to the WAAM process, as inaccuracies or keyhole defects on a deposited layer affect its quality and impede its ability as a good base for subsequent layers (Ermakova, Mehmanparast and Ganguly, 2019). Process parameters must therefore be selected for the characteristics of the material, viscosity and surface tension to avoid keyhole defects.

2.8 Bead Humping

Increasing the current, travel speed and wire-feed rate will improve WAAM productivity and reduce production costs. However, flaws, including bead hump formation, limit the efficiency of this increase (Soderstrom and Mendez, 2006). Increasing travel speed necessitates an increase in heat input – i.e. increase in arc current to maintain the melt-pool. Bead hump formation arises in several welding processes, including but not limited to GMAW, laser and GTA.

Bead humping is a deposited bead formation, which includes several peaks and troughs regularly spaced along the bead length. It arises when a specific value of the travel speed is exceeded (Cai, Wu and Gao, 2017; Nguyen and Weckman, 2007). The critical value decreases with increased arc current as a result of the increased arc pressure (Marinelli et al., 2019). At high currents and travel speed, the molten metal at the front of melt-pool either traverses to the back of the melt-pool, as in Figure 34 'A', via a thick rim around the melt-pool, or quickly freezes in milliseconds, forming a hump, as shown in Figure 34'E', which is dictated by the equilibrium of forces. The forces are arc pressure and shear from the arc, electromagnetic, Marangoni, hydrostatic and capillary forces, shown in Figure 34 'B'. At the base of the gouged region tip in Figure 34 'B' is a transition point, and to its left is a thin layer of molten metal under the arc, with no recirculating fluid flow on top of the substrate. To the right, the trailing region is fed the majority of the molten metal via the thick rim around the melt-pool. The transition line moves rearward with increased current. Bead hump formation occurs when the transition point moves sufficiently far from the arc that the heat source is insufficient to prevent freezing, shown in Figure 34 'E' (Mendez, Niece and Eagar, 1999; Soderstrom and Mendez, 2006).

Soderstrom et al. (2006) and Cai et al. (2017) both characterise two separate types of bead humping: gouging region morphology (GRM) and beaded cylinder morphology (BCM). Figure 33 'A' shows an example of GTA GRM, generated at high current and travel speed, and displays the characteristic deep open depressions, gouging regions below the substrate surface caused by the arc, alternating between humps, where the majority of the molten metal solidifies (Cai, Wu and Gao, 2017). BCM is shown in Figure 33 'B' and 'C', the evident difference with GRM being the absent depressions below the substrate surface between the humps. BCM is not considered further by this study (Soderstrom and Mendez, 2006).

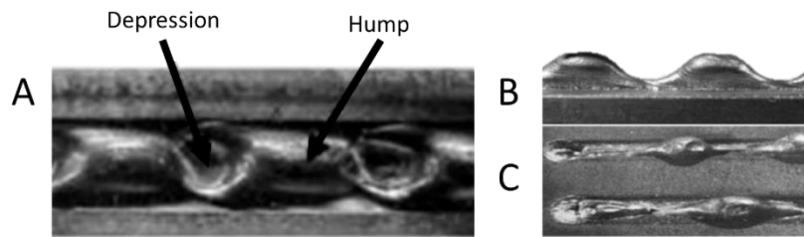


Figure 33 A] Plan view of GRM, B] Side elevation of BCM, C] Plan view of BCM. Images courtesy of Soderstrom and Mendez (2006).

In Mendez et al.'s (1999) study of bead hump with a depressed melt-pool, high current and travel speed, they outlined their explanation for GRM bead hump formation based on the concept of premature freezing of the gouging region, illustrated in Figure 34. Mendez et al. (2003) found that, for GTA at high currents, the deep depression shape generated resembles that of a keyhole.

As a result of the travel speed, the melt-pool, which would be directly under the arc at low speeds, moves rearwards. The arc pressure mainly acts on the front of the melt-pool, generating the gouged region with its thin layer of molten metal, shown in Figure 34 'A', and enabling the traverse of the molten metal, via the arc pressure pushing it, to the trailing region. The arc pressure has minimal effect on the trailing region because of the distance from the arc. The increase in penetration is a result of the thin liquid layer, without recirculation, in the gouging region, allowing the heat source to interact with the underlying material. As a result of the minimal recirculation, heat absorption and distribution, minimal increases in the efficiency of heat transfer to the underlying metal and enhancing penetration take place (Mendez, Niece and Eagar, 1999; Mendez et al., 2003).

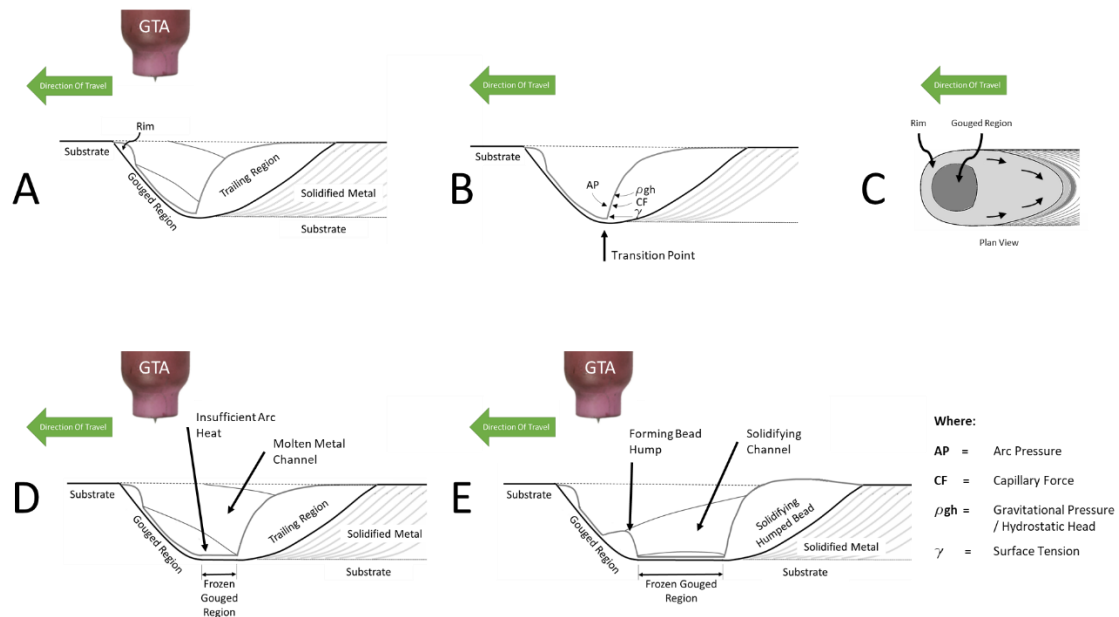


Figure 34 GTA formation of a bead hump. A] Small distance between arc and gouging region, B] Acting forces, C] Plan view of the rim and gouging region, D] Increased distance of the trailing region from the arc, E] Bead hump formation. Based on images from Mendez, Niece and Eagar (1999) and Mendez et al. (2003).

Figure 34 ‘A’ shows a relatively small gouged region, close to the arc and consequently sufficient heat to enable molten metal transition to the trailing region via the rim, ‘C’. ‘D’ depicts an increased distance of the transition line from the arc and aids penetration little – because of the reduced heat, the trailing region freezes. ‘E’ shows a further increase of the transition line from the arc, situated at the maximum penetration with a horizontal interface. At this point, the rim channels start to freeze/solidify and stop feeding the trailing region, which also solidifies. As new molten metal is no longer able to transition to the trailing region, a bead hump starts to form at the front of the melt-pool (Mendez, Niece and Eagar, 1999; Mendez et al., 2003).

Arc pressure has a strong effect on the initiation of GRM humping, as it creates the gouging region below the arc, and can increase the region beyond the influence of the heat source, resulting in premature molten metal freezing. The material surface tension strongly affects the bead and hump shape, and different material thermal conductivities affect humping. The faster heat is dissipated, the quicker the molten material

freezes/solidifies, giving insufficient time for humping to occur (Soderstrom and Mendez, 2006).

Figure 35 illustrates the GTA arc pressure distribution over the gouged region. Mendez et al. (2003) suggest that the arc pressure distribution, typically Gaussian when applied to a flat surface, changes for a deformed surface, as seen in keyhole and hump formation. This change skews the effect of arc pressure. Arc heat input to the deformed surface is equally skewed. The trailing region is too far from the arc to be affected by the arc pressure (Mendez et al., 2003).

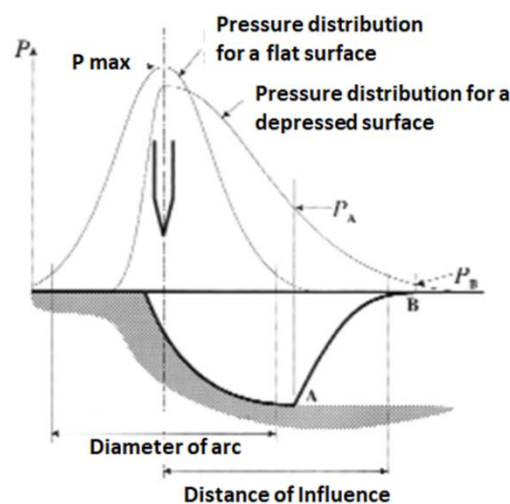


Figure 35 Arc pressure distribution for a depressed surface. (Mendez et al., 2003)

Marinelli et al. (2019), during his investigation into the effect of GTA shielding gas composition and welding speed when welding tungsten, established that bead hump formation occurred in gas mixes with a low percentage of helium, and when utilising high travel speeds, both as a result of their reducing effect on heat input.

Cai et al. (2017) suggest maintaining a high temperature in the melt-pool, preventing rapid molten metal cooling and enabling travel of the liquid metal, which suppresses bead hump formation. Alternatively, Soderstrom et al. (2006) postulate a means of reducing GTA GRM humping by reducing the arc pressure by means of changes to the electrode tip angle, using hollow electrodes, or different shielding gases or torch angle, and asserts that minimising the arc pressure restrains the initiation of humping and therefore enables the desired travel speed increase.

2.9 Gas Composition

PTA plasma gas composition and the consequential arc directly influence the melt-pool and its shape, the permitted travel speed, the aspect and geometry of the deposited bead, and potential deposit flaws. The correct selection is therefore crucial for WAAM operations (Martikainen and Moisio, 1993).

Argon gas is typically chosen for both shielding and plasma gases because of its availability and low cost. However, it is not always the best selection for all applications. Additionally, it has the drawback of poor heat transfer to the substrate, resulting in limits to the melt-pool width and depth compared with other gases (Traidia et al., 2011). There is no reaction between the melt-pool and argon gas, which does not dissolve into the molten metal. Argon also has a low coefficient of thermal conductivity. Argon helium plasma mixed gas results in a hotter arc and increased power density and consequently leads to more extensive and flatter melt-pools and deeper penetration (Martikainen and Moisio, 1993).

Figure 36 illustrates the gas properties of four gases, and argon has the lowest specific heat 'A' and thermal conductivity 'C', while hydrogen has one of the highest. The argon, hydrogen and nitrogen specific heat peaks, 'A', indicate the energy to ionise each gas. The equivalent for helium is considerably higher, at 20,000K. The electrical conductivity 'B' is comparable for three of the gases, helium being significantly lower as a result of its reduced electron density and higher ionisation temperature. The gas viscosities 'D' are comparable for three of the gases up to a specific temperature, but, at higher temperatures, helium's viscosity increases. At all temperatures, hydrogen has the lowest viscosity as a result of its reduced mass. Higher viscosity facilitates the widening of the gas flow distribution and reduces velocity. The shear stresses for helium are also less than the other gases because of its high viscosity. The arc voltage is affected by gas composition – e.g. increases in the percentage of helium in argon result in increases in arc voltage. Substrate temperature increases with increased percentage of hydrogen and helium in argon, with only small amounts of helium required to have an effect. Mixed gases – e.g. 50% argon and 50% helium – have gas properties intermediate to that of the separate undiluted gas (Tanaka et al., 2008).

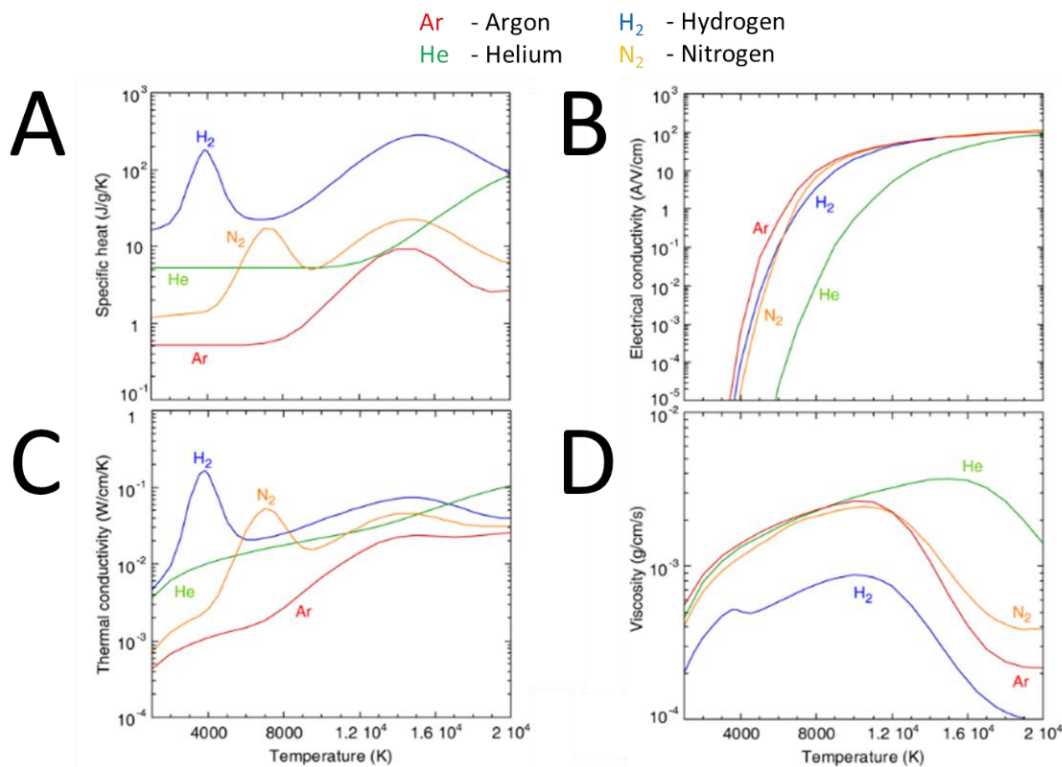


Figure 36 Properties of four gases against temperature, Kelvin. A] Specific heat, B] Electrical conductivity, C] Thermal conductivity, D] Viscosity. (Tanaka et al., 2008)

Tanaka et al. (2008) investigated different gas compositions for GTA and established that changes to the shielding gas significantly influenced the GTA arc properties. In addition to melt-pool protection, the shielding gas and its composition also enable current flow and is a significant characteristic of the GTA arc (Traidia et al., 2011). When compared with pure argon helium, hydrogen and nitrogen, either individually or combined with argon, increased the arc voltage, velocity, arc temperature, heat flux density and substrate temperature. They established that a decrease in electrical conductivity by increasing the helium percentage, shown in Figure 36 'B', reduced the region through which heat and current can flow and therefore constricted the GTA arc and increased the current density, reducing the arc column cross-section and increasing the arc temperature because of increased ohmic heating and high thermal conductivity of helium, shown in Figure 36 'C', as well as velocity because of the constricted arc and magnetic pinch. This all increases the heat flux at the substrate. The pressure gradient is relative to the arc current density and magnetic field strength (Tanaka et al., 2008; Traidia et al., 2011).

Oh, Kim and Cho (2005) investigated, for GTA, the effect of five different shielding gases (100% Ar, 67% Ar / 33% He, 50% Ar / 50% He, 33% Ar / 67% He, 100% He) on measured arc pressure. They established that, as the percentage of helium is increased and the percentage of argon decreased, the GTA arc pressure reduced and the pressure distributions increased in height with increased current values.

To improve the GTA melt-pool depth, helium is often added to argon shielding gas. The addition of helium raises the current density, shown in Figure 37 'B', heat flux density, shown in Figure 37 'A', and the energy transfer at the melt-pool surface, causing an enlarged melt-pool depth. Conversely, increasing the percentage of argon in helium by 10% reduces the melt-pool depth significantly. This is a result of the increase in electrical conductivity, shown in Figure 36 'B', and decreased heat flux, shown in Figure 37 'A', with the increased proportion of argon. Traidia et al. (2011) found that, for their GTA setup, 90% helium/10% argon shielding gas caused the on-axis heat flux, shown in Figure 37 'A', to rise by a factor of 2.3 and 6.5 for 100% helium. This is because of the decreased electrical conductivity of pure helium, shown in Figure 36 'B', compared with a helium–argon mix. The addition of helium to argon shielding gas also increases the plasma temperature and velocity. The percentage split of gas mixes has to be determined experimentally for different substrate materials and each application (Traidia et al., 2011).

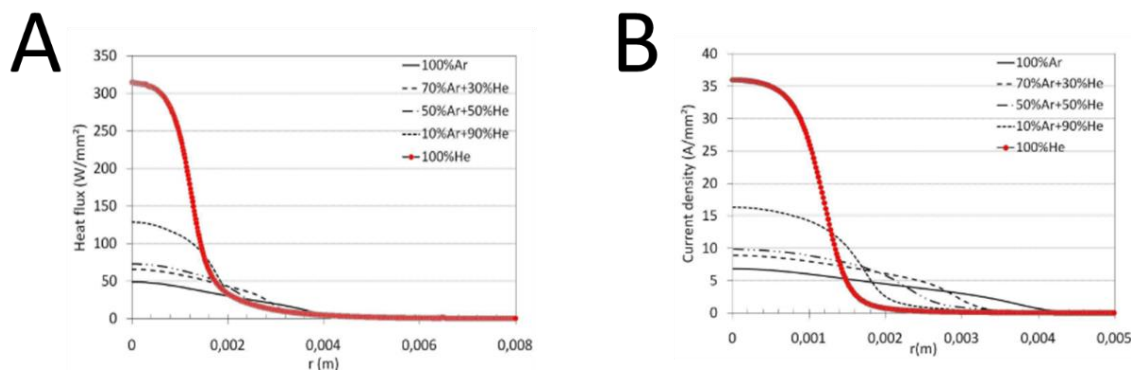


Figure 37 Effect of GTA shielding gas composition. A] Heat flux, B] Current density. (Traidia et al., 2011)

Schnick (2016) established that, for helium–argon plasma gas mixtures, the gas viscosity is the most influential property, and for hydrogen mixtures the thermal conductivity is dominant.

Tseng, Hsieh and Tseng (2003) found that by adding hydrogen to the argon GTA shielding gas, arc voltage and correspondingly arc power increased, and an increase in heat transfer to the substrate resulted in a larger melt-pool.

Different plasma gas compositions and their properties affect the internal protection boundary layer of colder, dense, non-ionised gas, acting as an insulator between the nozzle wall and arc. This can result in the nozzle overheating, double-arcing and nozzle damage (Colombo et al., 2007).

While utilising plasma gases that require more energy to ionise as a result of their higher work function values, shown in Table 5, the arc temperature increases (Weman, 2012).

Table 5 Ionisation energy for different plasma gases. (Weman, 2012)

Gas	Work function (eV)
Argon (Ar)	15.7
Carbon Dioxide (CO ₂)	14.4
Helium (He)	24.5
Hydrogen (H)	13.5

Langford (2018) asserted that PTA penetration depth decreased as a consequence of an increased percentage of helium in the argon plasma gas, once it transcended 60%.

2.10 Arc Pressure

Arc pressure (pressure on the melt-pool) comprises two pressures: the static axial electromagnetic (current induced magnetic field) and dynamic axial plasma pressure. Plasma pressure is the main factor, with electromagnetic pressure at its highest close to the electrode (Yang et al., 2017). Arc pressure is a momentum transfer phenomenon (Oh, Kim and Cho, 2005) that exerts an impinging force because of high-velocity plasma (Fan and Shi, 1996) to the melt-pool surface – stagnation pressure (Traidia et al., 2011; Oh, Kim and Cho, 2005; Adonyi, Richardson and Baeslack, 1992). This can overcome melt-pool surface tension (Short et al., 2011) and result in surface depressions and eventually defects (Lin and Eagar, 1986).

The arc pressure impinging on the melt-pool surface is a significant factor in penetration depth and deposit bead geometry. A high arc current is desirable with regards to productivity increases. However, this also raises the arc pressure, which in turn can increase the melt-pool depression depth and penetration, and the potential for defects such as humping, undercut and tunnel porosity (Campbell et al., 2013; Oh, Kim and Cho, 2005).

Arc pressure is a factor that determines the depth of GTA penetration. A high arc pressure is required to achieve depth of penetration. However, too high pressure can cause blow-through (Fan and Shi, 1996; Dai, Shen and Wang, 2018).

Lin and Eagar (1986) reported a linear relationship for GTA between rising arc pressure and increasing arc current. Fan, Ding, Ushio, Masao and Matsuda (1986) observed an arc pressure distribution approximating Gaussian for GTA below 250 A, but the distribution became sharper at higher currents. The author asserted that this was a result of an increasing magnetic force at higher currents. Fan and Shi (1996) suggest that pressure distribution and peak pressure increase with increasing current as a result of the power increasing, and consequently an increase in the arc column current density and conductive cross-section. The pressure distribution radius increases as a result of the cross-section radius increase. The increase in electromagnetic force with current is responsible for the rise in peak arc pressure (Dai, Shen and Wang, 2018).

Rokhlin and Guu (1993) investigated GTA arc force and its effect on pool depression and penetration and found that higher currents resulted in increased melt-pool depressions, which affected weld formation. Melt-pool depression has a powerful effect on penetration. The arc force pushes the molten metal to the sides of the depression, and the depressed melt-pool sinks with increased current and increases in width with raised arc force. Below 200 A, the depression was minimal. However, above 200 A the depression increased quadratically with the current, which aligns with the findings of the GTA arc force being proportional to current² (Oh, Kim and Cho, 2005).

Chen et al. (2015) measured the pressure of the plasma arc for parameters within keyhole regions, using a force sensor mounted below a 0.5 mm hole, incorporated within a water-cooled copper-block, and established that:

- Arc length, PGFR and arc current all affect the arc pressure. However, the impact of arc length and PGFR is limited to the centre of the arc and peak pressure, while arc current affects both the distribution radius and peak pressure. Chen et al.'s (2015) results indicate a narrowing arc pressure distribution and increasing peak pressure value with increased PGFR, as well as a widening arc pressure distribution and decreasing peak pressure value with increased arc length.
- The arc current predominantly defines the electron flow arc pressure distribution, and arc length and PGFR both have negligible effect.

Chen et al. (2015) proposed an explanation for the reduced arc pressure with increasing arc length, suggesting that, as the particles leave the PTA torch and its influence on the particle acceleration, they start to slow down, and the increase in distance further decelerates them, resulting in a reduction in arc pressure at the substrate surface. The arc diameter, from photographs, also increases at its base, resulting in an increased distribution width and reduced peak pressure value.

Schnick (2016) calculated the PTA plasma speed at 200 A and found for their PTA torch that it was three times higher than GTA and that the maximum speed is just below the nozzle. They attributed this increase to the expansion and increased flow-rate of the plasma gas. The increase in speed is an underlying reason for the rise in arc pressure at the substrate. The rate of heat transfer rises with increased PGFR. In addition, the arc current and PGFR influence the melt-pool by raising the arc pressure and heat flux density at the substrate. However, this is limited by the restriction nozzle diameter (Schnick, 2016).

Adonyi, Richardson and Baeslack (1992) established that, for GTA, arc force increases for welds undertaken with argon shielding gas as opposed to helium as a result of the difference in viscosity, reduced electrode tip to work-piece distance, and for titanium substrate compared with stainless steel, shown in Figure 38. The effect of substrate material is considered by the author to be a result of changes to the GTA arc composition because of vaporisation of the substrate affecting the arc force.

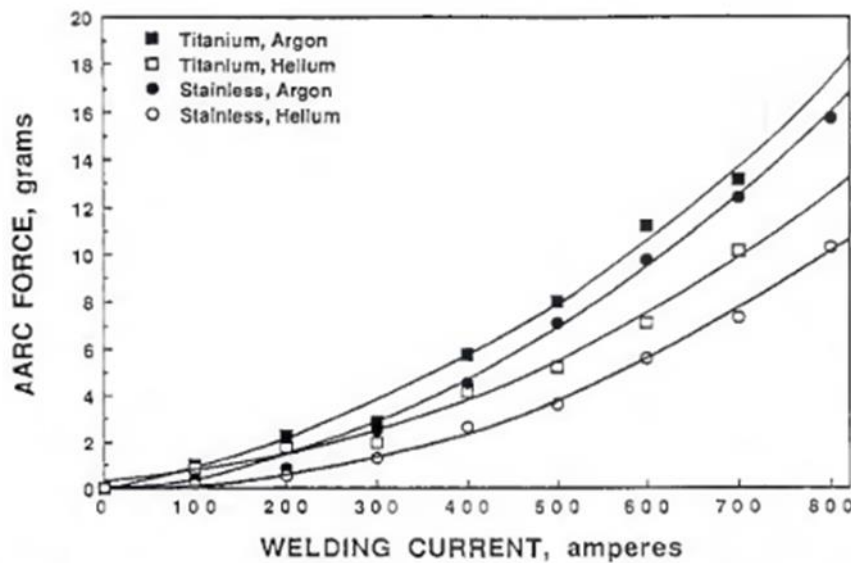


Figure 38 Comparison of GTA arc force versus current for titanium and stainless-steel substrate and argon and helium shielding gas. (Adonyi, Richardson and Baeslack, 1992)

Pan et al. (2002) measured PTA arc pressure utilising a monometer connected to atmosphere at one end and a 0.5 mm hole incorporated within a water-cooled copper-block at the other end. They identified that the gas flow stability of the plasma arc affects its velocity, pressure distribution and arc temperature, and, consequently, the interaction between the arc and the substrate, and energy transfer. In addition, arc pressure decreases with increased arc length for both laminar and turbulent plasma gas flow, but the peak pressure at the nozzle exit is higher for turbulent plasma gas flow. However, the pressure quickly dissipates for turbulent flow along the arc column axis with a broader distribution. For laminar gas flow, the pressure decreases gradually with a narrower distribution. Accordingly, the reduced flow velocities of the laminar arc gas flow could be exploited through torch design to reduce PTA arc pressure subjected on the substrate. During arc pressure measurements, they found stable readings for laminar flow and large-scale deflections and fluctuations for turbulent flow. An ideal PTA torch therefore provides a laminar plasma gas flow, with a reduction in arc pressure that is stable and exhibits a thin boundary layer between the arc column and the surrounding atmosphere. Pan et al. (2002) fail to consider that, to achieve the turbulent flow of his study, over 2.5 times more PGFR was used, which, in addition to the turbulence, strongly affects the arc pressure and distribution shape. In addition, the arc lengths used by the study are high – 20 to 130 mm

– and values recorded are therefore not representative of typical PTA operations (Pan et al., 2002).

Fan et al. (1986) examined, for GTA, the effect of electrode tip shape on arc pressure, establishing that the pressure decreases as the electrode tip changes in steps from a bevelled point and truncated cone to a full electrode diameter flat tip. Furthermore, the GTA pressure distributions approximate Gaussian up to a specific current but become more pointed as the current is further increased because of the increased magnetic force at higher currents.

Zhang et al. (2015) refers to the PTA torch as not only a heat source but also a pressure/force source. PTA current affects weld quality through the produced arc pressure and arc temperature (Martikainen and Moisio, 1993).

2.11 Arc Pressure Measurement Methods

Arc pressure is torch design specific as torch and electrode geometries play an essential role. Measurements therefore need to be undertaken for the particular PTA torch that is intended to be utilised. The Cranfield University WAAM research team and WAAM3D, the commercial spinoff company, have now adopted the PWP Industrial manufactured Viper MC water-cooled PTA torch. For this reason, all arc pressure measurements in this study have been undertaken with this torch.

A straight comparison between GTA and PTA arc pressure results within the literature is difficult because of the high number of variables and equipment settings used by each study, including electrode angle, arc length and current.

Arc pressure of PTA has been measured for various torch designs, with their associated diverse nozzle and electrode variations. The measurement methods include (Chen et al, 2016, 2015):

- Torsion balance.
- Barometers.
- ‘U’ type manometer.
- Piezoelectric pressure transducer.

- Pendulum with rotary optical encoder.

The advantages and disadvantages of each arc pressure measurement method are listed below:

Measurement Method	Advantages	Disadvantages
Torsion balance	• Ease of use. • Time-consuming. • Considered accurate if used correctly. • Relatively low cost. • Straightforward to set up. • Known resolution and accuracy. • No parallax errors.	• Operator interpretation required. • Subject to human error. • Manual reading required. • No data logging capability. • Not easy to see trending. • Conversion of measurement unit required.
‘U’ type manometer and barometers	• Less susceptible to heat. • Unaffected by high-frequency interference. • Low tech. • Low cost. • No measurement lag. • Straightforward to set up. • Does not require power. • Wide pressure range.	• Manual reading required. • Operator interpretation required. • Subject to human error. • No data logging capability. • Time consuming to read. • Parallax errors • Not easy to see trending. • Poor response time. • Messy to operate.
Piezoelectric pressure transducer	• Automatic reading. • No operator interpretation required. • Data is logged. • No parallax errors. • Known resolution and accuracy. • Easier to see trending. • Protected from contamination by a diaphragm. • High Sensitivity.	• Measurement lag. • Effected by high-frequency interference. • Susceptible to heat damage. • Set range. • Relatively high cost. • Requires power.
Pendulum with rotary optical encoder	• Automatic reading. • No parallax errors. • No operator interpretation required. • Data is logged. • Easier to see trending. • High Sensitivity.	• Complexity. • Delicate parts. • Less tolerant of mechanical abuse - shock or severe vibration. • Susceptible to heat damage. • Effected by high-frequency interference. • Harmed by contamination.

Zhang et al. (2014) used a pressure tapping within a chilled copper-block and a moving PTA torch to measure arc pressure of three-hole and straight-bore PTA nozzles.

Campbell et al. (2013) investigated, for pulsed GTA, the effect of alternating shielding gas between argon and helium on measured arc pressure. They found, utilising a piezo pressure sensor mounted below a 1 mm diameter hole within a water-cooled anode, that argon produced a higher arc pressure than helium. Further, adding helium to the argon shielding gas considerably reduced arc pressure, which was attributed to the lower density and higher viscosity of helium. The alternating shielding gas composition concept is considered to aid in increases to travel speed with minimal effect to the melt-pool geometry, reduce porosity and improve mechanical properties. The measured arc pressure

at gas composition changeover was found to peak at approximately 25% higher than pure argon, believed to be a result of pressure impulse at arc ignition.

Ham, Oh and Cho (2012), using a 'U' type manometer filled with dyed distilled water and connected to a copper-block containing a 1 mm diameter measurement hole investigated, for GTA, the effect of shielding gas pressure and gas cup diameter on arc pressure. They identified that, as the cup diameter is reduced or the gas pressure increased, the arc diameter decreased and the arc pressure marginally increased. This was arguably because of the increase in shielding gas velocity and the thermal pinch effect on the arc.

Oh, Kim and Cho (2005) investigated, for GTA, the effect of different shielding gases on measured arc pressure, also utilising a 'U' type manometer and a 1 mm diameter measurement hole. They established that GTA arc pressure reduced with an increased percentage of helium in the shielding gas and that peak pressure increases with current.

Also employing a water-filled 'U' type manometer, Ham, Oh and Cho (2012) examined the effect of GTA shielding gas on the melt-pool surface. They experimented with shielding gas pressure and GTA gas cup diameters and found that the shielding gas velocity increased with higher pressures or while a smaller cup size was applied, and observed that higher gas velocities cooled and constricted the arc through a thermal pinch. The increase of shielding gas pressure was found to have a minimal effect on the GTA arc pressure. However, the GTA gas cup diameter was found to reduce arc pressure as its diameter increased.

Pan et al. (2016) also utilised a water-chilled copper-block and pressure transducer for the arc pressure measurement of a PTA torch to validate their numerical keyhole model. The parameters were restricted to only one current, arc length, PGFR, and electrode design. Their measurements are thus very limited but show a Gaussian distribution.

Rokhlin and Guu (1993) applied a novel, balanced force measuring system, digital scale balance beam and pivot to measure arc and electromagnetic force, combined with real-time radiography to identify the relationship between GTA arc force, melt-pool depression and penetration. The arc force was calculated by subtracting the electromagnetic force from the total measured force.

2.12 Identified Research Gaps in the Literature

The following research gaps have been identified through the literature review:

1. To date, arc pressure measurement in literature has been focused on the pressure measurement of GTA, PTA cutting and PTA keyhole mode of operation, with limited data available for non-keyhole soft plasma PTA – the ideal operational regime for WAAM.
2. No correlation has yet been made with regards to WAAM keyhole defect formation with the PTA process arc pressure. In addition, there has been no in-depth study into the effect of PTA parameters and torch geometries on the arc pressure of the process.
3. WAAM build strategy has not been considered in current literature with regards to PTA arc pressure. An empirical model is needed to predict arc pressure for set PTA parameters to minimise arc pressure and enable keyhole defect avoidance.
4. A means of real-time arc pressure monitoring during WAAM operations is not available.
5. An investigation to identify if a correlation between arc pressure and arc voltage exists has not been undertaken.
6. To date, minimal attention has been given to the PTA non-consumable electrode utilised for long durations of continuous high current operation – typical for WAAM operations. The following identified areas therefore need investigation:
 - The effect of PTA electrode wear, tungsten oxide composition, tip angle and flat tip diameter/electrode length on arc pressure and arc voltage.
 - Cause of the change in the surface finish with use for 2% thorium tungsten electrodes.
 - Changes with use of PTA electrode tip geometry.
 - PTA 2% thorium tungsten electrode wear, mechanisms and effect of operational duration, arc ignitions and arc terminations of wear/erosion.
 - Influence of 2% thorium dopant on PTA tungsten electrodes.
 - The impact of different PTA tungsten oxide compositions on electrode longevity and wear-rates.
 - Consequences of PTA electrode length and tip geometry on arc starting.
 - Implications of specialist applications on electrode life.

- Identification of the best tungsten oxide composition, and alternatives to 2% thoriated tungsten, which can increase electrode longevity for the required long duty cycles necessary for WAAM applications.

Chapter 3

Effect of PTA Process Variables

3.1 Introduction

Many factors affect the arc pressure generated in both the GTA and PTA processes. Both GTA and PTA processes utilise a non-consumable electrode, which generates a plasma column as the heat source, and use an inert shielding gas. Features of the PTA arc include the higher velocity and temperature of the arc that the electrode must endure, the restriction nozzle, and the higher process arc pressure and its ability to produce deep penetrating cavities, detrimental for WAAM, by means of the concentrated plasma – keyholes. In this chapter, all the process, nozzle and electrode variables, including different states of wear, geometry and construction materials, have been independently examined in terms of their effects on arc pressure. A comparison between GTA and PTA arc pressure is also made.

3.1.1 Arc Pressure Measurement of GTA and PTA Process Variables

Figure 39, a refinement of Figure 1, illustrates the key PTA process parameters affecting arc pressure. These are the process variables and torch geometry, including the electrode.

This subsection presents the results of the study of the process variables shown in Figure 39 on arc pressure.

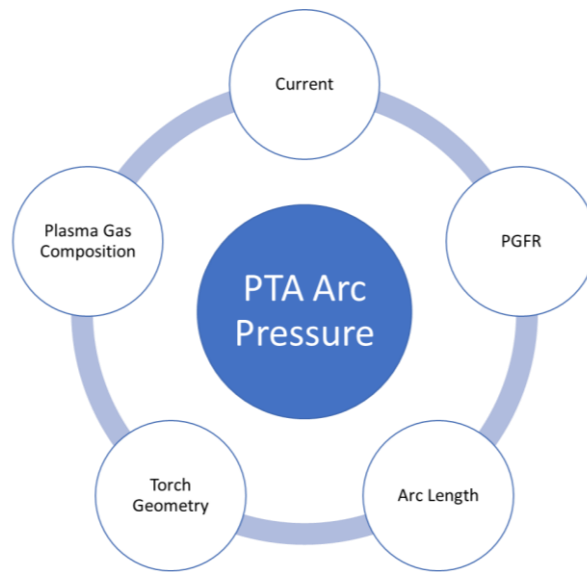


Figure 39 Critical PTA parameters, variables and geometries identified as affecting arc pressure.

3.1.2 Arc Pressure Measurement of PTA Nozzle Geometry

Figure 40 shows an extended version of the torch geometry bubble shown in Figure 39 and outlines the detailed torch geometries affecting the PTA arc pressure.

This subsection investigates variables, except for the electrode details, affecting arc pressure for various current and PGFR values.

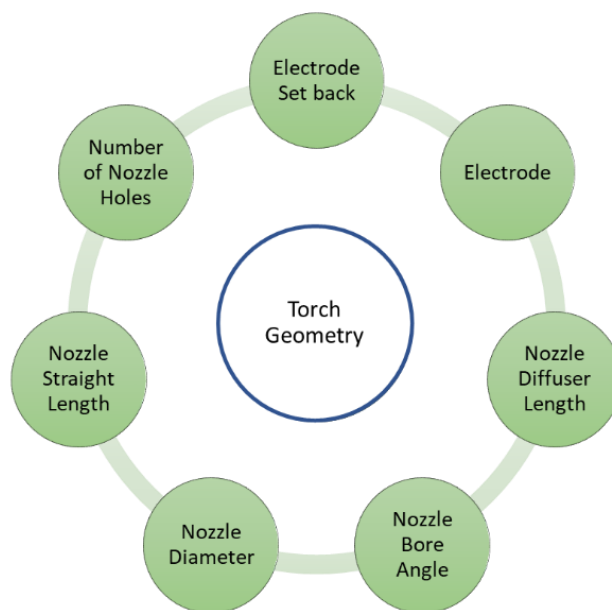


Figure 40 Arc pressure measurement of PTA torch geometry.

3.1.3 Arc Pressure Effects of PTA Electrode Details

Another fundamental component of the PTA torch is the non-consumable water-cooled electrode, housed within the restriction nozzle. The electrode is the conductor through which the torch current passes and, by means of ohmic heating, ionises the plasma gas, sustaining the PTA arc expelled from the tip. Figure 41 is an extended version of the electrode bubble shown in Figure 40 and outlines the specific electrode characteristics and geometry that affect PTA arc pressure.

This subsection investigates the effect of these variables on arc pressure.

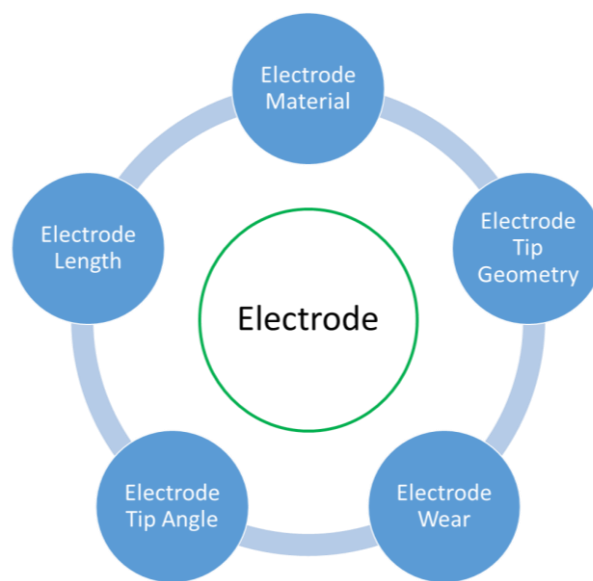


Figure 41 Arc pressure measurement of PTA electrode.

Chapter 6 investigates PTA electrodes in terms of other factors such as wear-rate, tip retention, arc starting and construction materials, including comparison, dopant depletion and tungsten electrode arc ring (TEAR) growth.

3.1.4 Associated PTA Torch Geometry Terminology

Figure 42 illustrates the PTA restriction nozzle terminology used for this study for both the standard straight-bore nozzle and specialist nozzles.

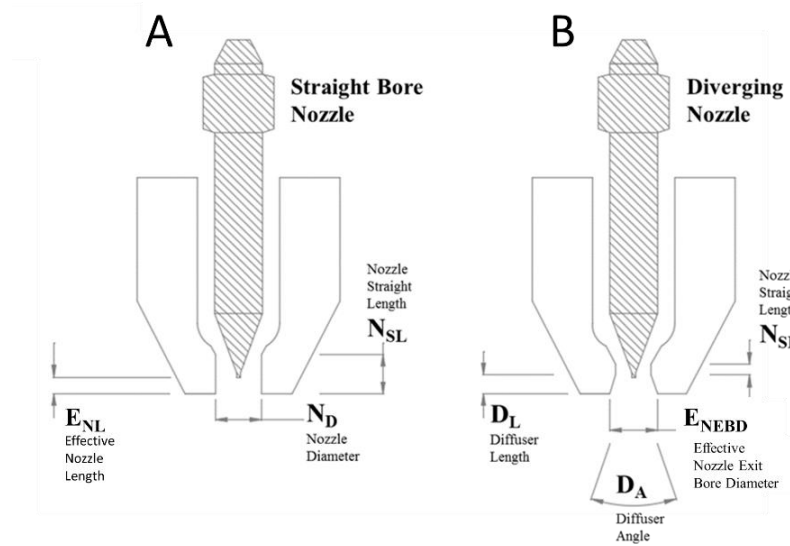


Figure 42 A] Standard straight-bore nozzle: nozzle diameter (N_D), nozzle straight length (N_{SL}) and effective nozzle length (E_{NL}) shown, B] Diverging nozzle: diffuser length (D_L), diffuser angle (D_A) and effective nozzle exit bore diameter (E_{NEBD}) shown. For a standard straight-bore nozzle $E_{NEBD} = N_D$, and for a diverging nozzle, bore diameter at the nozzle straight length (N_{SL}) = N_D .

3.1.5 Associated PTA Torch Electrode Geometry Terminology

Figure 43 illustrates the associated terminology for the PTA torch electrode used for this study.

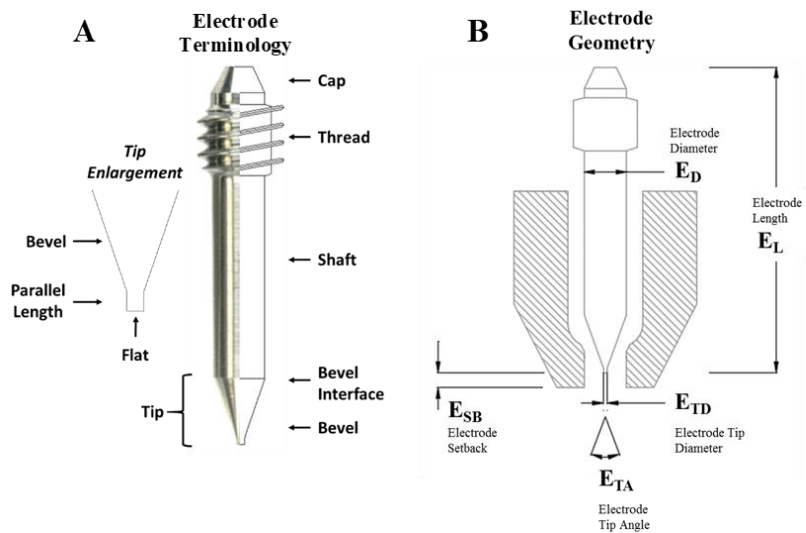


Figure 43 PTA electrode terminology A] Electrode elements, B] Standard electrode geometry within a straight-bore nozzle: electrode length (E_L), electrode setback (E_{SB}), electrode tip angle (E_{TA}), electrode tip diameter (E_{TD}) and electrode diameter (E_D). See Table 6 for dimensional values.

3.2 Methodology

An overview of the experimental setup is shown in Figure 44 and consisted of a PTA/GTA torch, power supply with auxiliary coolant, gas and process control, as well as integrated CNC torch positioning, a process environment (glovebox) enclosure, gas supply, arc pressure and process measurement equipment. The process parameters and equipment settings are listed in Table 6. The study was undertaken within an argon (99.998%) filled ($O_2 < 50$ ppm) environment: see Figure 45 'A'.

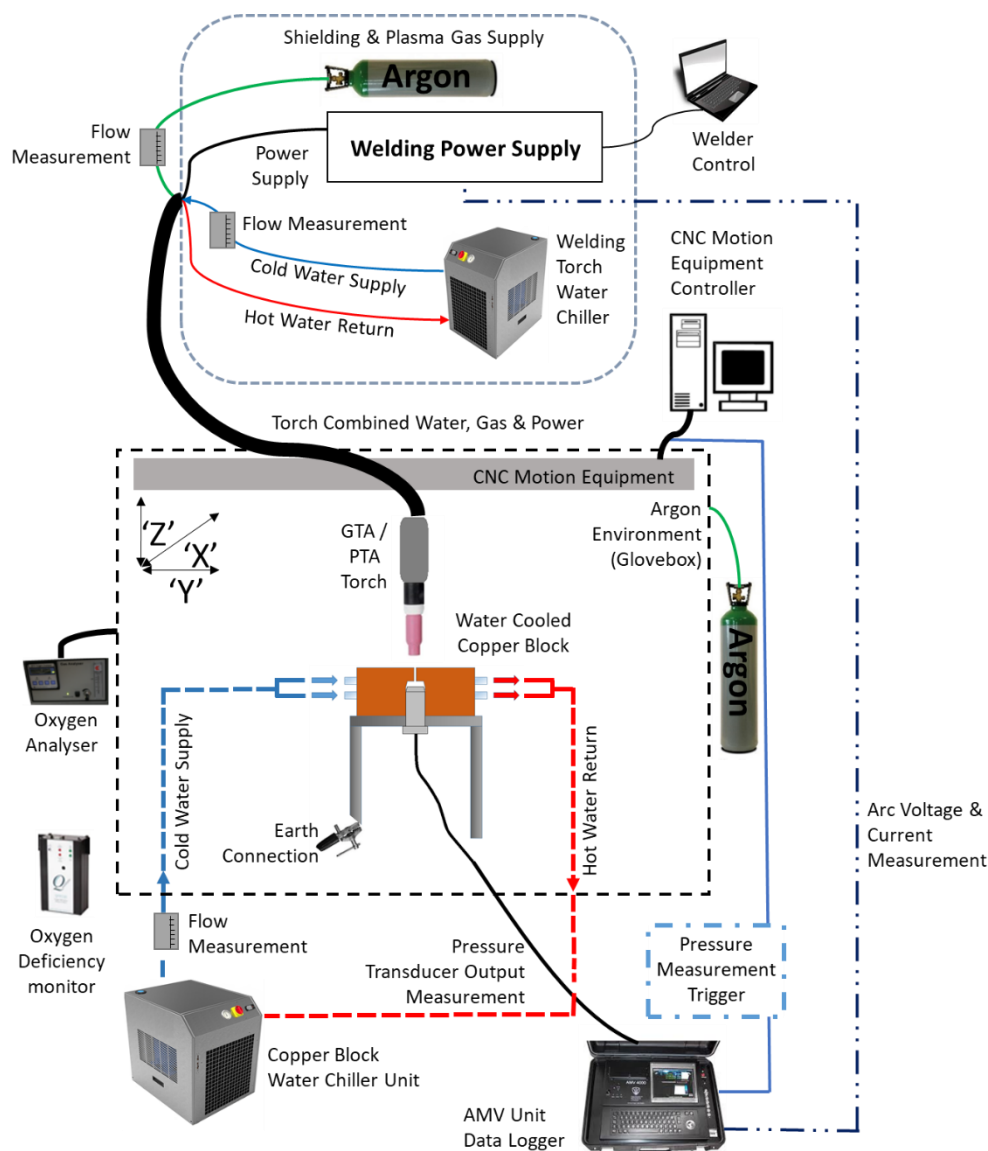


Figure 44 Equipment setup schematic (GTA and PTA). See Appendix D for pressure measurement trigger schematic.

A pressure transducer was mounted directly below a 0.3 mm orifice within a fixed, (120 mm L x 70 mm W x 50 mm H), anode copper-block, seen in Figure 45 ‘B’ and Figure 46 ‘A’, water cooled (5.5 l/min) to increase the longevity of the block and to protect the instrumentation.

Table 6 Process parameters and equipment settings – PTA and GTA study

Process Parameters and Equipment Settings	Values
Common – GTA and PTA	
Electrode Polarity	DCEN
Torch Angle to Substrate	90°
Shielding Gas Composition	99.998% Argon
Pressurised Glovebox Environment Gas Composition	Argon/O ₂ <50 PPM
Copper-block Orifice Diameter	0.3 mm
Copper-block and Start/Stop Block Chiller Flow-rate	13.6 l/min
Pressure Transducer	Omega PXM409-170HG10V (Note 2)
Pressure Transducer Operating Range and Accuracy	0–170 millibar (0–17000 N/m ²) / ± 0.08%
Process Monitoring/Data Logging Equipment	AMV 4000
Sample Rate of Data-logger	20,000 Samples per Second – 20 kHz
PTA Torch	PWP Viper MC (Water Cooled)
PTA Shielding Gas Flow-rate	15 l/min *
Electrode Type	2% Thoriated Tungsten *
Electrode Angle	40° *
Electrode Diameter	4.0 mm
Electrode Setback	1.4 mm *
PTA Torch Coolant Flow-rate	3.1 l/min
PTA Torch Umbilical Cable Length	12.5 Foot/3.81m
PTA DC 550A electrical power source supply	EWM Tetrix 552 RC Plasma CW GR & TecArc OptiArc Plasweld 400 AC DC HD (electrode negative - DCEN)
PTA – Independent Variable Study	
Current	140, 160, 180, 190, 200, 210, 220, 240, 260, 280 & 300 A
Arc Length	6.4, 9.4, and 11.4 mm
Nozzle Standoff Distance	5, 8, 10 mm (See Note 3)
Nozzle Diameter	3, and 3.9 mm Straight Bore
Plasma Gas Composition	• 100% Helium • 25% Argon/75% Helium • 50% Argon/50% Helium • 70% Argon/30% Helium

Investigation Of Plasma Transferred Arc Dynamic Effects In Wire + Arc Additive Manufacturing

	97.5% Argon/2.5% CO₂ 98.5% Argon/1.5% Hydrogen 100% Argon
Plasma Gas Flow-rate	0, 0.2, 0.6, 0.8, 1.4, 2, 2.2, 3, 4, 5 and 6 l/min
PTA – Nozzle Geometry Study	
Current	140, 160, 180, 200 and 300 A (Note 5)
Arc Length	6.4 mm (Note 3)
Nozzle Standoff Distance	5 mm (see Note 3)
Straight-bore Nozzle Diameter	3, 3.2, 3.4, 3.6, 3.9, 4.5 and 5 mm
Nozzle Straight Length	Nozzles with a 3.9 mm bore and nozzle straight lengths of: 3.72, 3.52, 3.32, 3.12, 2.92, 2.72, 2.52, 1.92, 1.32 – relative to the elective nozzle length of: 1.8, 1.6, 1.4, 1.2, 1, 0.8, 0.6, 0 and -0.6 mm.
Effective Nozzle Length	1.4 mm*
Plasma Gas Composition	100% Argon
Plasma Gas Flow-rate	0.6, 0.8, 2, 4, and 6 l/min.
Specialist Nozzles:	
▪ Three-hole Nozzle	1 x 3 mm straight centre bore and 2 x 1 mm radial holes
▪ Threaded Nozzle	3 mm straight-bore tapped with a 4 mm right-hand metric thread
▪ Slotted Nozzle	3 mm straight-bore with a through slot of 0.88 and 2 mm-long through slots, and a 2.33 mm-long 30° tapered slot
▪ Diverging Nozzle	36.8° diffuser nozzles with a 3 mm bore and diffuser lengths of 0.8, 1.6 and 2.4 mm
PTA – Electrode Study	
Current	140 and 200 A (Note 1)
Arc Length	6.4 mm (Note 3)
Nozzle Standoff Distance	5 mm (See Note 3)
Straight-bore Nozzle Diameter	3.9 mm
Plasma Gas Composition	100% Argon
Plasma Gas Flow-rate	0.8 l/min.
Electrode Type:	
Standard PWP DC Electrode	(Geometry Below)
▪ Electrode Diameter	4.0 mm
▪ Electrode Length	29 mm
▪ Electrode Setback	1.4 mm
▪ Electrode Tip Angle	40°
▪ Electrode Tip Diameter	0.36 mm
Specialist Electrode Angle:	20° and 60°
Specialist Blunt Electrode Length:	28.270, 27.545, 26.788 and 25.957 mm

Electrode Material:

- 2% (wt.) Thoriated Tungsten (Standard)
- 2% (wt.) Ceriated
- 2% (wt.) Pure Tungsten
- 2% (wt.) Lanthanated
- 0.8% (wt.) Zirconiated
- 2% (wt.) Rare Earth
- 2% (wt.) Material 'X'

GTA

Current	140, 160, 180 and 200 A
Arc Length	3, 6.4 mm (See Note 4)
Electrode Type	2% Thoriated Tungsten
Electrode Angle	42°
Electrode Diameter	3.2 mm
Electrode Stick Out	20 mm
GTA Torch	PWP WeldTec WT-28 Model 'A' (Water Cooled)
Gas Lens	3.2 mm 995795 Large Gas Lens Body (PWP 24-563L)
Shielding Gas Flow-rate	10 l/min
Shroud Cup Size	No. 10
240 – 320 & 400 AC/DC electrical power supply	Migatron TIG Commander MKIII 320 AC/DC

* Unless otherwise stated

Note 1 – No welding wire was used in the experiment.

Note 2 – Pressure readings taken whilst PTA and GTA torches were stationary.

Note 3 – As a result of a PTA ESB of 1.4 mm, the PTA nozzle standoff distances/CTWD equates to arc lengths of 6.4, 9.4 and 11.4 mm.

Note 4 – A standard 3 mm GTA arc length was utilised. To allow for comparison of the GTA results with those for PTA, the arc length of 6.4 mm was also undertaken.

Note 5 – Where possible without equipment damage 300 A measurements were undertaken.

Arc voltage, current and arc pressure were measured at seven points using the pressure transducer and data logger, each undertaken at equally increased distances from the orifice, shown in Figure 46 'B'. All trials were undertaken in the flat position.

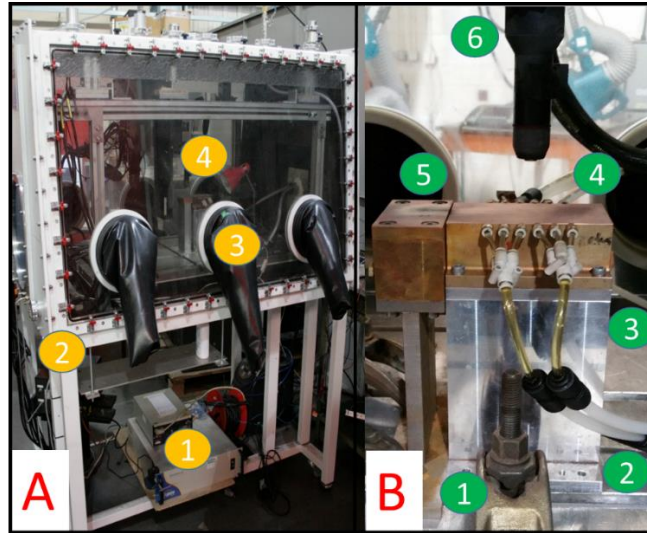


Figure 45 Equipment setup: A] Argon-filled glovebox; B] Copper-block and PTA torch arrangement; A1) CNC motion equipment controller, A2) Oxygen analyser, A3) Environment containment glove system, A4) Copper-block and PTA torch arrangement. B1) Machine clamp, B2) Coolant supply, B3) Coolant return, B4) Copper-block, B5) Start/Stop block, B6) PTA torch.

For the GTA arc pressure measurements, four currents and two arc lengths were used, shown in Table 6. Pulsed AC GTA was also undertaken with a current of 140 A at a fixed arc length of 3 mm. However, the AC process was too harsh and damaged the copper-block, melting the orifice closed and meaning that no measurements were possible.

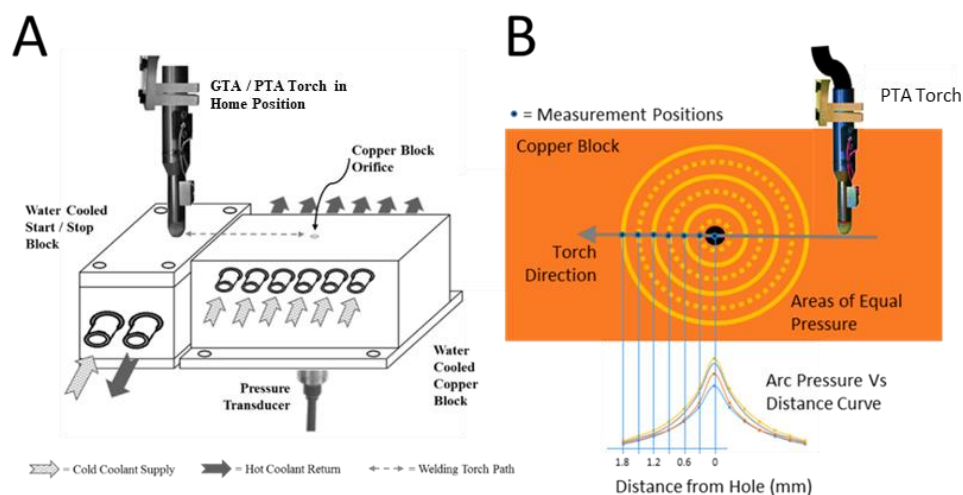


Figure 46 A] Copper-block and pressure transducer arrangement. 0.3 mm orifice within the copper-block located above a pressure transducer, B] Arc pressure measurement.

For the PTA, arc pressure measurements were undertaken for eleven currents and three arc lengths, shown in Table 6, for nozzle diameters of 3 and 3.9 mm.

For measurement equipment calibration and repeatability, prior to undertaking the experiments, the pressure transducer and data logger, shown in Table 6, were calibrated against a known calibrated source – a pneumatic test pump and gauge (Additel ADT914). On completion of experiments, this process was repeated.

A CNC torch positioning accuracy of 0.05 mm was verified and determined as repeatable.

To ensure system repeatability, experiments were repeated in random order on separate days (different ambient pressure), and the results compared.

As illustrated in Figure 47, four pressures are considered for the experiment.

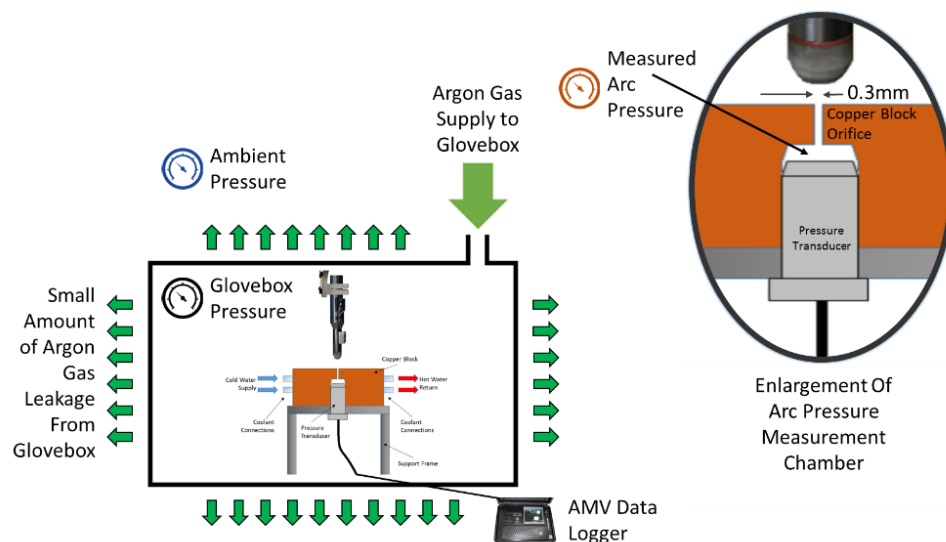


Figure 47 The pressures within the experiment setup. There are four pressures to consider: ambient pressure (absolute), glovebox pressure (gauge), measured arc pressure (gauge) and calculated arc pressure (gauge).

Ambient pressure – daily barometric pressure outside the glovebox, which changes throughout the day, and is affected by air density, air temperature and altitude.

Glovebox pressure – measured within the glovebox (approx. 10 to 1000 N/m²): argon environment pressure + ambient pressure. As the glovebox is positively pressurised by argon, the glovebox pressure is slightly higher than the ambient pressure. Equipment movement, shielding gas and increases in temperature because of the arc within the glovebox also increase the glovebox pressure.

Measured arc pressure – the direct measurement of the pressure exerted by the arc and the glovebox pressure above the measurement point.

Calculated arc pressure – the measured arc pressure minus the glovebox pressure, shown in Equation 1.

$$\text{Arc pressure (AP)} = M_{AP} - G_{BP} \quad \text{Equation 1}$$

Where:

AP = Arc pressure (N/m^2)

M_{AP} = Measured arc pressure (N/m^2)

G_{BP} = Glovebox pressure (N/m^2)

Gauge pressure (zero-referenced compared to ambient air pressure) is measured by the pressure transducer. Prior to each experimental run the glovebox pressure was measured and recorded. This value was then deducted from the measured arc pressure, Equation 1, for that specific run, to give the true arc pressure: calculated arc pressure. Where arc pressure and peak arc pressure are mentioned within this study, the calculated/true arc pressure is inferred. Using this method for multiple experimental runs with identical parameters undertaken at different times or on different days, the results are well within repeatable tolerances: less than 3%. Figure 46 and Figure 48 illustrate the measurement arrangement and torch movement, above the fixed copper-block.

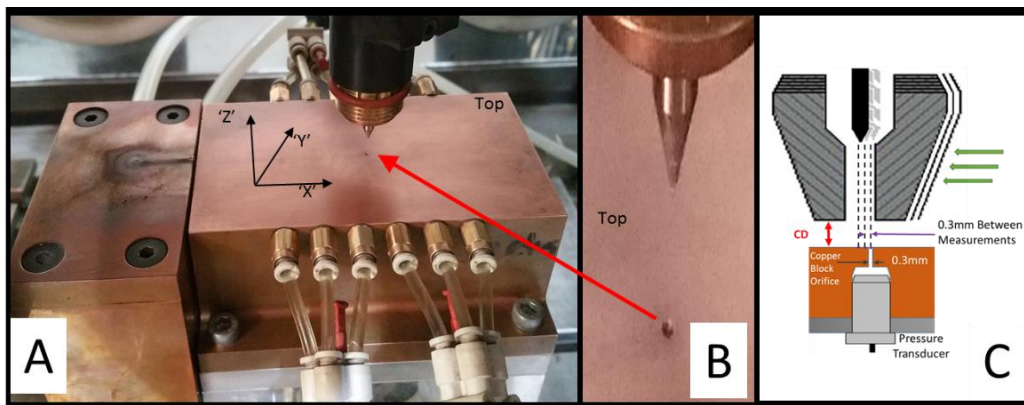


Figure 48 Copper-block orifice: A] Torch (nozzle and shielding cup removed), copper-block and orifice arrangement, B] Enlargement of orifice, C] PTA torch nozzle and copper-block pressure measurements, three nozzles/measurement locations shown (i.e. traversing nozzle).

To allow for direct comparison between GTA and PTA results, arc length (A_L) – electrode tip to work-piece distance – has been used for PTA in place of torch nozzle to work-piece distance (C_D); see Equation 2 for conversion.

$$\text{Arc length: } (A_L) = E_{SB} + C_D \quad \text{Equation 2}$$

Where:

A_L = Arc length (mm)

E_{SB} = Electrode setback (mm)

C_D = Torch copper nozzle to work-piece distance (mm)

As a result of a dynamic measurement lag of the pressure transducer, static measurements at each of the measurement locations were undertaken for 10 seconds. This allowed for pressurisation of the copper-block chamber, shown in Figure 49, and pressure stabilisation. The raw data acquired (see Figure 50) at each of the seven measurement locations during each stabilisation period for each measurement point contained a plateau – a total of seven, one per measurement point. The data acquired was analysed to determine the mean and standard deviation values for arc pressure, current and voltage. The average value for each point was calculated and plotted to form the arc pressure distribution curves.

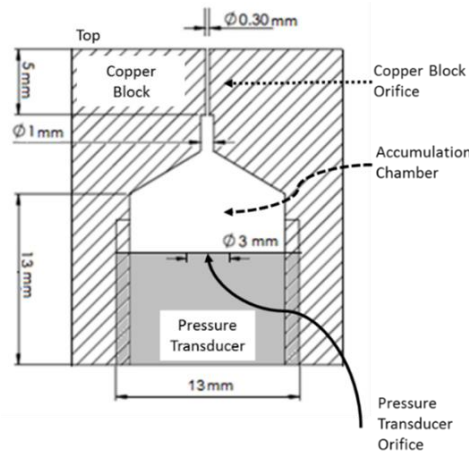


Figure 49 Cross-section of copper-block showing the orifice channel and accumulation chamber above the pressure transducer.

The arc remained initiated throughout each experiment to ensure an identical arc for all seven measurements. For each reading, the arc was moved in one direction with a radial incremental distance of 0.3 mm between measurements from the measurement orifice. Subsequent readings were taken at 0.3, 0.6, 0.9, 1.2, 1.5 and 1.8 mm, as illustrated in Figure 46 'B', to measure the pressure distribution from the measurement orifice.

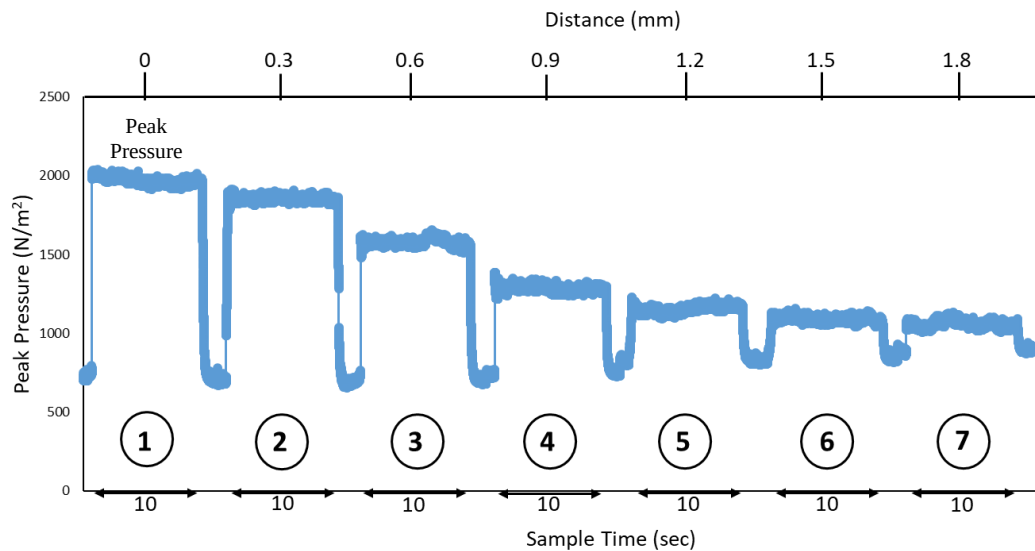


Figure 50 Ideal plot example of arc pressure recorded raw data, reducing with distance. The seven measurement plateaus, stabilisation periods and measurement distances from orifice are indicated.

If the raw data is different from the ideal plot shown in Figure 50, it is possible to identify measurement issues/errors in real-time by monitoring the raw data plot.

An incorrect raw data plot, unlike Figure 50, exhibits one or more of the below disparities. The cause for each identified issue has been determined, allowing them to be resolved and enabling subsequent measurements plots to be correct, similar to Figure 50.

<u>Issue Identified</u>	<u>Cause</u>
• Measurement plateau pressures increase with distance.	Measurement orifice is blocked.
• Measurement plateaus are not horizontal, but peaked.	Measurement orifice is partially blocked.

- Second measurement plateau pressure is higher than the first. The torch is out of alignment with the measurement orifice, or the torch angle is not at 90^0 to the copper-block.
- Fewer than seven plateaus measured. Incomplete set of data.

Without undertaking the seven measurements, full pressure distributions, each time, the outlined errors are not identifiable until completion of data analysis, when repeating measurements is no longer easily undertaken.

The cleanliness of the copper-block prior to each experiment was found to be essential to mitigate copper-block orifice channel obstructions. Prior to each experiment, the copper-block was therefore cleaned with fine grinding/polishing paper and acetone, removing oxidation and carbon deposits. The measurement orifice was also cleaned to establish that the orifice was clear and the measurement equipment functioning. Prior to each experiment, a jet of dry compressed air was applied to the orifice.

The PTA arc, unlike GTA, is restricted by a nozzle, resulting in a narrow straight arc. GTA, with an identical arc length, has a larger measurement block contact area because of its divergence. Consequently, for accurate pressure measurement, the alignment of the PTA arc is more critical. The required PTA electrode alignment accuracy to the measurement orifice was therefore within 0.05 mm in all directions, shown in Figure 48. The torch angle was 90^0 to the orifice.

To verify the effect of temperature on the arc pressure measurement, the copper-block coolant flow-rate was increased to 12.5 l/m and the results compared to measurements undertaken with a standard flow-rate (5.5 l/m). The difference measured was less than 2.5%, less than the expected 10% experimental error.

To mitigate against measurement differences because of inconsistent PTA torch coolant temperature and flow-rate, both were measured close to the torch. The measured flow-rate of coolant through the torch was found to be constant at 3.1 l/min. Thermocouples measured the torch coolant temperature at the torch inlet and outlet within the torch coolant channels, shown in Figure 51, for a fixed duration, with the main PTA arc initiated

at 200 A. The temperature was observed to stabilise after one minute, meaning that time was incorporated to allow stabilisation before undertaking measurements.

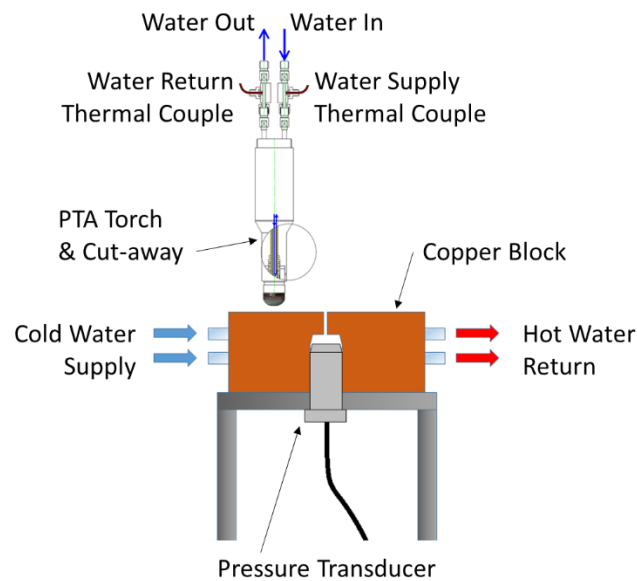


Figure 51 PTA torch coolant temperature measurement schematic.

By undertaking repeated arc pressure recordings using constant parameters for three different copper-block orifice diameters – 1.0, 0.7 and 0.3 mm – the effect of orifice size on the measurement was verified. A calibrated microscope was used to measure the exact size of the precision-machined hole before and after use.

For arc pressure measurement of different plasma gas compositions, shown in Table 6, additional equipment was required: seven gas cylinders, one per gas mix, a gas controller to switch between gases and a gas flow measurement device calibrated for each gas type/density, shown in Figure 52. It was not possible to initiate the PTA pilot and main arc directly with a low argon percentage plasma gas mix. The pilot and main arc were therefore initiated with 100% argon as an initiation gas, and the plasma gas switched once the arc had initiated. For accuracy and repeatability, additional time to stabilise the arc

was given to allow the 100% argon within the system to be entirely replaced with the plasma gas mix before undertaking arc pressure measurements.

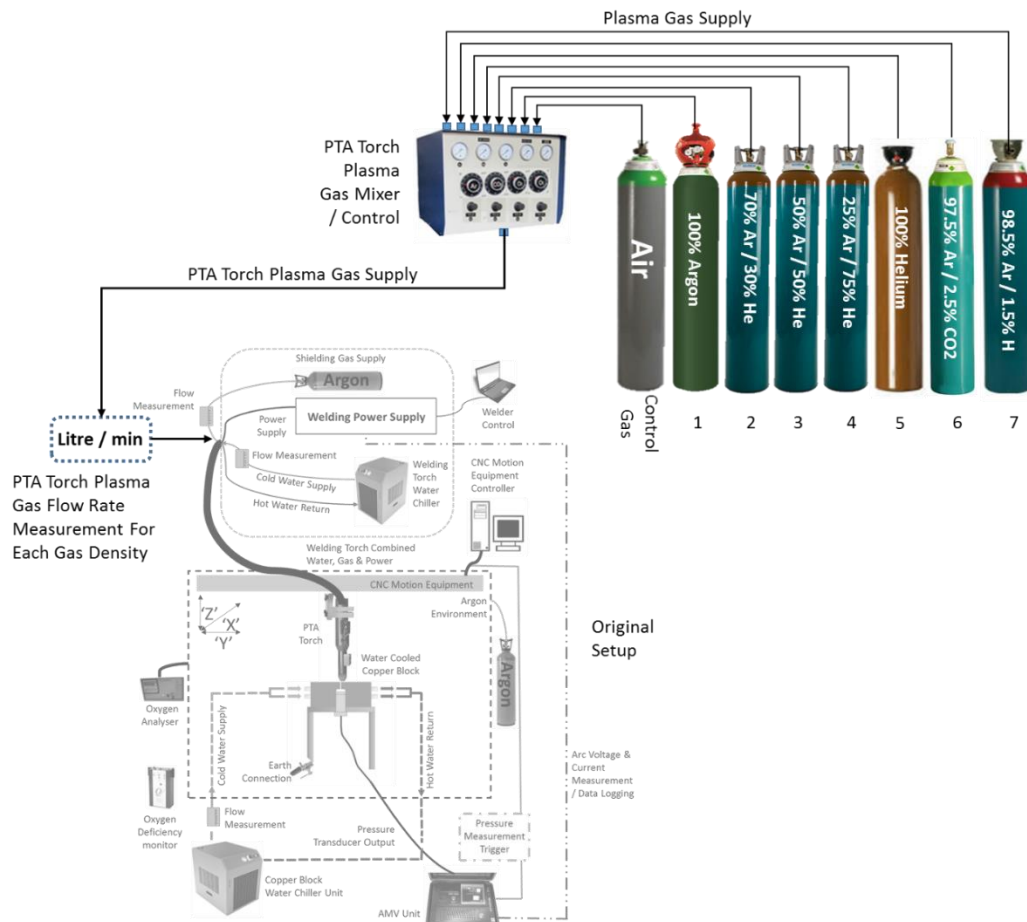


Figure 52 Variation to the equipment setup schematic, shown in Figure 44, incorporating the seven different plasma gas compositions, air-driven gas control unit and PGFR measurement for the various gas densities.

For information on measurement difficulties and errors, refer to Appendix C – Measurement Difficulties and Errors.

To approximate the PTA arc pressure width and identify parameters and variables that affect the arc pressure width, the full width at half maximum (FWHM) was calculated for varying arc pressure distributions of PTA: current, PGFR, arc length, nozzle diameter, nozzle length, specialist nozzles and electrode angles. For comparison, FWHM trends were also determined for GTA.

The FWHM was calculated, as shown in Figure 53: the distance between the two outer values of the distribution at half the arc pressure maximum value of the distribution. This was undertaken for each of the distributions measured.

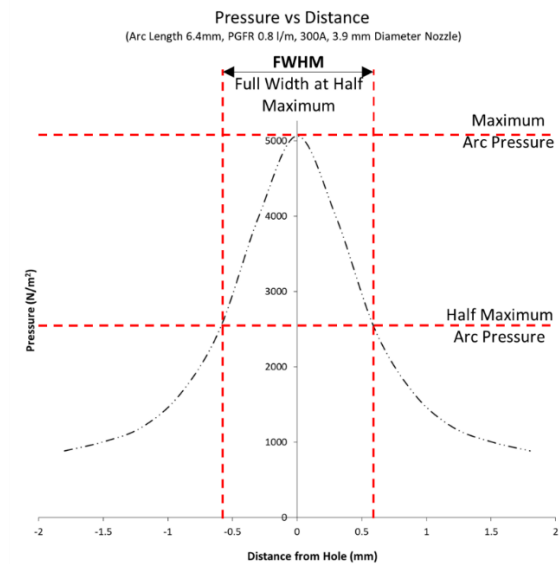


Figure 53 Arc pressure distribution curve for a 3.9 mm nozzle with the FWHM dimension illustrated.

The area under the arc pressure distributions was calculated, as shown in Figure 54, to investigate whether it is representative of total arc force. The area between the 'X' axis maximum and minimum values and the 'Y' minimum value, where the arc pressure value plateaued, was not included. This was undertaken for each of the arc pressure distributions measured.

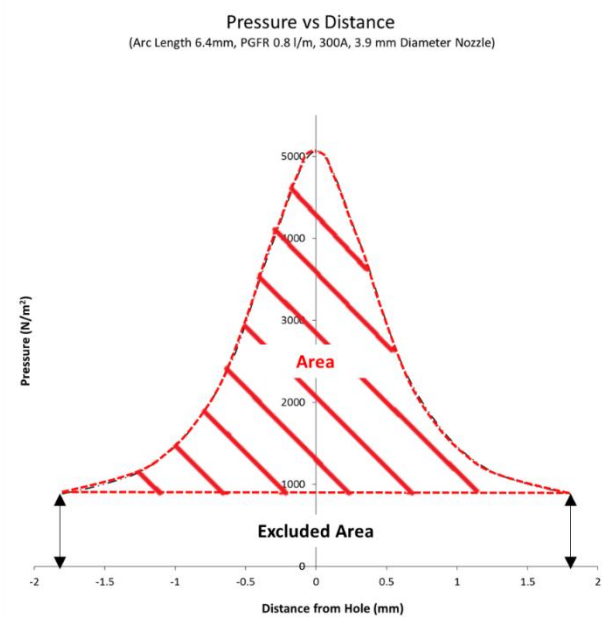


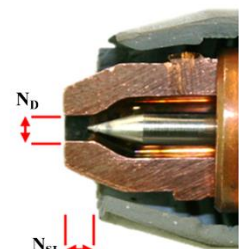
Figure 54 Arc pressure distribution curve for a 3.9 mm nozzle, with the calculated area under the distribution illustrated.

3.2.1 Nozzle Diameter

To study the effect of the PTA nozzle diameter, the arc pressure was measured for seven nozzle diameters, illustrated in Table 7, at an arc length of 6.4 mm, PGFR 0.8 l/m and five currents, set out in Table 6. The industry-standard PTA nozzle diameter, normally used for keyhole welding, is a straight-bore 3 mm. However, for WAAM part building, the standard straight-bore PTA nozzle diameter is 3.9 mm.

Table 7 Straight-bore nozzle diameters (N_D) and their equivalent nozzle straight lengths (N_{SL}).

Seven straight-bore nozzle diameters (N_D), with a standard ESB of 1.4 mm, and their equivalent nozzle straight lengths (N_{SL}).



Nozzle Diameter (N_D) (mm)	3	3.2	3.4	3.6	3.9	4.5	5
Nozzle Straight Length (N_{SL}) (mm)	2.50	2.68	2.86	3.05	3.32	3.87	4.13

3.2.2 Effective Nozzle Length

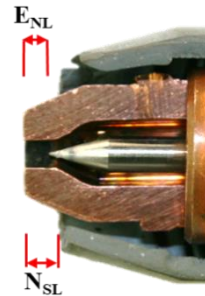
To study the effect of the PTA nozzle compared with GTA, with no nozzle, the arc pressure was measured for 3.9 mm diameter nozzles with nine nozzle lengths and effective nozzle lengths, shown in Table 8. The measurement took place at an arc length of 6.4 mm, PGFR 0.8 l/m and two currents: 140 and 200 A. The experiment was repeated for four further PGFRs: 0, 2, 4 and 6 l/min.

The reference point is the effective nozzle length, normally set at 1.4 mm for the PWP Industrial Viper MC PTA torch. For the minus 0.6 mm effective nozzle length, the electrode stands proud of the nozzle by 0.6 mm.

By increasing or decreasing the nozzle straight length, Table 8 shows that the effective nozzle lengths vary accordingly.

Table 8 Straight-bore 3.9 mm diameter nozzles with nine different nozzle lengths and effective nozzle lengths, Figure 42.

3.9 mm diameter straight-bore nozzles, with nine different nozzle straight lengths (N_{SL}) and effective nozzle lengths (E_{NL}). Standard effective nozzle length is 1.4 mm.



Effective Nozzle Lengths (E_{NL}) (mm)	1.8	1.6	1.4 (Standard)	1.2	1.0	0.8	0.6	0.0	-0.6
Nozzle Straight Length (N_{SL}) (mm)	3.72	3.52	3.32	3.12	2.92	2.72	2.52	1.92	1.32

3.2.3 Specialist Nozzle Geometries

Three-holed Nozzle

Zhang et al. (2014) developed a specialist three-hole nozzle to reduce the PTA arc pressure during welding. Their concept is that the three orifices lower the plasma gas velocity and consequently decrease the dynamic pressure of the plasma arc.

To investigate the effect of the three-hole PTA nozzle on the reduction of arc pressure, a similar three-hole nozzle with different hole geometries to suit the torch was manufactured with the consent of Zhang, shown in Figure 55, and the arc pressure was measured at an arc length of 6.4 mm for four currents, set out in Table 6. The central hole is an industry-standard 3 mm straight bore, and both additional holes had a 1 mm diameter. The measurements were taken with the two auxiliary holes perpendicular to the direction of travel to minimise their interference on the distance measurements from the pressure transducer.

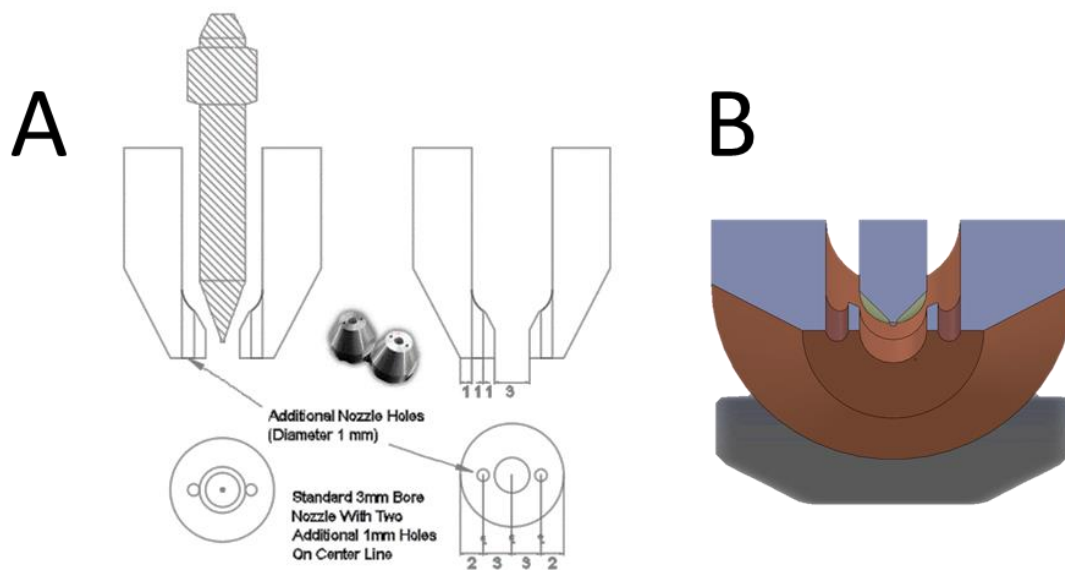


Figure 55 Three-holed PTA nozzle with a 3 mm straight-bore and two additional 1 mm holes on the centre line. A] 2D drawings, B] CAD model of nozzle and electrode cross-section, with additional holes visible.

Threaded Nozzle

To examine the effect of a thread nozzle on plasma gas flow, and to see if it assists arc ignition, a 4 mm right-hand metric thread was tapped into the straight-bore of a 3 mm

nozzle, shown in Figure 56, and arc pressure measurements were undertaken at 140 and 200 A. The results were compared with those for 3 and 3.9 mm nozzles.

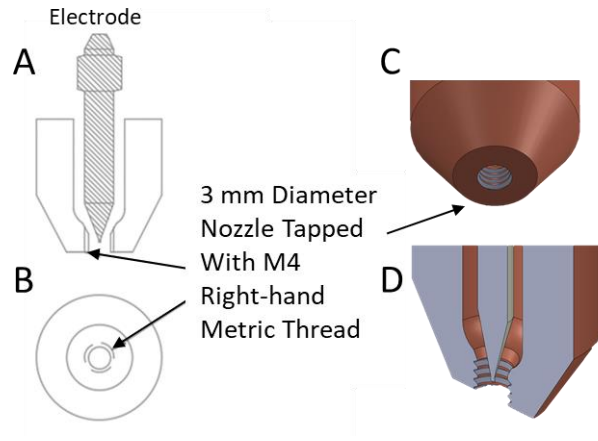


Figure 56 Threaded nozzle. A 3 mm nozzle straight-bore tapped with a M4 right-hand metric thread. A] 2D elevation of nozzle and electrode, B] Plan view, C] CAD model of nozzle and thread, D] CAD model of nozzle and electrode cross-section, thread visible.

Slotted Nozzle

Unique slotted nozzle designs – 3 mm nozzles including a pear-shape slotted hole – were investigated to determine the potential increase in wire melting efficiency through exploiting arc temperature. To verify their effect on arc pressure, peak pressure measurements were undertaken for the three nozzles, shown in Figure 57, at two currents: 140 and 200 A. Figure 58 illustrates the nozzle slot and electrode arrangement.

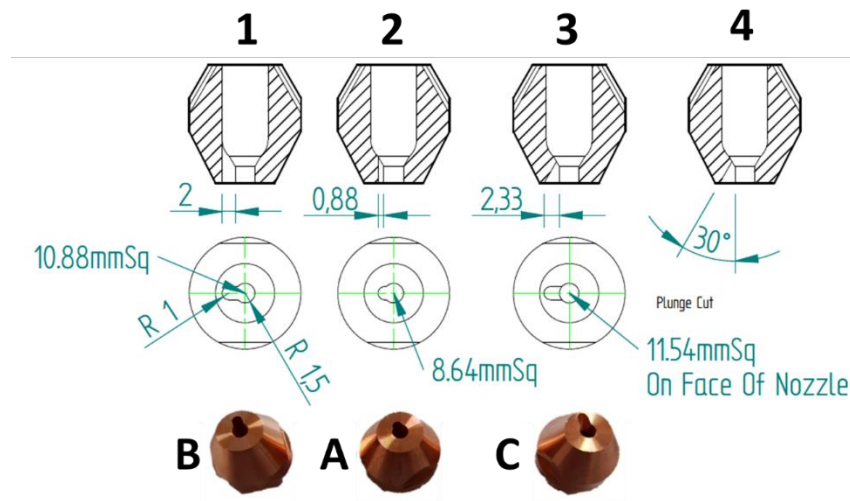


Figure 57 Slotted (pear shape) 3 mm nozzle geometry. 1] Nozzle drawing of 'B' 2 mm through slot, 2] Nozzle drawing of 'A' 0.88 mm through slot, 3] Nozzle drawing of 'C' 2.33 mm tapered slot, 4] Nozzle 'C' 30° tapered slot angle.

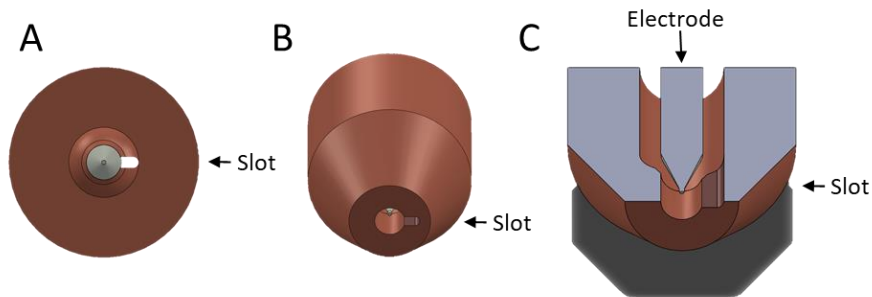


Figure 58 Slotted nozzle. A] 3 mm nozzle straight-bore with an asymmetric slot. A] CAD model of nozzle and electrode plan view, slot indicated B] CAD model of nozzle and electrode tip, slot indicated, C] CAD model of nozzle and electrode cross-section, slot indicated.

Diverging Nozzle

Sergio Ríos's (2017) study on the 'Effect of plasma gas flow-rate and nozzle design on weld pool surface depressions' developed several nozzle designs, incorporating a diffuser angle (D_A), shown in Figure 42 'B'. The study developed 36.8° nozzles with various nozzle diffuser lengths (D_L), shown in Figure 42 'B', and established their effect on the concavity on the melt-pool. Carrying on from this study, these nozzles were evaluated in terms of arc pressure measurement.

To examine the effect of angle and diffuser length of diverging nozzles, shown in Figure 42, the arc pressure was measured for three nozzles with a D_A of 36.8° and three diffuser

lengths, shown in Figure 59, measured at an arc length of 6.4 mm, a current of 140 A and a PGFR of 0.8 l/m.

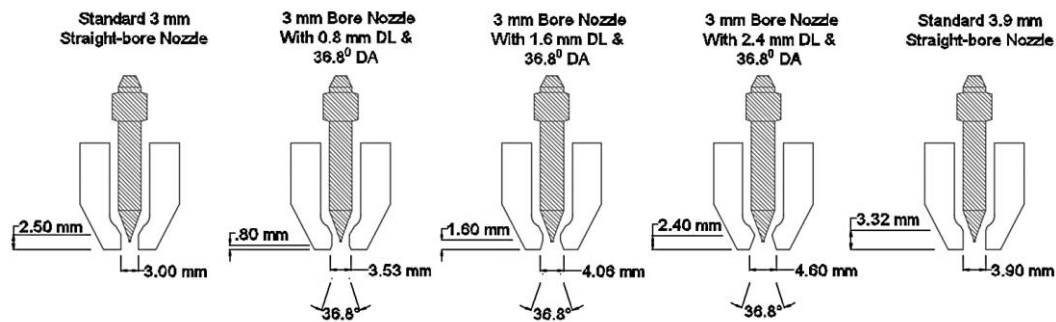
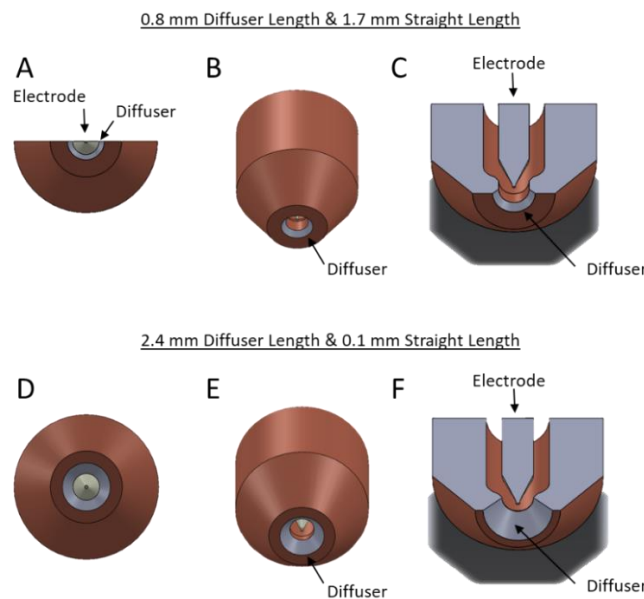


Figure 59 Five nozzle geometries: An industry-standard 3 mm straight-bore nozzle, three diverging nozzles and a 3.9 mm straight-bore nozzle for comparison.

Figure 60 illustrates, for the two extreme cases, the relationship between nozzle straight length (N_{SL}) and diffuser length (D_L). For the same D_A , the diffuser length increases with a reduced nozzle straight length and vice versa. The effective nozzle exit bore diameter (E_{NEBD}), shown in Figure 42, also increases with diffuser length.



- A] Nozzle and electrode plan view, small diffuser length.
- B] Nozzle and electrode tip, small diffuser length.
- C] Nozzle and electrode cross-section, small diffuser length. Small ENEBD.
- D] Nozzle and electrode plan view, large diffuser length.
- E] Nozzle and electrode tip, large diffuser length.
- F] Nozzle and electrode cross-section, large diffuser length. Large ENEBD.

Figure 60 Diverging nozzle extreme cases – two different 3 mm nozzles with angled diffusers.

3.2.4 Electrode Material

As off the shelf, PTA electrodes to suit this study's PWP Viper MC torch with compositions different to 2% thoriated tungsten were not available. Specialist electrodes were made specifically for this study, including the following materials: pure tungsten (W), ceriated tungsten (W-CeO₂), lanthanated tungsten (W-La₂O₃) and zirconiated tungsten (W-ZrO₂).

Arc pressure measurements of three electrode materials (zirconiated, ceriated and lanthanated) were undertaken and compared to the results of a standard 2% thoriated electrode. Measurements were undertaken with the electrodes within a straight-bore 3.9 mm nozzle at an arc length of 6.4 mm, a PGFR of 0.8 l/m and a current of 140 A.

3.2.5 Electrode Wear

To investigate the effect of electrode wear on arc pressure, measurements were undertaken for two 2% thoriated electrodes in different states of wear (used electrode after two hours and a heavily used electrode after seven hours). The results were compared with the measured results for a new electrode. Measurements were undertaken with the electrodes within a straight-bore 3.9 mm nozzle at an arc length of 6.4 mm, a PGFR of 0.8 l/m and a current of 140 A.

To account for differences in arc pressure because of loss of electrode length resulting from wear, and consequential increased arc length, a measurement was also undertaken with the arc length modified. This maintained the 6.4 mm arc length and accounted for the change in electrode length because of its wear.

3.2.6 Specialist Electrode Geometries

Electrode Tip Angle – to investigate the effect of electrode angle on arc pressure, measurements were taken for three electrode angles: 20°, 60° and the standard 40°, shown in Figure 61, measured within a straight-bore 3.9 mm nozzle at an arc length of 6.4 mm, a PGFR of 0.8 l/m and two currents: 140 and 200 A.

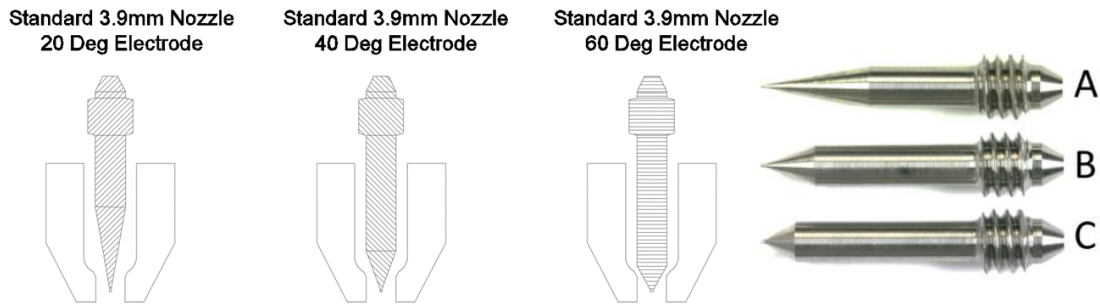


Figure 61 Three electrode geometries: 20° E_{TA}, 40° E_{TA}, 60° E_{TA}, each within a straight-bore 3.9 mm nozzle, with a standard electrode setback of 1.4 mm. Angled tungsten electrode prior to use photographs: A] 20° tip angle, B] 40° tip angle, and C] 60° tip angle.

Electrode Flat Tip – to investigate the consequences of flat tip electrodes on arc pressure, measurements were taken for four non-standard electrode lengths and tip diameters, shown in Figure 62. The results were compared with the measured results for a new standard electrode. Measurements were taken with the electrodes within a straight-bore 3.9 mm nozzle, with a contact tip work-piece distance (CTWD) of 5 mm, PGFR 0.8 l/m and a current of 140 and 200 A.

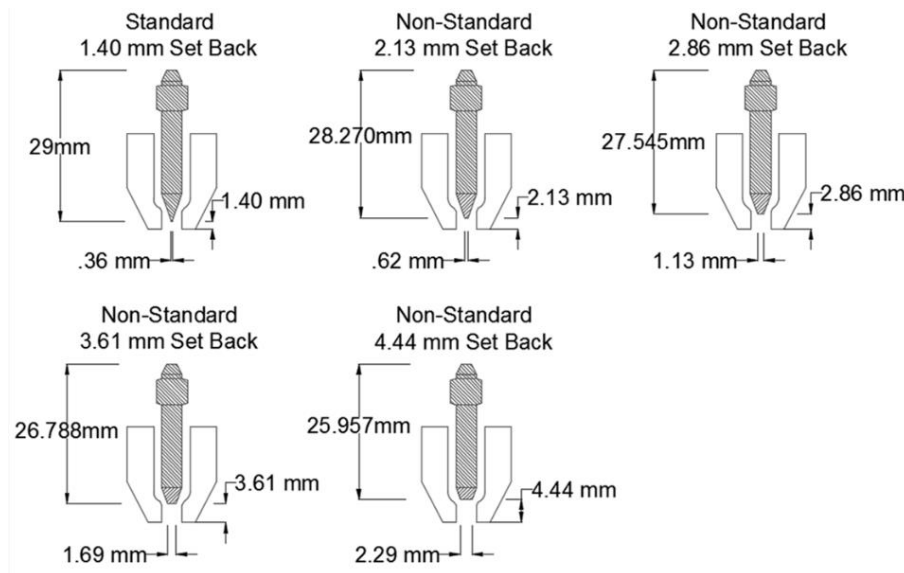


Figure 62 Four flat tip electrodes of non-standard length, and one standard electrode for comparison, each within a straight-bore 3.9 mm nozzle.

3.3 Results and Discussion

3.3.1 Measurement Orifice Diameter and Arc Pressure Measurement Repeatability

The measurement orifice diameter was found in this study to have minimal effect, on measured arc pressure, shown in Figure 63. Changing from 1 to 0.3 mm diameter a 91% difference in the cross-sectional area decreased arc pressure by 5.2%. Less than the expected 10% experimental error.

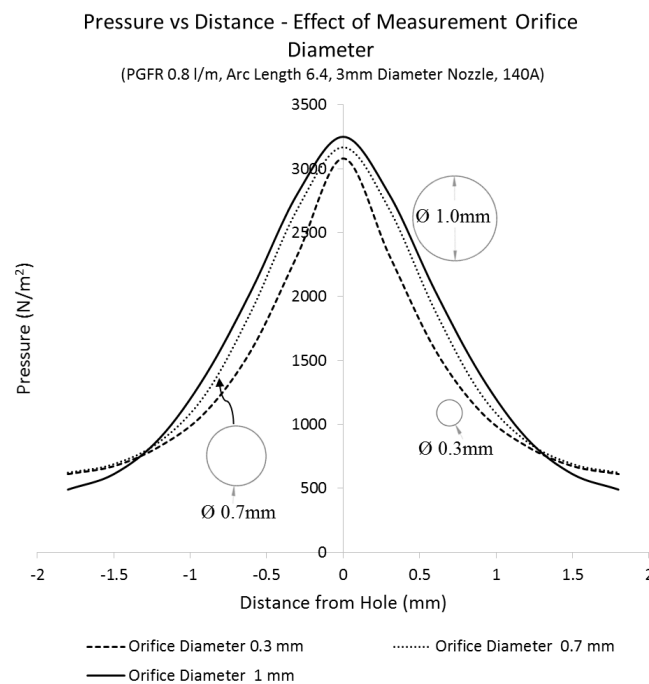


Figure 63 Effect of copper-block orifice diameter. Repeated measurement of arc pressure, constant parameters, for three different orifice sizes: 1.0, 0.7 and 0.3 mm.

However, this is in contrast to the findings of Schnick (2016), who established an increased peak arc pressure when changing from a 1 to 0.5 mm measurement orifice. This difference may be because the very small nozzle diameter used by Schnick (2016) – 1.5 mm – and the subsequently small arc column produced would be close to or smaller than their 1 mm measurement orifice. The 0.5 mm hole may have been closer to or smaller than their arc diameter and hence given a higher measurement. In addition, their short arc length – 4 mm – and low arc-current – 100 A – as well as the repeatability and accuracy of their torch alignment to the orifice and the torch angle, the method, not given, and their torch geometry differences, may account for their findings. Nevertheless, the orifice used

by this study was 0.3 mm and, as the arc column diameter was seen to be larger than the measurement orifice, the measured values should therefore result in more accurate measurement, in line with Schnick (2016).

An example of two non-consecutive arc pressure measurements undertaken with the same parameters and PTA torch geometries is illustrated in Figure 64. The results show a peak arc pressure difference of 2.9%, within 10% experimental error, indicating that the methodology is repeatable.

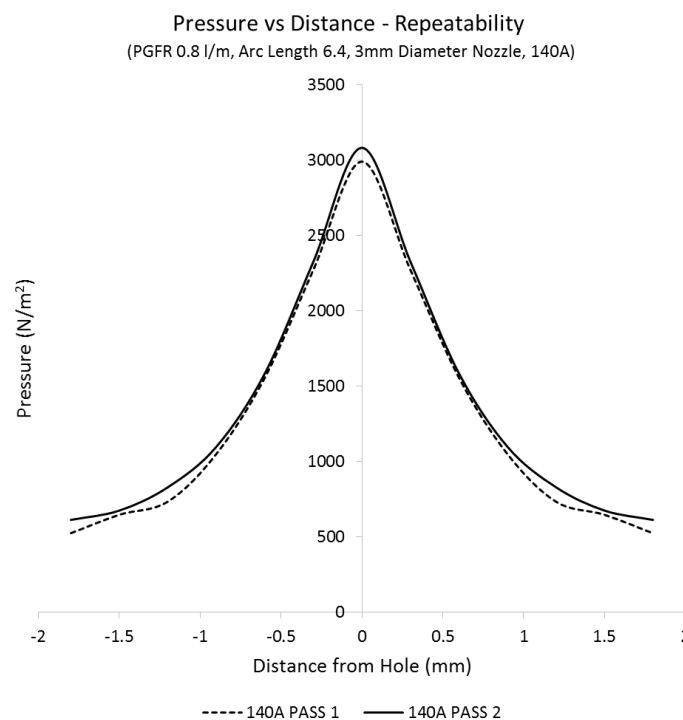


Figure 64 Example of arc pressure measurement repeatability: straight-bore 3.9 mm diameter PTA nozzle.

3.3.2 GTA Arc Pressure

The effect of arc length on GTA (DCEN) arc pressure is shown in Figure 65 ‘A’ for four currents (Table 6) and two arc lengths: left-hand side 3 mm and right-hand side 6.4 mm. The results show that GTA arc pressure increases with current and with a reduced arc length, and is greatest at the centre and diminishes with distance. For the 6.4 mm arc length it is clear that the arc pressure for the same values of current is lower than that for the 3 mm arc length. However, as they approach 200 A, the effect of arc length appears

to reduce significantly with a linear trend, shown in Figure 65 'B'. As the independent variable current is increased, the dependent variable arc pressure, increases accordingly.

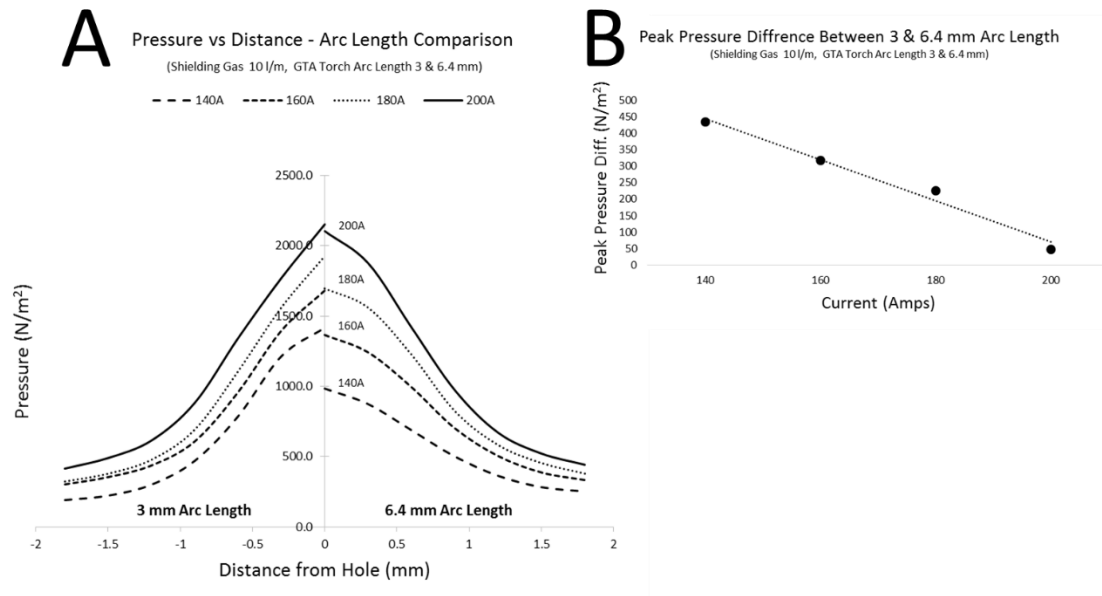


Figure 65. A] Comparison of GTA arc pressure for 3 mm (left of Y axis) and 6.4 mm (right of Y axis) arc length, B] Peak arc pressure difference between GTA arc lengths of 3 and 6.4 mm.

The distributions indicate that the arc pressure reduces with distance from the arc. The distributions appear to plateau, implying that the arc pressure does not reach zero. This is likely a result of the arc pressure and shielding gas deflecting and dissipating radially from the arc along the copper-block surface on impact with the copper-block.

The GTA arc diverges from its root at the electrode tip in a cone shape: as the distance from the electrode tip to the work-piece arc length increases, the area of the cone in contact with the work-piece increases accordingly. Conversely, decreases to arc length reduce the cone area, creating a narrow and more focused arc. This change in arc concentration with arc length could explain the differences in GTA arc pressure at lower currents, as in Figure 65 'A', for the two arc lengths, as pressure is force divided by area.

However, as the current is increased, the reducing effect on arc pressure from increased arc length reduces, as shown in Figure 65 'B'. The difference at 200 A is minimal. This

implies that the significance of the independent variable current is higher than that of arc length on GTA arc pressure at higher currents.

By increasing current for GTA, the following correspondingly increase: electrode temperature, the quantity of ionised shielding gas and, accordingly, electrical conductivity, arc voltage and arc power, magnetic flux density, arc current and energy density, and heat input. These increases result directly in the observed correlation between increased arc pressure and current.

3.3.3 Comparison of GTA and PTA

To provide a comparison between measured PTA and GTA arc pressures, both are shown in Figure 66 'A' (PTA on the left and GTA on the right) for an arc length of 6.4 mm and four currents, set out in Table 6. A 3 mm PTA nozzle diameter was used. It is clear from Figure 66 'B' that PTA peak arc pressure increases in a linear fashion with current and has a similar gradient to GTA, but with significantly higher values.

By comparing the arc pressure measurements of GTA and PTA for the same current and arc length, shown in Figure 66 'A', the effect of the PTA restricted arc, with an industry-standard 3 mm nozzle, is evident, with a substantial increase taking place in arc pressure for all values of current. The change in arc pressure with distance from the arc is more significant, showing a steeper distribution gradient, for PTA owing to the confined arc column and reduced arc divergence and arc cone, shown in Figure 67. The static arc pressure, induced electromagnetically in both the radial and axial directions, is illustrated for both GTA and PTA in Figure 67 (Lin and Eagar, 1986).

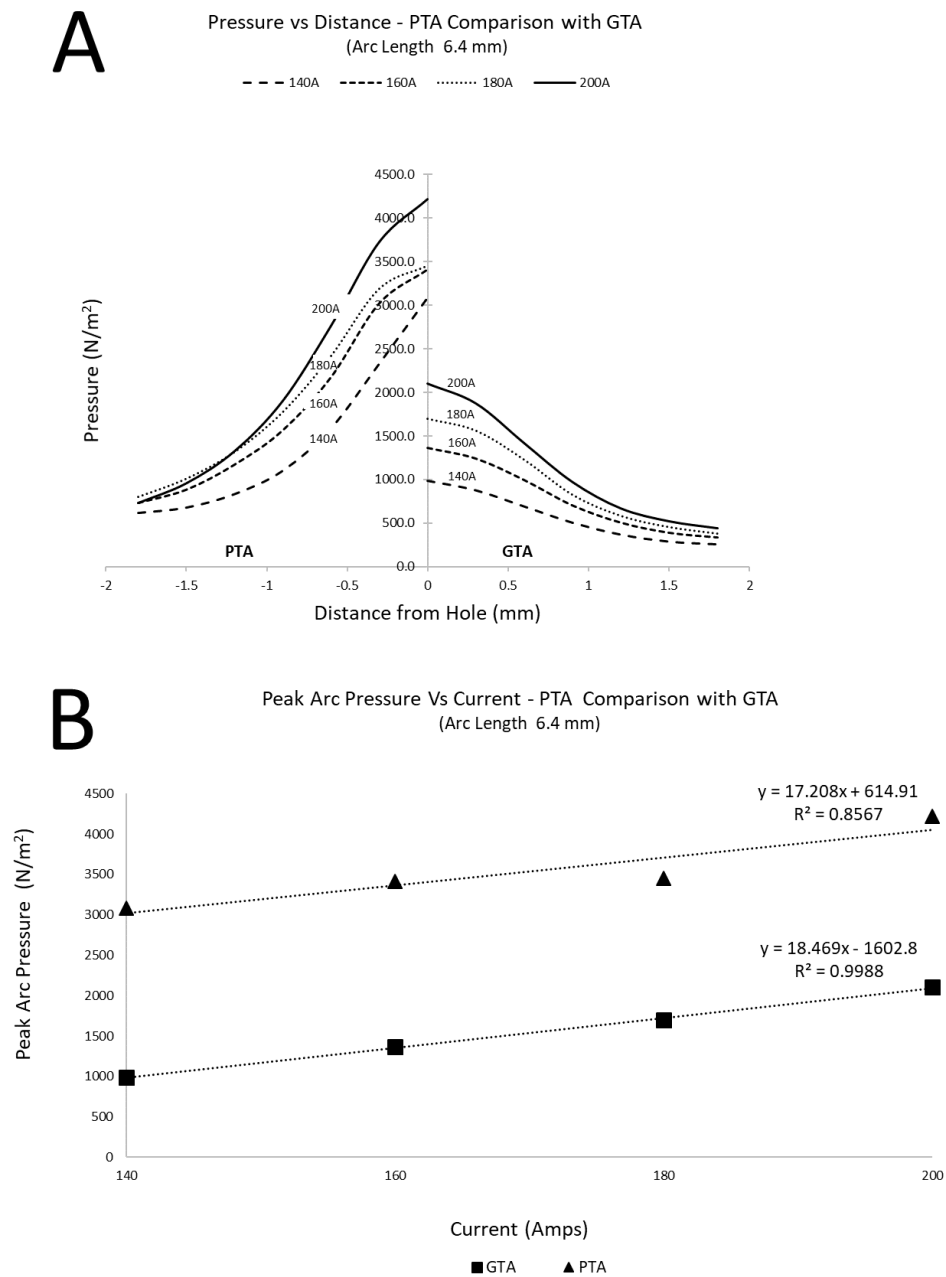


Figure 66 A] Comparison of PTA with a 3 mm nozzle (left) and GTA (right) arc pressure, B] Peak arc pressure comparison between PTA with a 3 mm nozzle and GTA.

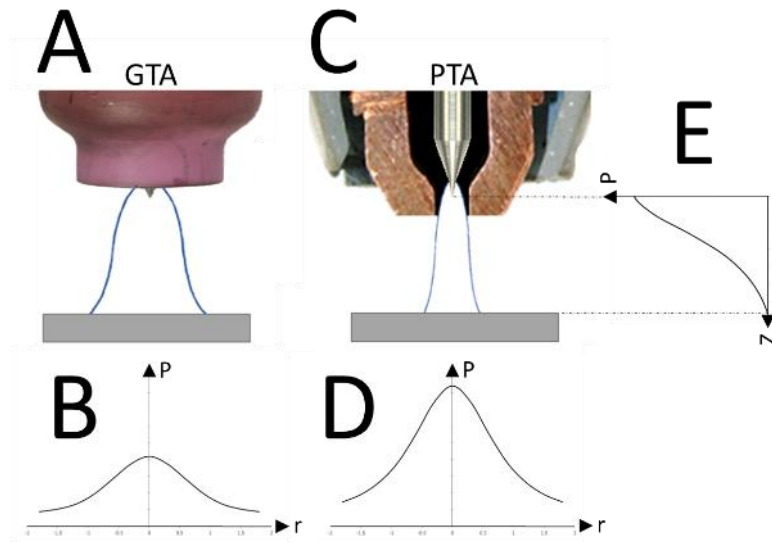


Figure 67 A] GTA diverging arc, B] GTA arc pressure distribution with distance, C] PTA narrow constrained arc, D] PTA arc pressure distribution with distance, E] Difference in arc pressure between the cathode and anode. Based on a sketch from Lin and Eagar (1986).

The difference in arc pressure between the cathode and anode generates the plasma stream and directs it towards the substrate. The current density is highest at the electrode tip – the cathode – and reduces at the substrate – the anode (Lin and Eagar, 1986).

The percentage difference between the measured peak GTA and PTA arc pressures is shown in Figure 68. The percentage difference reduces with current, stabilising at 200 A. This is possibly because of the unrestricted GTA arc being subjected to an electromagnetic pinch force, Lorentz force, acting on the arc, induced by the magnetic field resulting from the current flow through the electrode. The force increases with a quadratic trend as current rises, restricting the GTA arc and reducing the percentage increase between the two processes as current increases.

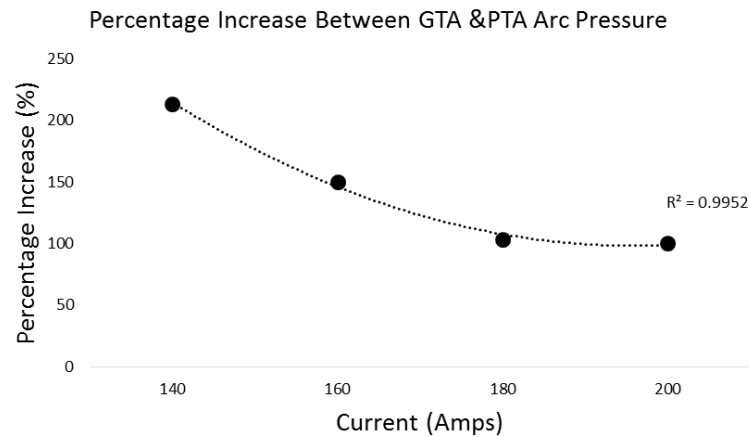


Figure 68 Percentage increase between the measured arc pressure values of GTA and PTA in Figure 66 ‘B’.

To establish, for PTA, a basis for comparison, four pressure measurements were undertaken with no arc: plasma gas only (0.8 l/min), shielding gas only (15 l/min), combined plasma gas and shielding gas, and combined plasma gas, shielding gas and pilot arc (current below 10 A), shown in Table 9. It is clear that, individually or combined, the measured pressures without the main arc are minimal.

Table 9 For comparison and elimination purposes, four pressure measurements were undertaken for PTA but with no main arc.

Measured Pressure for Shielding Gas, Plasma Gas and Pilot Arc				
(Arc Length 6.4 mm, Gas Compositions 100% Argon)				
	Plasma Gas Only (0.8 l/min) No Arc	Shielding Gas Only (15 l/m) No Arc	Plasma Gas (0.8 l/min) & Shielding Gas (15 l/m) No Arc	Plot Arc [Plasma Gas (0.8 l/min) & Shielding Gas (15 l/m) + Pilot Arc]
Peak Arc Pressure (N/m ²)	10	40	50	90

3.3.4 Arc Pressure Distributions

Figure 69 shows typical examples of PTA arc pressure distributions for a straight-bore 3.9 mm diameter nozzle for different values of current, shown in Table 6. The results show that the arc pressure decreases with horizontal distance from the arc core and that the peak arc pressure increases with current. Further PTA arc pressure distribution examples are located in Appendix B.

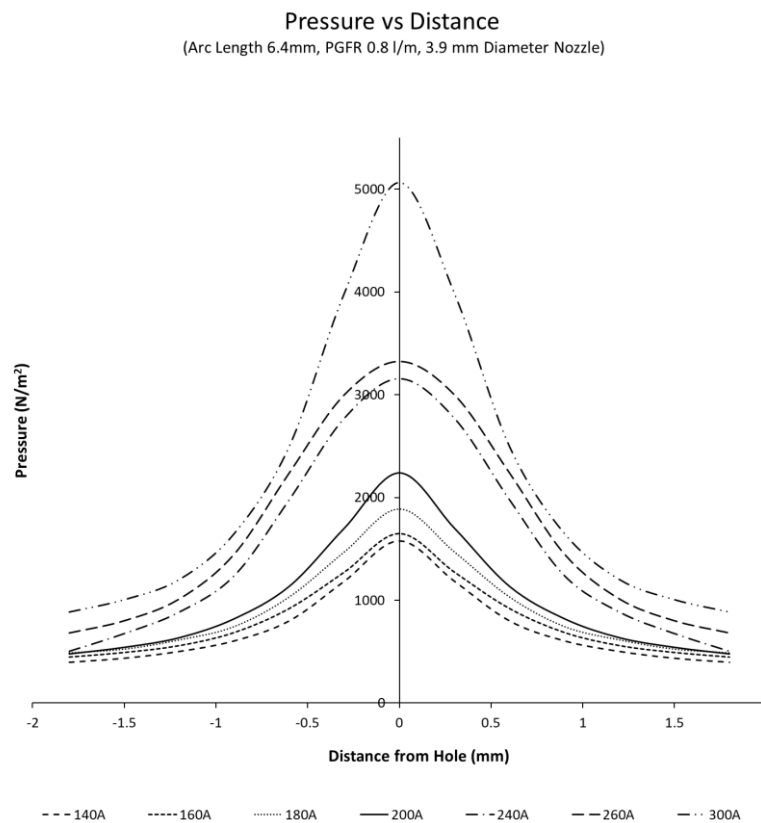


Figure 69 PTA pressure distributions for varying current.

To help visualise the arc pressure distribution, a 3D image is shown in Figure 70 ‘B’, alongside the 2D representation, shown in Figure 70 ‘A’, of the same PTA arc pressure measurement data. An interesting aspect of the arc pressure distribution is the confinement at the torch and directly below the arc, which then radiates outward from the centre at the substrate. The distribution flattens out with distance, gradually dissipating and reducing in pressure.

The results indicate that the measured arc pressure distributions plateau at higher values than the glovebox pressure. A possible explanation for this might be the interaction/collision between the arc and copper-block or substrate, resulting in a 90° change of direction, with the pressure radiating across the surface perpendicular to the arc, causing higher measured arc pressures with distance from the electrode than would ordinarily be expected, shown in Figure 71. This does not affect the peak arc pressure as this is a static measurement directly below the arc that is allowed to stabilise for a fixed duration.

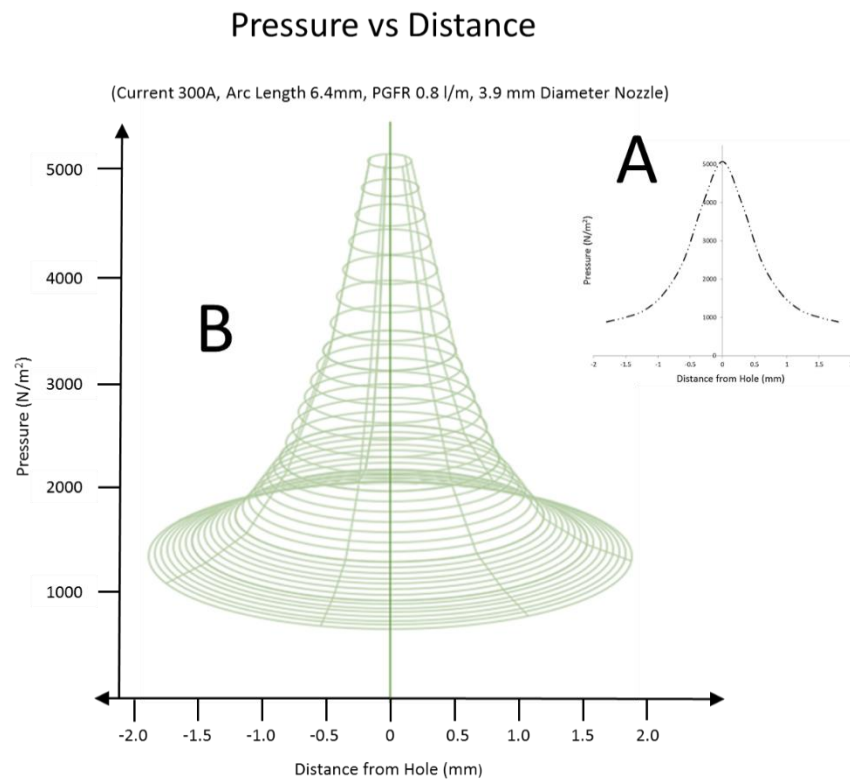


Figure 70 Arc pressure distribution illustration. A] 2D representation of measured arc pressure distribution with distance from the arc, B] 3D representation of the same distribution – inverted cone shape of the arc pressure distribution.

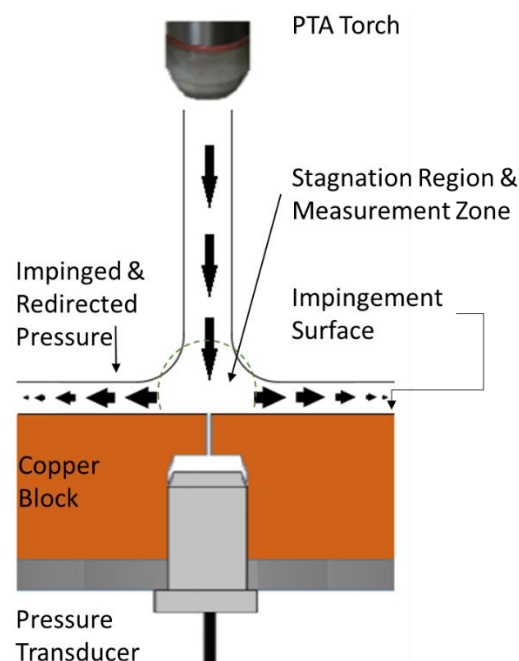


Figure 71 Impingement of arc pressure on the copper-block.

The inverse of the arc pressure distribution approximates the melt-pool depression shape, once surface tension has been overcome – i.e. increased depth directly below the arc, reducing with distance.

3.3.5 Results of Full Width at Half Maximum (FWHM)

Utilising FWHM and the arc pressure distributions, estimated arc pressure diameters were calculated, and the effects of each parameter and variable on arc pressure diameter determined.

Figure 72 illustrates the trends of GTA arc pressure diameters at two arc lengths. The results indicate that, for GTA at a 3 mm arc length, the arc pressure diameter increases, decreasing slightly with current at a 6.4 mm arc length. The difference between the two trends suggests that arc pressure diameter increases significantly with arc length for GTA, as the arc pressure diameter, at 6.4 mm arc length, is 38.3% higher at 140 A and 9.76% higher at 200 A than the 3 mm arc length. There is also a possible convergence of diameter with increasing current.

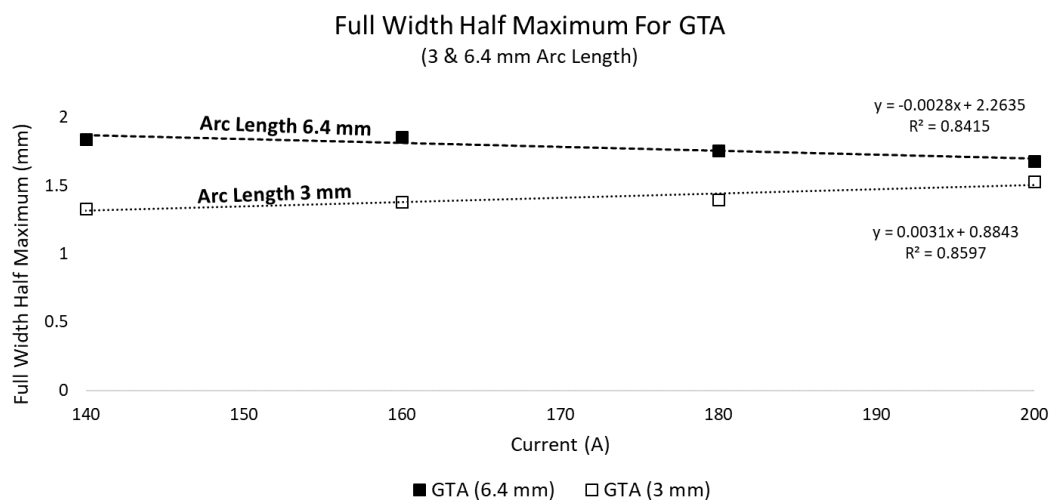


Figure 72 FWHM versus current comparison of GTA at two arc lengths: 3 and 6.4 mm.

A comparison of GTA and PTA FWHM is shown in Table 10. The restricted PTA is shown to have a significantly reduced arc pressure diameter to GTA for the same arc length and parameters: GTA arc pressure diameter 50.3% higher at 140 A and 37.4%

higher at 200 A than PTA. The GTA trends shows the diameter decreasing with the current. The PTA diameter approximates a set diameter with some data scatter.

Table 10 FWHM versus current comparison of GTA and PTA with a 3.9 mm nozzle diameter, 0.8 l/min PGFR, both at an arc length of 6.4 mm.

Process	Arc pressure diameter (FWHM) with current (mm)			
	140 A	160 A	180 A	200 A
GTA	1.837	1.853	1.757	1.680
PTA	1.222	1.423	1.356	1.223

Figure 73 illustrates the FWHM arc pressure diameter for the arc pressure distributions of current and PGFR. Figure 73 ‘A’ is calculated from the 3.9 mm nozzle distributions of Figure 69 for varying current. For Figure 73 ‘B’, the calculated value at 2 l/min PGFR is thought to be a possible data error, so the trends and gradients, including and excluding this point, are shown. From the three trend equation gradients, it is apparent that current and PGFR have minimal effect on the change to arc pressure diameter, once data point scatter and error – i.e. low R^2 values – are taken into account. A flat trend with an insignificant slope, similar to Figure 73, was found to be typical for most PTA variables, suggesting that the PTA arc pressure column is straight with little divergence.

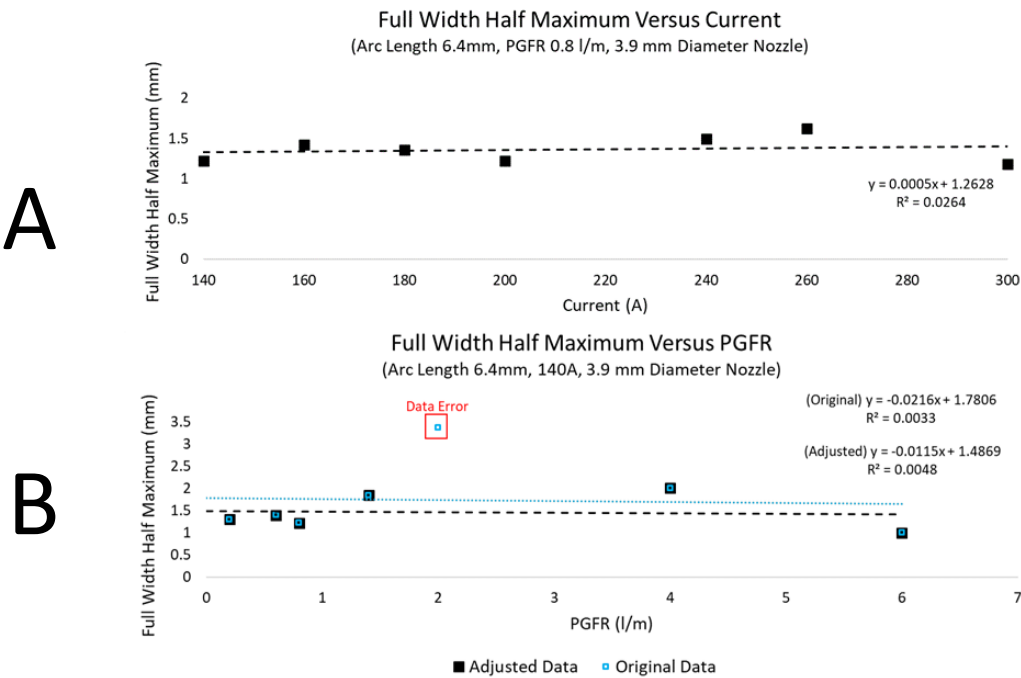


Figure 73 FWHM for the distributions of A] Current, B] PGFR.

Figure 74 shows the calculated FWHM trend for angled nozzles. Unlike the other variables investigated by the FWHM method, this trend indicates an increase in arc pressure diameter, in this instance with diffuser length.

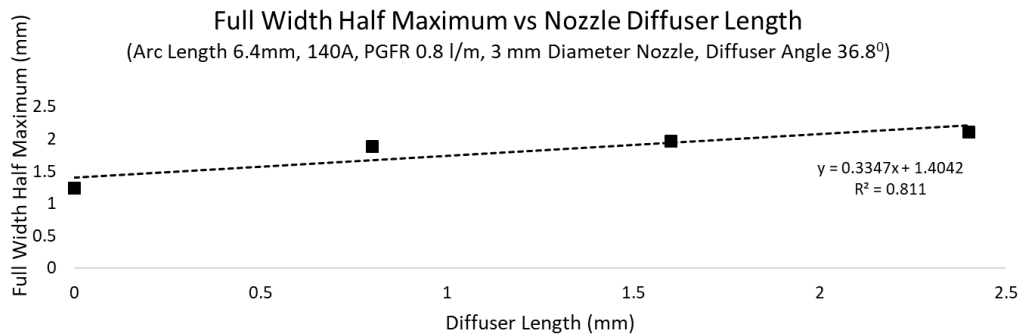


Figure 74 FWHM for the distributions of the angled nozzles against nozzle diffuser length.

The PTA arc column not only supplies heat input to the substrate but also a melt-pool geometry sculpting/shaping force. The arc diameter also has a significant effect on power density, as it dictates the area to which the arc power is applied. The shape/size of the PTA arc is therefore influential. The FWHM plots show arc pressure diameter and not arc diameter. Arc pressure diameter varies with changes to parameters and variables for

GTA. However, for PTA, there is minimal effect on arc pressure diameter with low trend gradients with changes to current, PGFR, arc length, nozzle diameter and nozzle length. This suggests that, for PTA, the arc pressure diameter is not much affected by changes to parameters and variables, and, consequently, the arc pressure column is straight.

The FWHM data points are scattered, resulting in low R^2 values, and based on the results of several parameters and variables, it is not possible to establish definite arc pressure diameters or dependencies.

3.3.6 PTA Current

The effect of current on PTA peak arc pressure is shown in Figure 75 for a straight-bore 3.9 mm diameter nozzle. It is apparent that peak arc pressure increases in a linear fashion with current.

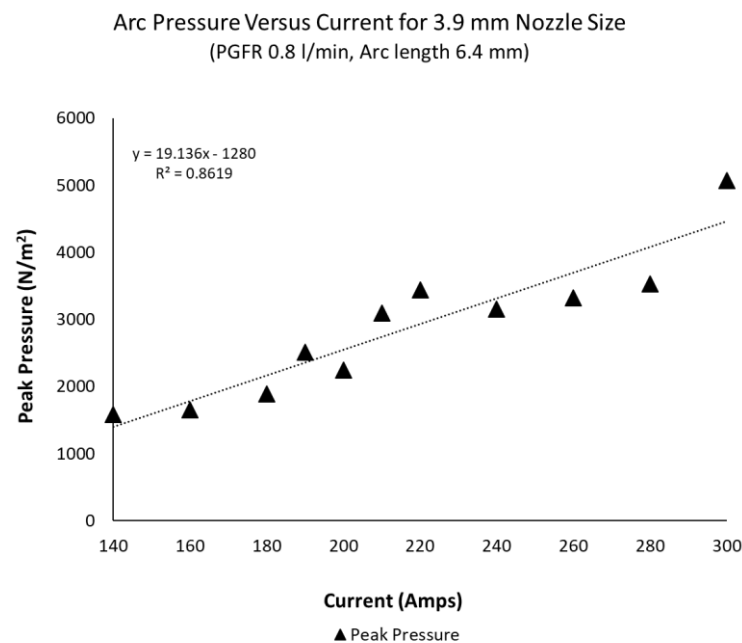


Figure 75 PTA peak arc pressure versus current.

The approximate 3.9 mm nozzle calculated PTA arc pressure width of 1.36 mm, using FWHM, shown in Figure 73 'A', implies that the arc pressure geometry is smaller than the nozzle diameter and not significantly affected by the magnitude of arc current. However, this is contrary to the Lorentz force, which increases with current, most significantly close to the electrode, which should influence the arc pressure geometry and

the validation data from the 1957 PTA patent, suggesting that PTA arc diameter, which should be proportional to the arc pressure column diameter, increases significantly with current, (Gage, 1957). Unfortunately, the method of arc diameter measurement is not stated in the patent.

The FWHM results in Figure 72 suggest that, for GTA, as the current increases, the difference in arc pressure diameter between two arc lengths diminishes. This relationship is reaffirmed in Figure 65 'B', which illustrates the significant reduction of 'arc pressure difference' between two arc lengths as the current is increased. The comparison of GTA and PTA arc pressure diameters in Table 10 indicates that GTA decreases with current, probably because of electromagnetic constriction, and PTA remains static. Figure 73 'A' also indicates minimal change to arc pressure diameter with current. However, this is unexpected: if arc pressure diameter is proportional to arc column diameter, they should both show change with current. Several studies, including that of Zhang et al. (2014), have involved photographing the PTA arc with high-speed cameras, showing an increase in PTA arc diameter with current, shown in Figure 17 'B' top. However, arc photography, especially without a scale, is not a quantifiable or reliable method of arc size measurement. Additionally, the PTA arc pressure diameter calculated by FWHM is not a good approximation of the PTA arc diameter, as it does not include the interface with the substrate where the arc diameter is at its maximum, and is therefore only an indication of the column width over which the arc pressure acts.

The distributions of Figure 66 'A' and the trends of Figure 66 'B' and Figure 75 indicate a relationship of increasing arc pressure with current. As arc pressure is a momentum transfer and the mass of gas is unaltered, increases of current must increase the arc velocity.

Increases in the current result in a rise in plasma gas heating, gas temperature and subsequently volume of gas ionisation. The resistance of the electric arc creates further heat, in turn ionising even more gas. With increased temperature, the gas thermal conductivity and electrical conductivity rise, shown in Figure 36, increasing the effectiveness of arc current transfer. The rise in current increases the energy density of the arc column and arc pressure accordingly.

Arc current affects the peak arc pressure and the radius of distribution, unlike arc length and PGFR, which predominantly affect the distribution centre (Chen et al., 2015). The melt-pool is therefore larger as a result of the higher heat input as the current is increased and is affected by the arc pressure at the centre, below the PTA torch, and across a larger area.

The effect of electromagnetic restriction, tighter focused at the electrode tip, increases with current, as the magnetic flux density increases and as electrical conductivity increases with temperature, further constraining the arc and increasing the plasma column energy density and arc pressure.

3.3.7 PTA Plasma Gas Flow-rate (PGFR)

For a varying PGFR, the effect on peak arc pressure is shown in Figure 76 for a straight-bore 3.9 mm diameter nozzle. For comparison, the peak arc pressure for GTA at 140 A and arc length of 6.4 mm is also shown. The peak arc pressure increases in linear fashion with PGFR.

For clarity, measured arc pressure results are only shown in Figure 76 for PGFRs at two currents – 140 and 200 A. The full set of recorded results is included within the arc pressure model in Chapter 5 and in Appendix A.

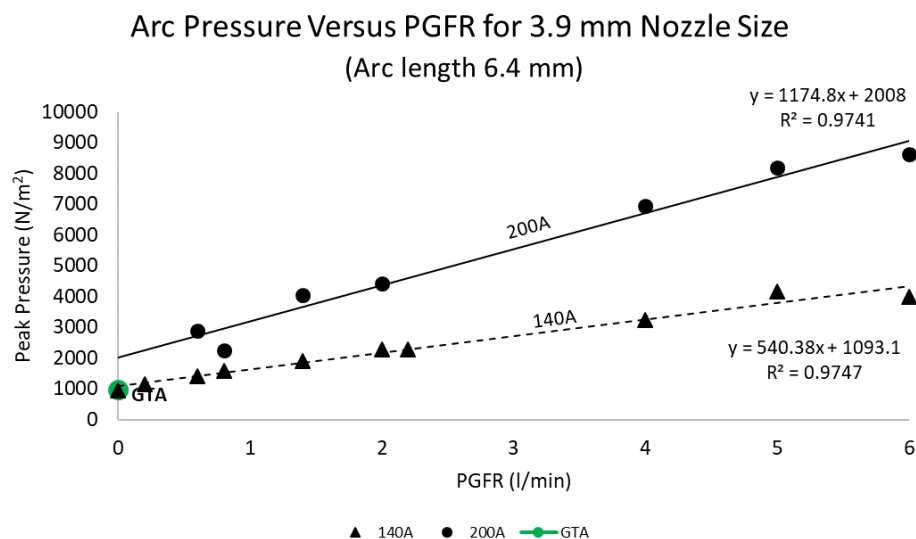


Figure 76 Effect of increasing PTA PGFR on arc pressure.

The no arc measurements of Table 9 demonstrate that plasma gas alone, at the low flow-rates commonly used (0.6–1.0 l/min), has a negligible effect on torch pressure. However, combined with the main arc, the PGFR has a significant impact.

At zero l/min of plasma gas, the PTA measured arc pressure, at 140 A, is equivalent to that of GTA, as shown in Figure 76, with the shielding gas, as in GTA, supplying the PTA arc with gas for ionisation. At even low values of PGFR (0.6 l/min), the arc pressure exceeds that of GTA for the same parameters.

This study did not experience double-arcing as a result of too low or no PGFR at moderate currents for the PWP Viper MC torch, as outlined in the literature review (Prevosto, Kelly and Mancinelli, 2011), emphasising the importance of a minimum PGFR to prevent the trigger of double-arcing. However, low, below 0.6 l/min, PGFRs were only applied for short durations of six minutes to avoid torch damage. This implies that the PTA torch can operate safely from double-arcing within an argon-filled environment with no or low PGFRs for very short periods – for example, for experimental work. However, this cannot happen for extended WAAM operational use, as this leads to destructive torch damage.

Increases to PGFR increase turbulence, resulting in arc pressure fluctuations, a broader pressure distribution, and reduced arc instability (Pan et al., 2002).

As gas volume is proportional to its temperature, as the plasma gas is heated, its velocity increases significantly through the nozzle straight length. Given the very high gas temperatures – around 7700 to 19800°C for argon – the velocities involved are very high. The high-velocity gas imparts momentum and kinetic energy to the arc, increasing the arc column momentum transfer with the substrate – arc pressure (Gage, 1957).

Jian (2015) undertook an analysis of PTA PGFR with a 3 mm nozzle at 200 A and found that the maximum velocity increased with PGFR, shown in Figure 77, therefore increasing arc pressure. For all PGFRs, the velocity decreases with arc axis distance. The PGFR was found to have a minimal effect on plasma arc temperature, and current density was only affected close to the electrode (Jian, 2015).

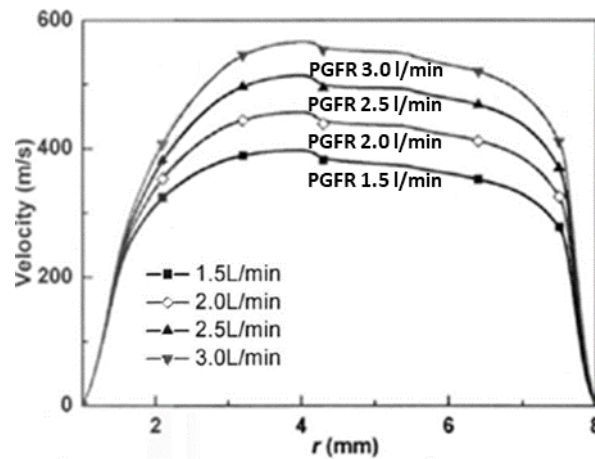


Figure 77 Distribution of velocity along the plasma arc axis with PGFR. (Jian, 2015)

As outlined in the literature review, heat flux density at the substrate and heat transferred to the melt-pool increases with PGFR (Schnick, 2016). PGFR is also a critical parameter for initiating and maintaining PTA keyhole (Short et al., 2011; Langford, 2018).

The results of this study show that, for combinations of high PGFRs and current, significant arc pressures are generated. The FWHM results, shown in Figure 73 'B', suggest a minimal change in arc pressure diameter with increased plasma flow-rates. However, there is likely a small focusing effect, not indicated by the FWHM method, because of the increase of thermal pinch on the arc by the plasma gas as the flow-rate increases (Miller and Zander, 1986). Higher PGFRs increase the cooling and pinch effect on the arc column extremities, reducing the arc diameter and increasing the arc velocity, increasing arc pressure (Prevosto and Risso, 2009).

PGFR affects the peak arc pressure, but predominantly only affects the centre of the distribution, unlike arc current, which affects both the peak arc pressure and the radius of distribution (Chen et al., 2015). The melt-pool is therefore principally affected by the arc pressure at the centre below the PTA torch.

Increasing the PGFR is a result of a rise in gas supply pressure – as the gas pressure is inversely proportional to volume. At very high PGFRs and high currents, the arc exhibits increased back pressure and a corresponding pressure drop, significantly reducing the predefined gas flow. This reduction in flow necessitates an increase in the PGFR to maintain the required flow.

Figure 78 illustrates the reducing cross-sectional area of free space within a 3 mm nozzle, taking into account the changing nozzle and electrode geometry.

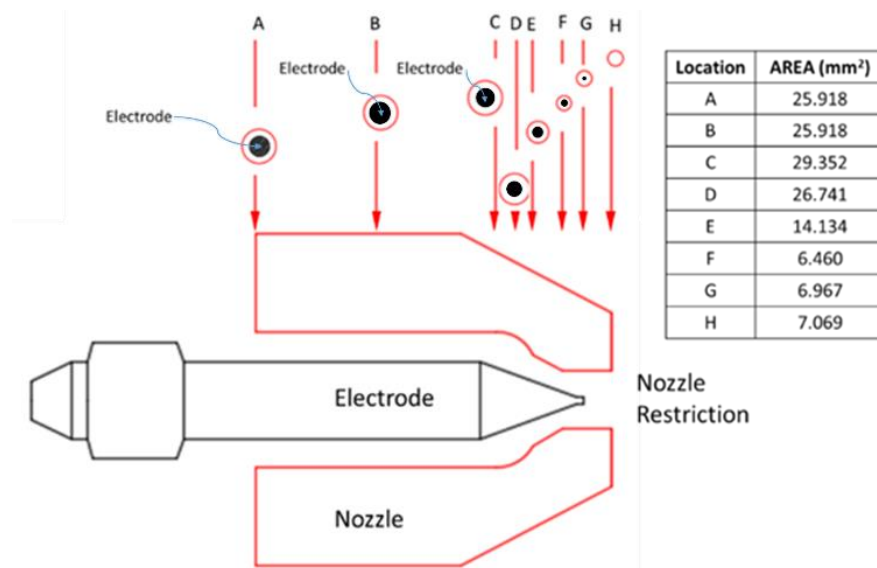


Figure 78 Calculated cross-sectional area of nozzle free space around the electrode – 3 mm diameter nozzle. Locations indicated along with scaled sketches of each location free cross-sectional area and electrode cross-sectional area.

For a fixed PGFR, as the plasma gas transitions through the nozzle, the gas volume decreases as the nozzle cross-section changes in geometry, shown in Figure 78, compressing the gas and increasing gas density and pressure. As temperature elevates, so does the pressure. Increased density enhances the ionisation of the gas, resulting in increased plasma density with improved electrical conductivity of the arc. The magnetic pinching effect, which focuses the plasma column and increases the energy density of the arc and raises the arc pressure, is enhanced with plasma density.

To an extent, raising PGFR enables a higher volume of plasma gas to be heated and ionised by the electrode, raising the temperature and electrical conductivity of the gas. The changes in gas properties increase the ability of the plasma column to transfer the arc current more effectively but also increase the magnetic restriction effect on the arc, which should marginally decrease the arc size, and increase energy density and arc pressure correspondingly.

It is proposed that, at high PGFRs, where not all the gas can be fully ionised, the increased flow through the fixed nozzle aperture squeezes the arc, an impinging force, further

restricting the arc, shown in Figure 79. Un-ionised argon is a poor electrical conductor, reducing the path through which the arc can travel. Additionally, as the un/partially ionised gas passes down the side of the arc column, depressurising to atmospheric pressure and reducing its temperature through the Joule–Thomson effect, the relatively colder gas extracts heat from the arc column boundary, applying a thermal squeeze on the arc. However, the low thermal conductivity of argon, shown in Figure 36, limits this effect. The compressibility of the plasma gas increases with PGFR (Zhang et al., 2014), increasing its effect on the arc. These phenomena result in a concentrated plasma column with increased energy density and arc pressure. As the PGFR increases, the arc diameter should also enlarge as the plasma column is enabled to grow. However, any increase in arc diameter is counteracted by the thermal and impingement constriction on the arc by the by-passing plasma gas, shown in Figure 79, resulting in a net decrease in arc diameter with flow-rate.

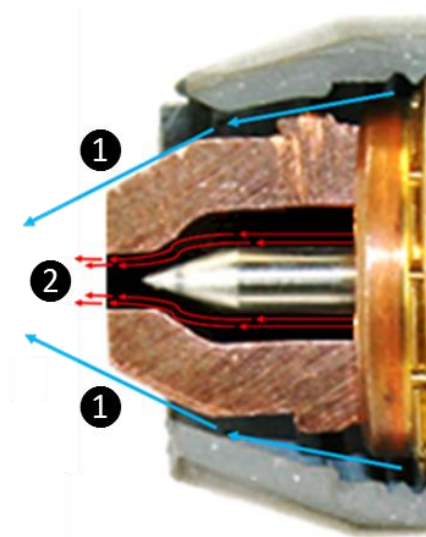


Figure 79 Gas flow within a PTA torch. 1] Shielding gas route, typically 10–15 l/min, 2] PGFR high flow-rate.

Increasing the PGFR proportionately is also beneficial to torch nozzle longevity. Plasma gas and the torch internal swirl ring developed originally for plasma cutting, resulting in the relatively colder denser gas along the inner nozzle boundary, as a result of centrifugal force, protecting the nozzle from damage through the high temperatures involved in the process. Too low flow at high currents results in unrecoverable nozzle damage as a result of double-arcing (Prevosto, Kelly and Mancinelli, 2011).

3.3.8 Arc Length

The dependence of PTA peak arc pressure on arc length is shown in Figure 80 for a straight-bore 3.9 mm diameter nozzle. As arc length increases, the relative peak arc pressure decreases: arc pressure is inversely proportional to arc length – a negative linear relationship.

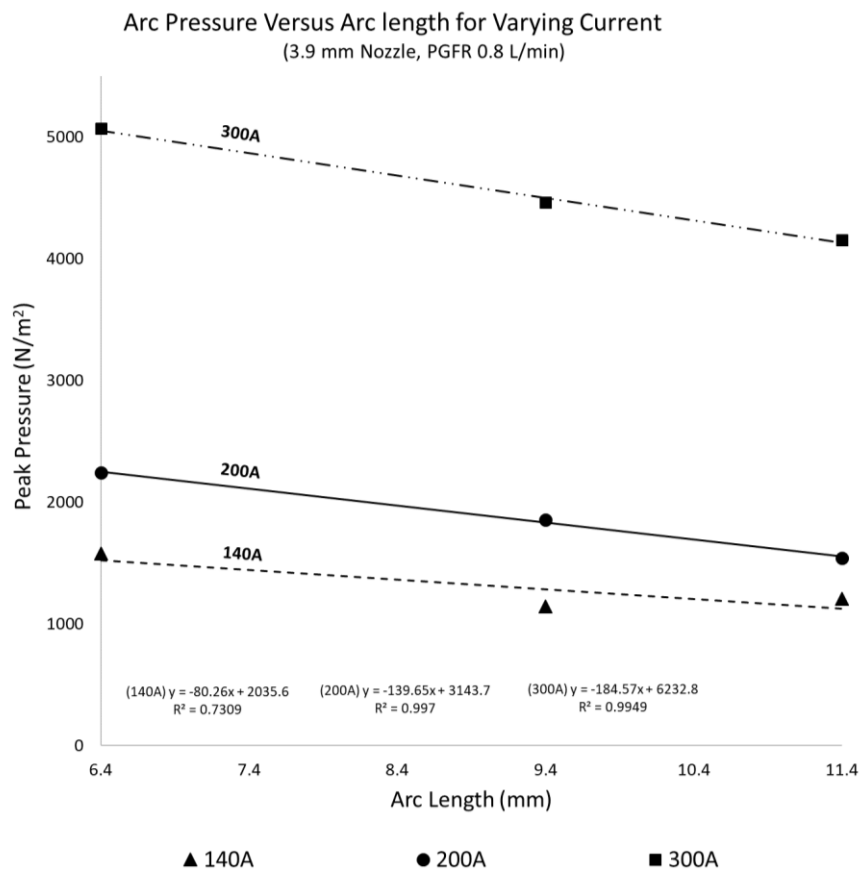


Figure 80 Peak arc pressure versus arc length for different current levels.

For clarity, measured arc pressure results are only shown in Figure 80 for the three arc lengths at three currents: 140, 200, and 300 A. The full set of recorded results is included within the arc pressure model in Chapter 5 and in Appendix A.

Figure 81 illustrates the rate of change in peak arc pressure with arc length at values of current, using the trend gradients from Figure 80. The correlation indicates that the arc pressure varies significantly with arc lengths at 300 A and that the variation generally

reduces with current: i.e. arc length has a more significant effect on arc pressure at higher currents.

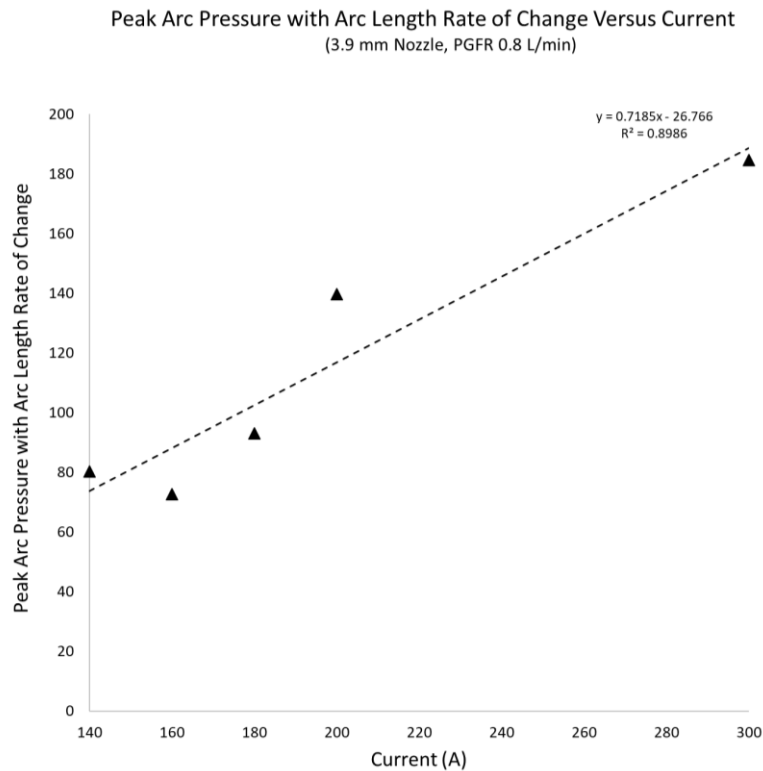


Figure 81 Rate of change of peak arc pressure with arc length.

The GTA pressure distributions of Figure 65 ‘A’ illustrate lower arc pressure values for the longer 6.4 mm arc length. However, as stated earlier, the effect of arc length is less significant than the current, which explains why the longer arc length values start to equate to those of the shorter arc length at higher currents, shown in Figure 65 ‘B’. As a result of arc divergence with arc length for GTA, therefore:

Arc radius at 3 mm arc length ‘ $r_{3\text{ mm}}$ ’ $\ll$ arc radius at 6.4 mm arc length ‘ $r_{6.4\text{ mm}}$ ’

This is validated by the FWHM plot comparison of GTA arc pressure width at different arc lengths, shown in Figure 72.

The Lorentz force is most significant close to the electrode, diminishing with distance, aiding arc divergence. In addition, as the arc length increases, the arc grows because of the divergence angle, shown in Figure 82, resulting in a decrease in the arc’s energy

density and arc pressure. During operation, a constant GTA arc length is therefore preferable to ensure a uniform arc power density to the substrate, as well as stable bead-width and penetration.

The PTA arc compared with GTA has a less diverging arc because of the nozzle restriction squeezing the arc, shown in Figure 83 'B'. However, with increased arc length, the arc cone widens, though less than that of GTA, resulting in a less concentrated arc, shown in Figure 83 'A'. For the same arc length, therefore:

$$\text{GTA arc radius 'r'} \gg \text{PTA arc radius 'r'}$$

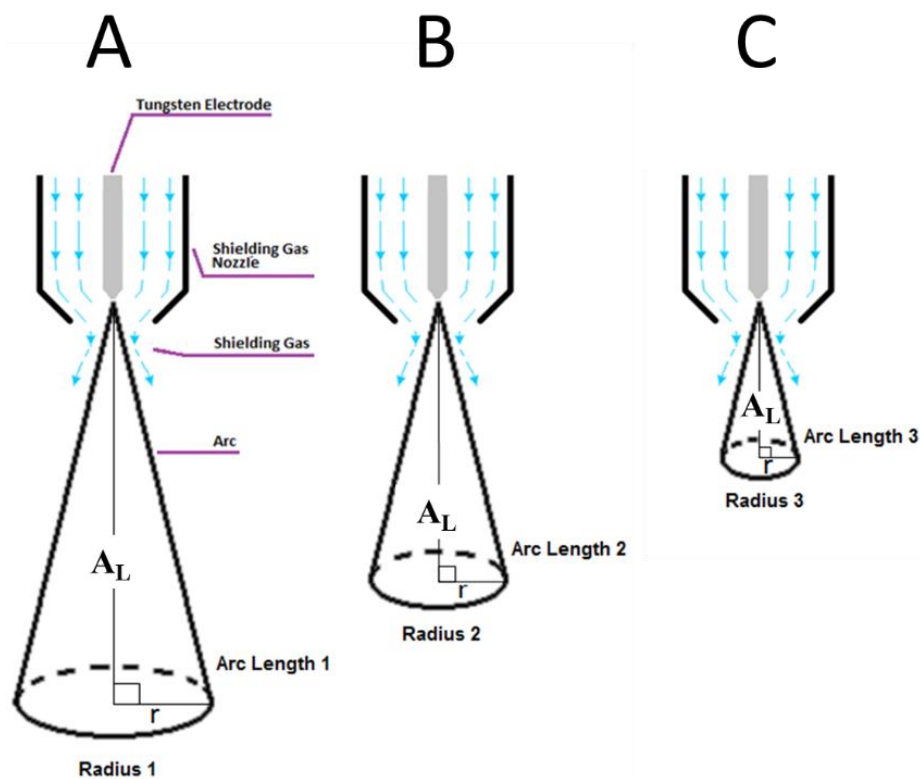


Figure 82 The effect of arc length (A_L) on the unrestricted GTA arc. A] The radius 'r' of the arc cone and arc contact area with the work-piece is larger because of the long arc length, B] Reduced arc cone as a result of a reduction in arc length, C] Small concentrated arc cone because of the short arc length.

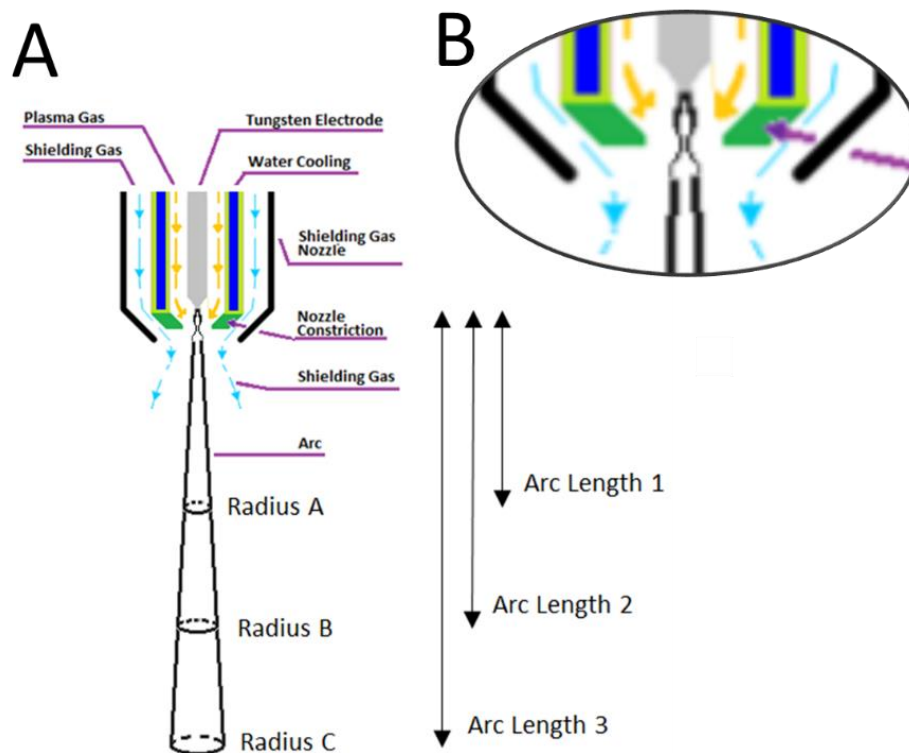


Figure 83 The effect of arc length (AL) on the restricted PTA arc. A] Increase in arc cone radius with arc length, B] Enlargement of the nozzle squeeze on the arc.

This is validated by the FWHM comparison of arc pressure width for GTA and PTA in Table 10. Chen et al. (2015) identified only small increases in PTA arc diameter with arc length.

For both PTA and GTA, but less so for PTA, the contact area with the substrate increases with arc length. The broader distribution of the arc energy and heat input on the substrate because of the arc divergence increases the melt-pool width and reduces the penetration for a fixed current.

The findings of this study demonstrate that PTA, compared with GTA, enables longer standoffs, critical for WAAM part building, and a reduction in arc divergence and corresponding arc pressure diameter that is more tolerant to arc length. The more concentrated, almost straight, arc column of PTA results in the heating of the work-piece is affected less by arc length than GTA. However, arc length does affect the heat supplied by the plasma arc and electron flow to the substrate (Chen et al., 2015). Arc starting of GTA becomes problematic, and the arc becomes unstable with increasing arc length, unlike PTA with its pilot arc initiation system.

Tseng, Hsieh and Tseng (2003) found for low currents that the PTA arc length can be increased up to 20 mm before arc stability became an issue, without excessive arc column broadening. The almost straight arc column enables the PTA tolerance to arc length. Schnick (2016) determined that the PTA arc column expands after leaving the nozzle, but the column is narrow and bell-shaped in comparison to GTA, and the low divergence is responsible for the high heat flux close to the arc centre at the substrate. Schnick (2016) and Chen et al. (2015) attribute the reduction in PTA arc pressure with arc length to decreases in arc velocity with increased distance, but surmise that the reduction in density with increased height could also cause this.

Chen et al. (2015) established that the effect of arc length on arc pressure distribution is limited to the arc centre and peak pressure. In comparison, current affects both peak pressure and the radius of distribution. The melt-pool is therefore principally affected by the arc pressure at the centre, below the PTA torch. This ties in with the arc length pressure distributions of this study, shown in Appendix B and Figure 225 A to C. Where the peak pressure increases with current, and, to a lesser extent, reduced arc length, the distribution radius does not appear to increase with arc length for a fixed current, shown in Appendix B and Figure 225 D, but with current for a fixed arc length, shown in Appendix B and Figure 225 A to C.

In addition to the PTA arc divergence, the particles leaving the PTA nozzle start to decelerate, which is enhanced with distance (Chen et al., 2015) and increased arc length. This reduction of velocity for the momentum transfer of arc pressure reduces its impact at the substrate surface.

The almost straight arc column does make PTA more directional but also more susceptible to torch misalignment issues, and the focused arc results in a higher power density and arc pressure for the same parameters, which can result in keyhole.

This study shows the potential for reducing, to an extent, arc pressure for WAAM operations by increasing the arc length of the PTA or GTA torch.

It is notable that the arc lengths are 6.4, 9.4 and 11.4 mm and not whole numbers because of the electrode setback from the nozzle tip of 1.4 mm – i.e. nozzle heights/CTWD of 5 mm are equivalent to arc lengths of 6.4 mm.

3.3.9 PTA Plasma Gas Composition

The effect of varying plasma gas composition on the PTA peak arc pressure is shown in Figure 84 for a straight-bore 3.9 mm nozzle at two values of current and with seven plasma gas compositions of argon, helium, hydrogen and CO₂, set out in Table 6. The peak arc pressure reduces significantly with increasing levels of helium.

Though not strictly a gas for PTA, and found to be detrimental to electrode life, argon/CO₂ does appear to lower the peak arc pressure. This gas composition has been specifically developed by BOC Group plc to be commercially available for MIG/MAG welding of stainless steel.

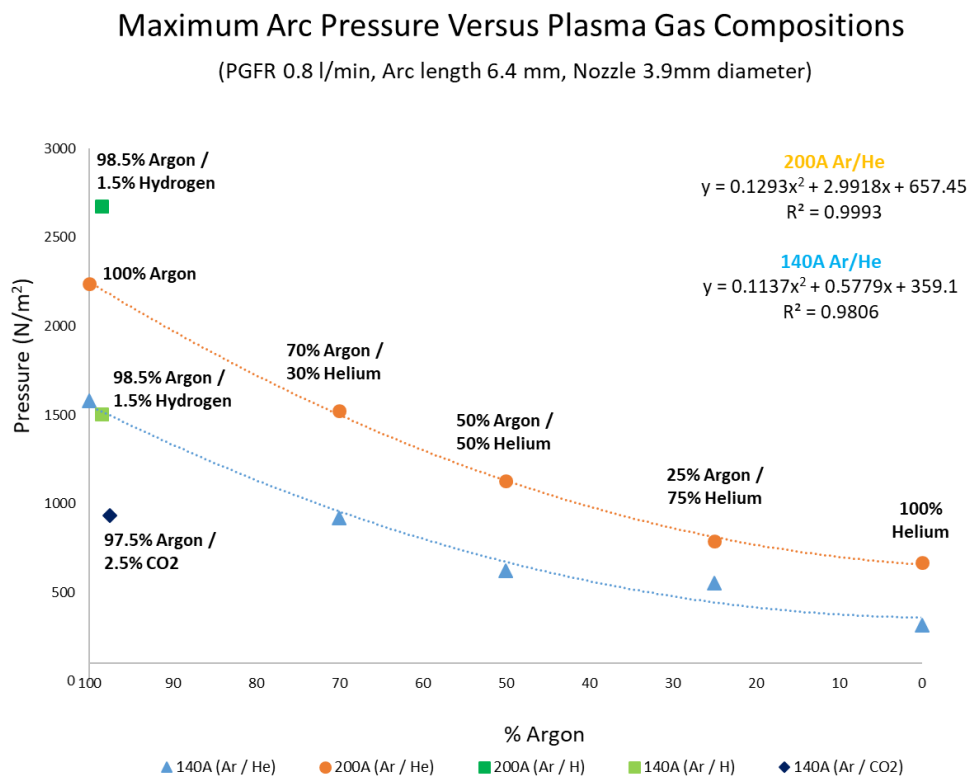


Figure 84 Effect of plasma gas composition on arc pressure.

The plots of Figure 85 show, for two currents – 140 and 200 A – the arc pressure distributions for a varying percentage of argon/helium plasma gas composition. The peaks of the 100% argon distributions diminish and flatten out with an increased proportion of helium, along with the maximum arc pressure values. The results indicate a levelling out of arc pressure from below the torch electrode to a radius of 2 mm, with increased amounts of helium.

Investigation Of Plasma Transferred Arc Dynamic Effects In Wire + Arc Additive Manufacturing

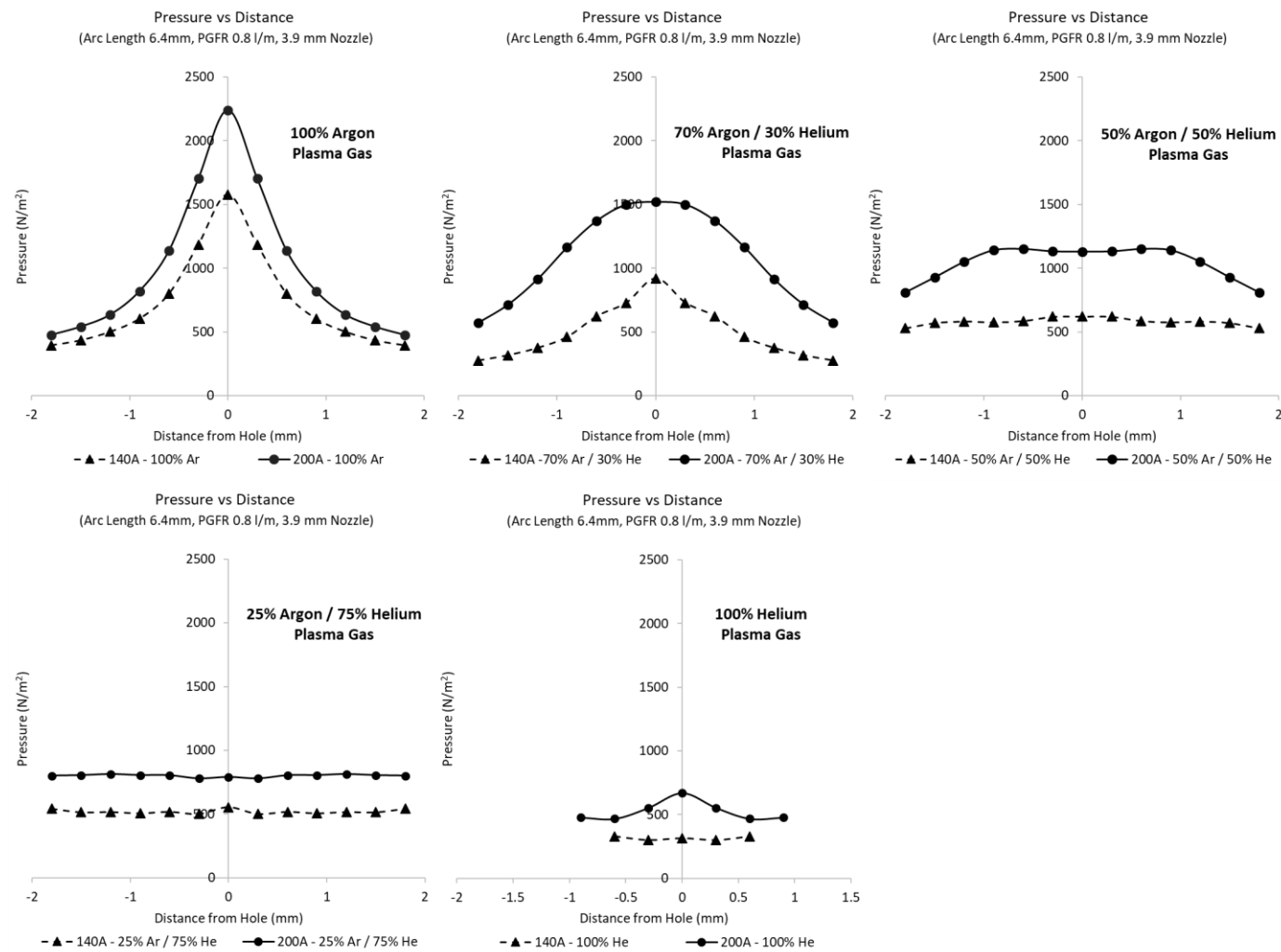


Figure 85 Comparison of PTA arc pressure distributions for varying percentage of argon/helium plasma gas composition.

Figure 86 shows the peak arc pressures for increasing values of PGFR for three different plasma gas compositions, measured at 140 A. Measurements were also undertaken at 200 A. However, PTA torch damage was sustained because of the high temperature of the arc with helium plasma gas, preventing further measurements.

The trends are linear, with peak arc pressure increasing with PGFR. However, the position of the trend decreases with plasma gas percentage of helium because of the different gas characteristics. For comparison, the equivalent GTA value with argon shielding gas is also shown.

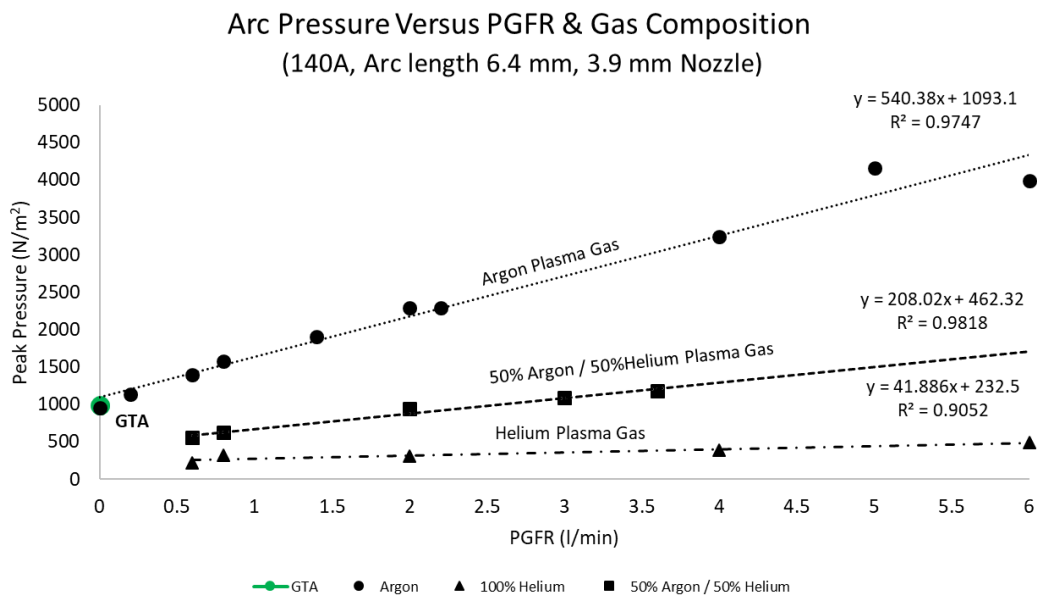


Figure 86 Peak arc pressure versus PGFR for three plasma gas compositions.

PTA, unlike GTA, utilises both a shielding gas and a plasma gas, and the composition of respective gases for PTA can be the same or separate. For this study, a second gas or gas mix were chosen for the plasma gas to explore the effects of different gas characteristics – e.g. electrical and thermal conductivity on arc pressure.

This study found that, for argon/CO₂ plasma gas composition, the CO₂ component acts as an oxidant, resulting in oxidation of the thoriated tungsten electrode. The oxidation occurred during the first arc ignition and electrode use, significantly increasing the electrode surface work function and consequently preventing further arc ignitions and use of the electrode.

The observed correlation between a reduction in arc pressure and a reduction in plasma gas percentage of argon by increasing the percentage of helium, shown in Figure 84, can be explained by the characteristics of helium and its effect on the process. Different gases exhibit different characteristics, and the specific traits that affect arc pressure are illustrated in Figure 87.

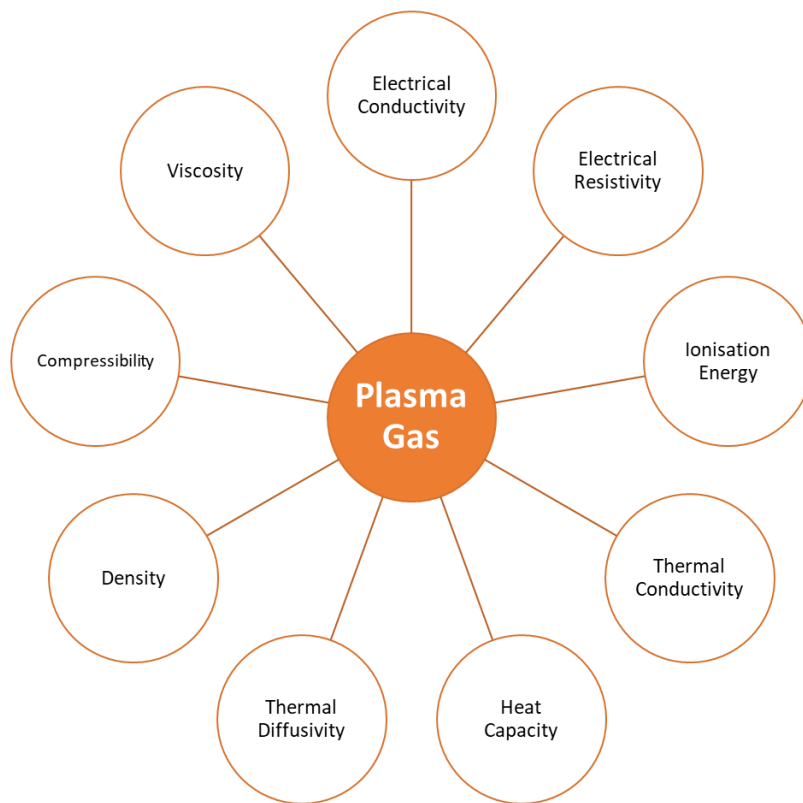


Figure 87 Plasma gas characteristics that affect arc pressure.

Table 11 outlines gas properties and includes, for comparison, air and torch materials of construction. The arc pressure therefore decreases with helium percentage, shown in Figure 84, because of the lower proportion of plasma gas being ionised as a result of the lower electrical conductivity, lower gas density and higher ionisation temperature of helium. A measure of transference of momentum transverse to the flow is viscosity, and an increased viscosity therefore encourages flow profile broadening (Tanaka et al., 2008). Consequently, the high viscosity of helium, shown in Figure 36 ‘D’, at temperature widens the gas flow distribution and reduces velocity, which, along with helium’s lower atomic radius and low-density results in the arc pressure distributions of Figure 85, reduces and levels out with increased helium percentage. The Lorentz force for argon is

higher than for helium (Campbell, Galloway and Mcpherson, 2013), extending the restriction of the argon PTA arc, increasing the power density and consequently raising the arc pressure.

Table 11 Plasma gas composition and PTA torch material properties, extracted from Carvill (2005) and Minoru Ozima (2004).

Gas/material Type		Ionisation Energy (eV)	Thermal conductivity (Wm-1K-1)	Specific heat capacity		Ratio of specific heats = C_p / C_v	Gas Constant (R) (kJ Kg-1K-1)	Molecular Weight (M)	Atomic Radius (pm)	Density for normal pressure and temperature (ρ) (kg m ⁻³)
				At constant pressure (Cp) (kJ Kg-1)	At constant volume (Cv) (kJ Kg-1K-1)					
Air	Oxidising	-	0.024	1.005	0.718	1.4	0.2871	28.96	-	1.293
Argon	Inert	15.76	0.016	0.5234	0.3136	1.668	0.2081	40	71	1.78
Carbon Dioxide	Oxidising	-	0.015	0.8457	0.6573	1.29	0.1889	44	-	1.98
Helium	Inert	24.48	0.142	5.234	3.1568	1.659	2.077	4	31	0.177
Hydrogen	-	13.54	0.168	14.323	10.1965	1.405	4.124	2	-	0.0899
Copper	-	-	386	0.384		-	-	-	-	8930
Tungsten	-	-	172	0.142		-	-	-	-	19300

The electrical conductivity of plasma gas changes with temperature, shown in Figure 36 'B'. However, the value is significantly higher for argon than helium (Nighan, 2000), and electrical conductivity for argon/helium mixes reduces with helium percentage. Both helium and argon are electrical insulators until they become an ionised plasma, at which point the electrons and protons are unrestrained, increasing the gas conductivity. However, the charged plasma particles are sensitive to magnetic fields, which increase with current. The increased electrical conductivity of argon increases the effect of arc magnetic restriction and the transfer of arc current and energy density of the arc, thus increasing the arc pressure.

The ionisation energy indicates the minimum energy required to initiate ionisation of a gas. The degree of ionisation of plasma gas increases with temperature. The energy

necessary for ionisation diminishes with increased gas atomic radius because of the increase in distance of the valence electrons from the nucleus: electrons less securely held. Argon's sizeable atomic radius, shown in Table 11, facilitates ionisation more readily than helium, which has a radius less than half that of argon. Accordingly, the extent of ionisation for argon/helium mixes decreases with helium percentage. The more easily a plasma gas is ionised, the easier arc ignition is. As a result, with argon, it is straightforward to initiate the arc. However, helium and high helium mixes are not, and therefore the arc ignition is required to be undertaken with argon before switching over to helium or high helium mixes of plasma gas.

Specific heat per unit mass and heat capacity per unit volume of the plasma gas represent its capacity to store heat. The thermal conductivity of plasma gas corresponds to its ability to conduct heat away. The thermal conductivity of tungsten remains relatively constant with temperature. However, for helium and argon plasma gas, conductivity increases with temperature. The thermal conductivity of helium is a factor of 10 higher than argon, shown in Table 11. The capacity to store heat is also a factor of 10 more for helium, also shown in Table 11. The higher thermal conductivity of helium, apparent in Table 11, results in a less focused heat concentration, reduction of gas ionisation and reduced arc size. It consequently decreases the arc's energy density and arc pressure, shown in Figure 84.

Plasma gas thermal diffusivity (m^2/sec) constitutes its ability to propagate heat through the gas – i.e. a plasma gas with a high thermal diffusivity, as in Equation 3, will have high thermal conductivity and low heat capacity.

$$\text{Thermal Diffusivity (T}_{\text{DIFF}}) = \frac{\text{Thermal Conductivity}}{\text{Density} \times \text{Heat Capacity}} = \frac{\text{Heat Conducted}}{\text{Heat Stored}} \quad \text{Equation 3}$$

Table 12 Calculated plasma gas thermal diffusivity utilising Equation 3 and values from Table 11.

Gas Composition	Thermal Diffusivity ($\text{m}^2 \text{s}^{-1}$)
Air	2.585×10^{-5}
Argon	2.866×10^{-5}
Carbon Dioxide	1.153×10^{-5}
Helium	2.541×10^{-4}
Hydrogen	1.833×10^{-4}

As a result of the high density and low heat capacity and thermal conductivity, shown in Table 11, of argon and carbon dioxide/argon mixes of plasma gas, their thermal diffusivity is small compared with helium, helium/argon and hydrogen/argon plasma gas mixes. Table 12 outlines the calculated values of thermal diffusivity for pure gases. Gas mixture values lie between the two constituent pure gas values, depending on the percentage of each constituent part, resulting in a reduction in the rate of heat transfer from the hot plasma gases to the colder surrounding gas. The resultant increased heat concentration of argon increases localised ionisation, reducing the size of the arc and consequently increasing the arc's energy density and arc pressure, shown in Figure 84.

Studies have found for GTA that the arc force is lower for helium shielding gas than with argon shielding gas and that this can be attributed to the lower density of the helium mixes (Lancaster, 1986). The gas density of argon is significantly higher than helium, shown in Table 11, with argon/helium gas mix densities lying in between and decreasing with helium percentage. Comparable to GTA, the PTA arc pressure/arc force results reduce with plasma gas density.

In addition, the significant difference in molar mass between helium and argon plasma gas, an increase of 900%, and increase of density 906% for argon, shown in Table 11, as well as the low viscosity and consequently high velocity of argon, shown in Figure 36 'D', compared with helium, affects the arc momentum and arc pressure, which is a momentum transfer, resulting in a higher arc pressure for argon and a low arc pressure for helium, shown in Figure 84. Bernoulli's impact pressure formula (Schnick, 2016), seen in Equation 4, where the dynamic pressure consists of the gas density and velocity,

as in Equation 5, further reinforces the importance of plasma gas density and velocity on arc pressure.

$$\text{Impact Pressure (P}_I\text{)} = P_S + P_{DY} \quad \text{Equation 4}$$

$$\text{Dynamic Pressure (P}_{DY}\text{)} = \rho \times \left(\frac{v^2}{2}\right) \quad \text{Equation 5}$$

Where:

P_I = Impact Pressure, P_{DY} = Dynamic Pressure, P_S = Static Pressure, ρ = Density, and V = Velocity

As a result of the low ionisation potential, low electrical conductivity and high work function value of helium and high-percentage helium gas mixtures, the PTA non-transferred high frequency arc ignition, with low voltage and current, is unachievable. Argon is therefore needed to initiate the arc before the plasma gas can be transferred over to the helium-based gas. Once the arc is established and the higher operating current in use, the transfer of gas is possible as the initiated transferred arc can ionise the introductory helium effectively. However, not only does this increase the complexity of the equipment setup and control, but changing plasma gas in practice can also affect the initially deposited material – e.g. there is a risk of higher arc pressure for argon.

The electrical energy absorbed from the tungsten by the plasma gas changes depending on the gas characteristics. The arc pressure distributions of gas composition, shown in Figure 85, illustrate the reducing peak arc pressure and levelling of the distribution with an increased percentage of helium within the plasma gas because of the characteristics of the gas discussed.

Argon, compared with helium and helium gas mixtures, is more readily available and relatively inexpensive. For this reason, argon is currently the gas of choice for most GTA and PTA applications. See Appendix E – Cost of Gas Compositions for a cost comparison.

Using helium can increase heat input, with a hotter arc, and transfer more heat to the substrate than argon – greater heating power is ideal for high-speed or high thermal

conductive materials without reducing travel speed or altering current and voltage, resulting in a broader, flatter melt-pool. Along with the reduced arc pressure, utilising helium should reduce the depth of WAAM deposited material, previous layer re-melting, and prevent keyhole. Helium/argon gas compositions are a compromise of both gas characteristics and allow easier arc ignition.

3.3.10 Nozzle Diameter

Figure 88 compares the effect on PTA peak arc pressure for various straight-bore nozzle diameters, shown in Table 7. It is evident from the results that there is a non-linear relationship.

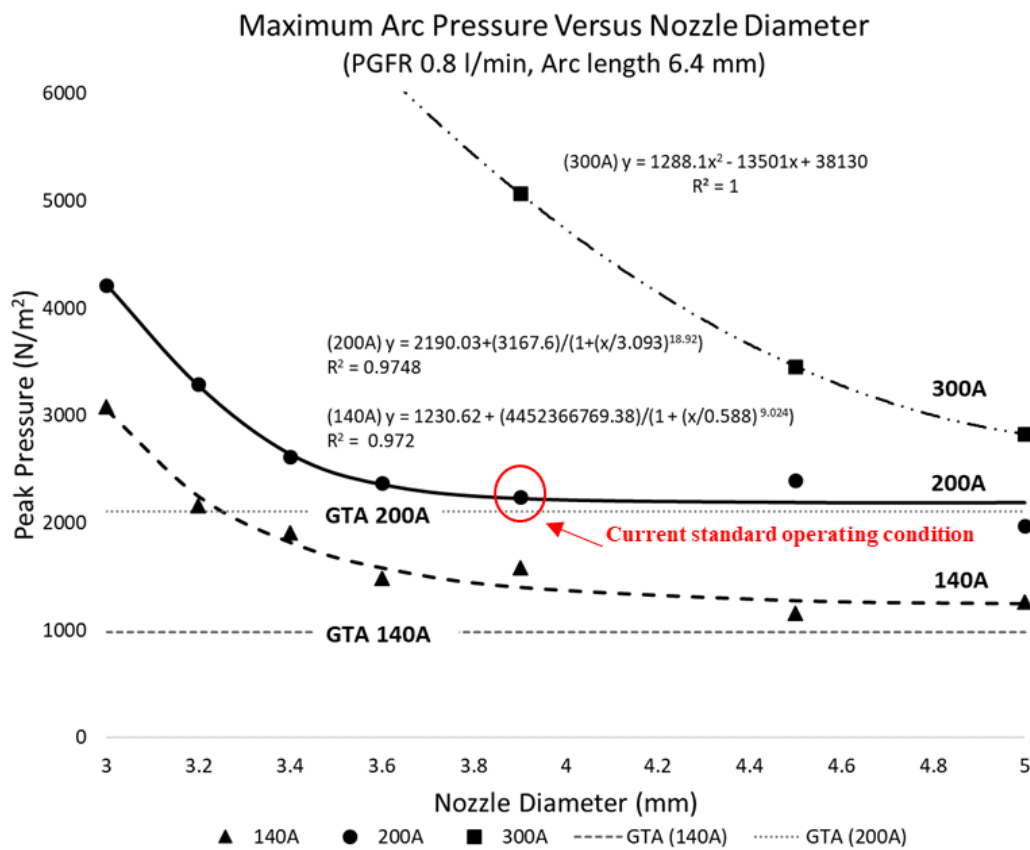


Figure 88 Peak arc pressure versus straight-bore nozzle diameter. Equivalent GTA measured arc pressures for comparison are shown as lines.

Figure 89 illustrates the arc pressure data from Figure 88 transfigured into $1/\text{Nozzle Diameter}^2$. In this form, the peak arc pressure relationship to nozzle diameter is linear, with a comparable gradient for the 140 and 200 A trends.

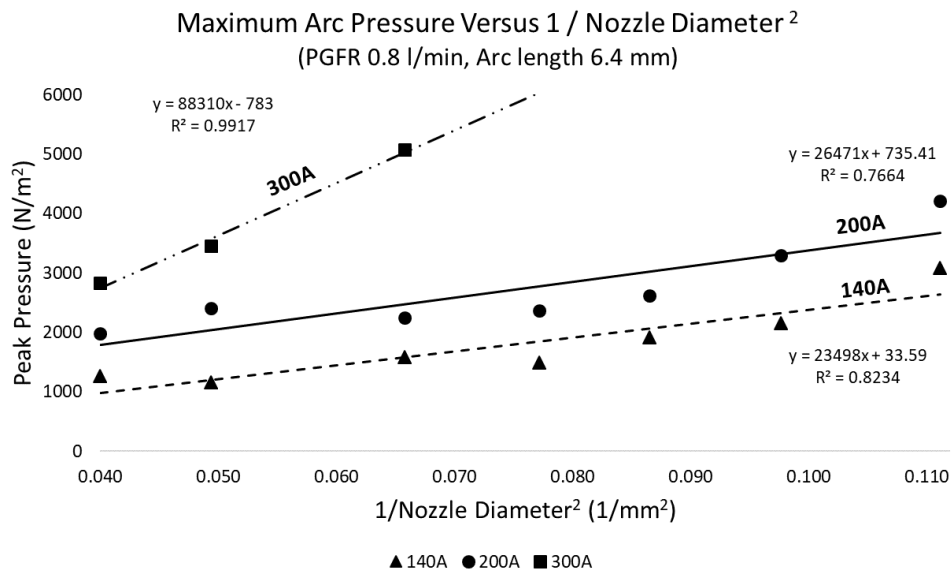


Figure 89 Peak arc pressure versus 1/square of nozzle diameter.

Peak arc pressure increases inversely proportionally to nozzle diameter, and, as current increases, the peak arc pressure rises correspondingly.

As a result of nozzle damage at high currents for 3, 3.2, 3.4 and 3.6 mm diameter nozzles, only values of peak arc pressure at 300 A were measured for 3.9, 4.5, 5 mm. In addition, nozzles below 3 mm diameter were unable to endure currents of 140 A and above without damage, meaning that these results have been omitted.

The trends of Figure 88, and the extended version in Appendix A, show that arc pressure versus nozzle diameter asymptotically approaches that of equivalent GTA values. This indicates that the nozzle diameter for the PTA nozzle effectively restricts the arc column and generates the increased pressure needed for plasma keyhole welding or cutting. The opposite applies for WAAM, where a soft plasma is required to avoid keyhole defects. Figure 88 indicates the minimum nozzle diameter for operating in the soft plasma regime. For standard operating conditions used currently for building parts (PGFR 0.8 l/min, max current 200A), the nozzle diameter of 3.9 mm is safely within the soft plasma regime. Notably, the nozzle diameter is current dependent, but it is likely that this value also depends on other parameters such as PGFR.

For clarity, measured arc pressure results are only shown in Figure 88 and Figure 89 for the three currents 140, 200, and 300 A. The full set of recorded results is included within the arc pressure model in Chapter 5, and in Appendix A.

Figure 90 and Figure 91 show the peak arc pressures for increasing values of PGFR for 140 and 200 A respectively. The trends are linear, with peak arc pressure increasing with PGFR and current. However, the slope of the trend decreases with nozzle diameter. As a result of pressure instrumentation limitations, a measurement of arc pressure for the 3 mm nozzle at a PGFR of 6 l/min could not be undertaken.

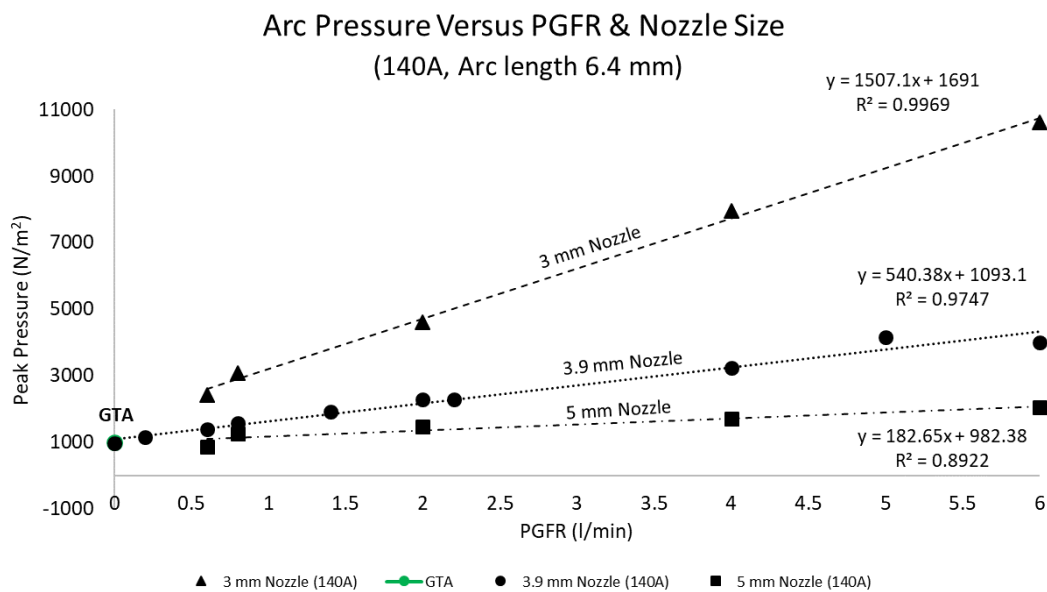


Figure 90 Peak arc pressure versus PGFR for three nozzle diameters, measured at 140 A.

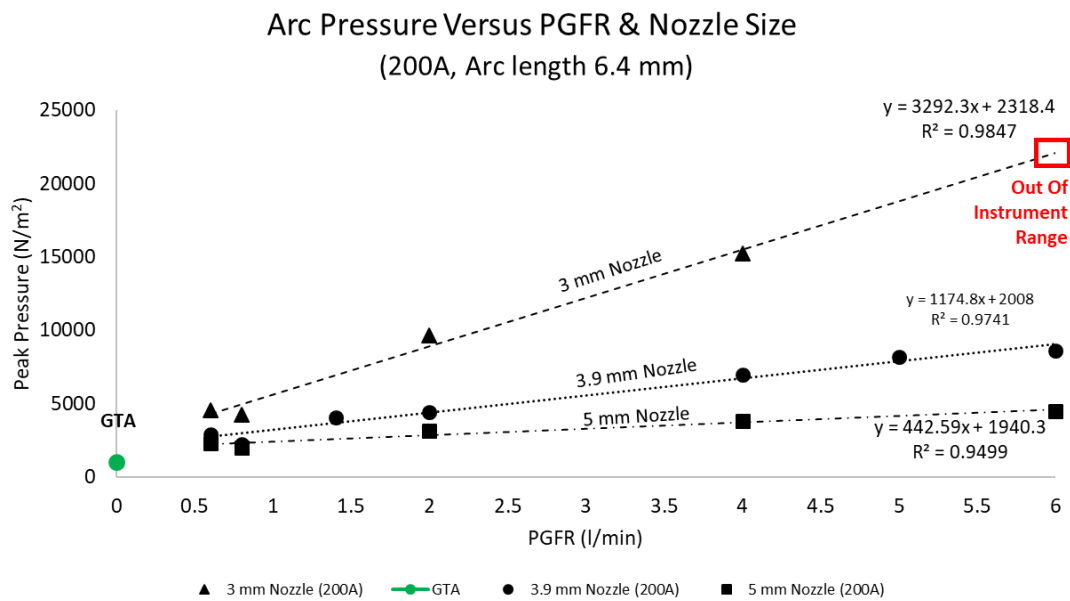


Figure 91 Peak arc pressure versus PGFR for three nozzle diameters, measured at 200 A.

The primary difference between GTA and PTA, with its significantly higher power density, shown in Figure 30, allowing keyhole mode of operation, is its water-cooled copper restriction nozzle, which stabilises the arc and directs the arc column (Venkatramani, 2002). Within the nozzle, the conditioning of the plasma gas, plasma formation and arc inception occurs. The nozzle design and geometry are torch specific, different for each manufacturer.

Depending on the PTA torch design, electrode tip and corresponding arc apex are located, either set back within the nozzle plenum chamber (Figure 10), or within the nozzle restriction bore, both possibilities are included in the original 1957 patent (Gage, 1957). For this study, a PWP Viper MC torch, with a water-cooled copper restriction nozzle and an electrode tip within the nozzle restriction, was used. As a result of this electrode tip location within the torch nozzle straight length, the arc is restricted during primary arc formation, unlike other PTA torches where the arc is created within the torch plenum chamber and then forced through the nozzle restriction, similar to passing through an orifice plate. The diameter of the arc column is smaller than the nozzle diameter and enlarges slightly after exiting the nozzle with a reduction in velocity and temperature (Venkatramani, 2002).

The torch nozzle straight length encircles and laterally confines the top section of the arc column, producing a channel through which the arc and plasma gas must traverse, constricting the arc and plasma gas and stabilising, focusing or broadening the arc dependent on the channel diameter. This enables energy distribution within the contained arc and directs the almost vertical discharged arc column towards the substrate (Gage, 1957).

This study found that, for the PWP Viper MC torch, PTA nozzle diameters of 2 and 2.5 mm suffered at moderate currents from sudden catastrophic failure. As outlined in the literature review, this is undoubtedly a result of double-arcing (Prevosto, Kelly and Mancinelli, 2011). This prevented further investigation of PTA nozzles below 3 mm in diameter. However, this study did not find a link between double-arcing and larger nozzle diameters, up to 5 mm, as suggested in the literature review. This implies that the torch restriction nozzle has, from double-arcing, a safe diameter region of WAAM operation between 3 and 5 mm, which can be selected from to reduce arc pressure.

As the nozzle diameter increases, the distance between the electrode and nozzle inner wall grows. The volume between the arc apex on the electrode tip and the nozzle tip expands, resulting in an increased interaction zone. As this zone increases, the density of the plasma gas and gas velocity decrease, and the effectiveness of gas heating and gas ionisation reduces. This reduction in plasma gas ionisation reduces the electrical and thermal conductivity of the plasma and, accordingly, the electromagnetic restriction effect on the arc.

Changes to the nozzle diameter result in related changes to the nozzle straight length, shown in Table 7. However, the interaction zone is unaffected by the shift in nozzle straight length, as this is above the arc apex location.

As the nozzle diameter reduces, the plasma gas velocity increases to maintain the flow through the orifice. However, for the same mass to pass through the smaller orifice, the plasma gas impinges on the arc, restricting/squeezing the arc, as shown in Figure 79. This should assist in reducing the arc diameter. This study has shown that increasing the nozzle diameter reduces the effectiveness of the nozzle restriction, as the physical and thermal pinch effect becomes less effective with distance from the arc. This should result in the

unrestrained arc diameter increasing and power density decreasing, with a less focused larger arc acting on the substrate with a correspondingly reduced arc pressure.

The trends of arc pressure versus nozzle diameter, shown in Figure 88, and the extended version in Appendix A, suggest a plateau starting at a nozzle diameter of 4.5 mm for both 140 A and 200 A, with the PTA values approaching that of GTA for the same currents. This implies that the effectiveness and limit of the nozzle restriction have been reached: power density and arc pressure are at their lowest. It is therefore anticipated that there will be minimal further effects if the nozzle diameter is increased beyond 5 mm. The trends of arc pressure versus nozzle diameter, shown in Figure 88, represent the only non-linear result, with the exception of plasma gas composition. The change in nozzle diameter does not correspond with a constant change in peak pressure, and is an inverse monotonic relationship resulting from the nozzle discharge area being proportional to the square of the diameter – by increasing the nozzle diameter from 3 mm to 3.9 mm, an increase of 30%, the area increases by 69%. The increase in area, with the square of the nozzle radius, influences the arc constriction, plasma gas conditioning and arc properties, which together result in a non-linear decrease in arc pressure with nozzle diameter.

As a result of Bernoulli's principle, the plasma velocity decreases with increased nozzle area and diameter. Qianhong et al. (2008) established that the decrease in velocity occurs for all nozzle lengths as nozzle diameter increases.

Conversely, as the arc column cross-section is reduced by small nozzle diameters, and the restriction effects come into play (electromagnetic, thermal pinch, plasma gas squeeze), the temperature of the arc column and the power density increases, and the plasma gas ionises more fully. This, in turn, increases its thermal and electrical conductivity, which increases the electromagnetic restricting effect and further restricts the arc, also increasing the power density and arc pressure.

This study has shown that, simply by reducing the nozzle diameter, the same arc pressure of a larger diameter nozzle with a higher current and PGFR can be reached, with a reduced heat input and gas expenditure. However, the smaller nozzle was found to last significantly less time.

During operation, if the wire is fed too close to the PTA torch, metal vapour from the melting wire rises and attaches to the copper restriction nozzle. Figure 92 illustrates a build-up within the PTA nozzle orifice, reducing the diameter, creating plasma gas turbulence and further restricting the orifice and consequently the PTA arc. Even with set parameters, the arc pressure may therefore increase with operation as a result of this type of build-up, making the correct location of the wire-feeder in relation to the PTA torch paramount. Though melted substrate metal also spatters occasionally and settles on PTA nozzles, its settling location is more random and sporadic, usually landing on the outer nozzle surface and not generally within the nozzle orifice, meaning that it is much less likely to coalesce and affect arc restriction, and increase arc pressure.

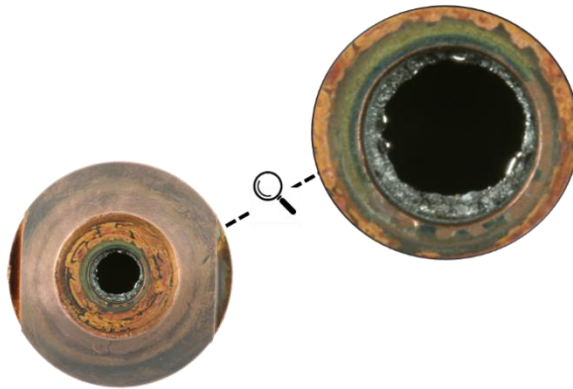


Figure 92 Metal vapour deposit within copper nozzle orifice, and an enlargement.

3.3.11 Nozzle Length

The effect of reducing the effective nozzle length of a PTA 3.9 mm straight-bore nozzle is shown in Figure 93 for currents of 140 and 200 A. The peak arc pressure trends between 0.0 and 1.8 mm effective nozzle length (right of the vertical dashed line) are linear, with the peak arc pressure for both 140 and 200 A approaching that of GTA at 0.0 mm, where the electrode tip is in line with nozzle surface. An increase in peak arc pressure takes place for the minus 0.6 mm effective nozzle length (left of the vertical dashed line), where the electrode stands proud of the nozzle.

Figure 93 additionally illustrates the effect of shielding gas on the arc. By reducing the shielding gas flow-rate from 15 l/min to 2 l/min for 140 A – labelled ‘Low SG’ – the change of peak arc pressure is insignificant for the confined arc (right of the vertical

dashed line): i.e. a data point on the same trend. However, the effect of shielding gas is significant for the non-confined arc (left of the vertical dashed line), with a noticeable drop in peak arc pressure at 140 A for the ‘Low SG’ point. These results suggest the influence/interaction of shielding gas, increasing peak arc pressure above the trend line and only on the non-confined arc, where the electrode stands proud of the nozzle protection.

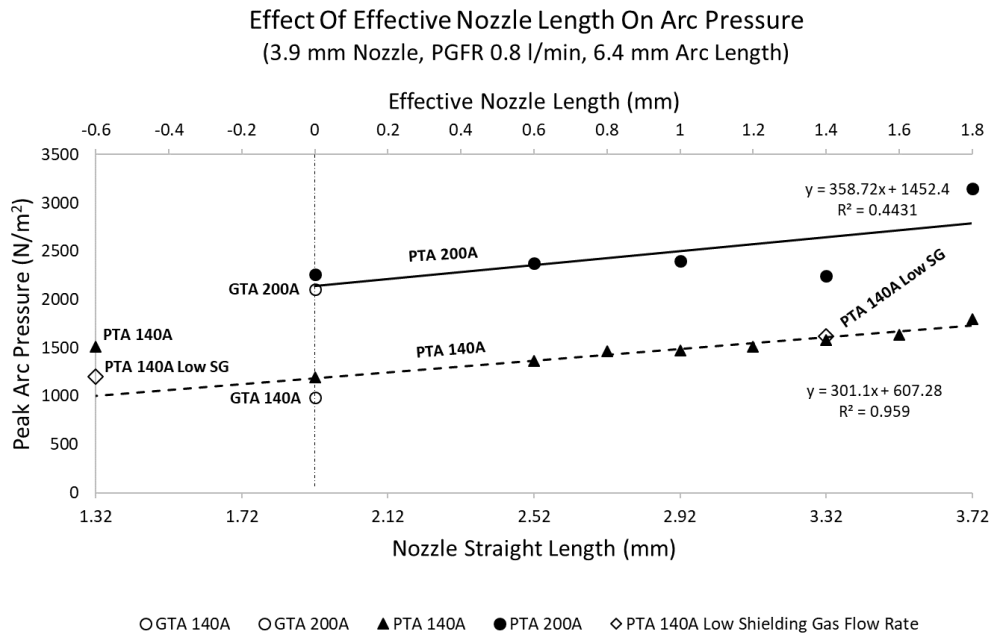
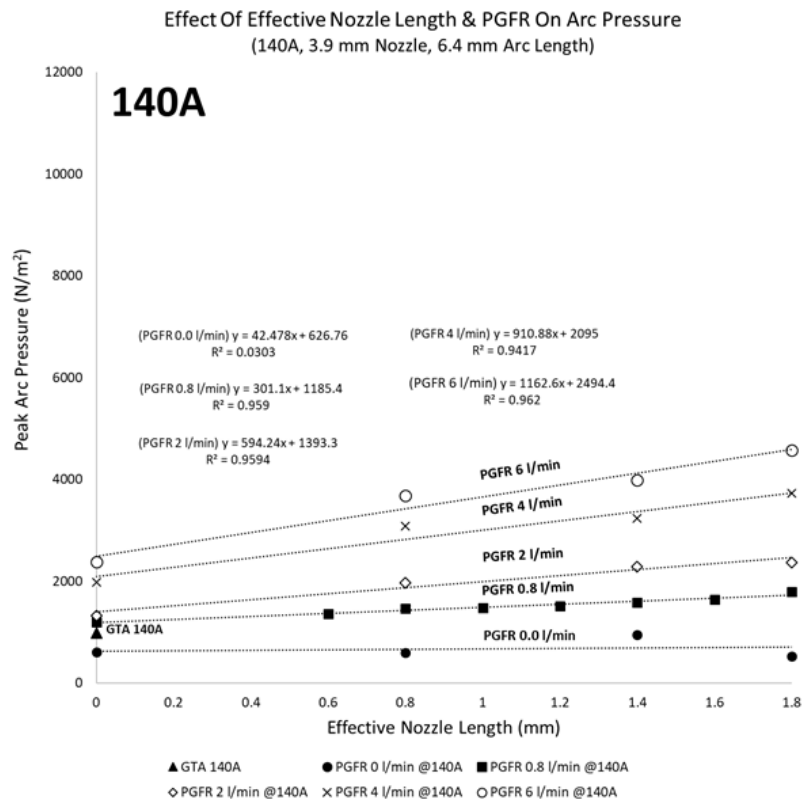


Figure 93 Peak arc pressure versus effective nozzle length. The dashed line indicates effective nozzle length zero. PTA measurements with a low shielding gas flow-rate (2 l/min) are shown alongside the equivalent GTA measured arc pressures for comparison.

The effect of current and PGFR on reduced PTA effective nozzle length is shown in Figure 94 for 3.9 mm diameter straight-bore nozzles with a fixed arc length of 6.4 mm. Figure 94 'A' and 'B' illustrates that, for currents of 140 A and 200 A respectively, the peak arc pressure versus effective nozzle length tends to be linear, increasing with effective nozzle length. Each subsequent trend line represents a different value of PGFR, with higher pressure values with increased PGFR. The exception is the 0.0 l/min PGFR trends, which have low or even negative gradients. For comparison, for GTA, with no nozzle, peak arc pressure points are included for the same arc length and currents. The peak arc pressure values at 200 A are correspondingly higher than 140 A. Figure 94

therefore indicates that peak arc pressure increases with effective nozzle length, increased PGFR and current.

A



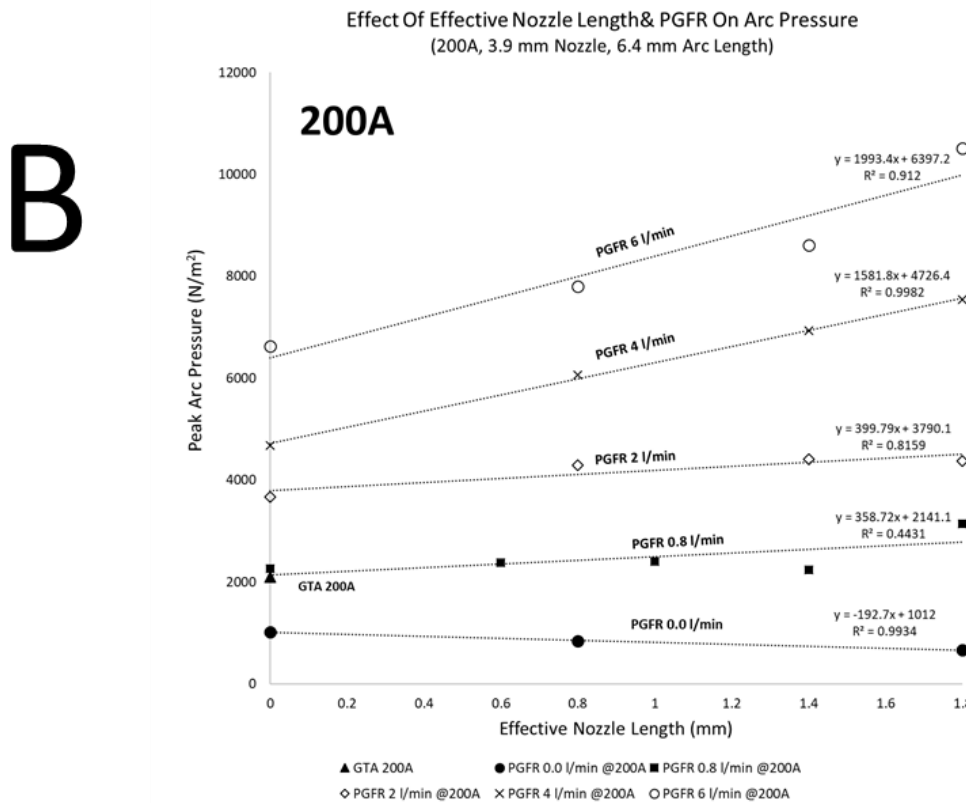


Figure 94 Peak arc pressure versus effective nozzle length for five PGFRs at: A] 140 A, B] 200 A.

At 0.0 l/min PGFR, the shielding gas and enclosure gas fortuitously replace the plasma gas. As these gases are not fed directly into the arc, within the nozzle, the measured peak arc pressures are intermittent, with values generally reducing as interaction becomes more problematic the further the arc is within the nozzle, increasing with ESB and effective nozzle length.

As the nozzle diameter increases, the nozzle N_{SL} , shown in Figure 42 'A', also increases because of the converging section of the PTA nozzle. Table 7 outlines the equivalent N_{SL} value for each corresponding nozzle diameter. Shohet (2017) outlines a general rule of N_{SL} and electrode setback resulting from the relationship affecting arc penetration and bead formation: $ESB \leq N_{SL}$. To satisfy this rule, the electrode setback of this nozzle length study never exceeds the 3.9 mm nozzle N_{SL} of 3.32 mm.

The increase of N_{SL} has minimal effect compared with the nozzle diameter cross-section increase, where the effective nozzle length (E_{NL}), shown in Figure 42, is unaffected as it

is within this zone that interaction with the arc occurs – the interaction zone. However, this study has shown that, by increasing the length of the interaction zone by increasing the E_{NL} , arc pressure increases, as shown in Figure 93. Decreasing the E_{NL} reduces the arc pressure, and, if the length reduction is continued to zero mm, the pressure value reaches that of GTA with no restriction nozzle. Approaching the arc pressure value of GTA is a result of removing the interaction zone entirely between the restriction nozzle and the arc.

As the plasma gas passes from the PTA torch body through the swirl ring into the nozzle chamber, between the copper nozzle and electrode, it begins to heat. As temperature increases, the kinetic energy, temperature and velocity of the gas increase, and the gas volume within the N_{SL} should increase. However, the fixed nozzle diameter and N_{SL} set a fixed volume, preventing volume increase and resulting in increased gas pressure and density. As the plasma gas enters the N_{SL} , the decrease in volume increases the gas density, following Equation 6.

$$\rho = m/V_o \quad \text{Equation 6}$$

Where:

ρ = Density, m = Mass, and V_o = Volume

As the temperature continues to rise, the gas ionises and forms a plasma. At higher densities and time, within the fixed interaction zone, the higher the quantity of gas ionisation transformation into plasma, increased electrical conductivity of the arc. The length of the interaction zone dictates the period of interaction time between the plasma gas, electrode heat source and arc.

Thermal pinch, explained in the literature review, of the arc column increases with nozzle length, resulting in a contraction of the concentrated arc column and increases in energy density and arc pressure.

Reducing the nozzle length decreases the nozzle's thermal mass, making it more susceptible to wear and diminishing its heatsink ability to disperse arc-radiated heat, reducing the longevity of the nozzle.

This study did not experience double-arcing as a result of increased nozzle length for the PWP Viper MC torch, as outlined in the literature review (Prevosto, Kelly and Mancinelli, 2011). This implies that the torch restriction nozzle has a safe from double-arcing region of WAAM operation between -6 and 1.8 mm effective nozzle length, which can be selected from to reduce arc pressure.

In addition, as the interaction zone lengthens and the CTWD reduces for the fixed arc length, the arc divergence is reduced. Prevosto and Risso (2009) and Zhou et al. (2008) refer to a plasma gas ‘clogging effect’ or ‘choking effect’ within more extended PTA cutting nozzles, impeding plasma gas flow. These observed effects support the PTA interaction concept, with the additional time the plasma gas spends within the more extended nozzles increasing the gas conditioning – e.g. increased temperature and percentage ionisation. Supplementary gas conditioning and reduced arc divergence result in a more concentrated, almost straight arc column with increased energy density and increased arc pressure, shown in Figure 93.

As more extended nozzles are less effective at reducing arc pressure than the WAAM standard 3.9 mm nozzle, they are deemed not suitable for WAAM operations. However, shorter nozzles, between the standard E_{NL} of 1.4 mm and 0.6 mm, shown in Table 8, reduce arc pressure while still integrating the benefits of PTA over GTA, increasing tolerance to arc length. Tungsten located within the torch body minimises tungsten inclusions, leading to easier arc starting and improved controllability – i.e. separate plasma gas – and is therefore considered best suited for WAAM operations.

After researching the design and discussions with the designer of the PWP Viper MC torch, it was discovered that, through engineering development, the location of the fixed electrode, at an effective nozzle length of 1.4 mm, was a compromise. They found that, with long effective nozzle lengths where the electrode tip was within the plenum chamber, like PTA cutting torches, this resulted in keyhole. At very short effective nozzle lengths penetration was also minimised and ideal for fillet welding. The current location, shown in Figure 10, in the middle, was the compromise. This study’s nozzle length investigation concurs with their findings and establishes the reason behind it.

3.3.12 Specialist Nozzles

PTA Three-hole Nozzle

Figure 95 shows the effect of a special three-hole PTA nozzle on the peak arc pressure. The results are linear, and show a reduction in peak arc pressure compared with the 3 mm nozzle, with a steeper gradient as a function of current. For the specialist nozzle, when compared to the standard WAAM 3.9 mm nozzle, the gradient with current is steeper.

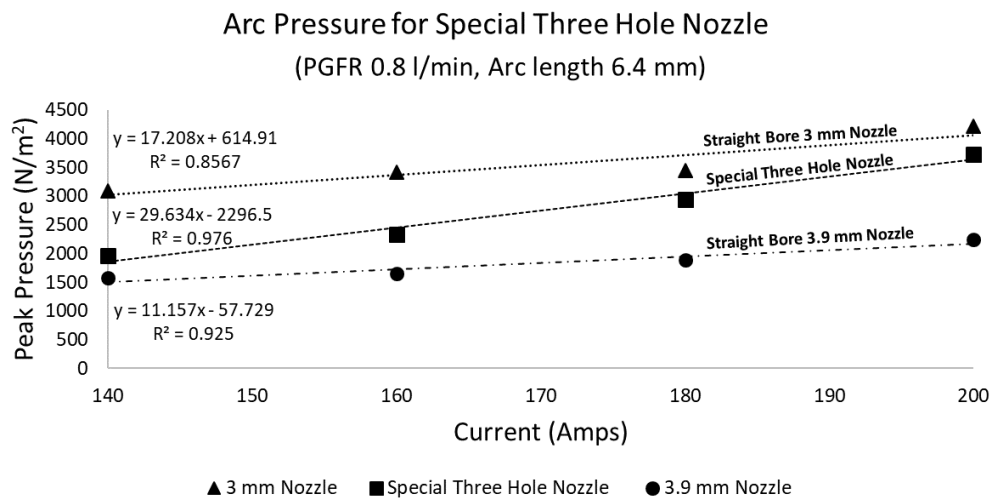


Figure 95 Peak PTA arc pressure for a special three-hole nozzle (1 x 3 mm and 2 x 1 mm hole) versus current.

The results of this study (Figure 95) corroborate the findings of previous work by Zhang et al. (2013) on their PTA three-hole nozzle design, outlined in the literature review. During this study, the specialist three-hole PTA welding nozzle is evaluated for WAAM applications.

The diversion of plasma gas may explain the reduced arc pressure results. Plasma gas is diverted before full ionisation and interaction with the arc, the arc being located below the secondary hole inlets, results in three streams, shown in Figure 96 ‘B’, of plasma gas exiting the nozzle, two non-ionised streams and a depleted, less dense main, generally ionised, stream, which interacts with the PTA arc, shown in Figure 96 ‘A’.

Zhang et al. (2014) credited the reduction in arc pressure to a decrease in velocity and reduced thermal pinch effect because of a reduction of the thermal mass of the three-hole nozzle.

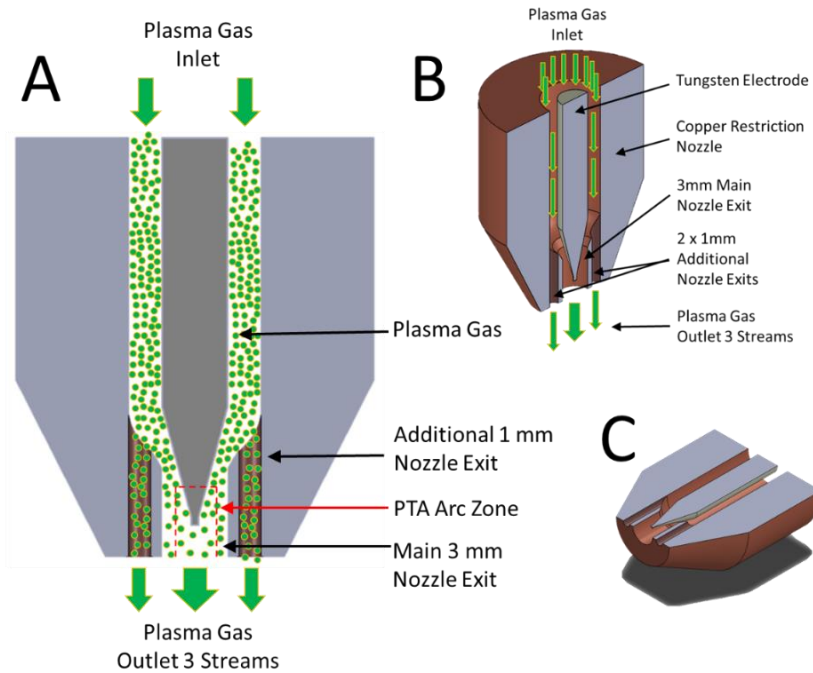


Figure 96 Specialist three-holed nozzle. A] 2D sketch of plasma gas through the nozzle with three separate exit streams; arc area indicated, B] Annotated 3D model of nozzle cross-section; PGFR path indicated, C] End view of 3D model nozzle cross-section.

Comparing this study's arc pressure results of a PTA 3 mm diameter nozzle and PTA three-hole nozzle, shown in Figure 66 and Figure 95, with those of Zhang et al., (2014), shown in Figure 17 'C', this study's 3 mm nozzle values are revealed as similar, with equivalent distributions though, with a slightly reduced arc pressure, which can be accounted for by torch geometry differences and the lower PGFR used: 0.8 l/min compared with their 1.4 l/min. This study's three-hole nozzle results follow a comparable trend but with higher values, even with the reduced PGFR. However, the nozzle designs are not identical and have resulted in some torch geometry differences. Notwithstanding, this study's three-hole nozzle still resulted in a significant arc pressure reduction compared with a 3 mm PTA nozzle, Figure 95.

Despite the promising results, the additional nozzle holes function as a plasma gas by-pass. An improved arc pressure reduction can also be achieved by reducing the PGFR into a standard 3 mm diameter nozzle, or by increasing the nozzle diameter, as illustrated in Figure 95, showing a similar linear trend. Both alternatives are more advantageous

than the specialist nozzle because of reducing plasma gas consumption, nozzle complexity and reducing nozzle fabrication cost and time.

The steeper linear trend of the three-hole nozzle (Figure 95) could be explained by a Venturi effect: as a fixed supply of plasma gas is ionised and incorporated within the arc, it accelerates from the nozzle and the gas needs to be replaced, while in a standard nozzle only the supplied plasma gas is available. This effect increases with current. However, for the three-hole nozzle, additional plasma gas by-passes the arc, exiting into atmospheric pressure at low velocity. As the demand for plasma gas at the 3 mm central hole increases with current, less is by-passed by the two secondary 1 mm holes, as it is sucked into the arc by means of a Venturi effect.

The increase in plasma gas with current for the three-hole nozzle can be calculated as follows:

Table 13 PTA peak arc pressures for a 3 mm and three-hole nozzle.

Measured peak arc pressure for two different PTA nozzle designs.			
(6.4 mm Arc Length, 0.8 l/min Plasma Gas, Gas Compositions 100% Argon)			
	Standard 3 mm Straight-bore Nozzle	Three-hole Nozzle	% Decrease
Arc Pressure at 140 A (N/m ²)	3081.43	1959.312	36.42
Arc Pressure at 200 A (N/m ²)	4216.03	3730.667	11.5

The required plasma gas for the three-hole-nozzle at 140 A, PGFR 0.8 l/min

The arc pressure for a standard 3 mm nozzle at 140 A is illustrated in Table 13. The trend Equation 7 is from Figure 90, with a 3 mm nozzle and peak arc pressure at 140 A versus PGFR plot.

$$y = 1507.1x + 1691 \quad \text{Equation 7}$$

As all other geometries and PTA independent variables are equal, the peak arc pressure for the three-hole nozzle and 3 mm nozzle should be equivalent. However, as the three-

hole nozzle value is less, it can be surmised that by-passed PGFR is responsible for the reduction.

Utilising Equation 7, a value of PGFR supplied to the 3 mm central hole of the three-hole nozzle at 140 A can therefore be calculated = 0.178 l/min. The remaining 0.622 l/min is by-passed.

The required plasma gas for the three-hole-nozzle at 200 A, PGFR 0.8 l/min

The arc pressure for a standard 3 mm nozzle at 200 A is illustrated in Table 13. The trend Equation 8 is from Figure 91, with a 3 mm nozzle and peak arc pressure at 200 A versus PGFR plot.

$$y = 3292.3x + 2318.4 \quad \text{Equation 8}$$

Utilising the same method as for 140 A, but with Equation 8 a value of PGFR supplied to the 3 mm central hole of the three-hole nozzle at 200 A can be calculated = 0.576 l/min. The remaining 0.224 l/min is by-passed.

The reduction in by-passed plasma gas with current suggests that the current, through arc demand, dictates how much plasma gas is by-passed for the three-hole nozzle – a Venturi effect. This supposition explains the increased gradient of the three-hole nozzle compared with the 3 and 3.9 mm nozzles in Figure 95.

The area of the three-hole nozzle is 8.64mm², which equates to that of a single-hole nozzle with a diameter of 3.32 mm, shown in Table 14. The measured arc pressure for the three-hole nozzle at 140 A is 1959.3 N/m², which is very close to the expected value of 1962.9 N/m² for 3.32 mm, based on the 140 A trend equation of Figure 88. There is thus no real benefit to this three-hole nozzle design in terms of arc pressure reduction as a similar effect can be obtained using a single-hole nozzle with an equivalent area, as the three-hole nozzle is less effective at reducing arc pressure than the WAAM standard 3.9 mm nozzle and has an increased rate of change for peak arc pressure with current (Figure 95). It is therefore deemed not suitable for WAAM operations.

Langford's specialist nozzle with a focusing gas, outlined in the literature review, is not beneficial to WAAM operations. However, the concept and evidence of the impact of a

channelled gas impinging on the arc, increasing power density and arc pressure, is valuable and could be reversed to minimise its effect. For example, if the three-hole nozzle was developed further, it might be worth considering angling the by-pass holes away from the arc to ensure that no by-pass gas impinges on the arc.

Threaded Nozzle

The effect of inserting a thread into the straight-bore of a 3 mm nozzle on peak arc pressure with current is illustrated in Figure 97. The results are linear, with a similar gradient to the 3 mm nozzle.

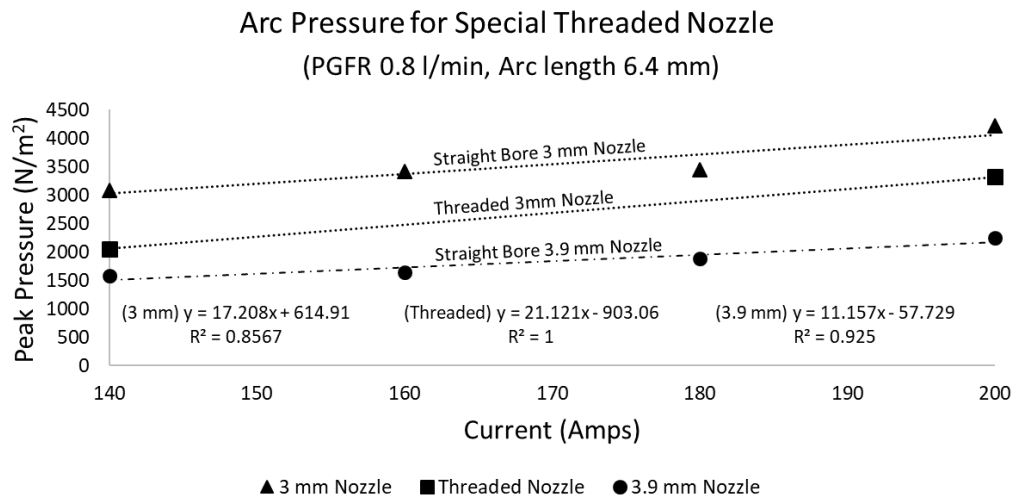


Figure 97 Peak PTA arc pressure versus current for a threaded 3 mm nozzle.

During the experiment, tungsten particles accumulated in the nozzle thread and were unseated by the plasma gas, resulting in the copper-block being covered by a visible layer of tungsten particles. Furthermore, nozzle cooling is reduced by a reduction in nozzle mass, and the colder, denser gas protecting the boundary along the nozzle wall is inhibited. Through use, the threads are melted and eroded by the transferred arc and non-transferred pilot arc during arc ignition, shown in Figure 98 ‘C’, reducing the longevity of the nozzle and increasing the potential for copper inclusions. Though arc ignition therefore initially appeared to be improved, and a reduction to the arc pressure measured, as in Figure 97, the potential for tungsten and copper inclusions in the melt-pool excludes its use.

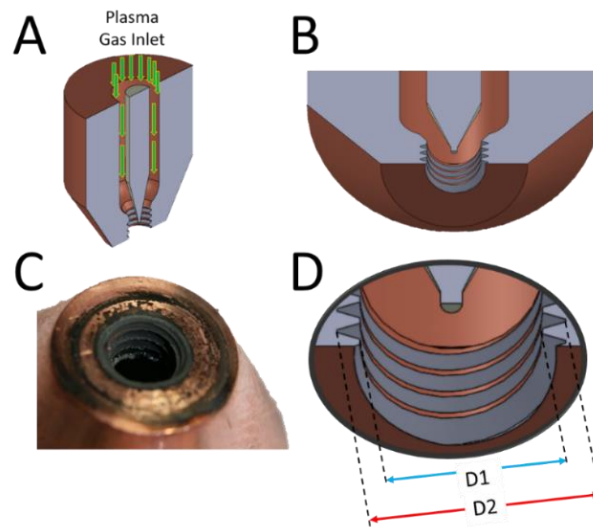


Figure 98 Threaded PTA copper nozzle. A] CAD model of nozzle isometric view, B] CAD model cross-section of electrode, nozzle and thread arrangement, C] Used threaded nozzle, arc erosion and melting of threads evident, D] CAD model thread enlargement: D1 = Minor Diameter, D2 = Major Diameter.

A possible explanation for the increased ease of arc initiation is the potential consequence of the increased number of sharp edges, and corresponding charge concentrations within the nozzle bore, shown in Figure 98 'D', close to the electrode tip. These are favoured by the pilot non-transferred arc, which is generally initiated across a longer distance from the electrode tip to the nozzle outside edge. The shorter distance from the tip to the thread edge, compared with the typical nozzle tip edge, aids arc initiation.

The reduction in arc pressure is likely to be related to the nominal increase in nozzle diameter from 3 mm to approximately 3.242 mm (minor diameter 'D1' of female thread Figure 98 'D'). Consequently, a lower arc pressure than the 3 mm nozzle but a higher arc pressure than the larger 3.9 mm nozzle diameter, but with a similar linear trend, results, shown in Figure 97. The increased plasma gas turbulence as a result of the thread also reduces the heating and ionisation of the plasma gas. By comparing the peak arc pressure results in Figure 99 for the threaded nozzle to a 3.2 mm nozzle diameter, the values from Figure 88 and the extended version of Figure 223 in Appendix A, the probability of the explanation becomes more credible. The difference between the two trends of Figure 99 result from the small differences in diameter, plasma gas turbulence, machining

tolerances, difference in R-squared (R^2) values and experimental measurement error, set out in Appendix C.

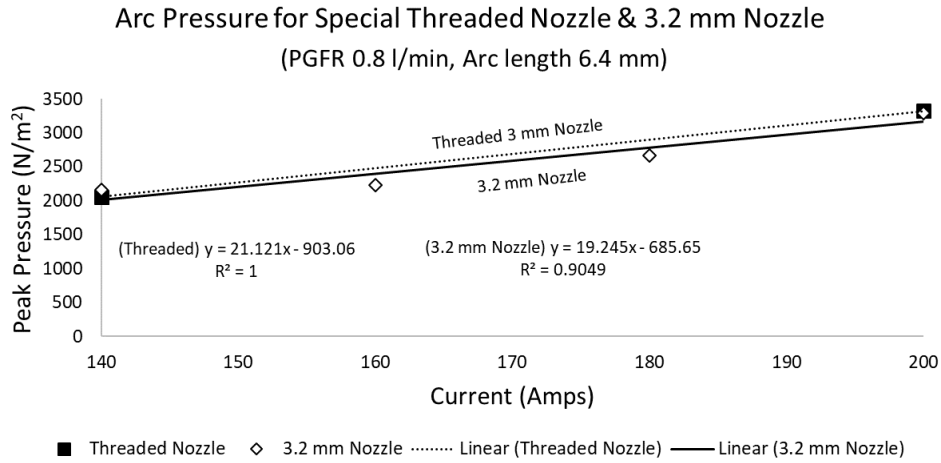


Figure 99 Peak PTA arc pressure for a threaded 3 mm nozzle and, for comparison, a 3.2 mm nozzle.

Slotted Nozzle

Figure 100 shows the peak arc pressure values as a function of current for the three special slotted nozzles. The comparison shows that the arc pressure is reduced for all three nozzles compared with the original 3 mm nozzle diameter. As the through slot area increases, the arc pressure also decreases.

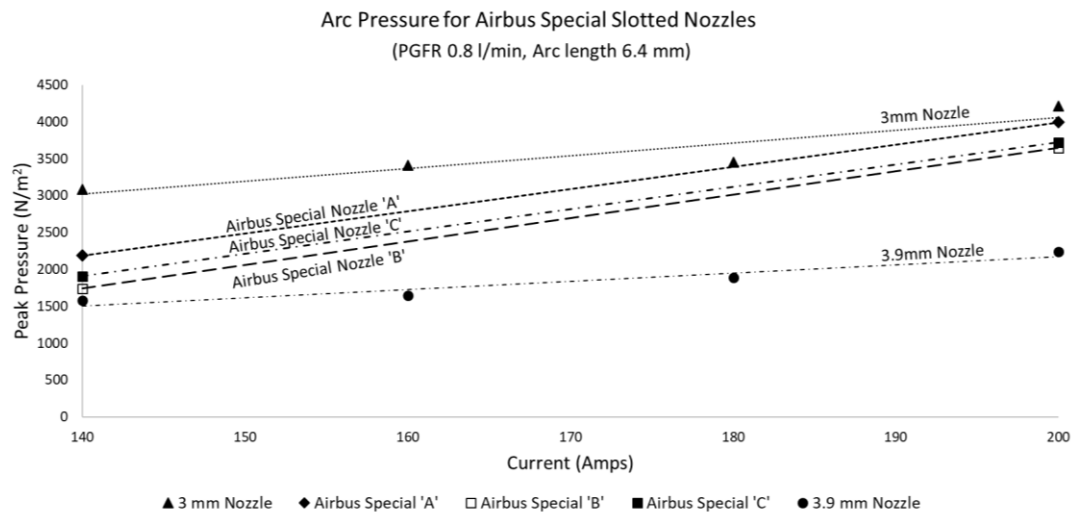


Figure 100 Peak PTA arc pressure for three special slotted 3 mm nozzles versus current.

The overall areas and equivalent single-hole diameters for the different types of nozzle are shown in Table 14.

Table 14 Comparison of calculated PTA nozzle areas and equivalent diameters.

Slotted Nozzle Calculated areas						
Nozzle Type	3 mm Nozzle	Three-hole Nozzle	Airbus Nozzle A	Airbus Nozzle B	Airbus Nozzle C *	3.9 mm Nozzle
Relative Nozzle Area (mm²)	7.07	8.64	8.64	10.88	11.54	11.95
Equivalent Single-hole Diameter (mm)	3	3.32	3.32	3.72	3.83	3.9

* Airbus Nozzle C is a tapered slot, and not a through-hole as per the other nozzles.

As the through slot area increases, the arc pressure also decreases, except for nozzle C, which is a tapered hole not a through-hole. However, compared with the WAAM standard 3.9 mm nozzle, the gradient is steeper, and, for the same parameters, the peak arc pressure values are higher, Figure 100.

The results, shown in Figure 100, indicate that incorporating a single-sided through slot within a 3 mm nozzle reduces the arc pressure. By plotting the through slotted nozzles ‘A’ 8.64 mm² and ‘B’ 10.88 mm² equivalent nozzle diameters of 3.317 mm and 3.722 mm and peak arc pressure values over the nozzle diameter plots of Figure 88, shown in Figure 101, the slotted nozzles of ‘A’ and ‘B’ fit the 140 A trend. However, for the slotted nozzles ‘A’ and ‘B’ at 200 A, the arc values are significantly higher than the equivalent straight-bore nozzles. The decrease of arc pressure of the slotted nozzles at 140 A is therefore a result of the increase in nozzle opening, but not at 200 A.

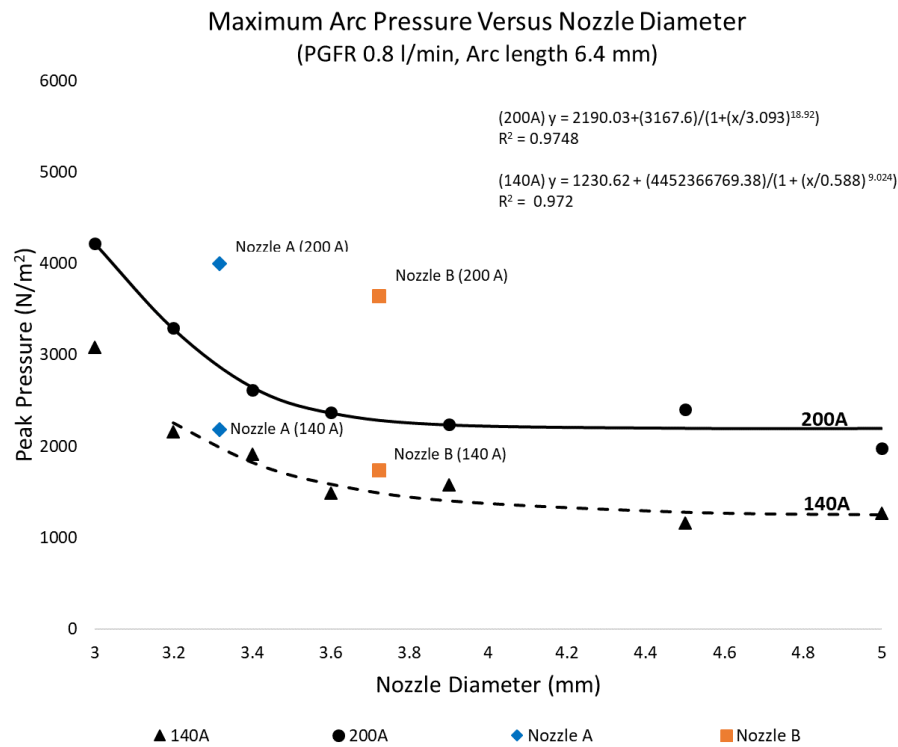


Figure 101 Peak arc pressure of slotted nozzles ‘A’ and ‘B’ versus their equivalent nozzle diameters, overlaid on Figure 88.

It is more likely that, similar to the three-hole nozzle, plasma gas is diverted away from the PTA arc via the slots. As with the three-hole nozzle, similar results can be achieved by reducing the PGFR through a standard 3 mm nozzle or by increasing the nozzle diameter.

The effect of the slotted nozzle on wire melting efficiency is not covered by this study, though reducing the arc pressure will change the force applied to the wire droplet, which typically assists in droplet detachment and potentially the metal transfer mode.

For the through slotted nozzles ‘A’ and ‘B’, the by-passed plasma gas can be calculated in the same way as the three-holed nozzle:

Table 15 PTA peak arc pressures for a 3 mm and through slotted nozzles.

Measured peak arc pressure for three different PTA nozzle designs.			
(6.4 mm Arc Length, 0.8 l/min Plasma Gas, Gas Compositions 100% Argon)			
	3mm Straight-bore Nozzle	Slotted Nozzle 'A'	Slotted Nozzle 'B'
Arc Pressure at 140 A (N/m ²)	3081.43	2185	1740
Arc Pressure at 200 A (N/m ²)	4216.03	3995	3645

Through slotted nozzles 'A' and 'B' at 140 A, PGFR 0.8 l/min

Using the same method and equation, repeated below, as the three-hole nozzle at 140 A, the by-passed plasma gas can be calculated. The arc pressure for a standard 3 mm nozzle at 140 A is illustrated in Table 15. The trend Equation 7 is from Figure 90, with a 3 mm nozzle – peak arc pressure at 140 A versus PGFR plot.

$$y = 1507.1x + 1691 \quad \text{Equation 7}$$

As all other geometries and PTA independent variables are equal, the peak arc pressure for the slotted nozzles 'A' and 'B' and 3 mm nozzle should be equivalent. However, as the slotted nozzle values are less, it can be surmised that by-passed PGFR is responsible for the reduction.

Therefore, utilising Equation 7, a value of PGFR supplied to the 3 mm central hole of the slotted nozzles 'A' and 'B' at 140 A can be calculated:

Slotted nozzle 'A' at 140 A = 0.328 l/min. The remaining 0.472 l/min is by-passed.

Slotted nozzle 'B' at 140 A = 0.033 l/min. The remaining 0.767 l/min is by-passed.

Through slotted nozzles 'A' and 'B' at 200 A, PGFR 0.8 l/min

Using the same method and equation, repeated below, as the three-hole nozzle at 200 A, the by-passed plasma gas can be calculated. The arc pressure for a standard 3 mm nozzle at 200 A is illustrated in Table 15. The trend Equation 8 is from Figure 91, with a 3 mm nozzle – peak arc pressure at 200 A versus PGFR plot.

$$y = 3292.3x + 2318.4$$

Equation 8

Utilising the same method as for the 140 A, but with Equation 8 a value of PGFR supplied to the 3 mm central hole of the slotted nozzles ‘A’ and ‘B’ at 200 A can be calculated:

Slotted nozzle ‘A’ at 200 A = 0.51 l/min. The remaining 0.29 l/min is by-passed.

Slotted nozzle ‘B’ at 200 A = 0.4 l/min. The remaining 0.397 l/min is by-passed.

Through slotted nozzles ‘A’ and ‘B’

The reduction in by-passed plasma gas with current suggests that the current, through arc demand, like the three-hole nozzle, dictates how much plasma gas is by-passed for the through slotted nozzles – a Venturi effect.

This hypothesis explains the increased gradient of the slotted nozzles ‘A’ and ‘B’ compared with the 3 and 3.9 mm nozzles in Figure 100.

Using the calculated areas and the equivalent single-hole diameters of the slotted nozzles, shown in Table 14, the measured arc pressure for each slotted nozzle type at 140 A can be compared to the calculated expected value for the equivalent single-hole diameter, shown in Table 16, based on Figure 101. For each of the slotted nozzle types, the measured arc pressure is higher than the calculated equivalent. The difference for nozzle ‘C’ is probably a result of the hole being tapered and not a through hole. For nozzle ‘C’, the tapered slot acts more like a diverging nozzle.

As there is no arc pressure reduction, there is no real benefit of these slotted nozzle designs in terms of arc pressure reduction, as a similar or better effect can be obtained by using a single-hole nozzle with an equivalent area.

The arc pressure reduction of the ‘A’ and ‘B’ slotted nozzles is as a result of an increased nozzle exit area and by-passed plasma gas. The calculated and measured values do not align as the slots are asymmetric.

Table 16 Comparison of measured and calculated equivalent arc pressures for the slotted nozzle designs.

Slotted Nozzles at 140 A			
Nozzle Type	Airbus Nozzle A	Airbus Nozzle B	Airbus Nozzle C *
Relative Nozzle Area (mm²)	8.64	10.88	11.54
Equivalent Single-hole Diameter (mm)	3.32	3.72	3.83
Measured Arc Pressure at 140 A (N/m²)	2185	1740	1905
Calculated Expected Arc Pressure at 140 A (N/m²)	1962.9	1493	1432

*Airbus Nozzle 'C' is a tapered slot, and not a through-hole as per the other nozzles.

Calculated expected arc pressure values based on equivalent single straight hole.

As the through slotted nozzles 'A' and 'B' are less effective at reducing arc pressure than the WAAM standard 3.9 mm nozzle and has increased rates of change for peak arc pressure with current, shown in Figure 100, they are deemed not suitable for WAAM operations.

Diverging Nozzles

The effect of a 36.8° PTA nozzle angle on arc pressure with three diffuser lengths – 0.8, 1.6, and 2.4 mm – is shown in Figure 102 ‘A’, left of the ‘Y’ axis. For comparison, the distributions of 3 and 3.9 mm straight-bore nozzles have also been plotted, right of the ‘Y’ axis.

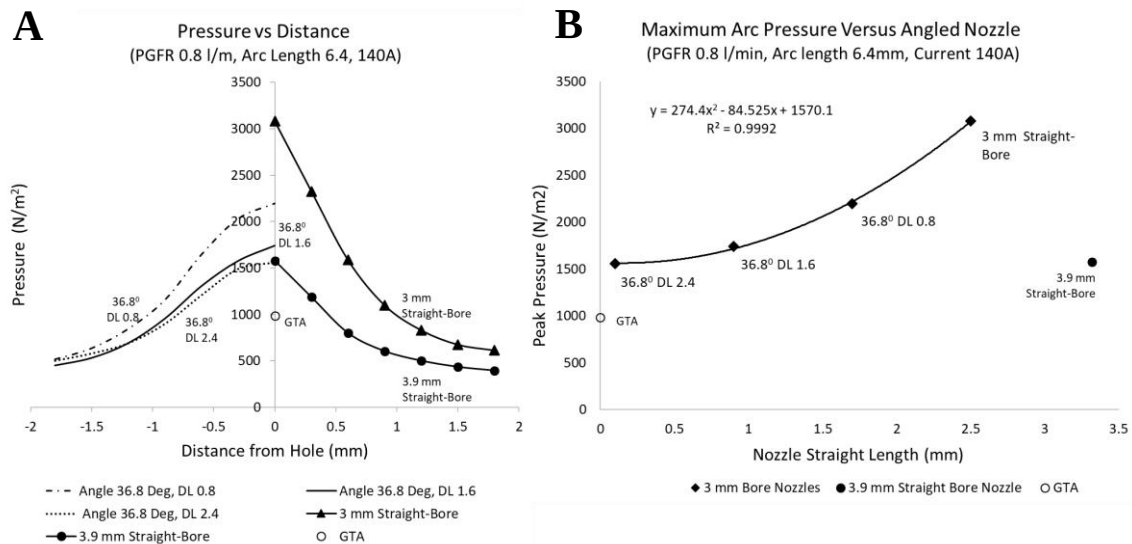


Figure 102 A] Comparison of arc pressure for diverging nozzles with various diffuser lengths and a DA of 36.8 degrees (left): with straight-bore nozzles (right) the GTA arc pressure is also shown. B] Peak pressures versus nozzle bore straight length for the same five nozzles geometries.

The relationship of nozzle straight length, shown in Figure 42 ‘B’, to peak pressure is illustrated in Figure 102 ‘B’. Each of the nozzles has a 3 mm nozzle diameter, and the peak pressure values for GTA and a 3.9 mm diameter straight-bore nozzle have been added for comparison. The graph indicates a non-linear relationship – a nozzle with a DA reduces arc pressure and a shorter diffuser length and subsequently longer straight length increases the pressure. The peak arc pressure is shown to increase inversely proportionately to the nozzle diffuser lengths. However, when compared with the measurements for a 3.9 mm nozzle with the same parameters, the arc pressure is generally higher.

The distributions of Figure 102 ‘A’ are also broader for the angled nozzles: nozzle plots exhibit flatter profiles at peak values compared with straight-bore nozzles.

For the 3 mm straight-bore nozzle with a DA of 36.8^0 and the most extended diffuser length (2.4 mm), and the corresponding small ‘nozzle straight length’ and large ENEBD, the peak arc pressure approaches that of the larger diameter 3.9 mm nozzle, suggesting that the change in nozzle geometry equates to that of a larger straight-bore diameter.

Figure 102 ‘B’ also suggests that, for a 3 mm straight-bore nozzle with a DA of 36.8^0 , as the diffuser length is reduced and correspondingly the ‘nozzle straight length’ increases and ENEBD decreases, the trend tends towards that of a straight-bore 3 mm nozzle.

The converging–diverging nozzles of Demars et al. (1973), outlined in the literature review, where the electrode stands proud of the neck/throat, shown in Figure 19 ‘C’, is similar to the 2.4 mm diffuser length and 0.1 mm straight length angled nozzle of this study, shown in Figure 60 ‘F’.

Similar to the nozzle length study, the nozzle straight length (N_{SL}) of an angled diffuser nozzle increased the arc pressure. However, the shape of the nozzle exit after the straight length affects the flow of the plasma gas and arc, resulting in a diverging arc column from the diverging nozzle when compared with a straight-bore nozzle, shown in Figure 103 ‘B’. The FWHM results, shown in Figure 74, coincide with arc divergence, with the arc pressure diameter increasing with diffuser length.

The E_{NEBD} is also proportional to the diffuser length (D_L), (Figure 42 ‘B’). For longer diffuser lengths the nozzle opening is therefore more extensive and the corresponding arc column/diameter wider, resulting in flatter pressure distribution, lower arc pressure and reduced current density, comparable to increases in arc length.

Figure 103 shows the numbered zones where the plasma gas changes in volume, as well as the density for a fixed PGFR while transitioning the diverging nozzle: [1] large plasma gas volume, [2] small increase in volume, [3] decrease in volume, [4] decrease in volume and increase in density as a result of the nozzle straight length, [5] increase in volume and decrease in density as a result of the increase in E_{NEBD} .

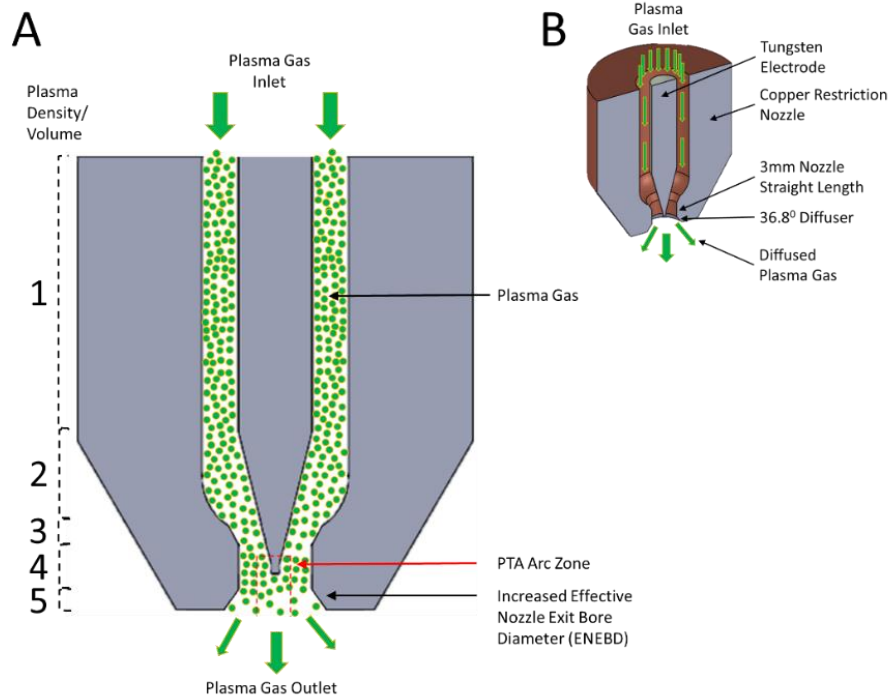


Figure 103 Specialist diverging nozzle. A] 2D sketch of plasma gas through the nozzle with diffused exit streams – arc area indicated. B] Annotated 3D model of nozzle cross-section – PGFR path indicated.

The density and volume of the plasma gas change as they pass through the nozzle (Figure 103 'A'). The arc zone straddles the high-density zone of the N_{SL} (Zone 4 Figure 103 'A') and the lower density plasma gas through the diffuser length (Zone 5 Figure 103 'A').

The N_{SL} for all the diverging nozzles is less than 2.5 mm of a 3 mm straight-bore nozzle with the same channel diameter (Table 17).

Table 17 Diverging nozzle percentage nozzle straight length compared with a 3 mm straight-bore nozzle.

Diffuser Length (D_L) (mm)	Nozzle Straight Length (N_{SL}) (mm)	Percentage Nozzle Straight Length of a 3 mm Straight-bore Nozzle
0.8	1.70	68%
1.6	0.9	36%
2.4	0.1	4%

As the N_{SL} is reduced, shown in Table 17, the effectiveness of the restriction decreases, resulting in flatter pressure distribution and lower arc pressure and current density. For

the diverging nozzles the plasma reduces in velocity as it passes through the diffuser, consequently decreasing the momentum and the arc pressure.

Igniting the pilot arc became an issue for combinations of large ESBs when used in conjunction with large D_A . This issue results from a longer distance from the electrode tip to the nozzle outside edge being too large to ignite the pilot arc with standard high frequency. This study's standard ESB of 1.4 mm was therefore utilised with the diverging nozzles of Figure 59.

The relatively sharp edge of a straight-bore nozzle aids arc ignition because of its charge concentration, as previously discussed. However, flow going through a sudden expansion over a sharp corner results in flow recirculation and turbulent flow (Figure 104). The incorporation of a small diffuser in the form of a rounded corner would reduce this effect. However, the impact on the ease of arc ignition would need to be investigated.

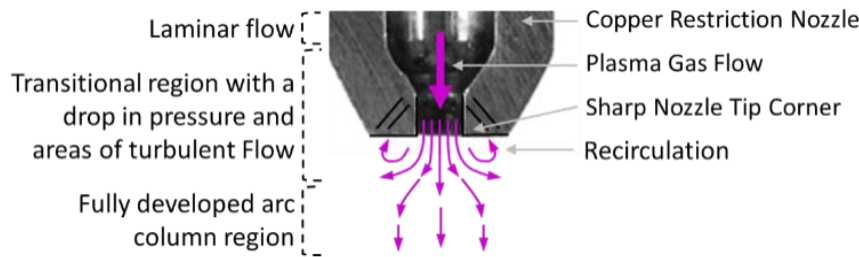


Figure 104 Effect of nozzle tip shape on gas flow.

Table 18 outlines angled nozzle values for comparison, in addition to the values of 3 and 3.9 mm straight-bore nozzles. As the nozzle straight length decreases, and, correspondingly, the diffuser length increases, so does the arc pressure. In addition, as the diffuser length increases, the E_{NEBD} increases accordingly. Using the trend equation for nozzle diameter at 140 A from Figure 88, the arc pressure can be calculated for the equivalent nozzle diameter using the E_{NEBD} values. These calculated arc pressures are significantly lower than the recorded values, with the percentage increase reducing with nozzle straight length (Table 18).

Table 18 PTA angled nozzle values

Measured peak arc pressure for angled PTA nozzle designs.								
(6.4 mm Arc Length, 0.8 l/min Plasma Gas, 140 A, Gas Compositions 100% Argon)								
Nozzle straight Length Length (mm)	Diffuser Length (mm)	E_{NEBD} (mm)	Arc Pressure (N/m ²)	% Increase of Arc Pressure (Note 1)	Arc Pressure Diameter (FWHM) (mm)	Nozzle Volume (mm ³) (Note 2)	Bore Diameter (mm) (Note 3)	Arc Voltage (V)
2.5	0	3	3081.43	-	1.2464	17.67	3	20
1.7	0.8	3.53	2196.565	33% Increase	1.892	28.78	3	20.3
0.9	1.6	4.06	1739.184	29% Increase	1.973	47.95	3	19.31
0.1	2.4	4.6	1556.784	22.7% Increase	2.112	76.89	3	17.57
3.32	0	3.9	1578.18	-	1.59 (Note 4)	39.66	3.9	19.26

Note 1. The percentage increase of arc pressure to the equivalent calculated straight-bore nozzle diameter; corresponding to the E_{NEBD} .

Note 2. Total nozzle volume refers to the volume of the nozzle straight length and additionally, where appropriate, the diffuser.

Note 3. The bore diameter refers to the nozzle straight length diameter.

Note 4. Calculated from nozzle diameter FWHM trend, actual distribution calculated value = 1.22 mm.

Figure 105 shows the angled nozzle peak pressures plotted against their E_{NEBD} , with higher values than would be expected for the equivalent nozzle diameter. The calculated arc pressure diameters, shown in Figure 74 and Table 18, align, with arc pressure diameter reducing with increasing arc pressure as the power density of the arc increases. Furthermore, and as the nozzle volume increases, shown in Table 18, the arc pressure decreases.

Figure 106 reuses the angled nozzle peak pressure versus nozzle straight length plot of Figure 102 'B', but with the 3.9 mm nozzle straight length results and trend overlaid. By assuming a similar linear trend for a 3 mm straight-bore nozzle, an 'anticipated' trend can be created, as indicated in Figure 106. The angled nozzle trend does not align with the anticipated trend and is in fact polynomial.

The change in arc pressure of the angled nozzles is therefore likely a result of a combination of two factors: nozzle straight length and E_{NEBD} .

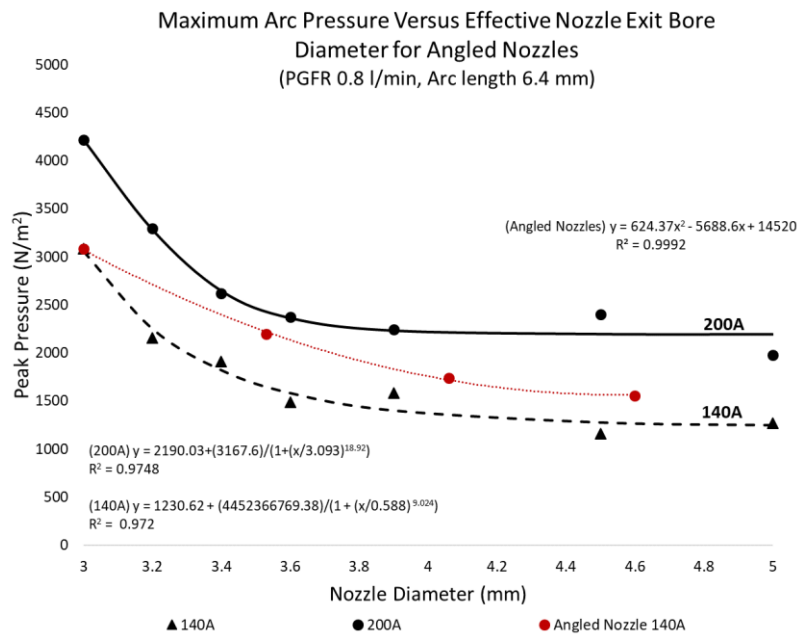


Figure 105 Angled nozzle peak arc pressure values plotted against their E_{NEBD} . Note 3 mm nozzle with no diffuser included. Values overlaid on extract of Figure 88 for comparison.

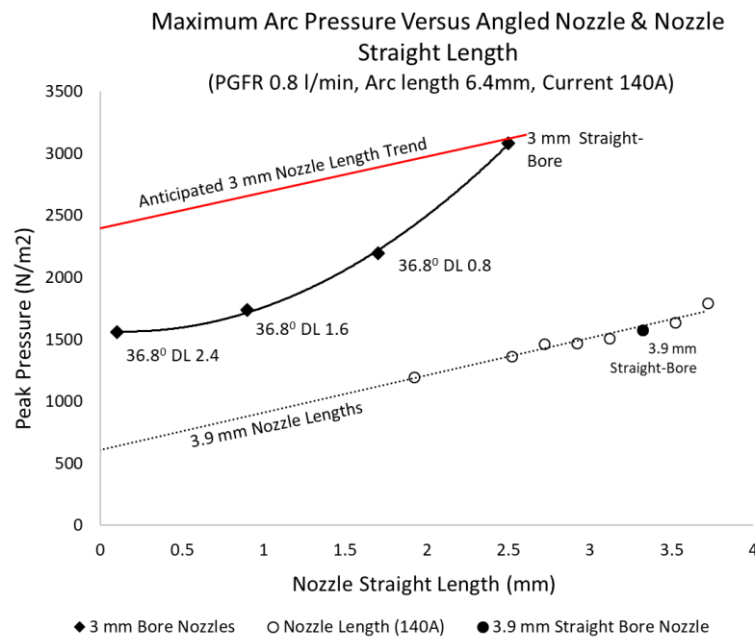


Figure 106 Angled nozzle peak arc pressure values plotted against nozzle straight length, with diffuser lengths (DL) indicated. Note 3 mm nozzle with no diffuser included. 3.9 mm straight-bore nozzle length results and trend shown. Anticipated 3 mm straight-bore nozzle length trend indicated. Values overlaid on Figure 102 'B' for comparison.

The arc pressure value of a 3.9 mm nozzle is within 4% of the arc pressure of the angled nozzle with 2.4 mm diffuser length for the same parameters. However, as the nozzle straight length, E_{NEBD} , arc pressure diameter and nozzle volumes, Table 18, do not align, the similar values are likely simply a coincidence.

Theoretically, like Demars et al.'s (1973) nozzles, arc ignition should be easier with the angled nozzles, while gaining the benefits of a large-bore nozzle – lower arc pressure. The damage to the nozzles through erosion should also be reduced because of the electrode standing through the restriction. However, the insufficient run time of the nozzles to date makes an erosion comparison impractical.

There is insufficient data to establish comprehensively how the angled nozzles function fully. However, from the results, it is clear that nozzle length, E_{NEBD} , nozzle restriction volume and potentially plasma gas restriction all play a part.

Sergio Eduardo Ríos (2017) undertook a study of diverging nozzles to enable the increase in PTA arc power, normally hindered by the onset of keyhole, to increase the rate of WAAM deposition. He established that the WAAM operating region was strongly affected by nozzle design, and, by reducing the nozzle restriction effect with the diverging nozzle, the operation envelope could be increased to allow higher current and PGFR to increase WAAM productivity potential. The results of this study indicate that the reduced arc pressure, not considered by Sergio Eduardo Ríos (2017), results from using a diverging nozzle, allowing an increase in current and PGFR before keyhole mode initiates. Other methods of reducing arc pressure are just as effective.

Though the 36.8° diverging nozzle with a 2.4 mm diffuser length has been shown to reduce arc pressure compared with a 3 mm nozzle, as in Figure 102, when compared to a straight-bore 3.9 mm nozzle the arc pressure is similar. The additional machining time and cost of a diverging nozzle may not therefore be justifiable. The angled nozzles used in this study are therefore not deemed suitable for WAAM operations.

3.3.13 Arc Force

The FWHM results indicate no significant change in arc pressure diameter for current, PGFR and several other variables tested with increasing arc pressure. Any increase in

area under the pressure distributions is therefore as a consequence of an increase in peak arc pressure. The area under the arc pressure distribution curves is representative of the total arc force.

Comparing the peak arc pressure and area under the pressure distribution values, it is evident from the trend equation gradients that the slopes are very similar: examples are illustrated in Figure 107, relating to current and PGFR. This indicates that peak arc pressure is a good indication of total arc force – i.e. peak pressure – and the area under the arc pressure distributions being representative of total arc force.

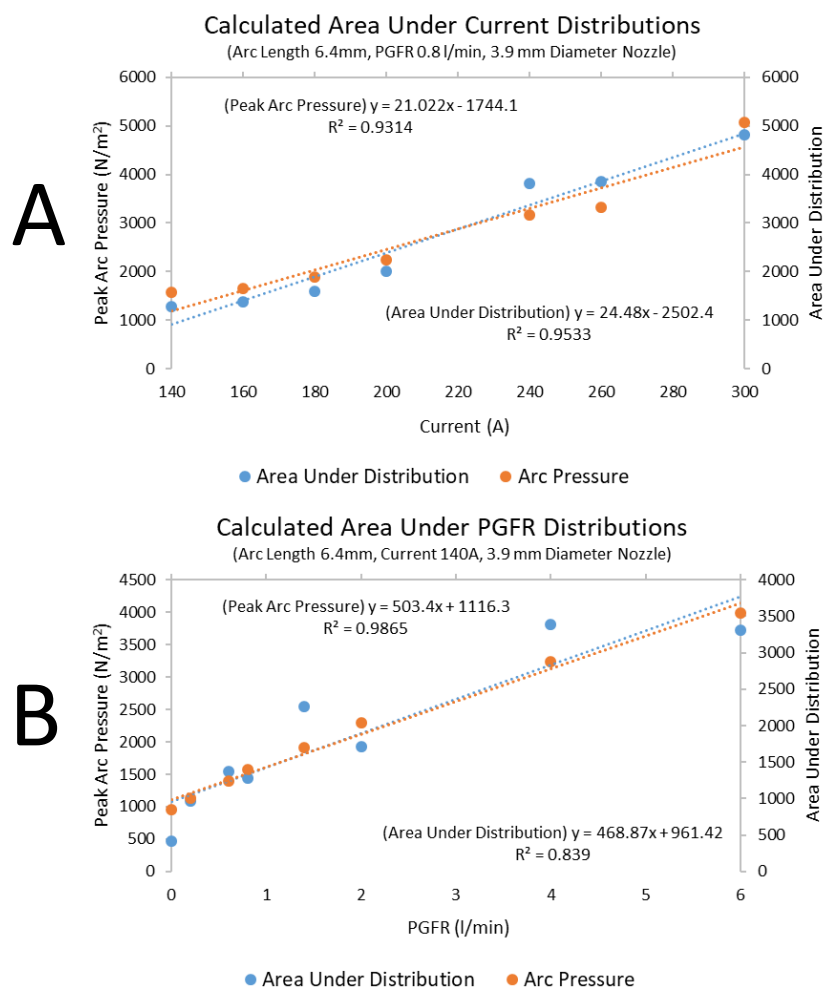


Figure 107 Comparison of peak arc pressure and area under arc pressure distributions. A] Current, B] PGFR.

3.3.14 PTA Electrode Types and Characteristics

Electrode Material

The 2% thorium used in thoriated electrodes is a radioactive element and should be considered hazardous to health, especially in operations generating radioactive dust – for example, during GTA electrode sharpening, though exposure is relatively low. It has been used for GTA within the UK for many years and PTA has followed GTA. As an alternative, safer materials are available, and these have therefore been considered and compared by this study.

Table 19 shows the difference in peak arc pressure caused by electrode material. The standard 2% thoriated tungsten electrode has the highest and zirconiated tungsten the lowest.

Table 19 Effect of electrode material on arc pressure

Measured arc pressure for different PTA electrode materials.				
(140 A, 3.9 mm Nozzle Diameter, 6.4 mm Arc Length, 0.8 l/min Plasma Gas, Gas Compositions 100% Argon)				
	Zirconiated	Ceriated	Lanthanated	Thoriated
Peak Arc Pressure (N/m ²)	883.297	1289.211	1545.116	1578.182

Significant reductions to arc pressure are possible with changes to electrode material, shown in Table 19. Zirconiated tungsten electrodes in this study led to a pressure decrease of 78.7%, compared with the standard 2% thoriated electrode. Compared with the GTA arc pressure values of Sadek et al. (1990) for the same electrode tungsten oxides measured in a similar method to this study, the values do not align. However, their findings established a relationship between reduced electrode tip deformations, resulting in higher arc pressures. As this study subjected electrodes to a PTA arc at a different current, electrode angle and arc length, with its corresponding higher temperatures and confined arc, the different conditions and correspondending reaction of the tungsten alloys to these may account for the difference in arc pressure.

Table 20 illustrates examples of allowable current per unit area for four electrode materials. Exceeding this limit could result in excessive wear or a reduction in electrode tip retention. Though some benefits may therefore come with different electrode materials, including reductions in arc pressure, the maximum allowable current for the material should also be considered during electrode selection.

Table 20 Allowable current per unit area for different electrode materials

Electrode Material	Allowable Current (A/mm ²)
Pure Tungsten	26
Thoriated Tungsten	44
Lanthanum Tungsten	36
Yttrium Tungsten	50

Note 1. Table generated from data contained within Shohet (2017) and Wu et al. (2014).

As a result of the ease of arc starting and reduced arc pressure and safety risk, PTA electrodes, such as lanthanum tungsten electrodes, are deemed worth trialling further for WAAM operations: see Chapter 6 for the PTA electrode study of material longevity and wear.

Electrode Length

Figure 108 illustrates the effects of electrode length and consequently electrode flat tip diameter on arc pressure. The results indicate that, as electrode length is shortened, the electrode tip setback and the diameter of the flat tip increase, while the arc pressure reduces. Two further observations were also made: the arc brightness increases as the electrode length decreases as the arc root is well within the nozzle, and, as the electrode flat tip diameter increases, a dense film of white tungsten powder forms across the surface of the copper-block.

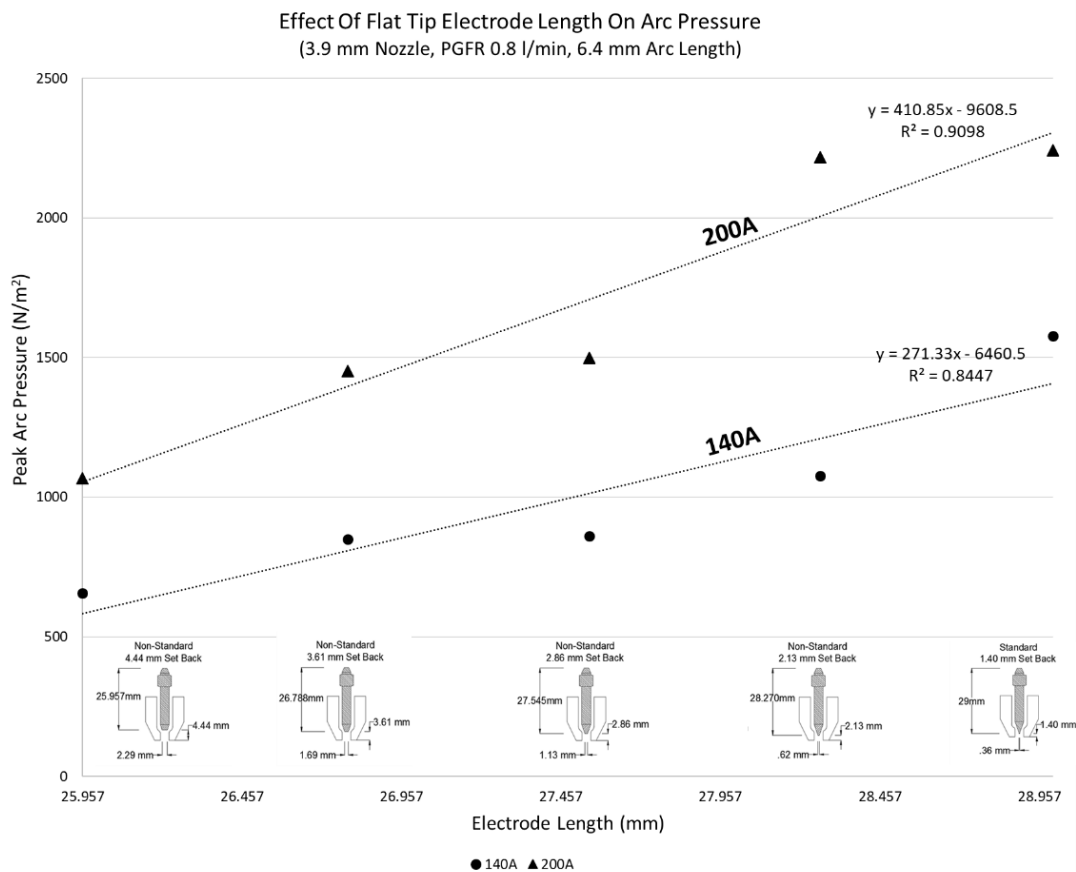


Figure 108 Effect of electrode length and electrode flat tip size on peak arc pressure.

Reducing the electrode shaft length enabled the electrode tip and bevel geometry to be unaffected, and the electrode shortened. However, this resulted in increased distance from the electrode tip to the nozzle face corner, preventing arc ignition. This study also therefore tried to change the electrode length by removing the electrode tip, but this also changed the tip shape and diameter, although the wider tip enabled arc starting. This study has therefore shown that the arc pressure does reduce with decreased electrode length but also with changes to tip diameter.

As outlined in the literature review, Fan et al. (1986) established that, for GTA, as the electrode tip is modified from a point to a truncated cone, and further to a full electrode diameter flat tip, the arc pressure reduces. However, they did not offer a satisfactory explanation for their results. Nonetheless, their findings align with the results of this study for PTA.

The general rule outlined by Shohet (2017) of $ESB \leq NSL$ has not been met for this electrode length study as the 26.788 and 25.957 mm-long electrodes have longer ESBs, shown in Figure 62, than the 3.9 mm nozzle NSL of 3.32 mm. This breach may explain the dramatic reduction in arc pressure for these two electrode lengths, shown in Figure 108, potentially affecting arc penetration and bead formation as outlined for the rule in the nozzle length results.

Electrode Wear

The influence of electrode wear on the arc pressure is shown in Table 21. The results show that the more worn an electrode is, the lower the arc pressure. After only two hours of electrode use, the reduction of arc pressure is measurable. After significant use of an electrode, the arc pressure difference is significant. It is not clear whether the reduced arc pressure with wear was a result of increased arc length because of loss of electrode length from electrode wear, or other factors such as TEAR formation and electrode tip shape changes. For a heavily worn and shortened electrode, the arc length was therefore adjusted back to 6.4 mm. This showed an increase in the arc pressure, confirming that loss of length is a factor.

Table 21 Effect of 2% thorium tungsten electrode wear on arc pressure

Measured peak pressure for 2% thorium tungsten electrode at different states of wear.				
(140 A, 3.9 mm Nozzle Diameter, 0.8 l/min Plasma Gas, Gas Compositions 100% Argon)				
	New Electrode	Used Electrode (2 hours of use)	Heavily Used Electrode (Approx. 8 hours of use)	Heavily Used Electrode (Approx. 8 hours of use) Arc Length Adjusted for Wear
Peak Arc Pressure (N/m ²)	1578.2	1399.8	1097.0	1367.3

With use, PTA electrodes wear, and arc ignition becomes more problematic: see Chapter 6. A reduction of arc pressure and electrode length takes place with wear, shown in Table 21. The loss of electrode length increases arc length, with a consequential increase in arc voltage. However, the difference in arc length from the new electrode to the heavily used electrode because of wear was measured at 0.27 mm. Using the arc length/peak pressure plot, Figure 80 trend equation for 140 A. The calculated arc length difference would need

to be 5.3 mm, a total arc length of 11.7 mm, to equate for the difference in arc pressure. As a result, the reduction in electrode length because of its wear cannot fully account for the decrease in arc pressure. The arc pressure discrepancy for worn electrodes is perhaps a result of the accumulated small effect on arc length as a result of wear but also the change in tip geometry shape/TEAR growth with electrode use. Nevertheless, restoring the original 6.4 mm arc length for the heavily used electrode did appear to increase, though not entirely, the arc pressure, shown in Table 21, by a disproportional amount to that set out in Figure 80.

Electrode Angle

Figure 109 'A' compares the effect of PTA arc pressure distributions for three electrode tip angles – 20° , 40° (standard) and 60° – within a straight-bore 3.9 mm nozzle diameter for two currents: left of the 'Y' axis 200 A and 140 A to the right. Figure 109 'B' shows the linear trends for each of the tip angles with the current. It is evident from the results that there is a linear relationship, with peak arc pressure increasing with electrode tip angle. The difference between the trend and peak arc pressure values between the 20° and 40° electrodes is minimal. However, compared with the 60° electrode, the difference is considerable, especially at higher currents. The observed arc pressure/electrode angle relationship is in line with findings for GTAW, where, when the electrode angle increases, the penetration increases and the width of the deposit decreases (O'Brien, 1991).

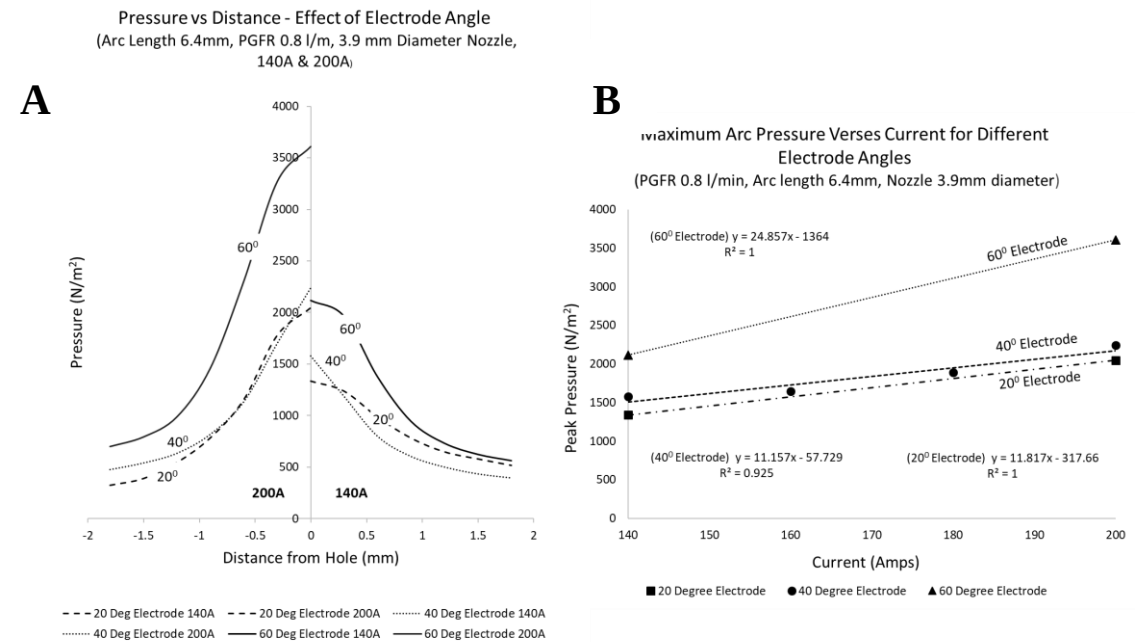


Figure 109 A] Effect of PTA torch electrode tip angle at 200 A (left) and 140 A (right) on arc pressure distribution. B] Peak PTA arc pressure versus current for three electrode angles.

The area of thermionic emission from tungsten electrodes varies with current, resulting in a change in arc location on the electrode. At the apex of the arc, a band or TEAR is formed on the electrode that pinpoints the location: see Chapter 6 for further details.

The location of the TEARs, within a 3.9 mm nozzle for three angled electrodes, is shown in Figure 110: the electrode geometry at arc apex is shown in Table 22 for each electrode angle.

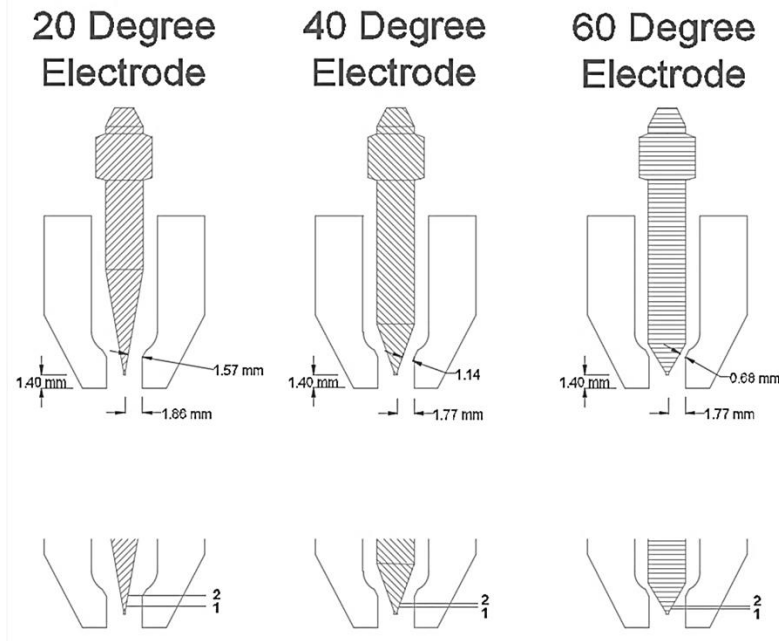


Figure 110 Comparison of TEAR location within a 3.9 mm nozzle for three electrode angles. Top] Geometry between the electrodes and the nozzle. Bottom] Location of TEARs at 140 A, labelled '1' and 200 A labelled '2'.

Table 22 Electrode geometry at arc apex

Geometry of Electrode at Arc Apex (6.4 mm Arc Length, 0.8 l/min Plasma Gas)						
Current (Note 1)	Electrode Diameter at TEAR (mm)			Height of TEAR (mm)		
	20 Degree Electrode	40 Degree Electrode	60 Degree Electrode	20 Degree Electrode	40 Degree Electrode	60 Degree Electrode
140 A – [1]	0.35	0.63	0.79	0.89	0.76	0.585
200 A – [2]	0.74	0.88	1.07	1.99	1.11	0.825

Note 1. [1] Refers to TEAR location '1' at 140 A, [2] Refers to TEAR location '2' at 200 A.

Note 2. Measurements taken from Figure 211 SEM images in Chapter 6, at the TEAR, using measurement software AxioVision.

Arc pressure increases with electrode angle, shown in Figure 109. Possible reasons for this include the decreased arc length because of the TEAR height lowering with electrode angle, Table 22, and decreased effective nozzle diameter and volume. As the electrode diameter at the TEAR height decreases from the standard 40⁰ electrode at the same height within the 3.9 mm nozzle, the effective nozzle diameter at this point increases for the 20⁰ electrode. Conversely, it decreases as the electrode diameter increases for the 60⁰

electrode. This effects gas density, velocity and consequently gas conditioning and arc pressure.

Change in effective free nozzle diameter:

For the 20° electrode at 140 A, the effective nozzle diameter increases by 9.5%, and at 200 A by 20% compared to the standard 40° electrode, with the diameter at the same TEAR height – reducing arc pressure.

For the 60° electrode at 140 A, the effective diameter decreases by 7.4%, and at 200 A by 10.3% compared to the standard 40° electrode, with the diameter at the same TEAR height – increasing arc pressure.

At 200 A, for the 20° electrode, the arc apex is almost within the nozzle chamber (Figure 110 location [2]) at the very top of the straight nozzle restriction, increasing the interaction time within the nozzle.

Distance between the electrode and the nozzle decreases significantly with the electrode angle, shown in Figure 110 – a decrease of 56.7% for the 60° electrode compared with the 20° electrode. This reduction affects the flow, velocity and density of the plasma gas to the arc, increasing arc pressure with electrode angle.

Though the 20° electrode of this study was found to reduce arc pressure and arc voltage at 140 A, and the arc column resistance, heat input at the substrate and arc energy accordingly, it is deemed not suitable for WAAM operations because of its wear-rate and brittleness – see Chapter 6. As the 60° electrode increased arc pressure, the standard 40° electrode angle is therefore regarded as best suited for WAAM operations.

Electrode Diameter and Hollow Electrodes

The electrode diameter is selected based on its operational maximum current – wider electrodes are best suited to higher currents. Although narrower electrodes may be easier for arc ignition, their tip retention and longevity from wear will be much reduced. Exceeding the electrode maximum current rating can result in tungsten contamination of the melt-pool through tip loss, (Diamond-Group, 2002). However, arc instability is a result of a too large electrode diameter being used too far below its maximum allowable

current. A compromise must therefore be reached for the application, with current limits set for PTA torches and standards/guidance followed.

The PWP Viper PTA torch used by this study has a fixed 4 mm electrode diameter – specified in accordance with BS EN ISO 6848:2015, which outlines an operating range between 100 and 400 A, DC/Electrode negative, shown in Table 47. However, the torch has a maximum rating of 240 A because of other components. As it was not possible to change the electrode diameter, this variable was not considered further within this study.

Other studies, outlined in the literature review, have considered the use of hollow electrodes, through which a plasma gas is channelled. However, this is not within the scope of this study as specialist equipment is required.

3.4 Interaction Time Concept Discussion

A concept that combines a number of the findings of this study is an interaction time within the PTA nozzle.

Assumptions:

1. Arc pressure depends on the momentum injected into the plasma gas.
2. The plasma gas is accelerated to a high velocity through the energy exchange with the plasma column in the interaction zone inside the nozzle.
3. Method of energy exchange between the plasma gas and the plasma arc column is the exchange of kinetic energy between the electrons flowing in the arc column and the plasma gas atoms.
4. Energy (velocity) of the arc electrons depends on the voltage drop across the arc, and the number of electrons, and therefore the number of energy exchanges, depends on the current.
5. The interaction time determines the period over which the energy exchange occurs, which depends on the nozzle interaction length and the gas velocity.

Figure 111 shows the PTA arrangement and the interaction length ‘L’.

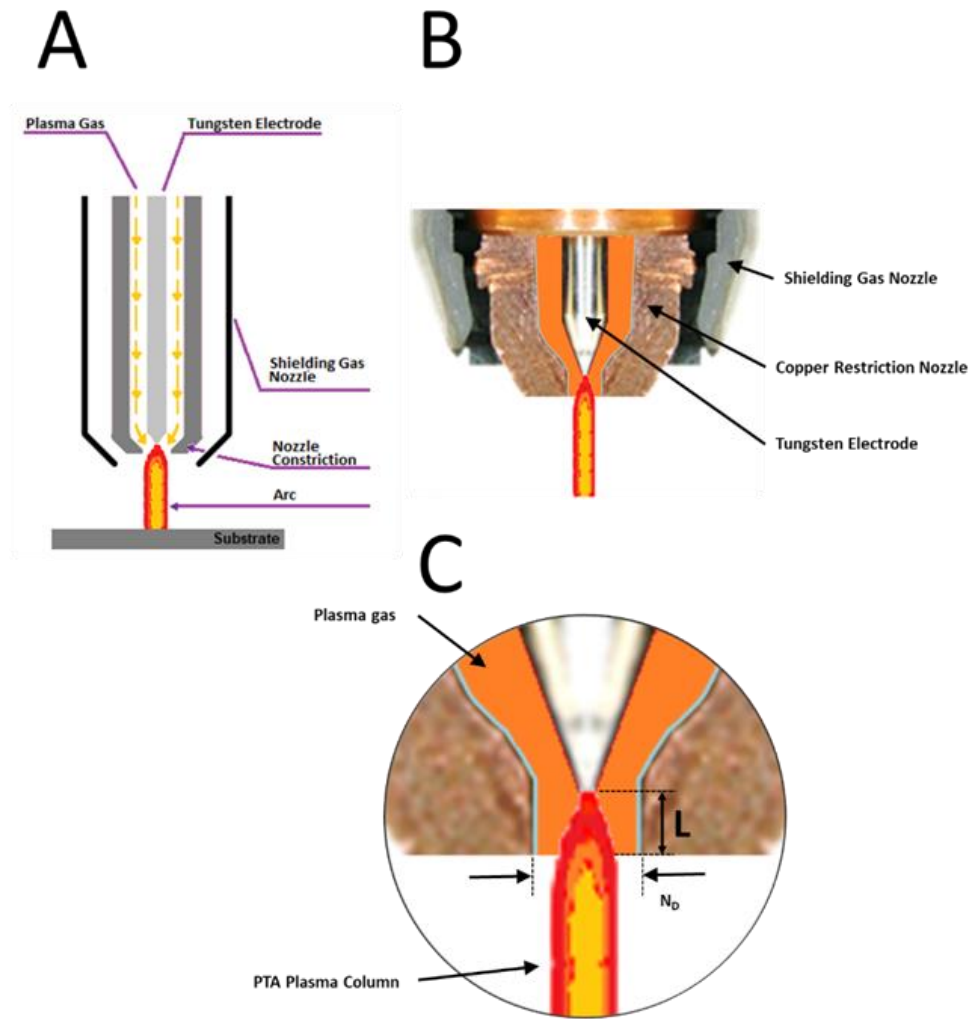


Figure 111 Interaction time and energy concept. A] General PTA arrangement, B] PTA Detail, C] Enlargement of 'B', interaction length (L) and nozzle diameter (N_D) indicated.

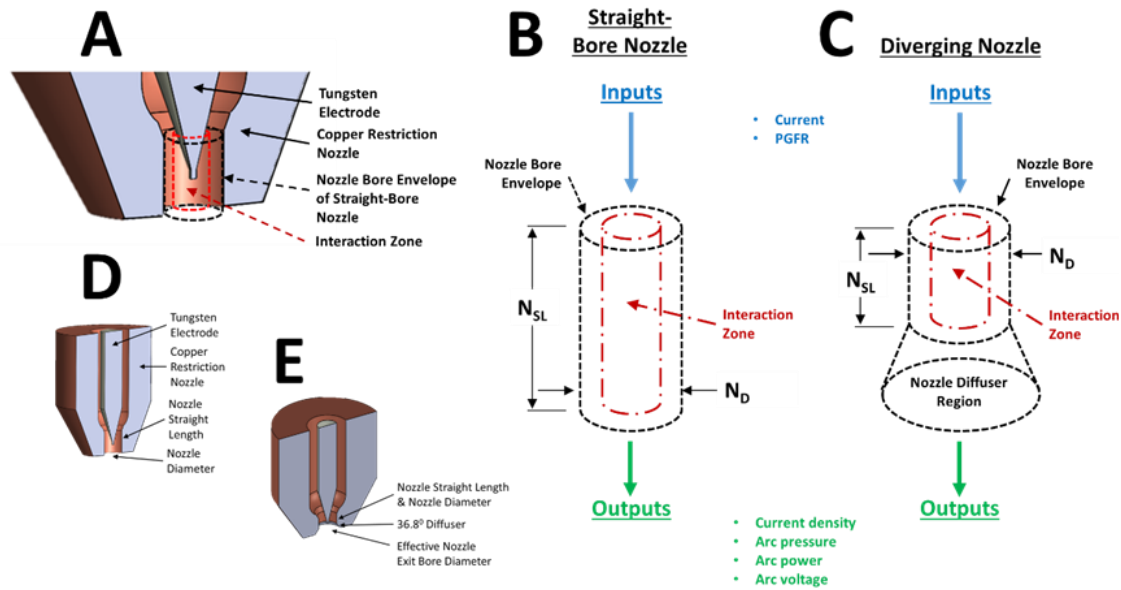
Expected Effect:

- Arc pressure is proportional to current (Chapter 3). Therefore, as Δ velocity increases and current increase, the overall energy of the arc column increases.
- Arc pressure is proportional to nozzle length (Chapter 3). Therefore, as the interaction zone length 'L' (Figure 111) increases, with nozzle length, interaction time increase, and the voltage drop across the arc increases (Chapter 4), increasing Δ velocity and increasing $\frac{L}{\text{Arc Length}}$, as Δ velocity increases as a fraction of voltage drop.

- Arc pressure is proportional to PGFR (Chapter 3). Therefore, as PGFR is increased more plasma gas can be accelerated and the voltage drop across the arc increases (Chapter 4) and accordingly Δ velocity increases.
- Arc pressure is proportional to $\frac{1}{(N_D)^2}$ (Chapter 3). Therefore, as nozzle diameter (N_D) is decreased the interaction zone's volume decreases and the voltage drop across the arc increases (Chapter 4) and accordingly Δ velocity increases.

The combined peak arc pressure results of nozzle diameter (Figure 88), effective nozzle length (Figure 93) and diverging nozzles (Figure 102) suggest that a quantifiable interaction occurs within the nozzle straight-bore envelope, which is time dependent – interaction time. This concept is further supported by the unexpected change in recorded arc voltage for a fixed current and arc length with nozzle geometry, covered in Chapter 4. Changes to the nozzle diameter or length affect the nozzle bore envelope, volume and, subsequently, the interaction zone within, shown in Figure 112.

Within the interaction zone, with the PTA electrode and arc, the gas is mostly ionised at a high temperature increasing its electrical conductivity and sensitivity to electromagnetic effects: Lorentz force.



- A] Annotated 3D model, enlargement, of a straight-bore nozzle cross-section, with nozzle bore envelope and interaction zone indicated.
- B] Nozzle bore envelope and interaction zone schematic for a straight-bore nozzle.
- C] Nozzle bore envelope and interaction zone schematic for a diverging nozzle, with diffuser region also indicated.
- D] Reference annotated 3D model of a straight-bore nozzle cross-section.
- E] Reference annotated 3D model of diverging nozzle cross-section.

Figure 112 Nozzle bore envelope and interaction zone.

The distribution of ionised gas leaving the PTA nozzle is similar to a normal distribution, with the higher gas ionisation at the centre under the electrode tip resulting in high current density at the arc centre. The percentage of gas ionisation decreases with distance, with the ionised gas dictating the arc geometry. The bright visible emission is the high-temperature plasma.

For diverging nozzles, the straight-bore nozzle diameter and nozzle straight length dictates the nozzle bore envelope and interaction zone, which is unrelated to the nozzle diffuser, shown in Figure 112 ‘C’.

The nozzle diameter and length dictate the effect of plasma gas squeeze and nozzle thermal pinch on the arc and the duration of impingement.

The PTA inputs of current and plasma gas passing through the nozzle bore envelope are subjected to the envelope volume, which affects the gas density and ohmic heating by the

electrode within the interaction zone, dictating the value of the PTA outputs: arc pressure, arc power, arc voltage, and current/power density.

Plasma gas passing within this PTA interaction zone is exposed to higher energy concentrations than a non-confined GTA.

Increases to nozzle length for the same plasma gas ohmic heating (current) and fixed diameter enhances ionisation as the gas is confined for longer, resulting in higher arc pressure and current density and increased arc voltage. Short or zero-length nozzles approximate the arc pressure of GTA, shown in Figure 93, where no nozzle exists.

A reduction of nozzle diameter decreases the margin between the nozzles bore envelope and the interaction zone within. For the same ohmic heating (current) and fixed PGFR, an increase in plasma gas ionisation takes place as the gas is confined in proximity to the heat source and the higher density because of the nozzle change in geometry. Although larger nozzle diameters reduce velocity and consequently increase interaction time, the reduced confinement with the heat source and reduced gas density balance the effect. Smaller nozzle diameters therefore result in higher arc pressure and current/power density and increased arc voltage. Large diameter nozzles, where the interaction zone is too large, approximate the arc pressure of GTA, shown in Figure 88, where no nozzle exists.

The effect of the nozzle diameter is more evident than that of nozzle length, possibly because of the more significant geometry changes possible with nozzle diameter than nozzle length alone while still enabling arc ignition. The area is proportional to the square of the diameter, and the volume is proportional to nozzle length.

Higher currents marginally increase the arc size, shown in Figure 17 'B', within the interaction zone, and enhance the ohmic heating of the plasma gas, resulting in increased gas ionisation and consequently a more substantial arc with a high arc pressure and current/power density.

Increases to PGFR, for a fixed nozzle diameter, require a velocity change to allow continuous flow through the orifice, overcoming the pressure drop. Increasing the flow-rate also increases the gas available to the interaction zone for ionisation and incorporation within the arc. However, the higher flow-rate also reduces the interaction

time. The excess gas forces down the side of the interaction zone and squeezes the arc, further focusing it by means of impingement and outer boundary cooling. The results of Langford's (2018) specialist PTA torch with a third focusing gas suggest similar gas effects on the PTA arc. For the same PGFR within larger nozzle diameters, the flow is less restricting on the arc, resulting in reduced gas ionisation, a less focused arc and lower arc pressure and current/power density.

For angled nozzles, the nozzle bore envelope, and, consequently, the interaction zone is smaller, as it is inversely proportional to the diffuser length, shown in Figure 112 'C'. The interaction time is also shorter, resulting in reduced gas ionisation and therefore a smaller, less powerful arc with reduced arc pressure (Figure 102). The DA and length result in a broader cone-shaped arc at the work-piece, reducing the arc pressure and current density, with a similar effect to that of arc length.

The interaction time concept can be considered in terms of energy transfer. Electrical energy from the electrode is converted into light – a visible bright plasma – and primarily heat. As the plasma gas passes through the interaction zone in a time 't', dependent on the nozzle length, work is done and gas molecules gain internal energy through ohmic heating, increasing with duration. The specific interaction zone length dictates the time and rate of heat transfer: interaction time. The longer the interaction time, the higher the volume of ionised gas but also the longer the arc restrictions are applied.

As the potential difference/arc voltage increases, reduced interaction zone diameter or increased interaction zone length, for a fixed current and PGFR, the amount of energy transferred to the plasma gas increase: ionised gas molecules become charged, and the following relationships come into play:

$$\text{Interaction Energy (J)} = \text{Current (I)} \times \text{Voltage (V)} \times \text{Time (Sec.)} \quad \text{Equation 9}$$

$$\text{Charge (C)} = \text{Current (I)} \times \text{Time (Sec.)} \quad \text{Equation 10}$$

And therefore:

$$\text{Energy (J)} = \text{Voltage (V)} \times \text{Charge (C)} \quad \text{Equation 11}$$

3.5 Conclusion

In this chapter, a large number of critical PTA process parameters, variables and equipment settings were identified that affect or control arc pressure (Figure 39), PTA torch geometries (Figure 40) and PTA electrodes (Figure 41). Each have been investigated in relation to their influence on arc pressure and, where possible, how their effect can be exploited to reduce arc pressure in PTA WAAM was determined, thus enabling the use of higher currents and therefore larger deposition rates without the risk of keyhole defects occurring.

Factors identified as affecting PTA arc pressure include:

- Critical parameters affecting PTA arc pressure are current, arc length, PGFR and plasma gas composition. Increased current, PGFR and reduced arc length increase PTA peak arc pressure, while increasing the plasma gas percentage of helium in argon reduces the peak arc pressure.
- PTA restriction nozzle geometry also affects arc pressure with reduced nozzle diameters, and extended nozzle straight lengths increase the arc pressure. Specialist nozzles such as a diffuser or slotted or multi-hole nozzles reduce arc pressure, but not as effectively as increased diameter nozzles.
- In addition to electrode wear, PTA electrode geometry and electrode material have also been determined as influencing arc pressure.

The importance of the arc pressure measurement orifice diameter was investigated, and a smaller diameter used than outlined in the literature relating to this study, theorised to be more accurate. However, the diameter was found to have a minimal effect on the arc pressure measurement, contrary to findings in the literature, if the arc is larger than the orifice and where a static measurement with a constant dwell time is utilised.

A comparison of GTA and PTA peak arc pressure showed that PTA is significantly higher. However, both peak arc pressure trends are linear, with a similar gradient for increasing current, and arc pressure distributions both approximate Gaussian, bell-shape encircling the arc column core, with the pressure reducing with distance from the arc centre. PTA provides the advantage of more protracted standoffs, longer arc lengths, which are critical for WAAM part building to facilitate access.

The calculated area under the arc pressure distributions, when compared to the peak arc pressure trends, is very similar. Allowing peak arc pressure to be utilised as a good indication of total arc force, i.e. peak pressure and area under the arc pressure distributions, is representative of total arc force.

The calculated arc pressure diameter values, determined by the FWHM of the arc pressure distributions for each process variable and parameter, was expected to equate to changes in arc column diameter. However, the method was found to be insufficiently sensitive, indicating no or minimal diameter change, whereas results in the literature showed significant change.

Investigation into the effect of nozzle geometry on arc pressure has led to an interaction time concept, where the geometry dictates the density of the plasma gas, and the velocity and duration of gas conditioning.

Chapter 4

Arc Voltage

4.1 Introduction

During the arc pressure study in Chapter 3, the arc voltage was additionally measured, and several findings identified. For each of the tested arc pressure variables, outlined in Figure 39, Figure 40 and Figure 41, all were found to have a significant effect on arc voltage.

Arc voltage values are specific to the torch design, and knowing the corresponding values of arc voltage to arc current allows, in advance, the calculation of factors such as arc energy and heat input.

Changes to arc voltage are of interest as there is a possibility that arc voltage could be used as a way of remotely monitoring arc pressure for the purposes of process control if a correlation between arc pressure and arc voltage is identified.

A typical method of maintaining PTA CTWD is via an arc voltage height control system. However, if arc pressure monitoring via arc voltage can be established, an alternative for CTWD height measurement must be utilised – e.g. a laser sensor.

4.2 Methodology

The methodology is the same as in Chapter 3, as the measured arc voltage was undertaken concurrently with the arc pressure measurement.

To ascertain whether substrate material type affects the measured arc voltage, the results of Chapter 3, undertaken on a copper-block, and from the keyhole study in Chapter 5 on both stainless-steel and titanium, were collated and plotted: arc current against arc power and arc current against arc voltage for the three materials. The fixed parameters for all compared values were as follows: 0.8 l/min, nozzle diameter 3.9 mm, 6.4 mm arc length, gas 100% argon.

For clarity, a number of the supplementary arc voltage plots are located in Appendix F.

4.3 Results

To evaluate the arc voltage of both PTA and GTA, the arc voltage versus arc current is plotted in Figure 113. Both sets of results are at an arc length of 6.4 mm and four currents, shown in Table 6. The arc voltage trends are linear and increase with the current.

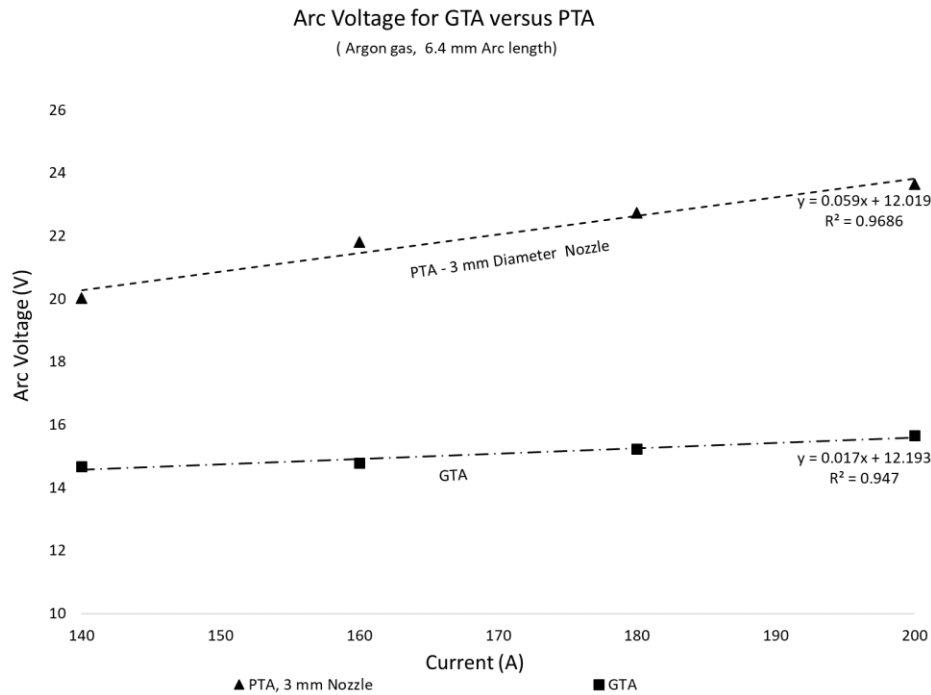


Figure 113 Arc voltage versus current for both GTA and PTA.

PTA compared with GTA shows an increase in arc power, resulting in an increased heat input for PTA (Gage, 1957). The power density of PTA is also significantly higher than GTA, shown in Figure 30, allowing a keyhole mode of operation.

Arc length for GTA and PTA is proportional to arc voltage, the voltage drop across the electric arc. The longer the distance of arc length for the current to travel, the higher the resistance experienced and the greater the heat loss and the voltage drop, resulting in lower arc energy and reduction of energy density and arc pressure.

The arc voltage/arc current relationship for DC PTA electrode negative is shown in Figure 114. The trend is linear with the voltage increasing with the current. The slope of arc voltage/current trend is representative of the overall resistance of the arc column – constant resistance.

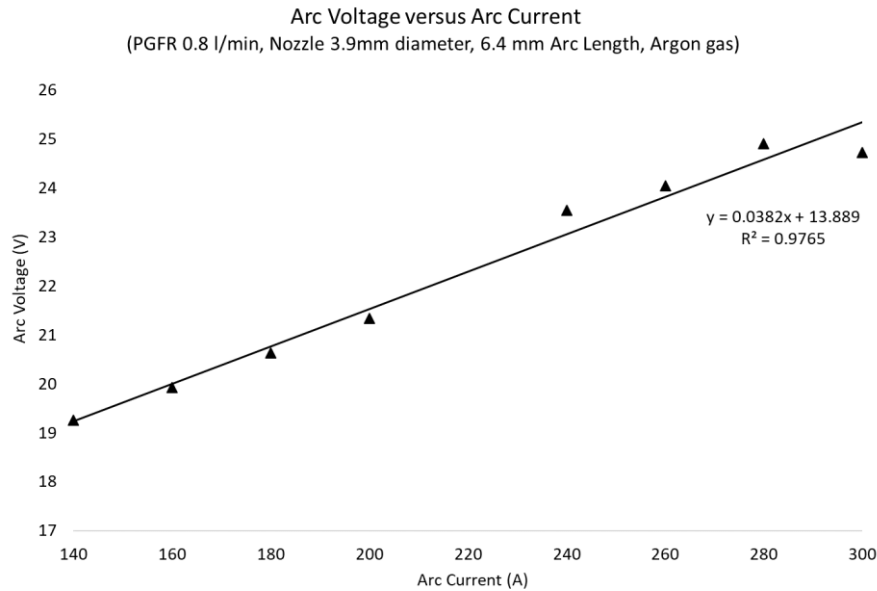


Figure 114 DC PTA electrode negative arc voltage/arc current relationship for a straight-bore 3.9 mm nozzle.

Towards the higher current, the recorded values increase slightly. This could be because of an increasing resistance (impedance to electron flow) at a higher temperature. However, there is insufficient data to confirm this with certainty. High current results in a rise in arc voltage, and, correspondingly, heat input to the substrate and deposited material. High current can also be detrimental to the PTA process as it results in electrode and nozzle damage as a result of double-arcing (Prevosto, Kelly and Mancinelli, 2011). However, to increase the rate of WAAM deposition, higher currents are crucial.

By combining the PTA peak pressure plot of Figure 69 and the arc voltage plot of Figure 114, Figure 115 was generated, which shows the PTA measured arc pressure increasing with voltage for a straight-bore 3.9 mm nozzle. The arc pressure was varied by adjusting the arc current. The trend is linear and shows that arc pressure increases with arc voltage for a fixed arc length.

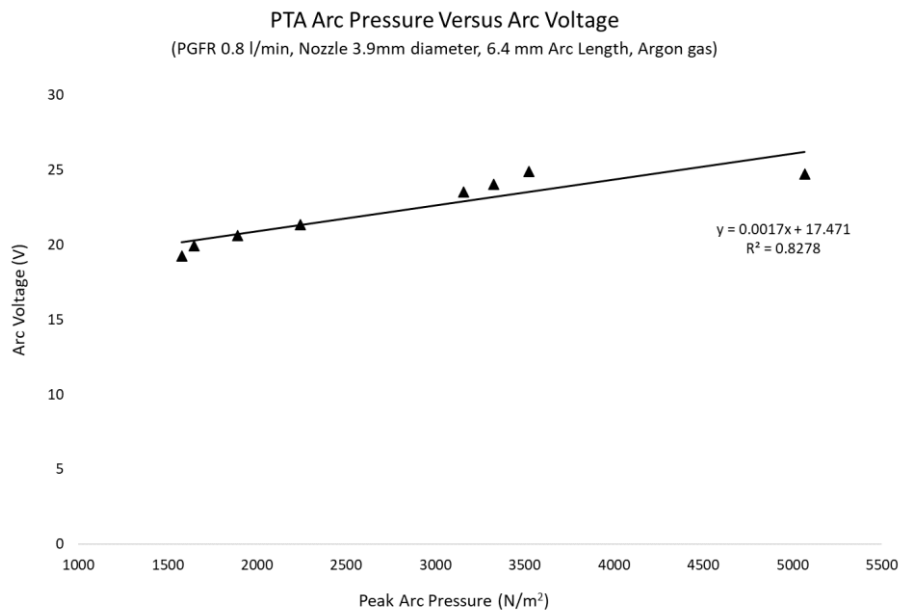


Figure 115 PTA arc voltage versus arc pressure for a straight-bore 3.9 mm nozzle, with arc pressure varied by arc current.

The effect of argon PGFR on the arc voltage is shown in Figure 116, with a positive linear trend of increasing arc voltage with rising PGFR. As the PGFR increases, the additional gas through the nozzle straight length increases the arc voltage and arc power for a given current, as a higher portion of the gas is incorporated within the arc and requires heating to arc temperature (Gage, 1957). Additionally, with increased PGFR, there is increased turbulence and cooling effect on the exterior of the arc column, which increases energy dissipated and reduces the cross-section of the arc column, increasing electrical resistance like a narrower wire, and consequently resulting in a higher arc voltage. Chen, Yan and Jiang (2019) established a relationship between PGFR and arc voltage, which aligns with this study's results. They attributed it to the availability of gas for ionisation and the consequential changes to the electric field intensity – reduced electric field intensity as a result of low PGFR reduces the arc voltage, suggesting arc voltage is proportional to PGFR.

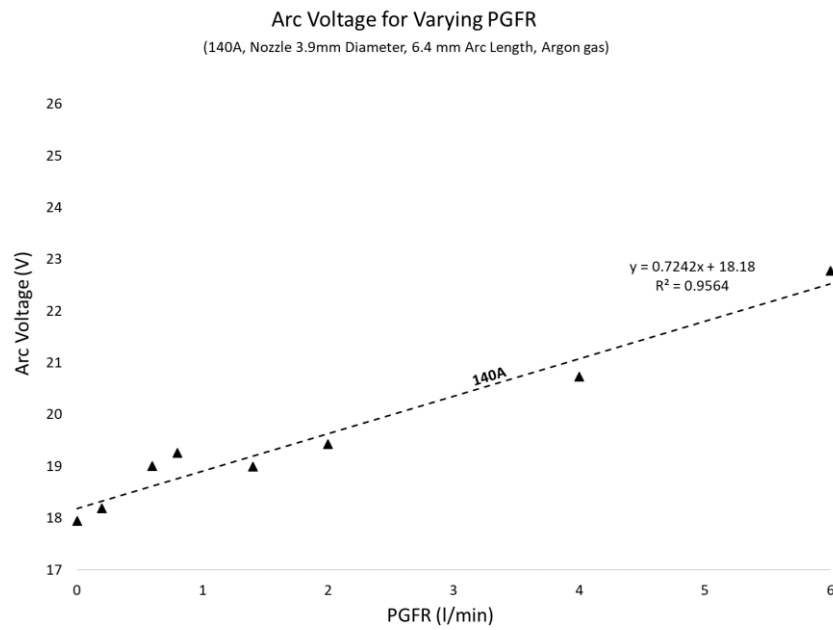


Figure 116 PTA 3.9 mm nozzle arc voltage for varying PGFR.

By combining the PTA peak pressure plot of Figure 76 and the arc voltage plot of Figure 116, Figure 117 was generated, which shows the PTA measured arc pressure increasing with voltage. The arc pressure was varied by adjusting the PGFR. The trend is linear and shows that arc pressure increases with arc voltage at a higher rate of change than by varying the arc current (Figure 115).

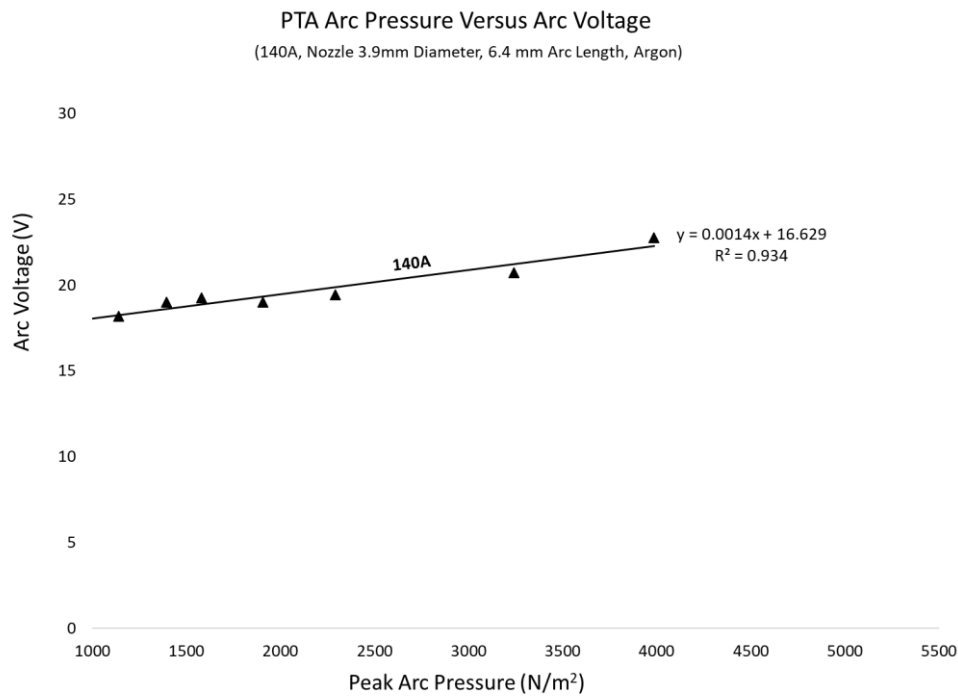


Figure 117 PTA arc voltage versus arc pressure for a straight-bore 3.9 mm nozzle, with arc pressure varied by PGFR.

The arc voltage values for straight-bore nozzle diameters are shown in Figure 118 for currents of 140 and 200 A at a fixed arc length of 6.4 mm. The trends are linear, with arc voltage decreasing with nozzle diameter. By utilising a smaller nozzle diameter, constricting the PTA arc, the arc voltage increases and consequently the arc power and heat input increase for a given current.

As the nozzle diameter and interaction zone widens, the arc voltage is reduced, shown in Figure 118. Accordingly, the arc column resistance and arc energy, at constant current and arc length, reduces. Arc energy, arc resistance and potentially electromagnetic constriction strength therefore also reduce with diameter.

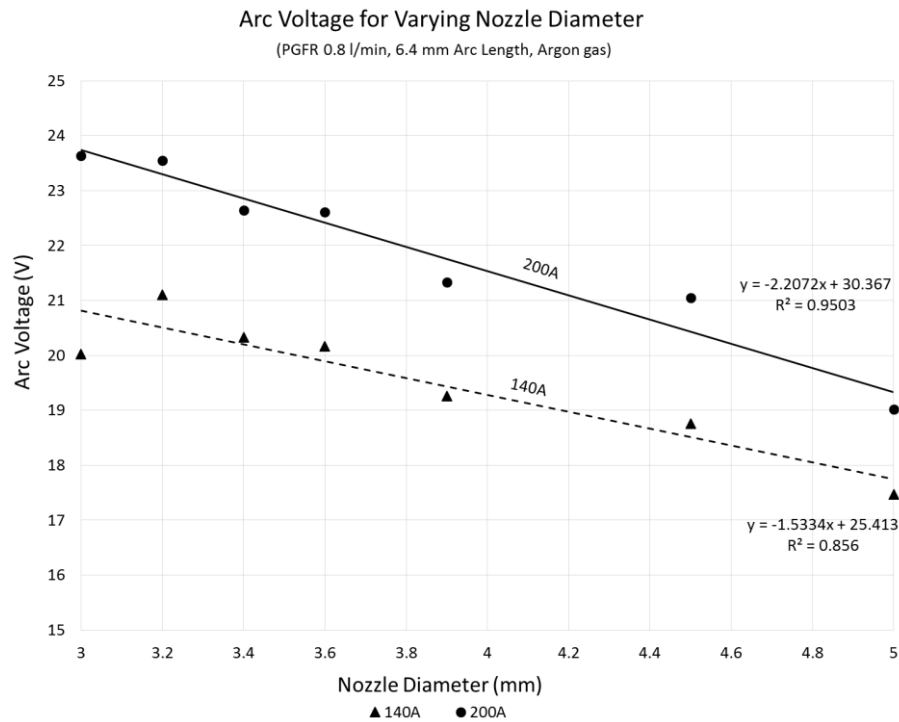


Figure 118 PTA 3.9 mm nozzle arc voltage versus nozzle diameter.

The arc voltage values for the reduced length PTA 3.9 mm straight-bore nozzles are shown in Figure 119 for currents of 140 and 200 A for a fixed arc length of 6.4 mm. The trends are linear, with arc voltage increasing with effective nozzle length. For comparison, the GTA's arc voltage values with no nozzle are included for the same arc length and current and show a significant difference in arc voltage. Prevosto and Risso (2009) also established a link between increased arc voltage with increased nozzle length, which concurs with this study's arc voltage results shown in Figure 119.

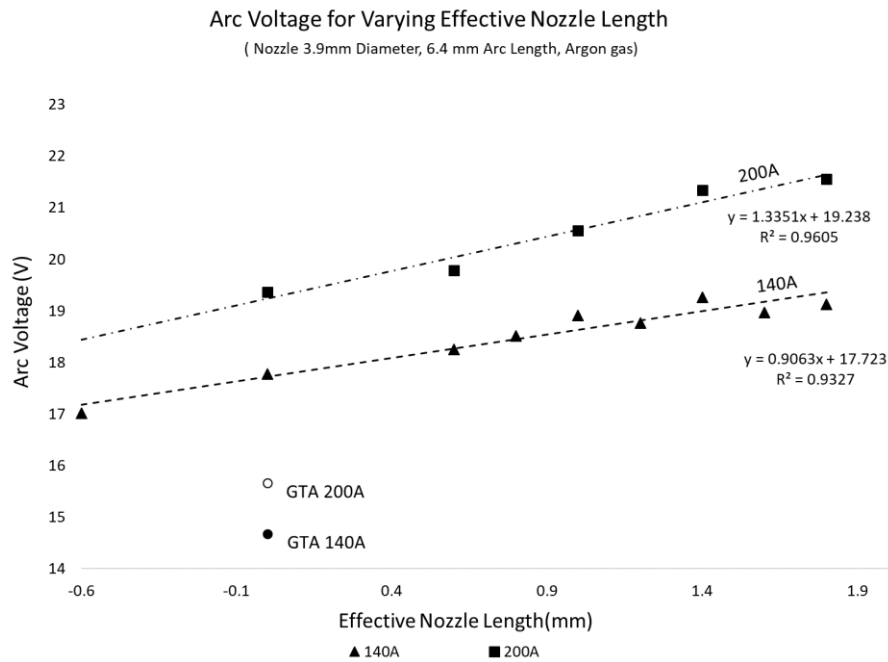


Figure 119 PTA 3.9 mm nozzle arc voltage versus effective nozzle length.

Figure 119 illustrates the increase of arc voltage with interaction zone length. The change in arc voltage because of arc length variation is illustrated in Figure 120. The trends are linear, with arc voltage increasing with arc length. The arc voltage rate of change with arc length increases with current, as indicated by the gradient of the trends: i.e. arc length has a more significant effect on arc voltage at higher currents.

The arc length is a secondary variable that is controlled by setting the PTA nozzle height. Arc voltage is directly related to arc length and can be monitored. The recorded arc voltages for the three arc lengths and three values of current, shown in Figure 120, confirm the correlation between arc length and arc voltage for PTA.

The increase of arc voltage with reduced arc pressure is contrary to other parameter voltage results. However, the rise is in line with the increase in electrical resistance as a result of the increased travel distance of the arc through argon gas.

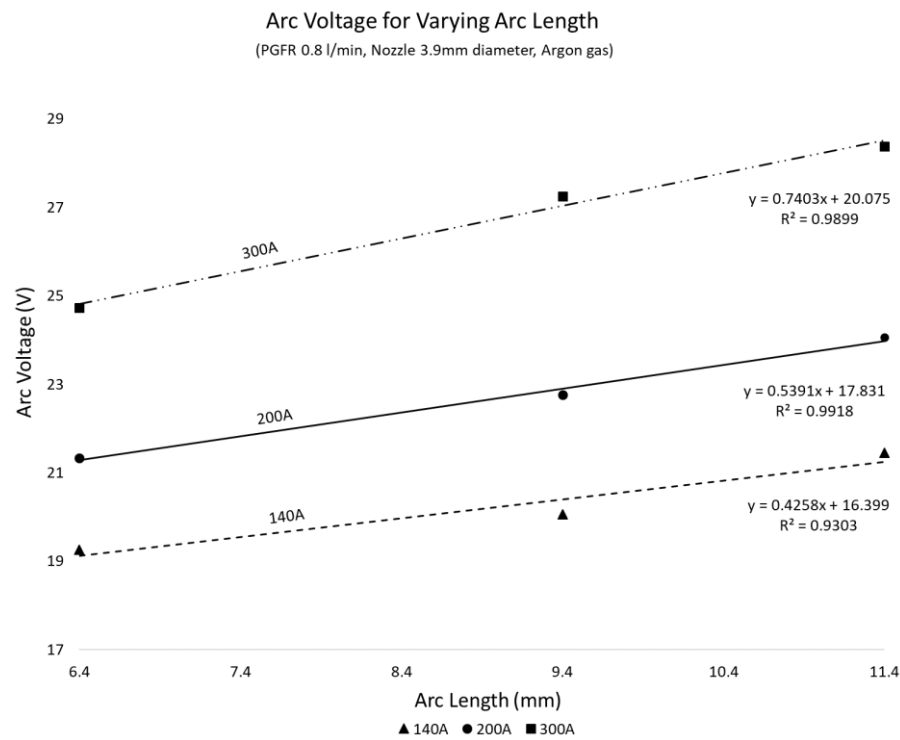


Figure 120 PTA 3.9 mm nozzle arc voltage for varying arc length.

The arc voltage/arc current relationship for DC PTA electrode negative is shown in Figure 121 for three arc lengths. The trends are linear, with the voltage increasing with current. The slope of arc voltage/current trends is representative of the overall resistance of the arc column: electrical resistance increasing with arc length.

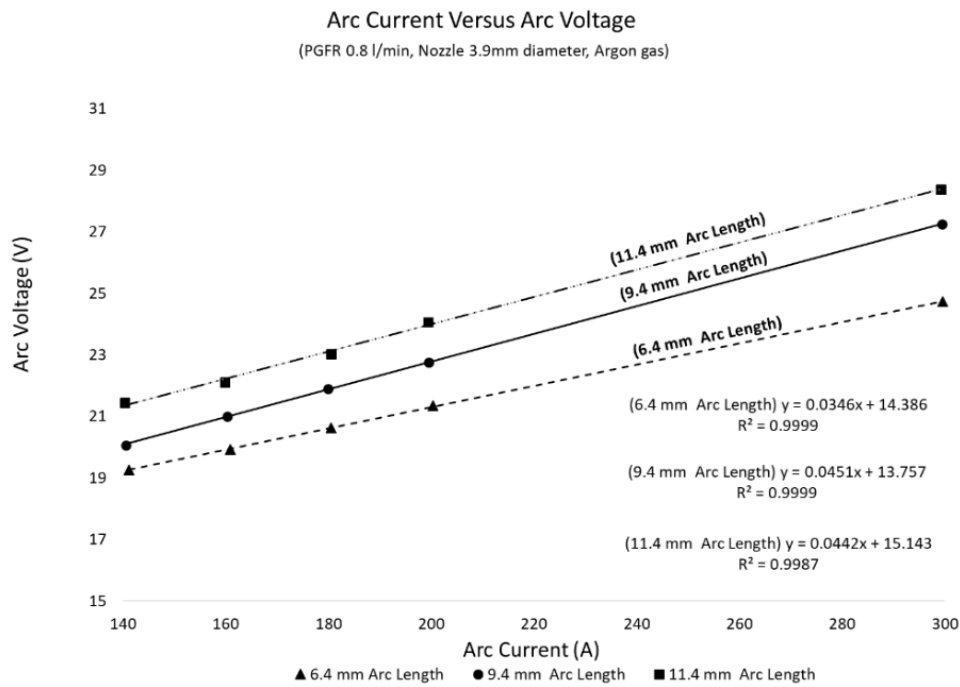


Figure 121 Arc voltage versus current for PTA at three arc lengths.

By combining the PTA peak pressure plot of Figure 80 and the arc voltage plot of Figure 120, Figure 122 was generated, which shows the PTA measured arc pressure decreasing with voltage for a straight-bore 3.9 mm nozzle for three currents. The arc pressure was varied by adjusting the arc length. The three trends are linear and show that arc pressure decreases with arc voltage. This is contrary to the trends of arc pressure versus arc voltage where the arc pressure was varied by current and PGFR.

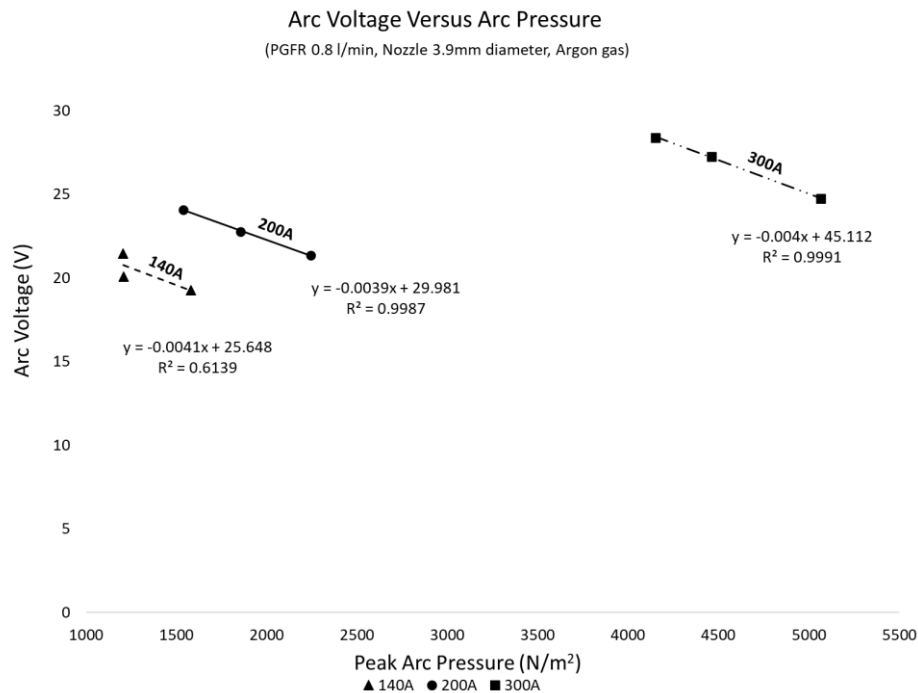


Figure 122 PTA arc voltage versus arc pressure of a straight-bore 3.9 mm nozzle, with arc pressure varied by arc length.

Figure 123 shows the arc voltage for the different plasma gas compositions, with voltage rising with the increase in the percentage of helium and a decrease in the percentage of argon. However, the increase is in line with the increase in electrical resistance, reduced electrical conductivity and reduced potential for ionisation of helium, and the trend lines are similar to the helium/argon voltage trends found in the original 1957 PTA torch patent validation data (Gage, 1957). The rise of arc voltage with reducing arc pressure is contrary to other parameter voltage results, with the exception of arc length.

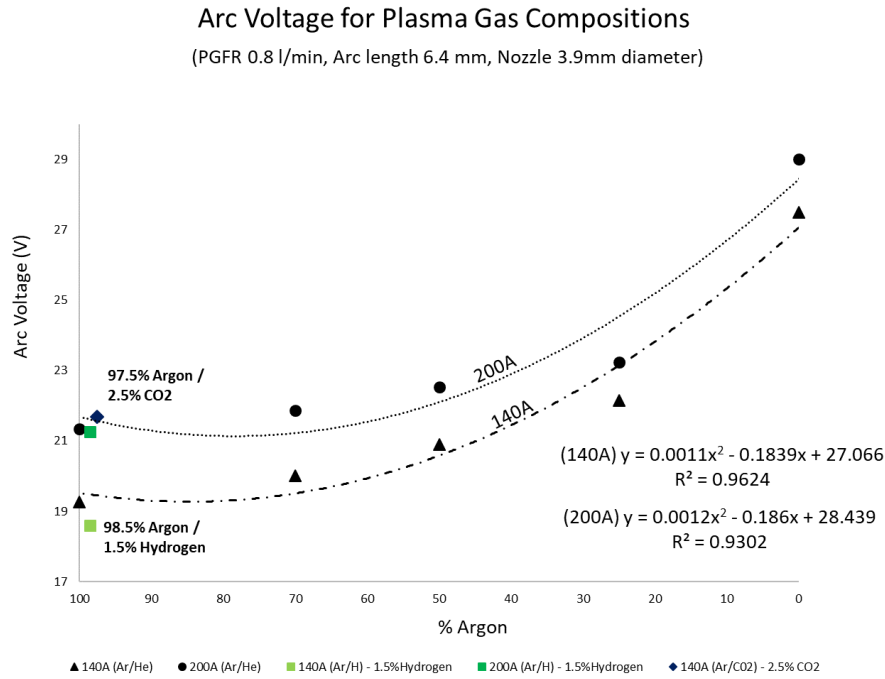


Figure 123 Effect of plasma gas composition on arc voltage, with percentage argon shown – the remainder is helium unless otherwise stated.

The voltage rise with percentage helium is well known (Tanaka et al., 2008; Marinelli et al., 2019) and results from higher electrical resistivity, lower electrical conductivity (Figure 36 ‘B’) and, predominantly, the higher ionisation potential of helium compared with argon (Lancaster, 1987; Tanaka et al., 2008).

4.4 Discussion

The PTA arc voltage distribution across the smaller diverging arc is shown in Figure 124, along with GTA for comparison, with an addition of the ‘arc constriction drop’ zone.

Changes to PTA electrode material alter the ability for electron release and therefore affect the ‘cathode fall voltage’. In addition, changes to substrate material affect the ‘anode fall voltage’, shown in Figure 127. Subsequently, changes to either or both materials have a small effect on the total arc voltage.

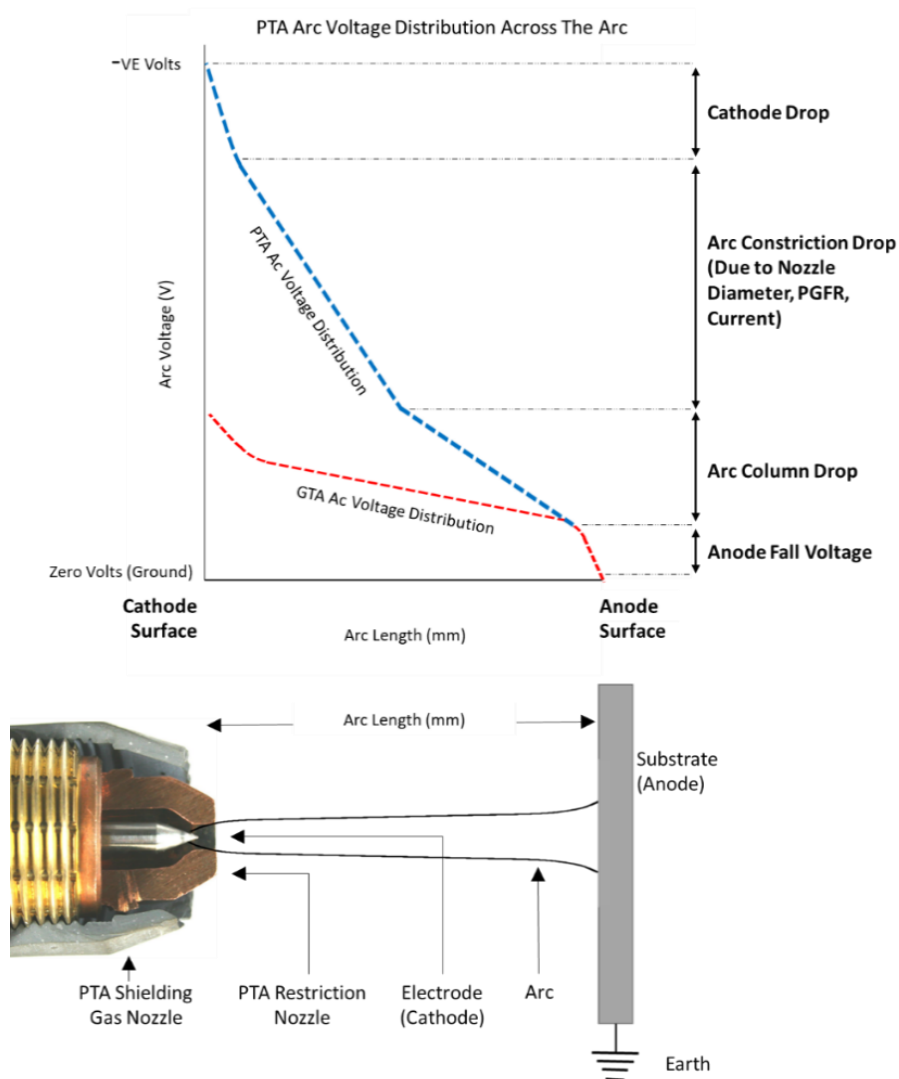


Figure 124 PTA arc voltage distribution across the narrow arc. Electrode negative polarity. Top] Plot of PTA voltage distribution and GTA for comparison, Bottom] PTA arc arrangement. Based on images from PWP Welding Basics – Plasma Welding Basics 2, Richardson, 1991 and Lancaster, 1984.

The ‘arc constriction drop’ increases with PTA arc constriction and has a significant effect on the total arc voltage, shown in Figure 124. PTA parameters and variables that affect arc constriction include:

- Increasing current and consequently the induced electromagnetic arc constriction.
- Reducing nozzle diameter.
- Increasing PGFR.
- Increasing nozzle straight length.
- Reducing the diffuser length of angled nozzles.

As a result of the straighter, narrower restricted PTA arc, the downward slope of the ‘arc column drop’ has an increased rate of change than GTA. As the cathode, shown in Figure 124, moves towards the anode, the shorter the arc length, like GTA, that results in a lower arc voltage.

The PTA arc constricting parameters, which have been shown by this study to increase arc pressure, also increase the ‘arc constriction drop’, shown in Figure 124, and consequently the arc voltage. Arc length, on the contrary, has been shown to reduce arc pressure because of arc divergence, changes to velocity and increased arc voltage. An explanation of this independent effect of arc length is given in Figure 124, where arc length does not affect a drop/fall zone but their span of influence.

The power source is designed to compensate for changes in arc voltage resulting from arc length changes by adjusting the current – thereby maintaining constant power (Figure 125).

As a result of the power supply characteristics, as the arc length is changed, and the arc voltage changes accordingly, a small change also therefore takes place in the arc current to maintain constant power, shown in Figure 125.

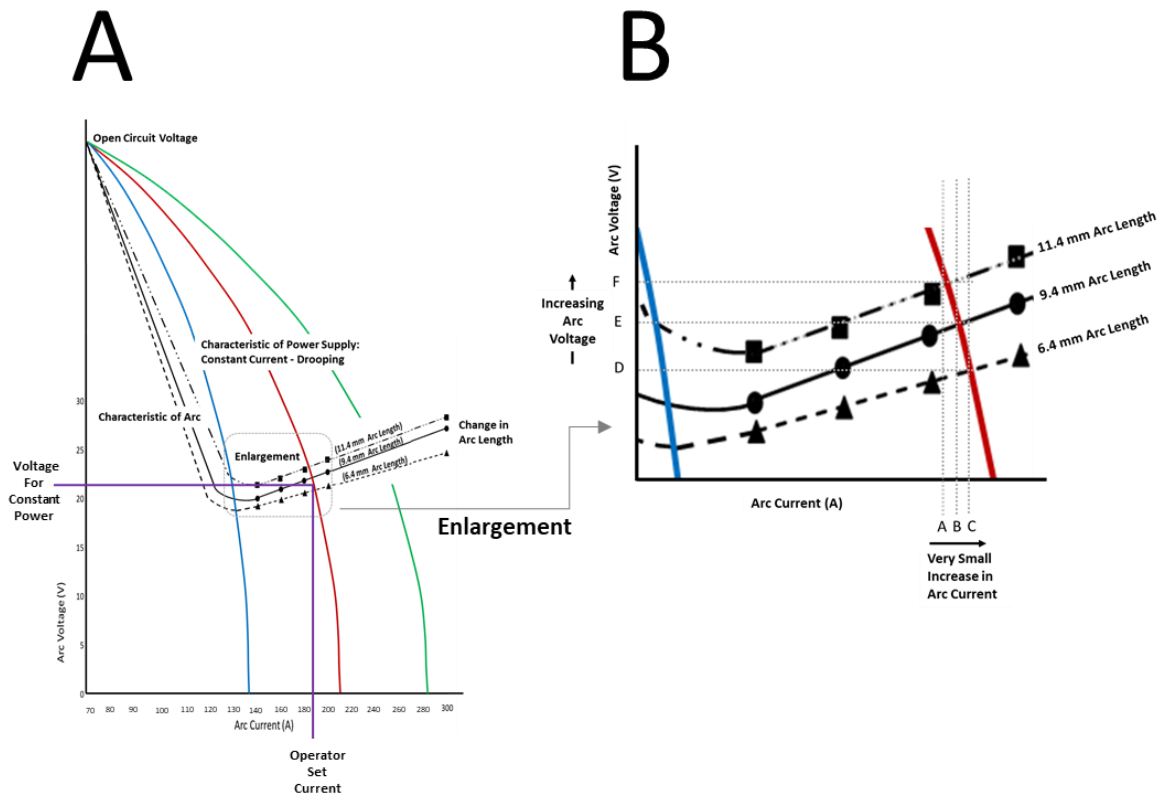


Figure 125 A] PTA Power source characteristic plot: constant power – drooping, with the measured volt/current trends overlaid. B] Enlargement of ‘A’. Based on images from O’Brien, 1991 and Mathers, no date.

4.5 Conclusion

An unexpected and potentially beneficial finding of the study is that the linear trends and the relationship between measured arc voltage and measured peak arc pressure for each parameter combination see arc voltage increasing with peak arc pressure. This correlation could be utilised to allow real-time indication and monitoring of arc pressure changes during WAAM operations through arc voltage measurement, using readily available arc voltage data logging equipment. Figure 126 is a collation of arc voltage/pressure results to illustrate the arc voltage versus PTA arc pressure relationship. It indicates a linear trend of increasing arc voltage with rising arc pressure, with the exception of arc length, where arc voltage decreases with arc pressure, as mentioned previously.

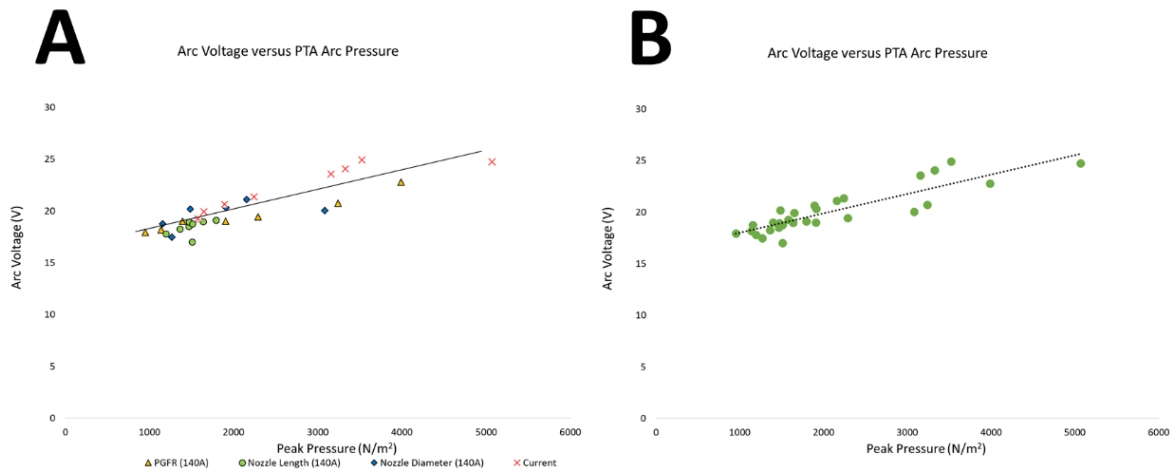


Figure 126 Arc voltage versus PTA arc pressure. A] Measured arc voltage at 140 A for parameters of PGFR, nozzle length, nozzle diameter and current. B] Same results as ‘A’ combined for clarity.

This relationship suggests that arc pressure could be indirectly measured via existing/ongoing arc voltage measurements. It is proposed that real-time monitoring of changes to arc pressure is possible for a fixed arc length through arc voltage measurement, enabling operator notification and consequently timely intervention to unplanned increases of arc pressure before the WAAM process suffers detrimental issues or challenges. This represents a possible means of real-time keyhole defect avoidance and is an indication of peak arc pressure during WAAM operations. However, this method only functions if the arc length remains constant.

Figure 127 illustrates the change in measured arc voltage and consequently arc power for fixed parameters by changing the substrate material. Three materials were investigated: copper, used for the arc pressure measurement in Chapter 3, stainless-steel and titanium, both used for the keyhole study in Chapter 5. All three trends show a linear increase, with the current, copper having the highest values and titanium the lowest values.

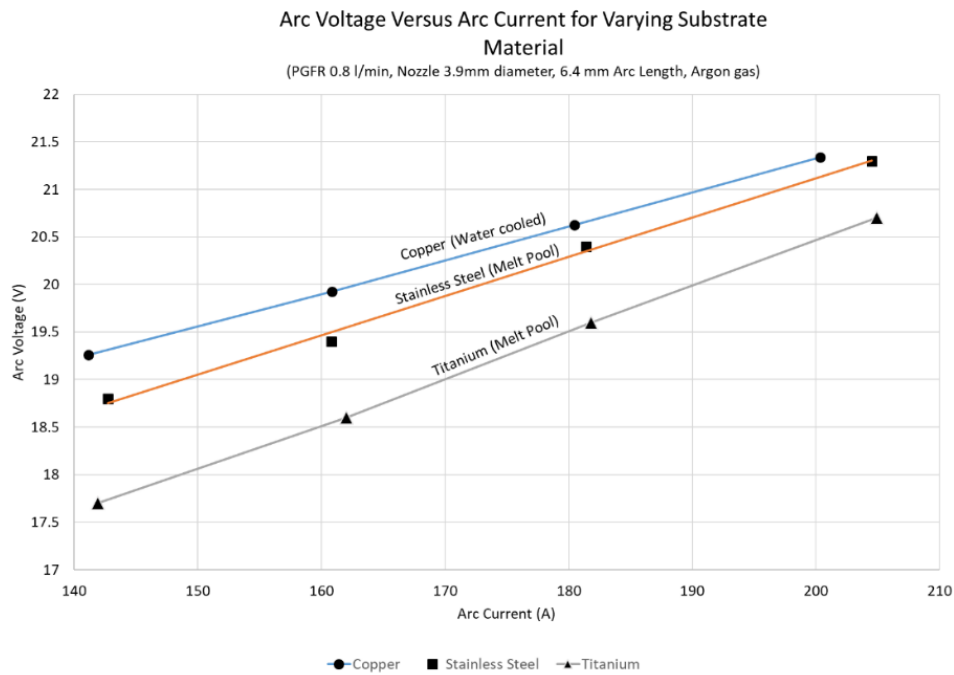


Figure 127 Effect of substrate material on arc voltage for varying currents.

All parameters that did not affect either the length or composition of the arc meant that the arc voltage behaved in an analogous way to the arc pressure. For a fixed arc length and gas composition, arc voltage can therefore be used as a direct indicator of arc pressure. This can then be used to monitor the WAAM process and warn if the arc pressure becomes too high, with the possibility of keyhole defects forming. This system must be calibrated for different materials, as shown in Figure 127.

Chapter 5

Keyhole Formation in WAAM and the Role of Arc Pressure

5.1 Introduction

Keyhole formation in WAAM is highly undesirable, nearly always leading to a defect and unacceptable properties for the component. It is therefore necessary to understand the formation of the keyhole and what controls it. This study aimed to understand the mechanism of keyhole defect formation in WAAM and what factors affect this. It was postulated that there would be a threshold arc pressure for the formation, which depended primarily on arc pressure independently of how the arc pressure was generated. Furthermore, it was expected that the actual value of the arc pressure needed to initiate the keyhole would depend on material properties and the thermal conditions in the melt-pool, which are controlled principally by heat input and travel speed. To enable this study, the results from previous studies of process parameters and torch geometry, set out in Chapter 3, were developed into an empirical model. This model was then used to allow precise control of the arc pressure under a range of conditions so that a systematic study of keyhole formation under a range of conditions could be made.

This chapter comprises three parts, as shown below:

- To enable arc pressure prediction, an empirical model of the arc pressure data generated in Chapter 3 was developed using statistical analysis of variance (ANOVA).
- To predict when keyhole defect formation is likely during WAAM using the empirical model of arc pressure, an investigation into the effects of arc pressure on titanium and stainless-steel keyhole defect formation and the effects of heat input, travel speed and plate thickness on keyhole defect formation was undertaken.
- A validation study of this approach to predicting keyhole defect formation was also undertaken.

5.2 Arc Pressure Empirical Model

The data within Chapter 3 was examined statistically using the analysis of variance (ANOVA) approach. See Appendix H for a definition of ANOVA.

The arc pressure data measured was incorporated into the ANOVA and an empirical model produced Equation 12 and Table 23. The arc pressure model was derived as part of the ANOVA analysis, in terms of model actual factors of the inputted experimental data, and was refined through the model fit process.

Arc Pressure (Pa) =

$$3433.823 + (6.703 \times I) - (1.58007E+5 \times A_L) - (7.55919E+5 \times N_D) - (7.94052E+7 \times P_{GFR}) + (6.08596E+5 \times E_{SB}) + (7.67809E+5 \times I \times P_{GFR})$$

Where:

Equation 12

I = Current (A)
A_L = Arc Length (m)
N_D = Nozzle Diameter (m)
P_{GFR} = Plasma Gas Flow-rate (m³/sec)
E_{SB} = Electrode Setback (m)

The model, with 6 degrees of freedom, has a model F-value of 248.96, indicating that the model is significant and that there is only a 0.01% chance that the results are because of noise. The P-value of less than 0.0001 indicates that the six factors are all significant and that it is unlikely that the differences observed result from random variations.

Table 23 ANOVA analysis for response: arc pressure

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	P-Value
Model	2.328E+08	6	3.880E+07	248.96	< 0.0001
A-Current	8.024E+07	1	8.024E+07	514.86	< 0.0001
B-Arc Length	5.356E+06	1	5.356E+06	34.37	< 0.0001
C-Nozzle Diameter	9.903E+06	1	9.903E+06	63.55	< 0.0001
D-PGFR	1.016E+08	1	1.016E+08	651.63	< 0.0001
E-E _{SB}	7.565E+06	1	7.565E+06	48.54	< 0.0001
AD	3.073E+07	1	3.073E+07	197.18	< 0.0001

Table 24 Model fit statistics

Standard Deviation	394.78	R²	0.9384
Mean	2691.17	Adjusted R²	0.9347
C.V. %	14.67	Predicted R²	0.9249
		Adequate Precision	85.0565

The test of fit of the statistical model with the experimental measured data is shown in Table 24.

The term **R²**, coefficient of determination, is a statistical measure representing the proportion of the variance/variability for a dependent variable that can be explained by the model (Montgomery, 2013). The model **R²** value of 93% indicates that this percentage of variance can be explained by the derived model.

Adjusted R² is utilised to make allowances for the effect of the **R²** value increasing as additional variables to the model are added.

Predicted R² is a measure of the quality of the ability of the model to predict new data; in this case over 92%.

The **Predicted R²** and **Adjusted R²** have a difference of less than 0.2, and are therefore in agreement. The **Adequate Precision**, which is the measure of signal to noise ratio, is 85 and therefore much higher than the minimum value of four, indicating an adequate signal.

The model statistical tests therefore indicate a satisfactory model with significant factors, which can predict with reasonable accuracy arc pressure values from the experimentally measured data within the model data boundaries. Figure 128 illustrates the model's predicted peak arc pressures versus the actual measured values.

Design-Expert Software PTA Arc Pressure Model

Point colour code by value of Arc Pressure



Lowest measured peak pressure: 528.108 (N/m²)

Highest measured peak pressure: 8612.19 (N/m²)

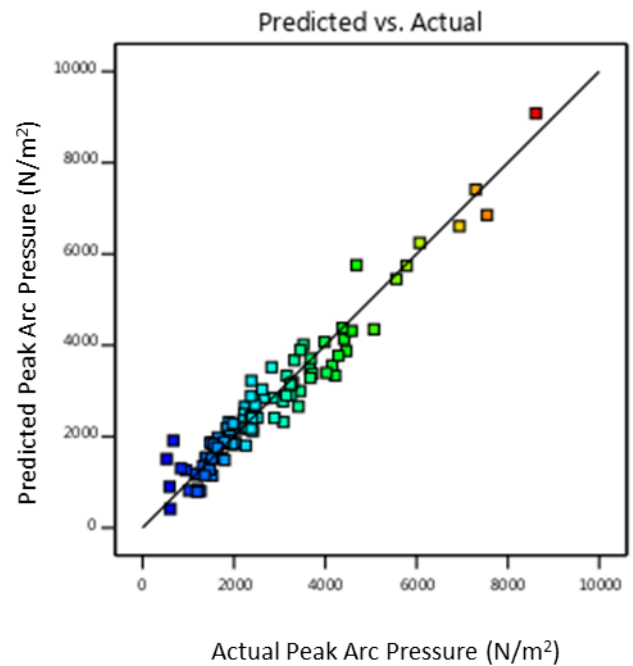


Figure 128 Model arc pressure prediction comparison. The closer the point to the line, the smaller the difference between actual measured value and a model predicted value for the same parameters.

5.2.1 Model Data Boundaries

The limits of the data put into the model results in model boundaries. Figure 129 illustrates the input data boundaries for arc length, PGFR, nozzle diameter and current.

Figure 129 input data model boundary parameter constants:

- A] Arc length: PGFR 0.8 l/min, nozzle diameter 3.9 mm.
- B] PGFR: nozzle diameter 3.9 mm, arc length 6.4 mm.
- C] Nozzle diameter: PGFR 0.8 l/min, arc length 6.4 mm.

Outside these boundaries, model predictions are made by extrapolation – inferring unknown values from trends in the known data, which may lead to an increase in prediction error.

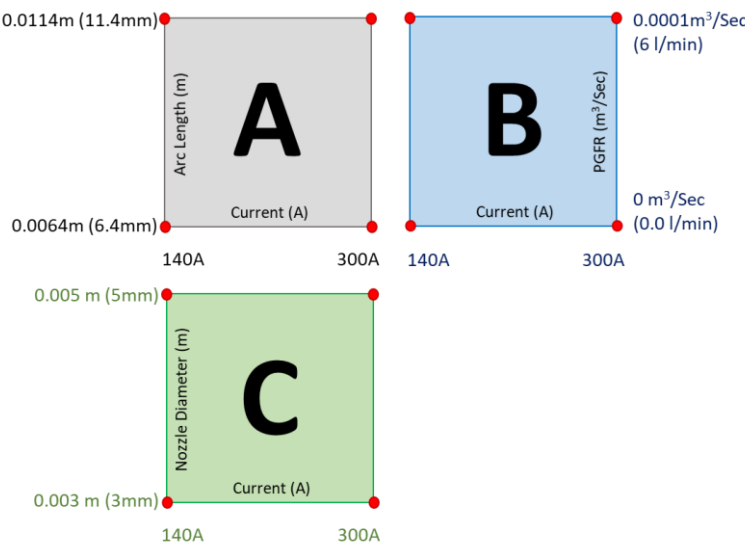


Figure 129 Input data model boundaries: A) Arc length, B) PGFR, C) Nozzle diameter.

5.2.2 Model Plots

Examples of the relationships between the parameters are shown in 3D surface and contour plots in Figure 130 to Figure 132. The colour coding is based around the highest and lowest experimentally measured values – 8612.19 and 528.108 N/m²: red and blue respectively.

The 3D surface plot of current and PGFR versus arc pressure, shown in Figure 130, is in line with the results set out in Chapter 3.

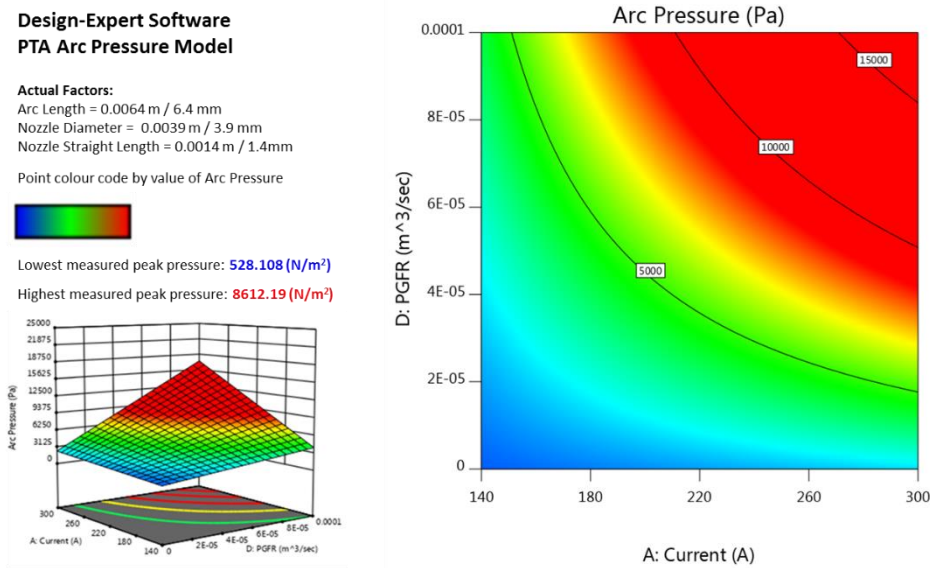


Figure 130 Model 3D surface (left) and contour plot (right): current versus PGFR. Values in SI units.

The 3D surface plot of current and arc length versus arc pressure, shown in Figure 131, is in line with the results in Chapter 3.

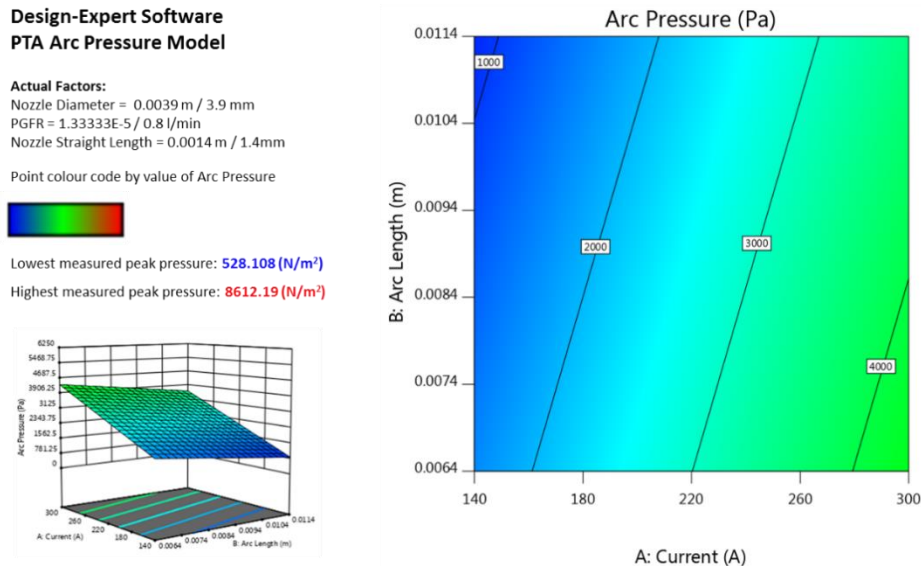


Figure 131 Model 3D surface (left) and contour plot (right): current versus arc length. Values in SI units.

The 3D surface plot of current and nozzle diameter versus arc pressure, shown in Figure 132, is in line with the results in Chapter 3.

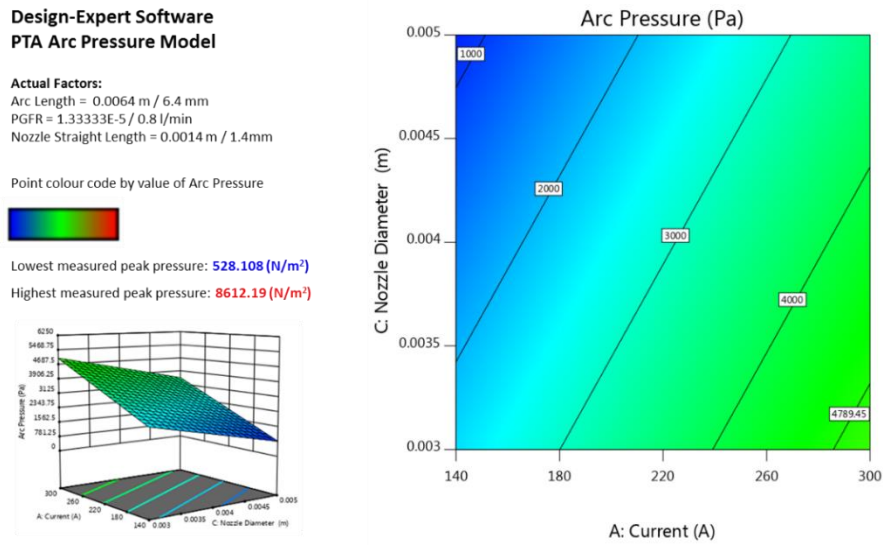


Figure 132 Model 3D surface (left) and contour plot (right): current versus nozzle diameter. Values in SI units.

5.2.3 Model Validation

To validate the arc pressure model, 13 independent experimental measurements were undertaken, utilising randomly selected parameters (model factors), shown in Table 25. Each measurement was undertaken three times to check repeatability, and an average was calculated. The values were incorporated into the existing experimental data plots to check their status as acceptable measurements. All were found to fit with existing measurement trends.

Table 25 Model validation test parameters.

Test No.	1	2	3	4	5	6	7	8	9	A	B	C	D
Current (A)	210	220	190	140	140	140	200	200	190	210	140	160	210
PGFR (l/min)	0.8	0.8	0.8	2.2	5	3	3	5	0.8	2.2	1.4	2	2.2
Nozzle Diameter (mm)	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.4	3.9	3.9	3.2	3.9
Arc Length (mm)	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	9.4	9.4	5.3	4.5	6.4
ESB	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.6	1.4	1.4
Constants: shielding gas 15 l/min, gas composition 100% argon.													

Utilising Equation 12 for the same model factors, predicted arc pressure values were calculated. Calculated and measured values were compared and % error calculated to gauge the accuracy of the model and equation.

As a result of randomly selecting parameters, nine of the experimental measurements were found to be within the original model input data boundaries, with four outside the boundary.

As shown in Figure 133, the model and equation generated points within the model boundaries are reasonably comparable to experimental data points for the same parameters: as low as 0.35% error in one case. Outside the model boundary, the percentage error is as high as 26.7%, though the model can be improved, and the boundaries redefined by adding all the new experimentally measured data to the original model input data.

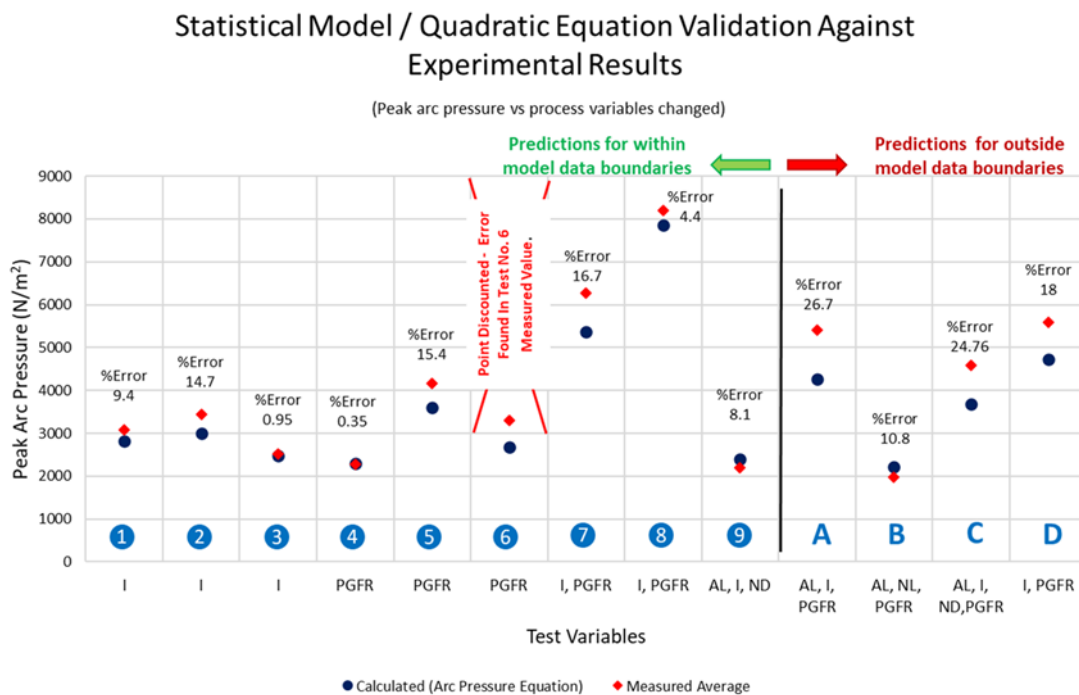


Figure 133 Arc pressure empirical model/equation validation: experimental measurements compared against model predicted values. Percentage error is shown. Data points outside the original model input data boundaries are shown to the right. Test no. shown in blue.

Following this investigation, it was concluded that the model is statistically significant and that it can be used to predict arc pressure as a function of all the variables investigated.

5.3 Effect of Arc Pressure on Keyhole Formation

The objective of this study is to determine if there is a distinct threshold for keyhole defect formation and to establish if this is primarily controlled by arc pressure. The arc pressure was therefore varied by changing different parameters to establish if the threshold was independent of how the arc pressure was varied. This study was undertaken for two materials, shown in Table 26, and different thermal conditions in the melt-pool.

Table 26 Physical characteristics of titanium (TI 6AL-4V Grade 5) and stainless-steel (15-5 PH). (ASM International, 2009; Wunderlich, 2008; AK Steel, 2014; Boyer and Gall, 1985; Li et al., 2005)

Physical Characteristic	Titanium (TI 6AL-4V Grade 5)	Stainless-Steel (15-5 PH)
Density (kg/m ³)	4430	7780
Electrical Resistance ($\mu\text{ohm.cm}$)	168–174	98
Melting Point (°C)	1600–1680	1405–1440
Specific Heat Capacity (J/kg. K)	563–588	460
Surface Tension (N/m)	1.52 @1655°C	1.5 (Note 1)
Thermal Conductivity (W/m. K)	6.54–6.87	17.8 @149°C
Dynamic Viscosity (mPa s)	4.76	6 (Note 2)
Kinematic Viscosity (m ² /s) (Note 3)	1.074×10^{-6}	7.712×10^{-7}
Temperature Coefficient of Surface Tension (N/(m K))	-0.26×10^{-3}	-0.43×10^{-3}
Calculated Thermal Diffusivity (m ² s ⁻¹) (Note 4)	$2.622 \times 10^{-6} - 2.637 \times 10^{-6}$	4.974×10^{-6}

Note 1. A value for stainless-steel (15–5 PH) surface tension could not be found, so it was calculated using a formula from Li et al. (2005).

Note 2. A value for stainless-steel (15–5 PH) dynamic viscosity could not be found, so a general value for stainless-steel is shown.

Note 3. Kinematic viscosity was calculated from the dynamic viscosity and density shown in the table.

Note 4. Thermal diffusivity calculated using data from Table 26 and Equation 3.

Note 5. Temperature stated where available.

5.3.1 Methodology

An overview of the experimental setup is shown in the schematic of Figure 134 and consisted of a PTA torch, power supply with auxiliary coolant, gas and process control, gas supply, process measurement equipment and integrated CNC torch positioning, housed within an argon (99.998%) filled ($O_2 < 100$ ppm) enclosure (glovebox), shown in Figure 135.

Before use, the stainless-steel and titanium plates were finished with dedicated pads and cleaned with acetone to ensure they were contaminant free.

For information on measurement difficulties and errors, refer to Appendix C.

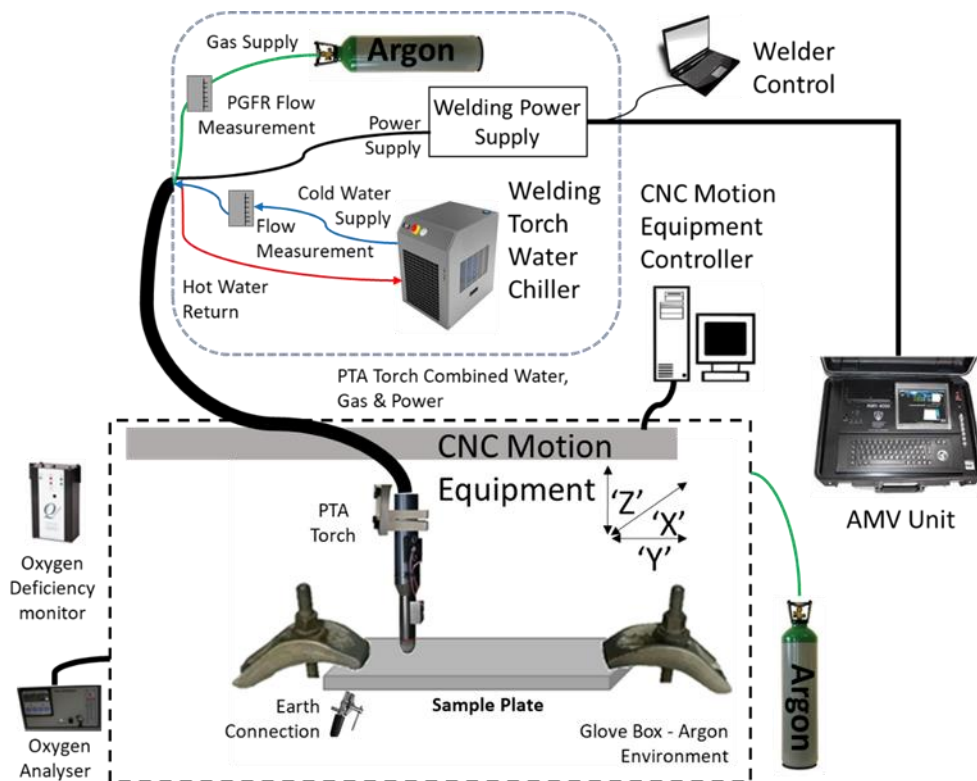


Figure 134 Keyhole experiment equipment setup schematic.

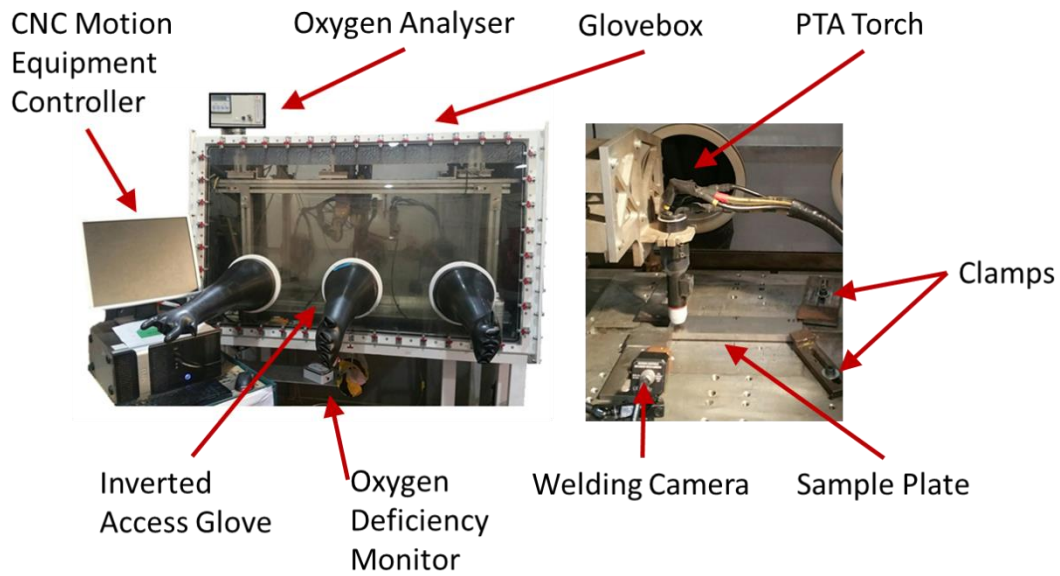


Figure 135 Argon-filled glovebox exterior (left), inside glovebox (right) and sample plate clamping arrangement.

The arc voltage and current were recorded via an AMV 4000, and the process was monitored using a welding camera. The process parameters and equipment settings are listed in Table 27.

Table 27 Process parameters and equipment settings – PTA keyhole study

Process Parameters and Equipment Settings	Values
PTA Keyhole Study Common	
Electrode Polarity	DCEN
Plate Material	Titanium (TI 6AL-4V Grade 5) and Stainless Steel (15-5 PH)
Plate Material and Dimensions (Length x Width x Height)	200 x 50 x 12 mm
Torch Angle To Substrate	90 ⁰
Shielding Gas Composition	99.998% Argon
Pressurised Glovebox Environment Gas Composition	Argon/O ₂ <100 PPM
Process Monitoring/Data logging Equipment	AMV 4000
Sample Rate of Data Logger	20,000 Samples Per Second – 20 kHz
Arc Length	6.4 mm (Note 1)
Nozzle Standoff Distance	5 mm (Note 1)
Straight-bore Nozzle Diameter	3.9 mm (unless otherwise stated)
Standard Electrode Angle	40 ⁰

Electrode Diameter	4.0 mm
Electrode Material	2% Thoriated Tungsten
Electrode Setback	1.4 mm
PTA Torch	PWP Viper MC (Water Cooled)
Shielding Gas Flow-rate	15 l/min
Plasma and Shielding Gas Composition	100% Argon
PTA Torch Coolant Flow-rate	3.1 l/min
PTA Torch Umbilical Cable Length	12.5 Foot / 3.81 m
DC 550A electrical power source supply	TecArc OptiArc Plasweld 400 AC DC HD (electrode negative - DCEN)

PTA Keyhole Study NO Wire-feed

Current	130 to 280 A
Heat Input	0.54, 0.64, 0.74 and 0.84 kJ/mm
Travel Speeds	1.95, 2.5, 3, 3.48, 3.5, 4, 5.3, 5.86, 6.49 and 7 mm/sec
PGFR	0.5 to 7.5 l/min

PTA Keyhole Study WITH Wire-feed

Current	160 and 180 A
Heat Input	0.54, and 0.64 kJ/mm
Travel Speeds	3.48 mm/sec
PGFR	3.5 to 4.5 l/min
Wire-feed Speed	1.8 & 4 m/min
Wire Material	Titanium
Wire Diameter	1.2 mm

Note 1 – A PTA ESB of 1.4 mm plus the PTA nozzle standoff distances equates to an arc length of 6.4 mm.

Effect of PTA Nozzle Diameter on Keyhole

To determine that arc pressure is the primary variable determining whether a keyhole defect will or will not form, the arc pressure was varied by changing the PTA nozzle diameter. All other work for this study was undertaken using a 3.9 mm nozzle diameter, but, for this part of the study, the nozzle diameter was reduced to 3 mm to achieve the same arc pressure as a 3.9 mm but at a lower PGFR.

A PTA torch with an arc length of 6.4 mm was passed over titanium plates with a nozzle diameter of 3.9 mm and no consumable wire to ascertain for each arc pressure value if keyhole defects resulted. Arc pressure was varied by changing the PGFR. For the fixed parameters and equipment settings, shown in Table 27, Table 28 and Figure 39, a heat input of 0.54 kJ/mm was calculated, utilising previously measured arc voltage data presented in Figure 136 and arc energy and heat input, as outlined in Equation 13 and Equation 14. For increasing values of PGFR, the corresponding arc pressure values were calculated utilising the derived empirical model.

Table 28 Effect of 3 mm PTA nozzle diameter on keyhole study specific process parameters and equipment settings.

Effect of 3 mm PTA nozzle diameter on keyhole study: specific process parameters and equipment settings in addition to Table 27.	
Process Parameters and Equipment Settings	Value
Nozzle Diameter (mm)	3.9 and 3
Current (A)	160
Travel Speed (mm/sec)	3.48

By repeating the outlined experiment with a nozzle diameter of 3 mm and a reduced PGFR, the same arc pressure values were achieved, and the relationships between arc pressure and keyhole defects, and PGFR and keyhole defects were compared.

Effect of Heat Input Study

For the fixed parameters and equipment settings, shown in Table 27 and Table 29, a heat input of 0.64 kJ/mm was calculated, utilising previously measured arc voltage data from Figure 136 and the arc energy and heat input, shown in Equation 13 and Equation 14. For increasing values of PGFR, the corresponding arc pressure values were calculated utilising the derived empirical model.

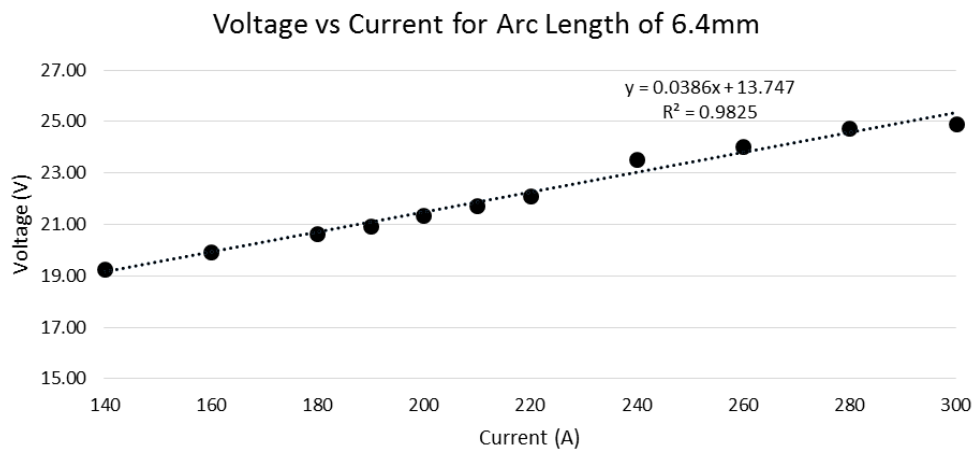
Table 29 Effect of heat input study specific process parameters and equipment settings.

Effect of heat input study specific process parameters and equipment settings in addition to Table 27.	
Process Parameters and Equipment Settings	Value
Nozzle Diameter (mm)	3.9
Current (A)	180
Travel Speed (mm/sec)	3.48

The PTA torch, with an arc length of 6.4 mm, was then passed over stainless-steel plates, without any filler wire. This was repeated at increasing values of arc pressure, obtained by changing the PGFR, until the no keyhole/keyhole transition pressures were identified.

This was repeated for the same travel speed but at three increasing values of heat input: 0.54, 0.74 and 0.84 kJ/mm and their corresponding currents of 160, 200, and 220 A respectively.

In this way, the no keyhole/keyhole transitions for multiple heat inputs were determined and a plot of heat input vs arc pressure generated. Consequently, the boundary for ‘keyhole/no keyhole’ was identified for stainless-steel for increasing values of heat input. This was repeated for titanium to ascertain the effect on different material.

**Figure 136 Plot of measured PTA arc voltage and current for an arc length of 6.4 mm.**

Using the following equations and the values from Figure 136, the heat input for different sets of parameters was calculated:

$$\text{Arc Energy: } A_E = \frac{60 \times V \times I}{1000 \times T_s} \quad \text{Equation 13}$$

$$\text{Heat Input: } H_I = \eta \times A_E \quad \text{Equation 14}$$

Where:

A_E = Arc Energy (kJ/mm)

V = Voltage (Volts)

I = Current (Amps)

T_s = Travel Speed (mm per minute)

H_I = Heat Input (kJ/mm)

η = Process Efficiency (0.6 for PTA process)

Effect of Travel Speed Study

For a constant heat input of 0.64 kJ/mm, values of current and voltage were therefore varied to maintain the heat input for different travel speeds: 1.95, 2.5, 3, 3.5, 4, 5.3, 5.86, 6.49 and 7 mm/sec.

Arc pressure was varied by changing the PGFR, and the corresponding arc pressure values were calculated utilising the derived empirical model.

The PTA torch, with an arc length of 6.4 mm, was then passed over stainless-steel plates without filler wire. This was repeated at increasing values of arc pressure, obtained by changing the PGFR, until the no keyhole/keyhole defect transition pressures were identified.

This technique was repeated for the same heat input but at the other travel speeds and their corresponding values of current and voltage. A plot of travel speed vs arc pressure was generated and, consequently, the boundary for ‘keyhole/no keyhole’ defect was identified for stainless-steel for increasing values of travel speed. This approach was repeated for titanium to ascertain the effect on different material.

Influence of Titanium Plate Thickness/Thermal Loss Effect on Keyhole Defects

The effect of thermal mass on the required arc pressure to initiate a keyhole defect was investigated. A PTA torch with an arc length of 6.4 mm was passed over titanium plates of different thickness (5.6, 9.5, 13.4 and 20.2 mm), with a nozzle diameter of 3.9 mm and no consumable wire, to ascertain for each arc pressure value if a keyhole defect resulted. Arc pressure was varied by changing the PGFR. For the fixed parameters and equipment settings, shown in Table 27 and Table 30, a heat input of 0.54 kJ/mm was calculated, utilising the previously measured arc voltage data in Figure 136 and the arc energy and heat input, shown in Equation 13 and Equation 14. For increasing values of PGFR, the corresponding arc pressure values were calculated utilising the derived empirical model.

Table 30 Influence of titanium plate thickness/thermal loss effect on keyhole defect specific process parameters and equipment settings.

Influence of titanium plate thickness/thermal loss effect on keyhole study specific process parameters & equipment settings in addition to Table 27.	
Process Parameters and Equipment Settings	Value
Nozzle Diameter (mm)	3.9
Current (A)	160
Travel Speed (mm/sec)	3.48

A plot of plate thickness vs arc pressure was generated and, consequently, the boundary for ‘keyhole/no keyhole’ defects was identified for titanium for increasing values of thickness.

Effect of Wire-feed on Keyhole Defects

A similar experimental setup and method, as outlined above and illustrated in Figure 134, was applied, but with the addition of consumable wire-feed to investigate its effect on the keyhole defect threshold. The process parameters and equipment settings are listed in Table 27. For information on measurement difficulties and errors, refer to Appendix C.

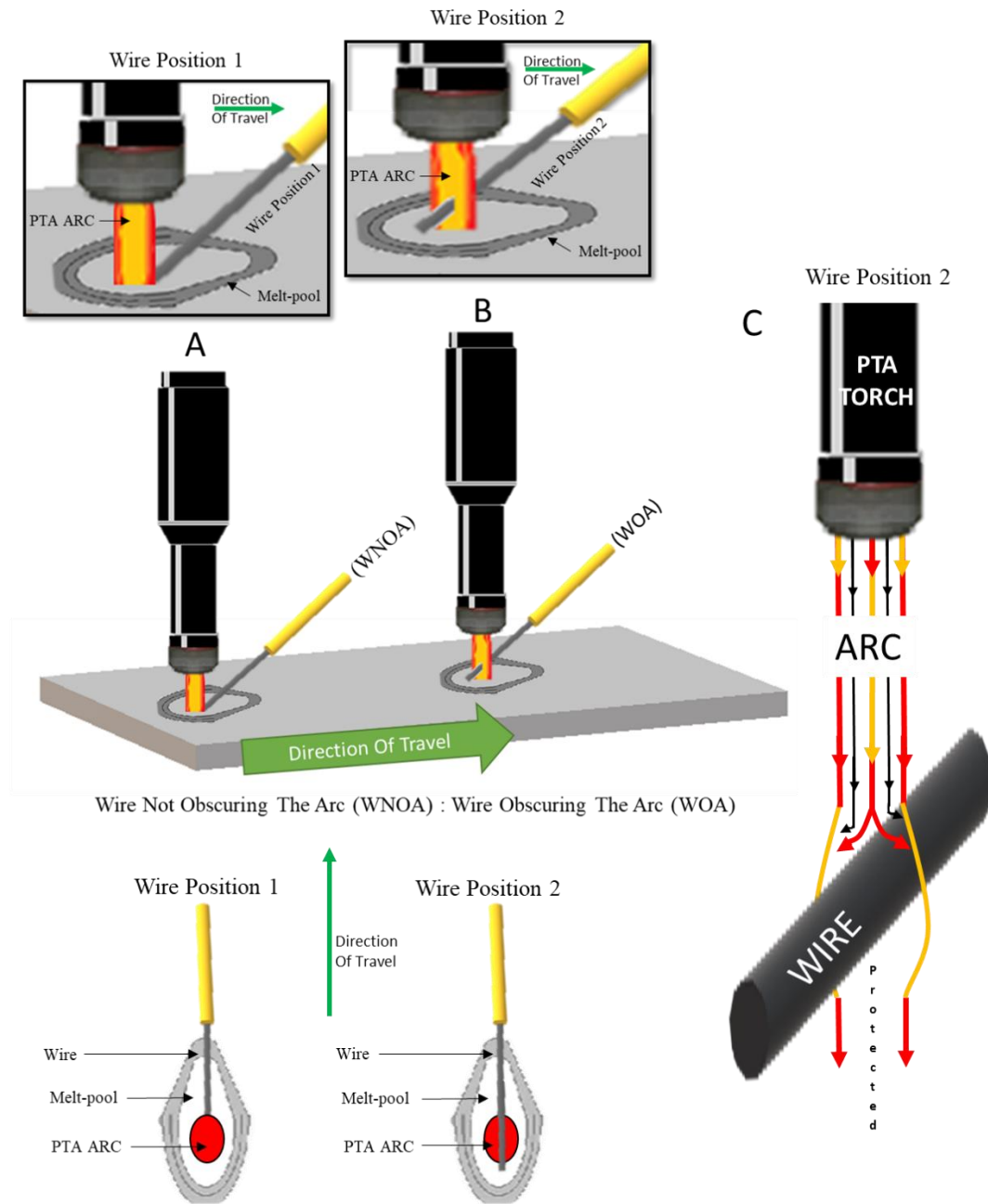


Figure 137 Front wire-feed position and direction. A] Wire to the side of the arc, B] Wire across the arc, C] Arc shielded region behind the wire.

For this investigation into the effect of wire-feed on keyhole defect formation and depth, a 1.2 mm diameter titanium wire was introduced, front feeding in two positions, as shown in Figure 137: wire position [1] directed at the near side of the PTA arc – wire not obscuring the arc (WNOA), shown in Figure 137 ‘A’, and wire position [2] directed at the opposite side of the melt-pool through the PTA arc – wire obscuring the arc (WOA),

shown in Figure 137 'B'. The WOA disrupts the arc and near laminar plasma gas flow, resulting in a pocket, as in Figure 137 'C', mostly free of downstream arc and flowing plasma gas that is likely to be unstable, turbulent flow on the downstream side of the wire. The photographs in Figure 138 also show the wire-feed positions in relation to the PTA arc.

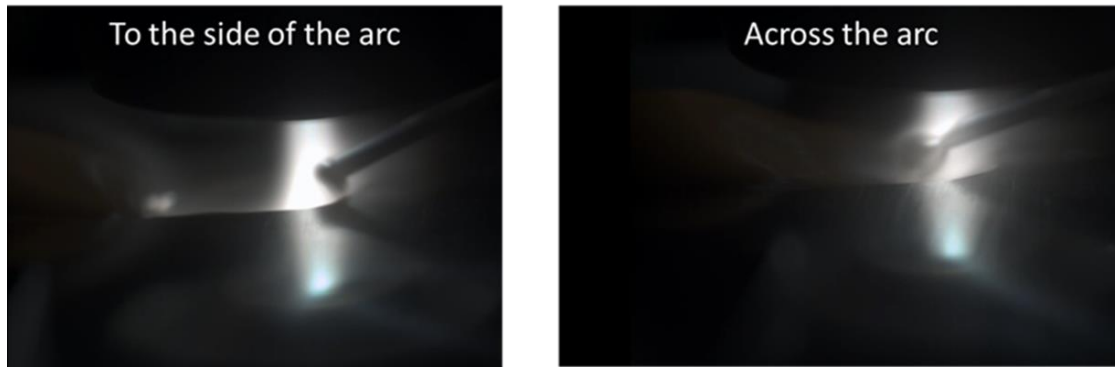


Figure 138 Consumable wire-feed position in relation to the PTA arc.

By obscuring the arc, the arc pressure and its effect on the melt-pool should be affected, as well as the keyhole defect.

For consistency, the arc length, current, travel speed and heat input were kept constant, shown in Table 27. To enable the change in wire-feed position in relation to the arc (Figure 138), in addition to changing the position and angle of the wire-feed nozzle, the wire-feed speed was also changed. By increasing the wire-feed speed from 1.8 m/min to 4 m/min, the wire could transition across the arc before melting, obscuring the arc.

On completion of one layer of deposition, measurements of bead-height and average keyhole defect depth, if applicable, were measured for comparison. The results were also compared with the previous autogenous keyhole results with the same parameters.

Measurement of Bead and Keyhole Geometry

To enable a comparison of deposited bead and keyhole defect geometry from the outlined experiments and their heat input, travel speed, plate thickness and wire position, the following measurements were undertaken and plotted for both stainless-steel and titanium:

- Keyhole defect depth.
- Deposited bead-height.
- Deposited bead-width.
- Visual inspection for undercut.
- Visual inspection of process video and still images.

To measure keyhole defect depth, a specialist calibrated height gauge with small diameter depth probe, fixed through the scriber arm measuring face, was utilised. Lengths were measured using a calibrated Vernier caliper.

For each measurement, the equipment was zeroed, with each measurement repeated three times and an average calculated and plotted. For information on measurement difficulties and errors, refer to Appendix C.

The shapes of different bead geometries were sectioned and photographed to categorise the effect of arc pressure on bead shape.

5.3.2 Results

5.3.2.1 Effect of 3 mm PTA Nozzle Diameter on Keyhole Defects – Titanium

Figure 139 illustrates the effect of nozzle diameter on keyhole defect formation by identifying the transition point between keyhole and no keyhole. For the 3 mm diameter nozzle, a reduced PGFR, 1.5 l/min, is required to produce a keyhole defect, compared with the 3.9 mm nozzle, with a PGFR of 4.5 l/min.

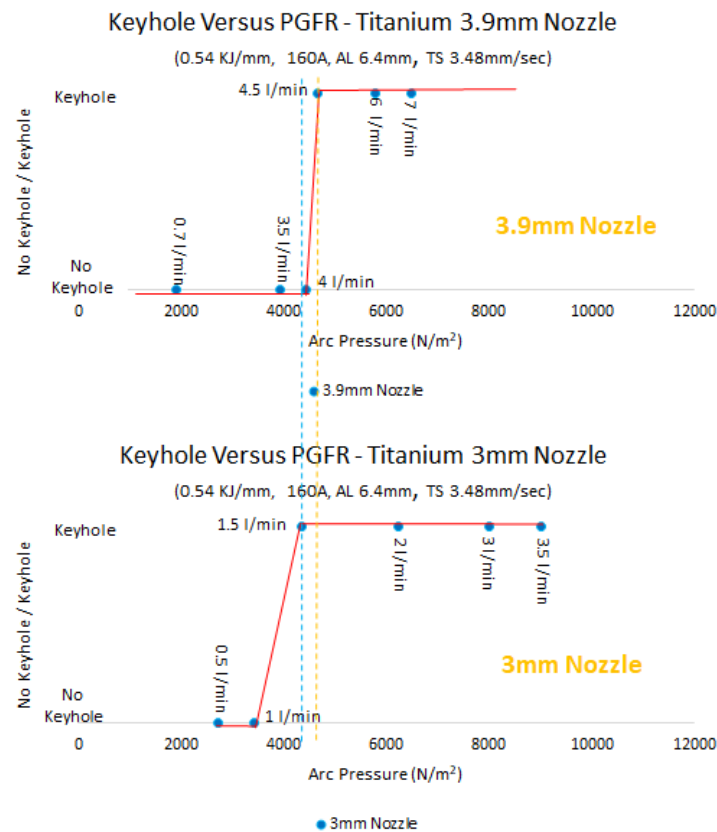


Figure 139 Titanium keyhole defect transitions for two nozzle diameters: 3 and 3.9 mm. All parameters and torch geometries constant. Dotted lines indicate the transition arc pressure for each nozzle diameter for comparison.

Figure 140 illustrates each of the arc pressure values of Figure 139 and the linear trends for both nozzle diameters.

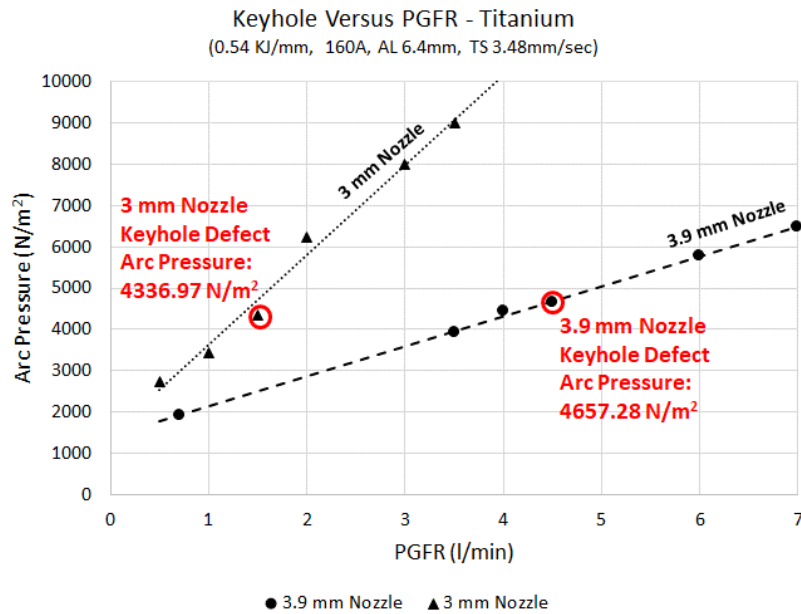


Figure 140 Peak arc pressure versus PGFR of titanium keyhole defect transitions in Figure 139. Two nozzle diameters: 3 and 3.9 mm. Keyhole defect arc pressure values indicated.

5.3.2.2 Effect of Heat Input on Keyhole Defects

Stainless-steel

To identify the transition point for stainless-steel between keyhole and no keyhole for four different heat inputs, numerous autogenous passes were undertaken at increasing values of arc pressure. Figure 141 indicates each attempt, and the transition, for each heat input determined.

Using the transition arc pressures from Figure 141, the effect of heat input on keyhole defect transition is shown in Figure 142 for stainless-steel material. The results indicate a linear relationship, and show that, to generate a keyhole defect, a higher arc pressure is required at higher heat inputs for parameter combinations of arc pressure and heat input:

- Below the linear ‘no keyhole’ trend line, no keyhole defect is generated.
- Above the linear ‘keyhole’ trend line, a keyhole defect is generated.
- Between the two trend lines is a boundary zone.

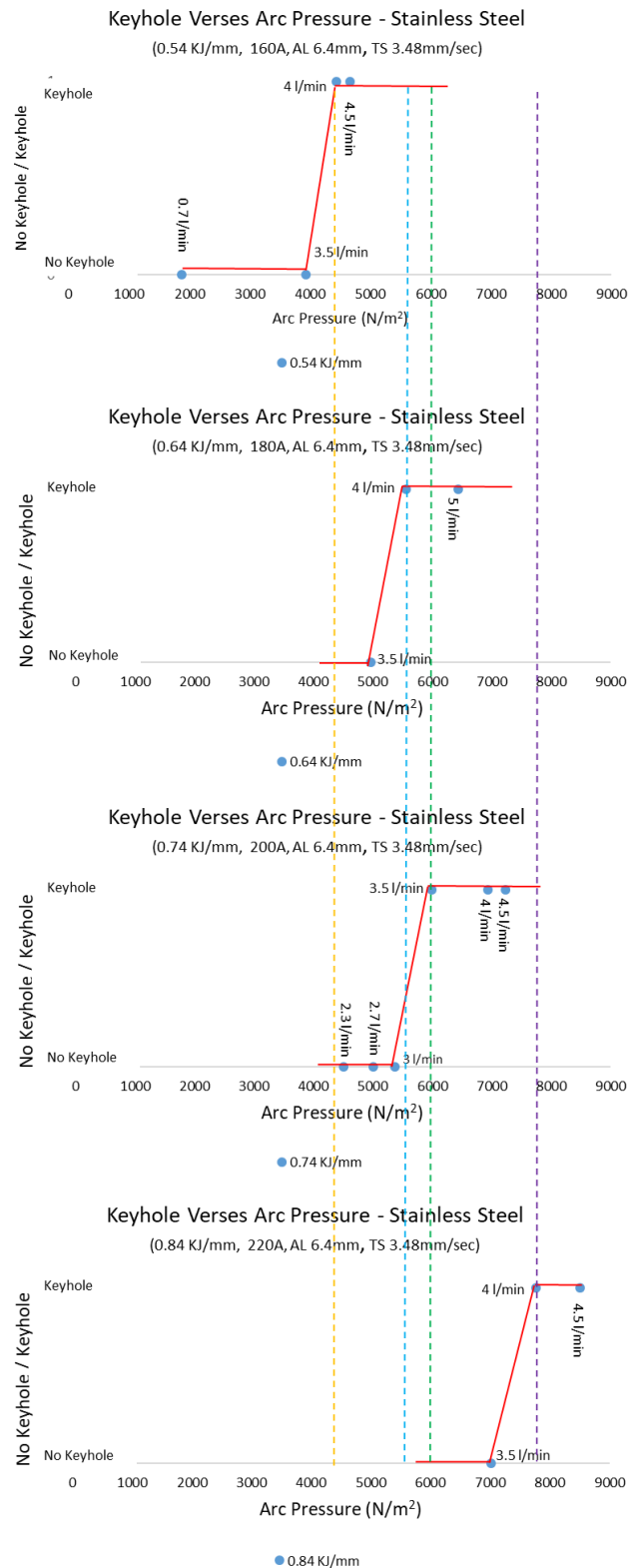


Figure 141 Stainless-steel keyhole defect transitions for four heat inputs: 0.54, 0.64, 0.74 and 0.84 kJ/mm. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for each heat input for comparison.

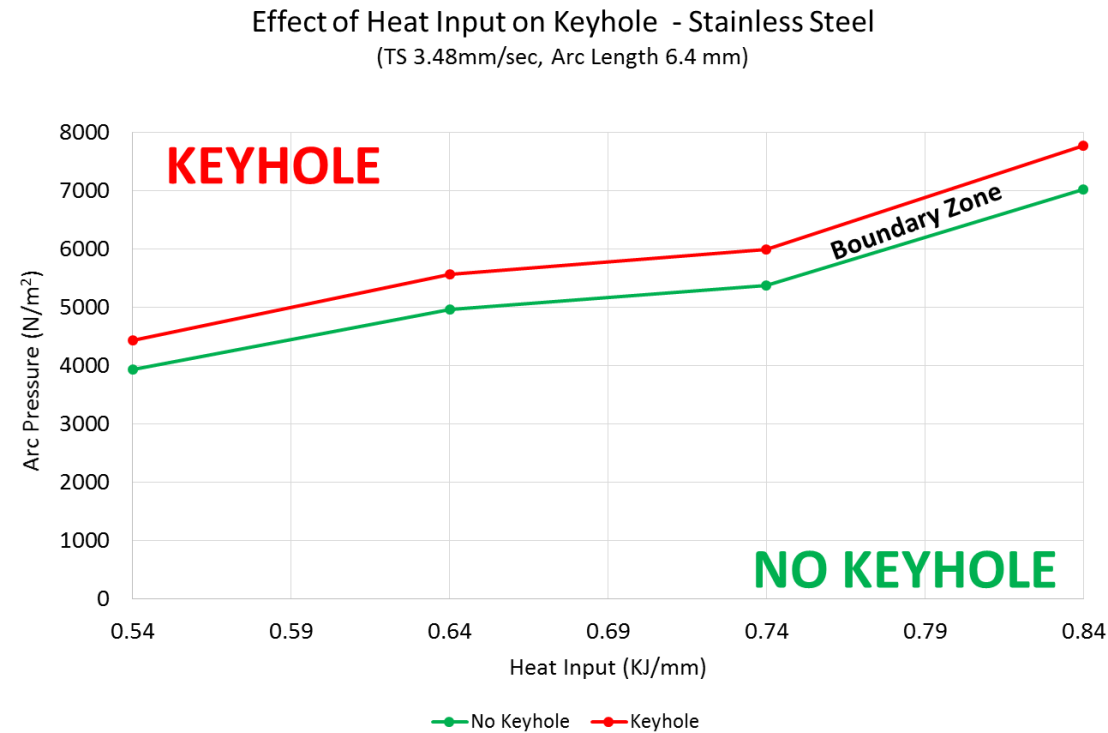
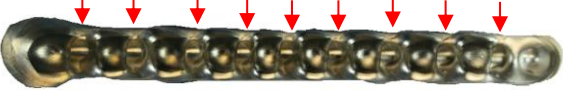
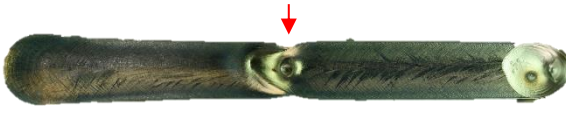


Figure 142 Effect of heat input on keyhole defect formation in stainless-steel plate material.

Images of the stainless-steel plates, the parameters for each heat input and the arc pressure applied are shown in Table 31. The effect of heat input on keyhole and the change in geometry of the keyhole with increased arc pressure are illustrated.

Table 31 Effect of heat input on keyhole defect study – stainless-steel depositions from each side of the boundary for each heat input: ‘no keyhole’ and ‘keyhole’. Keyhole defects indicated.

Heat Input	No keyhole /Keyhole	Images	Travel Speed	Current
0.54 kJ/mm	No keyhole	 PGFR 3.5 l/min, AP 3933.207 N/m ²	3.48 mm/sec	160 A
	Keyhole	 PGFR 4 l/min, AP 4431.077 N/m ²		

0.64 kJ/mm	No keyhole	 PGFR 3.5 l/min, AP 4963.038 N/m ²	3.48 mm/sec	180 A
	Keyhole	 PGFR 4 l/min, AP 5558.247 N/m ²		
0.74 kJ/mm	No keyhole	 PGFR 3 l/min, AP 5374.89 N/m ²	3.48 mm/sec	200 A
	Keyhole	 PGFR 3.5 l/min, AP 5992.8 N/m ²		
0.84 kJ/mm	No keyhole	 PGFR 3.5 l/min, AP 7022.700 N/m ²	3.48 mm/sec	220 A
	Keyhole	 PGFR 4 l/min, AP 7768.642 N/m ²		

Titanium

As per the stainless-steel results, using the transition arc pressures from Figure 143, the effect of heat input on keyhole defect transition is shown in Figure 144 for titanium material. The results are not linear, like stainless steel, with a peak at a heat input of 0.64 kJ/mm.

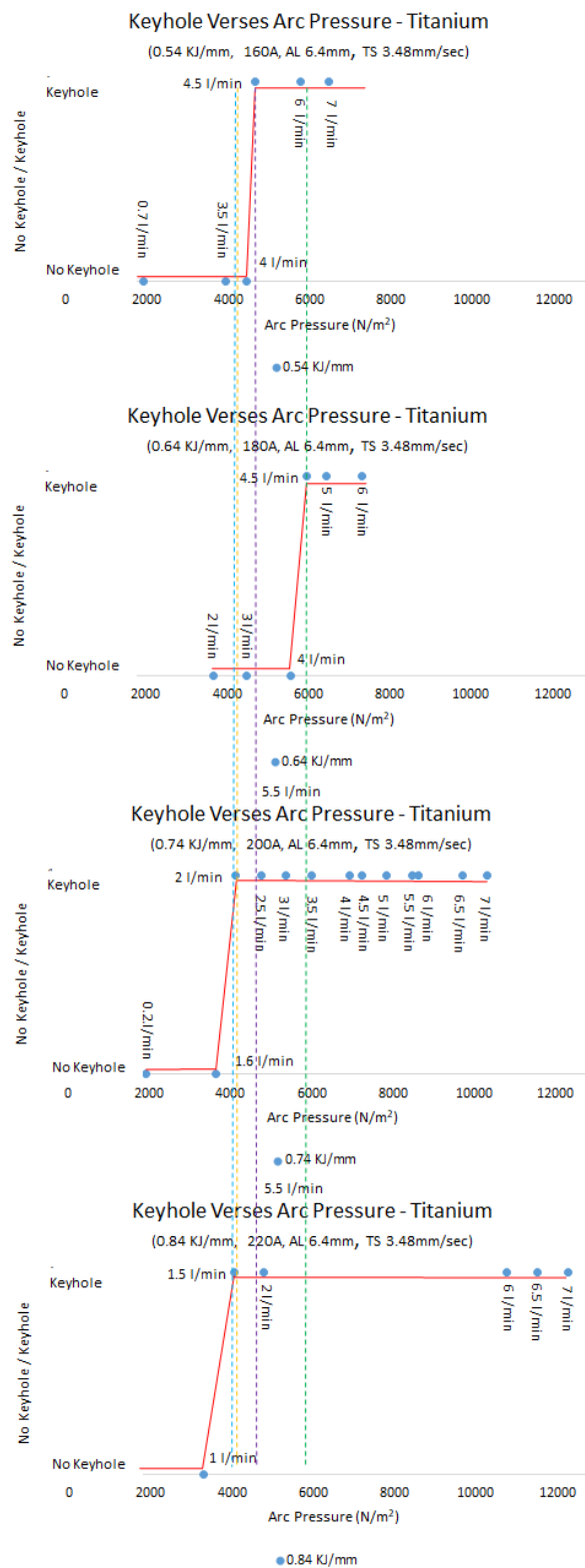


Figure 143 Titanium keyhole defect transitions for four heat inputs: 0.54, 0.64, 0.74 and 0.84 kJ/mm. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for each heat input, shown for comparison.

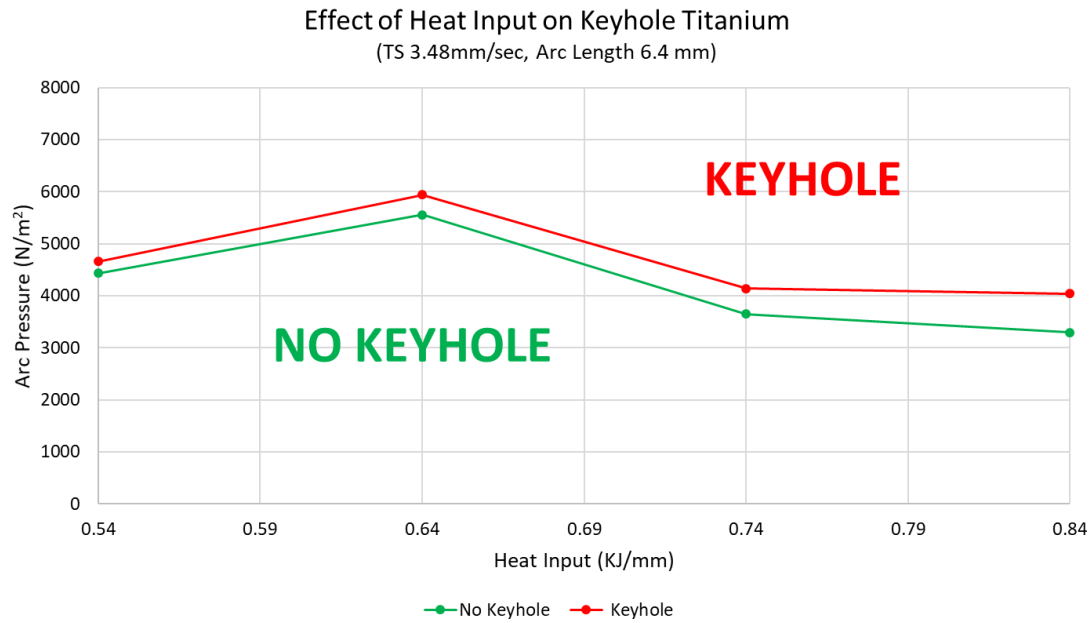
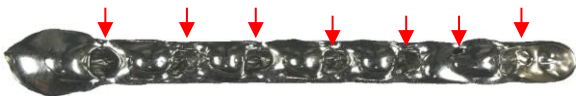
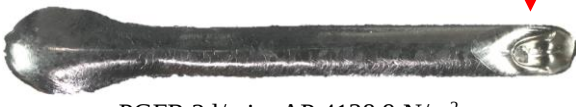


Figure 144 Effect of heat input on keyhole defect formation in titanium plate material.

Table 32 illustrates the parameters and deposition pictures for each heat input and the arc pressure values for both sides of the keyhole defect transition for titanium: no keyhole/keyhole.

Table 32 Effect of heat input on keyhole defect study – titanium depositions from each side of the boundary for each heat input: ‘no keyhole’ and ‘keyhole’. Keyhole defects indicated.

Heat Input	No keyhole /Keyhole	Images	Travel Speed	Current
0.54 kJ/mm	No keyhole	 PGFR 4 l/min, AP 4431 N/m ²	3.48 mm/sec	160 A
	Keyhole	 PGFR 4.5 l/min, AP 4657.3 N/m ²		
0.64 kJ/mm	No keyhole	 PGFR 4 l/min, AP 5558.2 N/m ²		180 A

	Keyhole	 PGFR 4.5 l/min, AP 5943 N/m ²	3.48 ⁽²⁾ mm/sec	
0.74 kJ/mm	No keyhole	 PGFR 1.6 l/min, AP 3644.6 N/m ²	3.48 mm/sec	200 A
	Keyhole	 PGFR 2 l/min, AP 4138.9 N/m ²		
0.84 kJ/mm	No keyhole	 PGFR 1 l/min, AP 3293 N/m ²	3.48 mm/sec	220 A
	Keyhole	 PGFR 1.5 l/min, AP 4038.9 N/m ²		

Bead-width and height for titanium were investigated to ascertain whether a correlation between heat input and arc pressure exists. Figure 235 in Appendix G shows a comparison of the four heat inputs, 0.54, 0.64, 0.74 and 0.84 kJ/mm, and the effect of arc pressure and heat input on bead-width and height for titanium for the data points of Figure 143.

² Actual travel speed is 3.5 mm/sec as data is from section 5.3.2.3. Effect of travel speed on keyhole defects – Titanium as duplicate parameters.

5.3.2.3 Effect of Travel Speed on Keyhole Defects

Stainless-steel

To identify the transition point for stainless-steel between keyhole and no keyhole for nine different travel speeds, numerous autogenous passes were undertaken at increasing values of arc pressure. Figure 145, Figure 146 and Figure 147 indicate each attempt, and the transition, for each travel speed determined.

Using the transition arc pressures from Figure 145, Figure 146 and Figure 147, the effect of travel speed on keyhole defect transition is shown in Figure 148 for stainless-steel material, with the keyhole, no keyhole and boundary zone indicated.

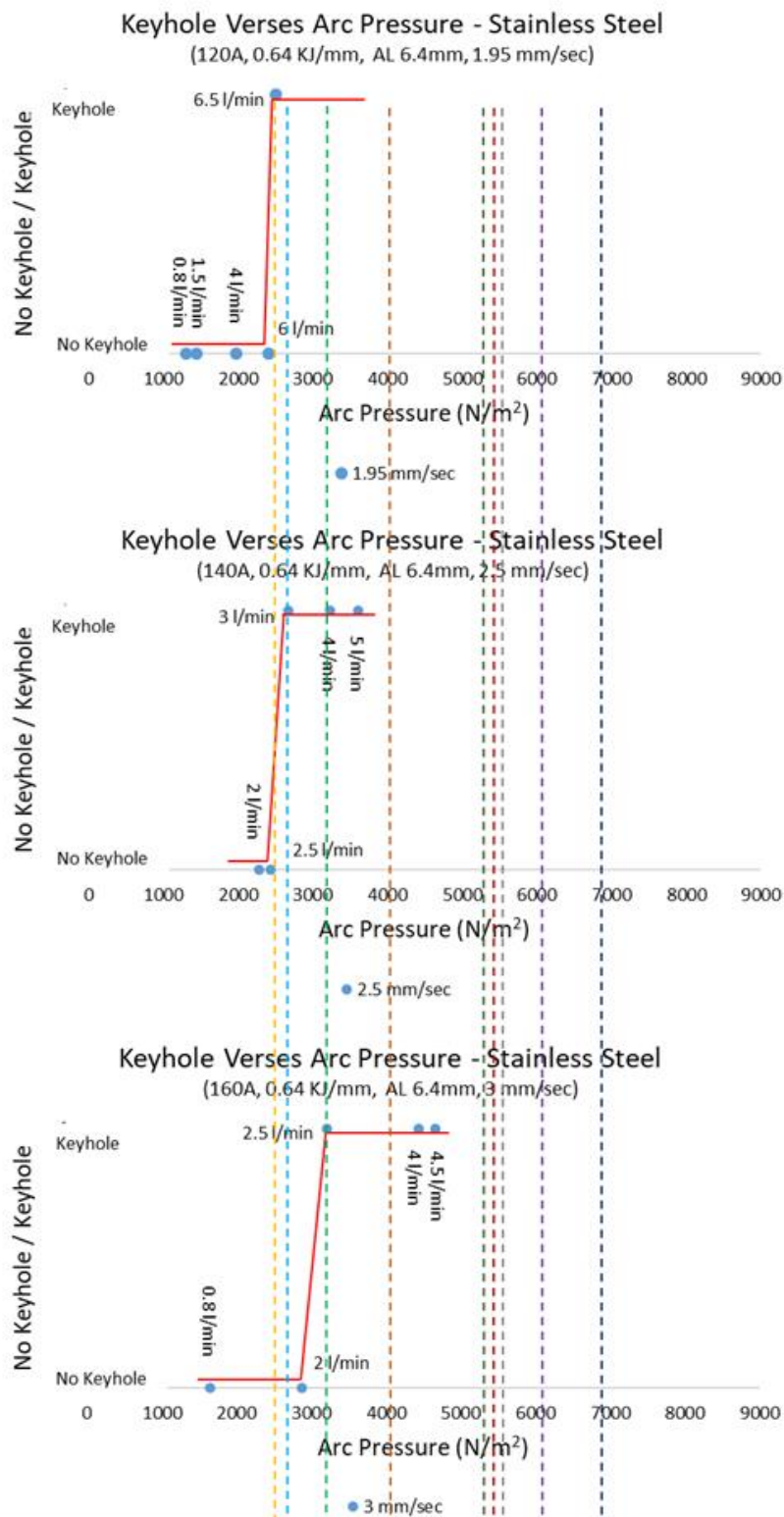


Figure 145 Stainless-steel keyhole defect transitions for three travel speeds: 1.95, 2.5 and 3 mm/sec. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for travel speed for comparison. Continued in Figure 146 and Figure 147.

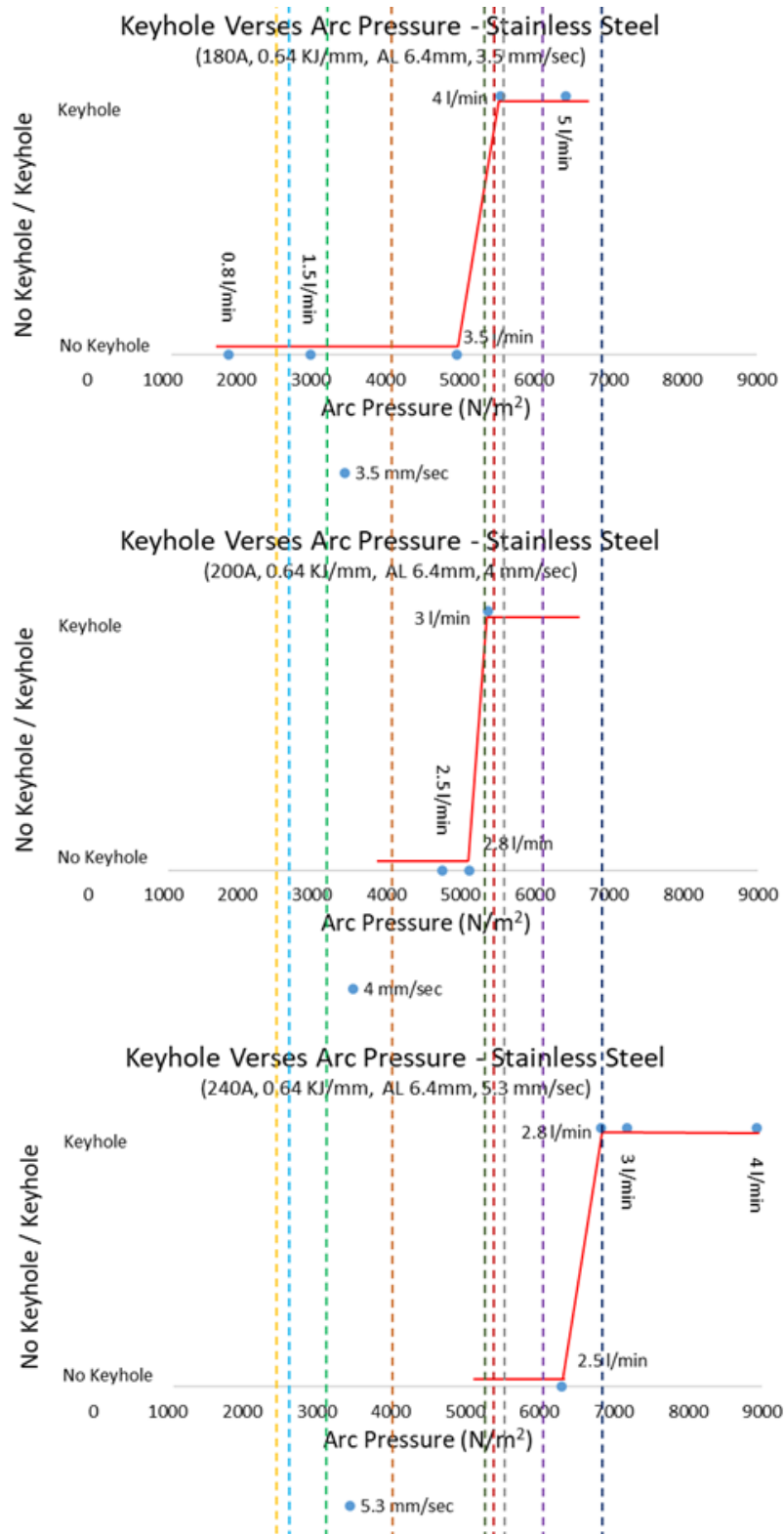


Figure 146 Stainless-steel keyhole defect transitions for three further travel speeds: 3.5, 4 and 5.3 mm/sec. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for travel speed for comparison. Continuation of Figure 145.

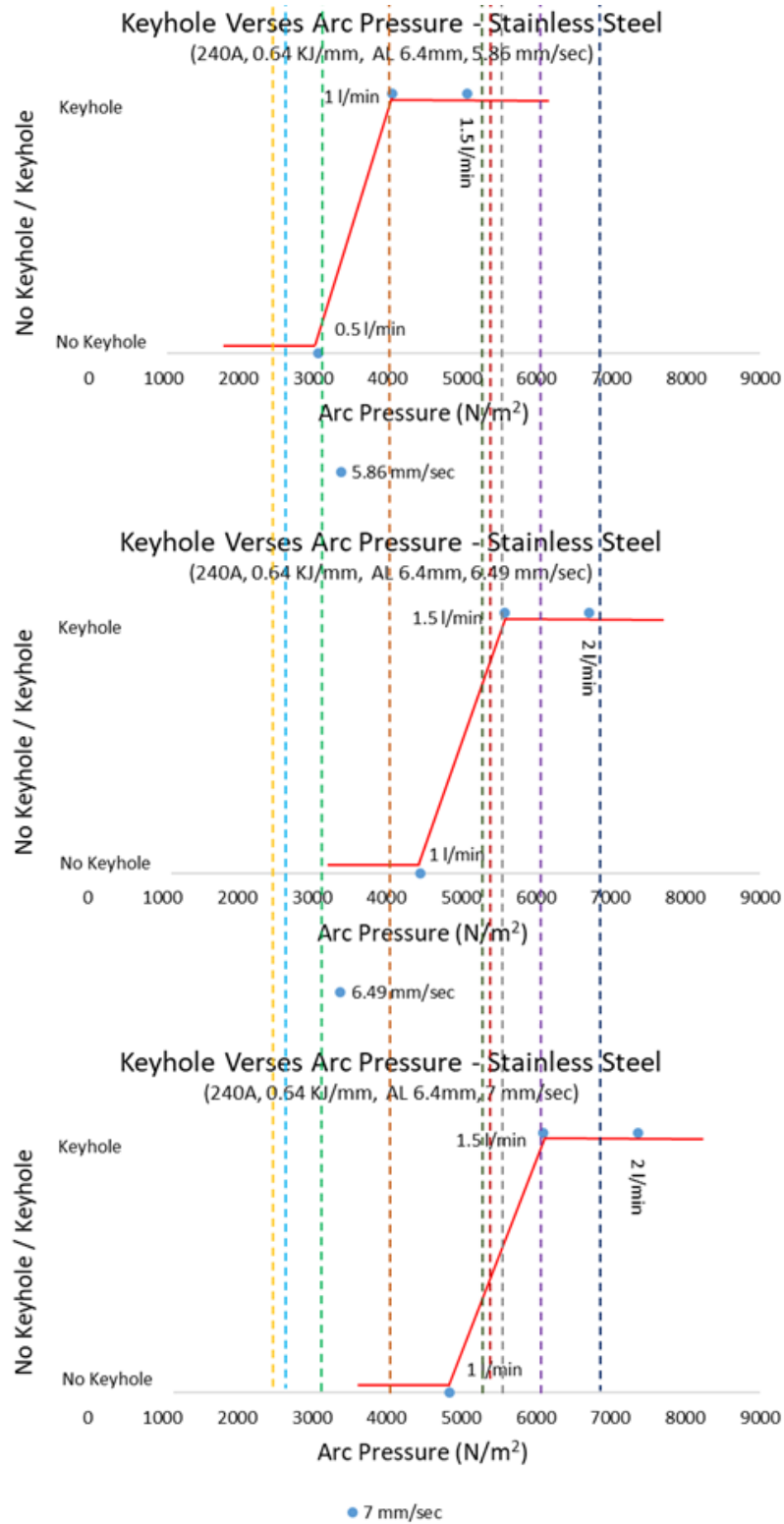


Figure 147 Stainless-steel keyhole defect transitions for three further travel speeds: 5.86, 6.49 and 7 mm/sec. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for travel speed for comparison. Continuation of Figure 145.

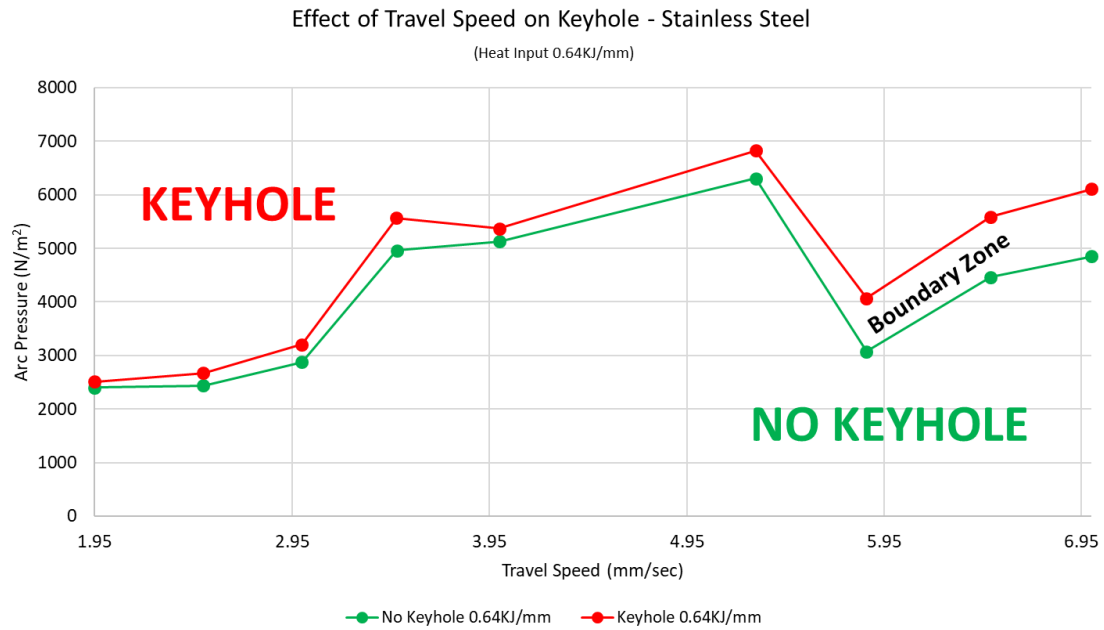
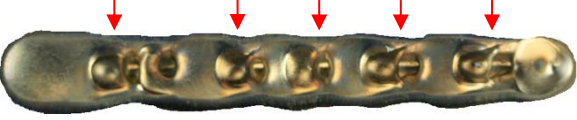
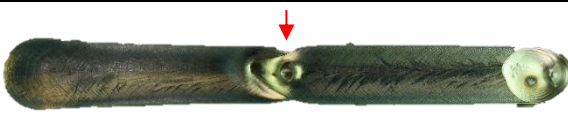


Figure 148 Effect of travel speed on keyhole defect formation in stainless-steel plate material.

Images of the stainless-steel plates, the parameters for each travel speed and the arc pressure applied are shown in Table 33. The effect of travel speed on keyhole defect formation and the change in geometry of the keyhole with increased arc pressure are illustrated.

Table 33 Effect of travel speed on keyhole defect study – stainless-steel depositions from each side of the boundary for each travel speed: ‘no keyhole’ and ‘keyhole’. Keyhole defects indicated.

Travel Speed	No keyhole /Keyhole	Images	Heat Input	Current
1.95 mm/sec	No keyhole	 PGFR 6 l/min, AP 2404.04487 N/m ²	0.64 kJ/mm	120 A
	Keyhole	 PGFR 6.5 l/min, AP 2510.14487 N/m ²		

2.5 mm/sec	No keyhole	 PGFR 2.5 l/min, AP 2435.23933 N/m ²	0.64 kJ/mm	140 A
	Keyhole	 PGFR 3 l/min, AP 2669.3077 N/m ²		
3 mm/sec	No keyhole	 PGFR 2 l/min, AP 2877.1870 N/m ²	0.64 kJ/mm	160 A
	Keyhole	 PGFR 2.5 l/min, AP 3209.133803 N/m ²		
3.5 ⁽³⁾ mm/sec	No keyhole	 PGFR 3.5 l/min, AP 4963.038 N/m ²	0.64 kJ/mm	180 A
	Keyhole	 PGFR 4 l/min, AP 5558.247 N/m ²		
4 mm/sec	No keyhole	 PGFR 2.8 l/min, AP 5127.7067 N/m ²	0.64 kJ/mm	200 A
	Keyhole	 PGFR 3 l/min, AP 5374.89607 N/m ²		

³ Actual travel speed is 3.48 mm/sec as data is from section 5.3.2.2. Effect of Heat Input on Keyhole Defects as duplicate parameters.

5.3 mm/sec	No keyhole	 PGFR 2.5 l/min, AP 6304.71167 N/m ²	0.64 kJ/mm	240 A
	Keyhole	 PGFR 2.8 l/min, AP 6829.05767 N/m ²		
5.86 mm/sec	No keyhole	 PGFR 0.5 l/min, AP 3071 N/m ²	0.64 kJ/mm	260 A
	Keyhole	 PGFR 1 l/min, AP 4072.97 N/m ²		
6.49 mm/sec	No keyhole	 PGFR 1 l/min, AP 4462.96 N/m ²	0.64 kJ/mm	280 A
	Keyhole	 PGFR 1.5 l/min, AP 5592.8 N/m ²		
7 mm/sec	No keyhole	 PGFR 1 l/min, AP 4852.95 N/m ²	0.64 kJ/mm	300 A
	Keyhole	 PGFR 1.5 l/min, AP 6110.77 N/m ²		

Titanium

As per the stainless-steel plate, to identify the transition point for titanium between keyhole and no keyhole for six different travel speeds, numerous autogenous passes were undertaken at increasing values of arc pressure. Figure 149 and Figure 150 indicate each attempt, and the transition, for each travel speed determined.

Using the transition arc pressures from Figure 149 and Figure 150, the effect of travel speed on keyhole defect transition is shown in Figure 151 for titanium material, with the keyhole, no keyhole and boundary zone indicated.

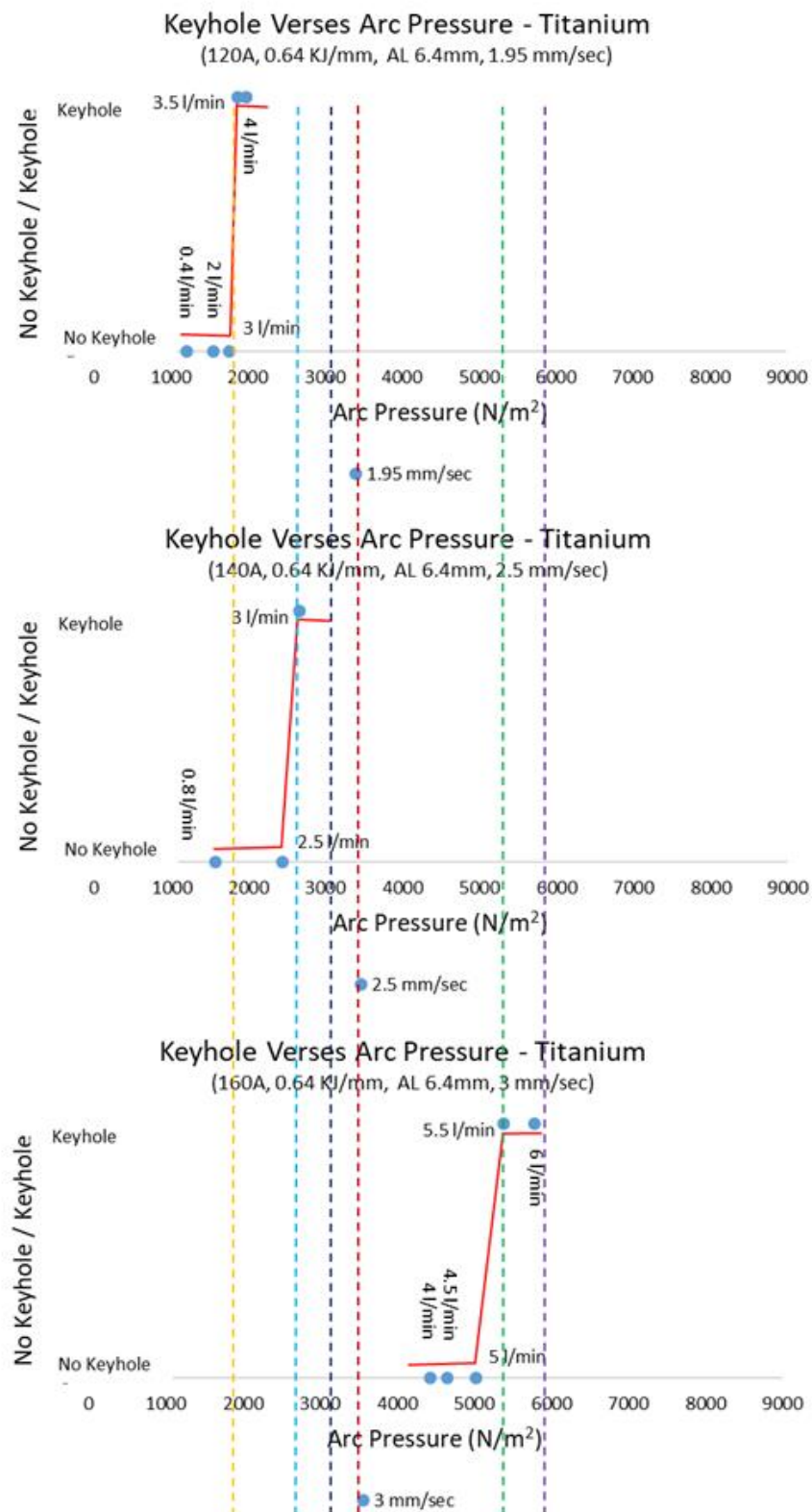


Figure 149 Titanium keyhole defect transitions for three travel speeds: 1.95, 2.5 and 3 mm/sec. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for travel speed. Continued in Figure 150.

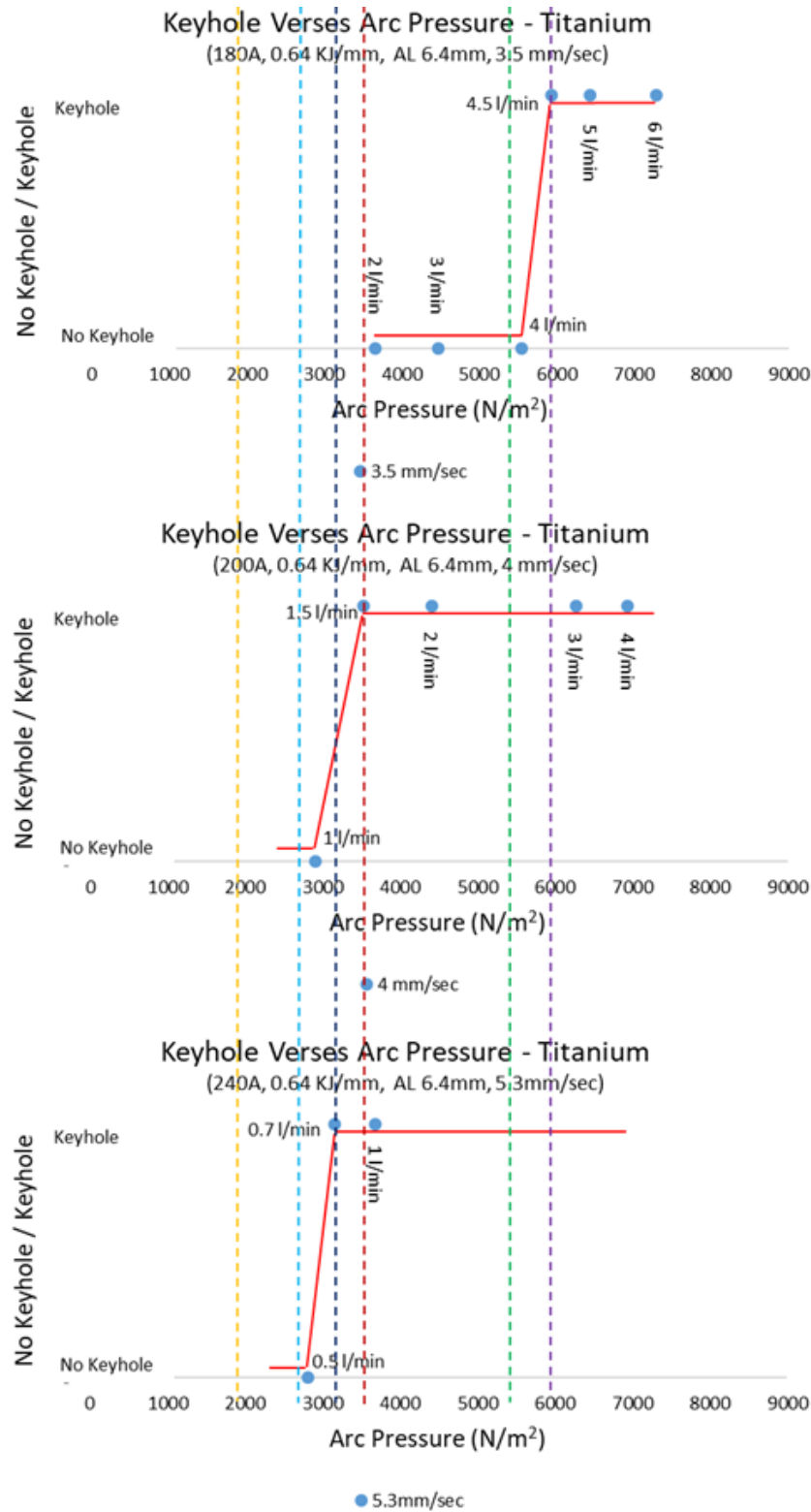


Figure 150 Titanium keyhole defect transitions for three further travel speeds: 3.5, 4 and 5.3 mm/sec. Nozzle diameter 3.9 mm. Dotted lines indicate the transition arc pressure for travel speed. Continuation of Figure 149.

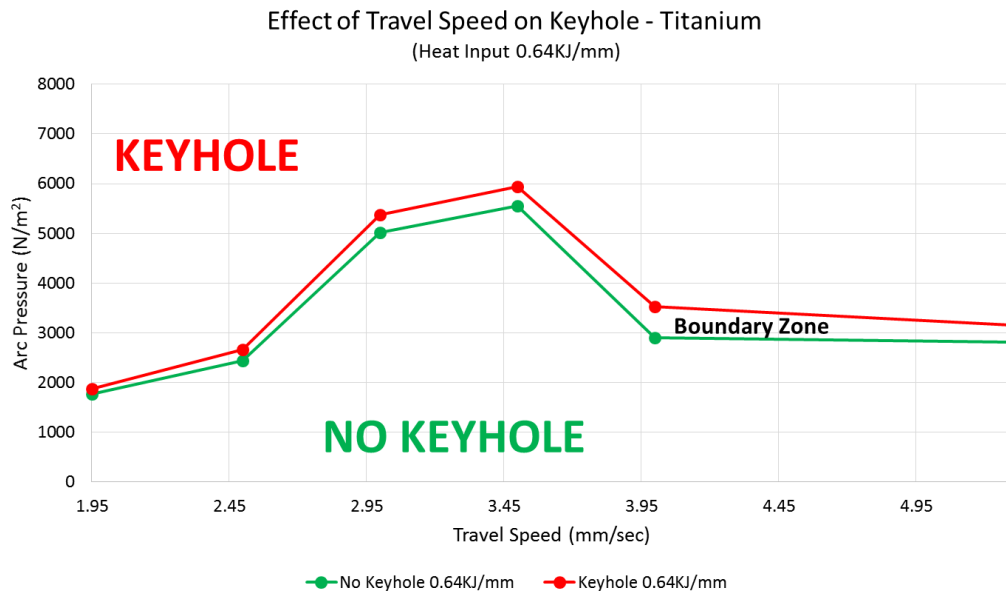


Figure 151 Effect of travel speed on keyhole defect formation in titanium plate material.

Table 34 illustrates the parameters and deposition pictures for each travel speed and the arc pressure values for both sides of the keyhole defect transition for titanium: no keyhole/keyhole.

Table 34 Effect of travel speed on keyhole defect study – titanium depositions from each side of the boundary for each travel speed: ‘no keyhole’ and ‘keyhole’. Keyhole defects indicated.

Travel Speed	No keyhole /Keyhole	Images	Heat Input	Current
1.95 mm/sec	No keyhole	 PGFR 3 l/min, AP 1767.4 N/m ²	0.64 kJ/mm	120 A
	Keyhole	 PGFR 3.5 l/min, AP 1873.5 N/m ²		
2.5 mm/sec	No keyhole	 PGFR 2.5 l/min, AP 2435.2 N/m ²	0.64 kJ/mm	140 A

	Keyhole	 PGFR 3 l/min, AP 2669.3 N/m ²		
3 mm/sec	No keyhole	 PGFR 5 l/min, AP 5019.3 N/m ²	0.64 kJ/mm	160 A
	Keyhole	 PGFR 5.5 l/min, AP 5381.4 N/m ²		
3.5 mm/sec	No keyhole	 PGFR 4 l/min, AP 5558.2 N/m ²	0.64 kJ/mm	180 A
	Keyhole	 PGFR 4.5 l/min, AP 5943 N/m ²		
4 mm/sec	No keyhole	 PGFR 1 l/min, AP 2903 N/m ²	0.64 kJ/mm	200 A
	Keyhole	 PGFR 1.5 l/min, AP 3521 N/m ²		
5.3 mm/sec	No keyhole	 PGFR 0.5 l/min, AP 2809.1 N/m ²	0.64 kJ/mm	240 A
	Keyhole	 PGFR 0.7 l/min, AP 3158.6 N/m ²		

Bead-width and height for titanium were investigated to ascertain if a correlation with travel speed and arc pressure exists. Figure 236 in Appendix G shows a comparison for the six travel speeds, 1.95, 2.5, 3, 3.5, 4 and 5.3 mm/sec, and the effect of arc pressure and travel speed on bead-width and bead-height for titanium for the data points in Figure 149 and Figure 150.

5.3.2.4 Effect of Plate Thickness on Keyhole Defects

Using the transition arc pressures from Figure 152, the effect of plate thickness on keyhole defect transition is shown in Table 35 for titanium material, with the keyhole and no keyhole indicated. The data suggests that the required arc pressure to generate a keyhole defect changes inconsistently with plate thickness.

Bead-width and height for titanium were investigated to ascertain if a correlation with plate thicknesses and arc pressure exists. Figure 237 in Appendix G shows a comparison of the four plate thicknesses – 5.6, 9.5, 13.4 and 20.2 mm – and the effect of arc pressure and plate thickness on bead-width and height for titanium for the data points in Figure 152.

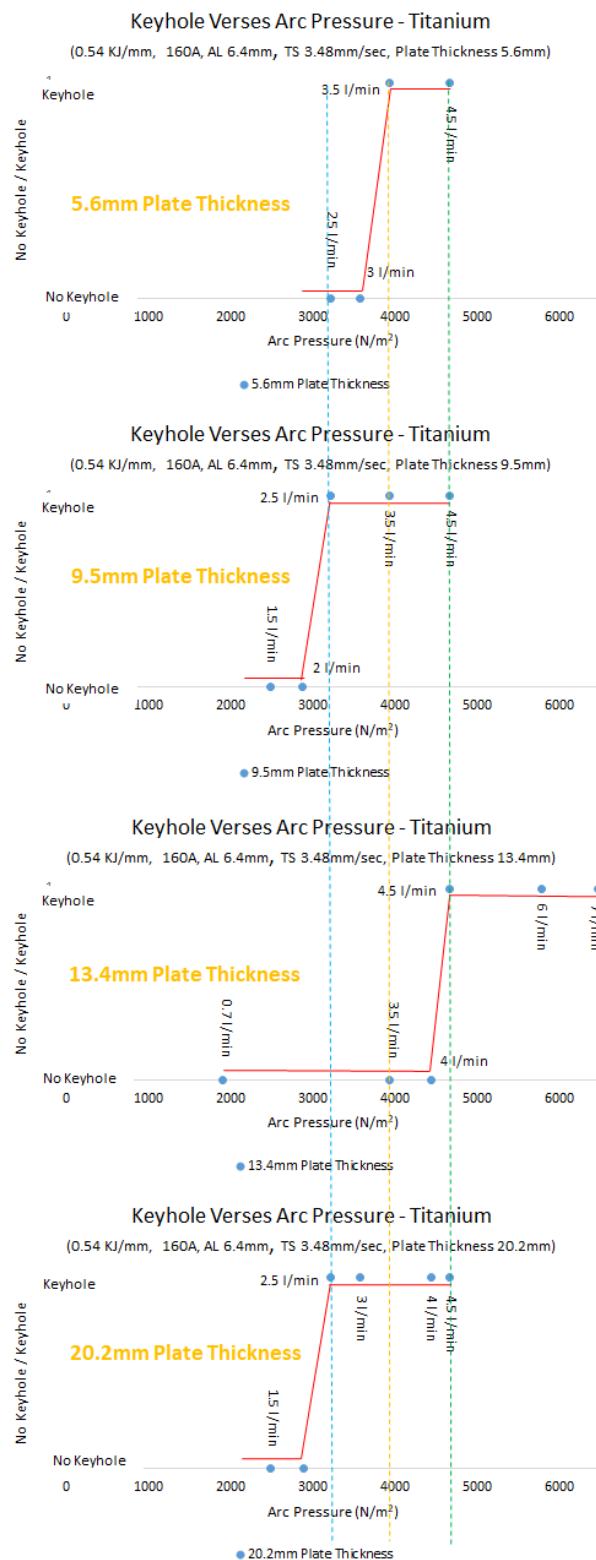


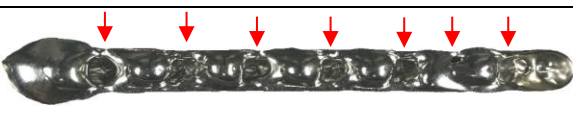
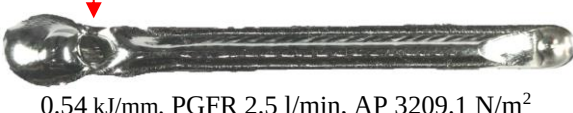
Figure 152 Titanium keyhole defect transitions for four plate thicknesses: 5.6, 9.5, 13.4 and 20.2 mm. Nozzle diameter 3.9 mm. All parameters and torch geometries constant. Dotted lines indicate the transition arc pressure for each thickness.

Table 35 Effect of plate thickness on keyhole defects – titanium.

Effect of Plate Thickness on Keyhole for Titanium, Four Plate Thicknesses 5.6, 9.5, 13.4, and 20.2 mm		
(160 A, Heat Input 0.54 KJ/mm, TS 3.48 mm/sec, Arc Length 6.4 mm)		
Plate Thickness (mm)	Transition Arc Pressure (N/m²)	
	No Keyhole Defect	Keyhole Defect
5.6	3571.170	3933.207
9.5	2877.187	3209.134
13.4	4431.077	4657.280
20.2	2877.187	3209.134

Images of the titanium weld beads, the parameters for each plate thickness and the arc pressure applied are shown in Table 36. The effects of plate thickness on keyhole defect formation and the change in geometry of the keyhole defect with increased arc pressure are illustrated.

Table 36 Effect of plate thickness on keyhole defect study – titanium depositions from each side of the boundary for each thickness: no keyhole and keyhole. Keyhole defects indicated.

Plate Thickness	No Keyhole /Keyhole	Images	Travel Speed	Current
5.6 mm	No keyhole	 0.54 kJ/mm, PGFR 3 l/min, AP 3571.2 N/m ²	3.48 mm/sec	160 A
	Keyhole	 0.54 kJ/mm, PGFR 3.5 l/min, AP 3933.2 N/m ²		
9.5 mm	No keyhole	 0.54 kJ/mm, PGFR 2 l/min, AP 2877.187 N/m ²	3.48 mm/sec	160 A
	Keyhole	 0.54 kJ/mm, PGFR 2.5 l/min, AP 3209.13 N/m ²		
13.4 mm	No keyhole	 0.54 kJ/mm, PGFR 4 l/min, AP 4431 N/m ²	3.48 mm/sec	160 A
	Keyhole	 0.54 kJ/mm, PGFR 4.5 l/min, AP 4657.3 N/m ²		
20.2 mm	No keyhole	 0.54 kJ/mm, PGFR 2 l/min, AP 2847.1 N/m ²	3.48 mm/sec	160 A
	Keyhole	 0.54 kJ/mm, PGFR 2.5 l/min, AP 3209.1 N/m ²		

5.3.2.5 Effect of Wire-feed on Keyhole Defects

Effect of Wire-feed Position on Keyhole/no Keyhole Defect Transition

To identify the transition point for titanium between keyhole and no keyhole for wire-feeding, numerous passes were undertaken at increasing values of arc pressure by increasing PGFR. Figure 153 indicates each attempt, and the transitions for WOA and WNOA are determined. For comparison, the no wire-feed keyhole defect transition data for an autogenous pass with the same parameters as in Figure 143 is shown.

The arc pressure transitions are the same for both WOA and WNOA. Wire-feed shows no effect on the keyhole defect transition.

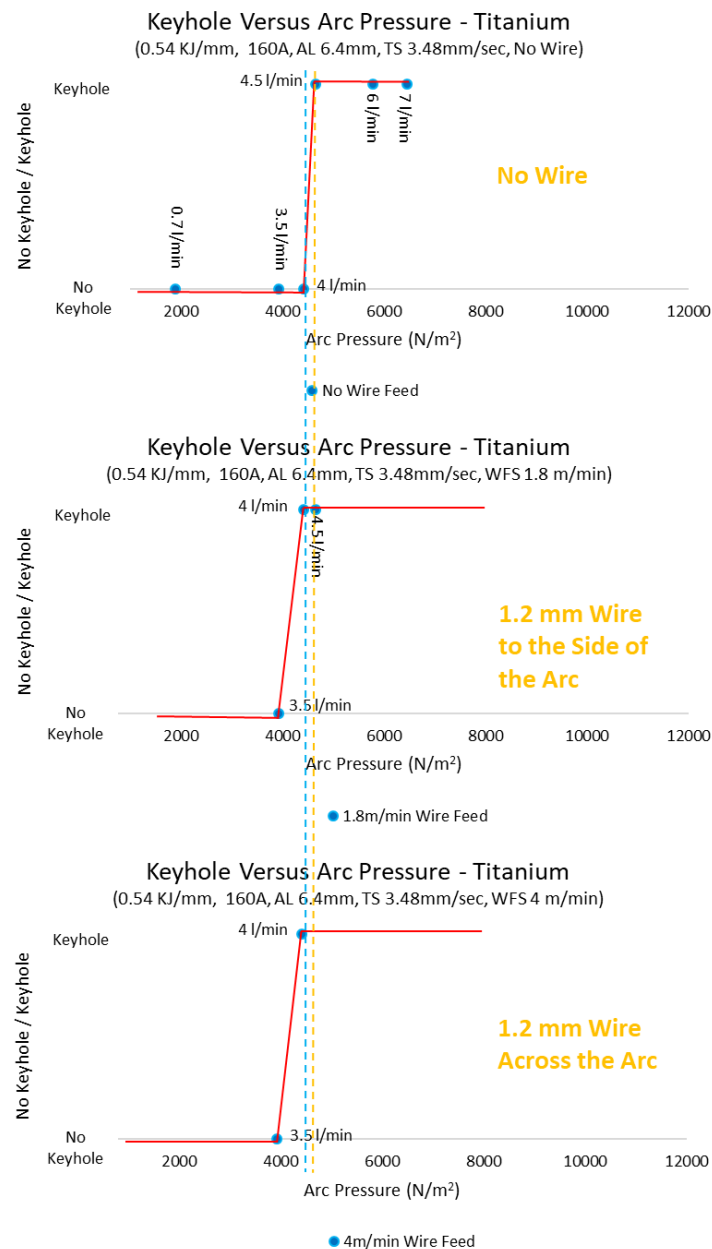
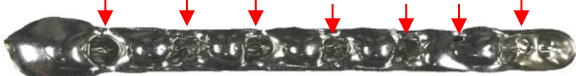


Figure 153 Titanium keyhole defect transitions for wire-feed/no wire-feed: [Top] No wire-feed, [Middle] 1.2 mm wire-feed to the side of the arc, and [Bottom] 1.2 mm wire-feed across the arc. Nozzle diameter 3.9 mm.

Table 37 illustrates the parameters for each transition pair and the arc pressure applied for titanium. The effect of wire-feed on keyhole defect formation and the change in geometry and number of keyholes with increased arc pressure and wire-feed are illustrated.

Table 37 Effect of wire-feed on keyhole defect study – titanium depositions from each side of the boundary for each wire position: no keyhole and keyhole. Keyhole defects indicated.

Wire Position	No Keyhole /Keyhole	Images	WFS	Wire/ No Wire
No Wire	No keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 4 l/min, AP 4431 N/m ²	N/A	No Wire
	Keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 4.5 l/min, AP 4657.3 N/m ²		
Side of the Arc (WNOA)	No keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 3.5 l/min, AP 3933.2 N/m ²	1.8 m/min	1.2 mm Wire
	Keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 4 l/min, AP 4431 N/m ²		
Across the Arc (WOA)	No keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 3.5 l/min, AP 3933.2 N/m ²	4 m/min	1.2 mm Wire
	Keyhole	 0.54 kJ/mm, 160 A, 3.48 mm/sec Travel Speed, PGFR 4 l/min, AP 4431 N/m ²		

Effect of Wire-feed and Heat Input on Keyhole/no Keyhole Defect Transition

The effect of wire-feed and heat input on keyhole defect formation and transition points for titanium between keyhole and no keyhole are illustrated in Figure 154. For both heat inputs, the transition pressures reduce with wire-feed.

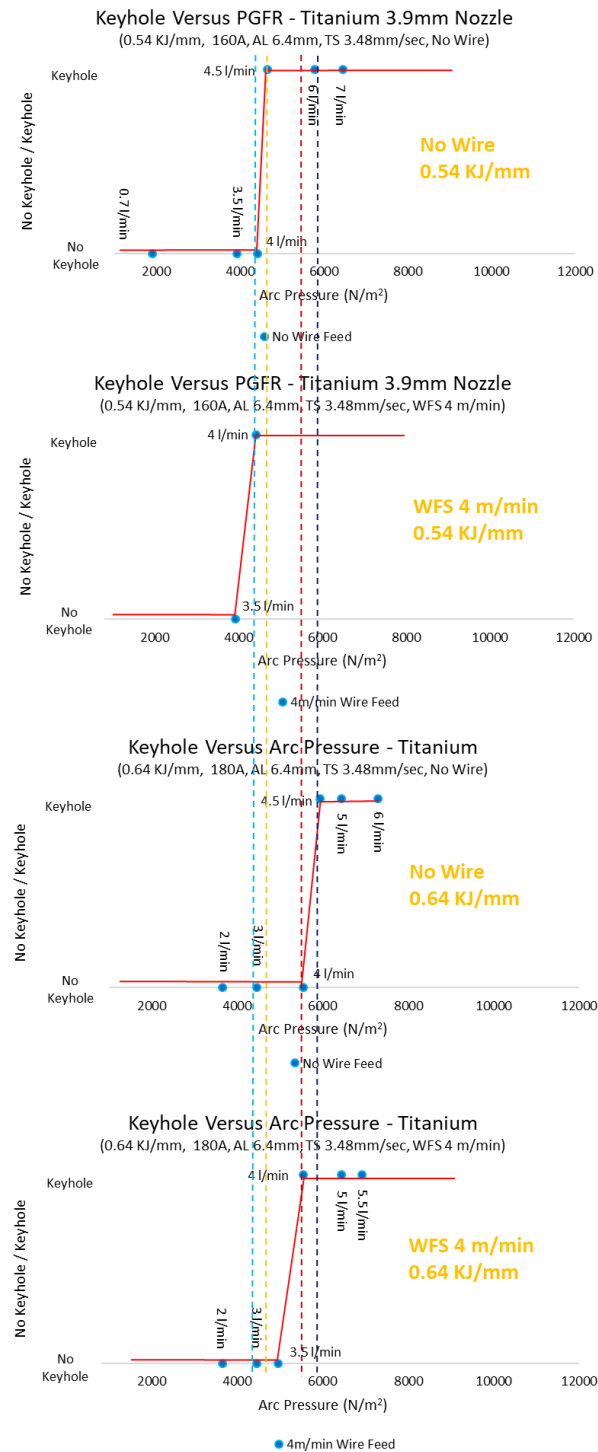


Figure 154 Titanium keyhole defect transitions for wire-feed and no wire-feed at two heat inputs: 0.54 and 0.64 kJ/mm. 1.2 mm diameter wire at a feed rate of 4 m/min. Nozzle diameter 3.9 mm.

5.3.2.6 Keyhole Defect Depth

Effect of Heat Input on Keyhole Defect Depth

The effect of arc pressure and heat input on stainless-steel and titanium keyhole defect depth is shown in Figure 155 and Figure 156 respectively. Individually for each value of heat input and combined, both materials show a linear increasing trend with arc pressure – keyhole defect depth increases with arc pressure. Also evident is that keyhole defect depth is significantly deeper for titanium for the same parameters, and keyhole defect depth is generally dependent on heat input for both materials.

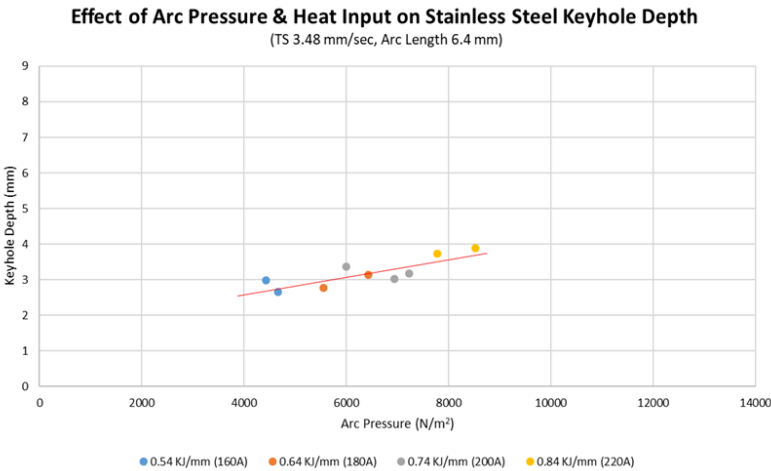


Figure 155 Effect of arc pressure and heat input on stainless-steel keyhole defect depth.

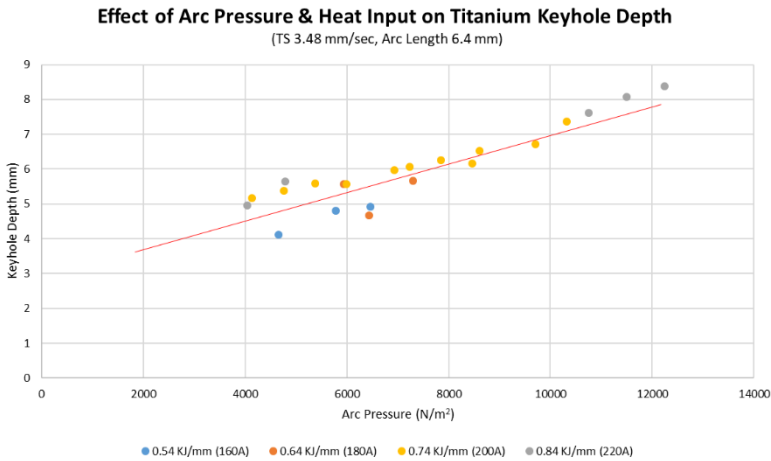
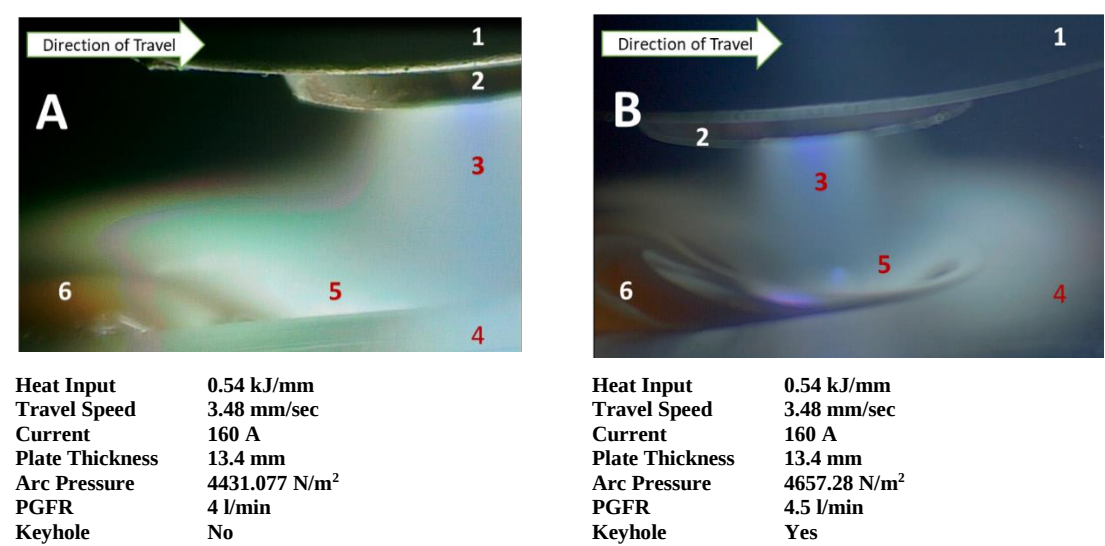


Figure 156 Effect of arc pressure and heat input on titanium keyhole defect depth.

Figure 157 shows a comparison of two melt-pool images and the shape of the solidified titanium deposit for non-keyhole defect (left) and keyhole defect (right). The images are from either side of the keyhole transition for a heat input of 0.54 kJ/mm, shown in Table 32. The images suggest a deeper melt-pool depression and steeper incline at the rear of melt-pool up to the solidified titanium deposit with increased arc pressure.



1) PTA Shielding gas nozzle/cup, 2) PTA copper restriction nozzle, 3) PTA arc, 4) Titanium substrate, 5) Melt-pool depression, 6) Solidified deposit and rear of melt-pool incline.

Figure 157 Effect of arc pressure on the shape of the solidified titanium deposit. A] Shape of non-keyhole defect sample, small rear of melt-pool incline, B] Shape of keyhole defect sample, larger rear of melt-pool incline visible.

Effect of Travel Speed on Keyhole Defect Depth

The effect of arc pressure and travel speed on stainless-steel and titanium keyhole defect depth is shown in Figure 158 and Figure 159 respectively. Individually for each value of travel speed and combined, both materials show an increasing linear trend with arc pressure – keyhole defect depth increases with arc pressure. Also evident is that keyhole defect depth is deeper for titanium for the same parameters and keyhole defect depth is independent of travel speed for both materials.

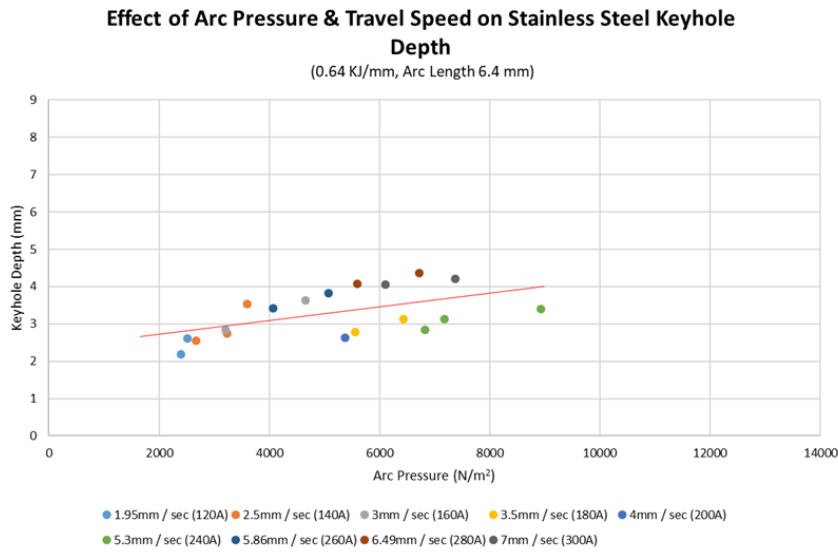


Figure 158 Effect of arc pressure and travel speed on stainless-steel keyhole defect depth.

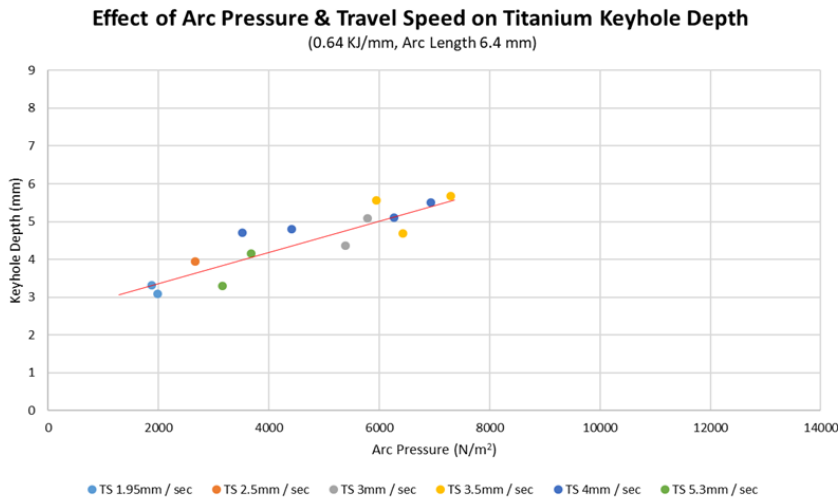
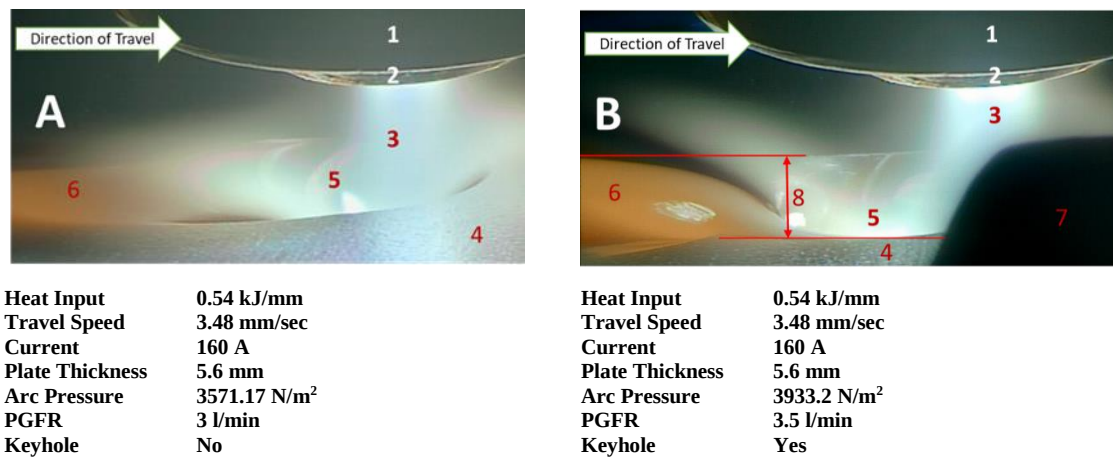


Figure 159 Effect of arc pressure and travel speed on titanium keyhole defect depth.

Effect of Plate Thickness on Keyhole Depth

Figure 160 shows a comparison of two melt-pool images and the shape of the solidified titanium deposit for non-keyhole defect (left) and keyhole defect (right) on thin 5.6 mm plate. The images are from either side of the keyhole defect transition for 5.6 mm plate, shown in Table 36. The images suggest a deeper melt-pool depression and steeper incline at the rear of melt-pool up to the solidified titanium deposit with increased arc pressure.



1) PTA Shielding gas nozzle/cup, 2) PTA copper restriction nozzle, 3) PTA arc, 4) Titanium substrate, 5) Melt-pool depression, 6) Solidified bead deposit and rear of melt-pool incline, 7) Clamp, 8) Bead-height and melt-pool incline.

Figure 160 Effect of arc pressure on the shape of the solidified titanium deposit – thin 5.6 mm plate. Parameters indicated below image. A] Shape of non-keyhole defect sample, no rear of melt-pool incline, B] Shape of keyhole defect sample, large rear of melt-pool incline visible.

The effect of arc pressure and plate thickness on titanium keyhole defect depth is shown in Figure 161. For each plate thickness, the trends are linear, increasing with arc pressure – denoting keyhole defect depth increases with arc pressure. The keyhole defect depth appears to increase with plate thickness except for 5.6 mm. However, the trend of the 5.6 mm plate is horizontal as a result of full penetration of the plate. Keyhole defect depth is generally dependent on plate thickness for titanium.

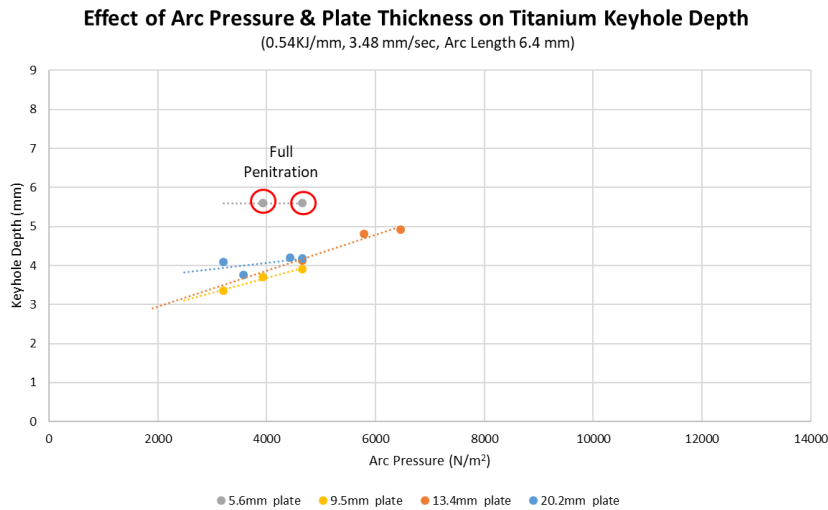


Figure 161 Effect of arc pressure and plate thickness on titanium keyhole defect depth. Full penetration of 5.6 mm plate indicated.

5.3.3 Discussion

5.3.3.1 Autogenous Solidified Titanium Deposit Shape and Keyhole Defect Types

This study observed several kinds of keyhole defect that fit within two categories: open and closed. These have been further classified into three main types, shown in Table 38.

Table 38 Three keyhole defect types experienced during the study.

Type	Description
Type 1 (Open)	Smooth bead with one open partial penetration keyhole defect with a pursuing hump.
Type 2 (Open)	Multiple open partial penetration keyhole defects with pursuing humps.
Type 3 (Closed)	Smooth bead with one internal partial penetration keyhole defect closed channel within bead – titanium plate only.

Figure 162, Figure 163, and Figure 164 show time-lapse melt-pool photographs of a smooth bead, type 1 and type 2 defects respectively – for titanium.

All PTA depositions start after arc ignition and stabilisation with a bowl-shaped crater with an encircling rim, shown in Figure 162, Figure 163, and Figure 164. At one second, the depth of the crater depends on the torch stationary duration, heat input and, primarily,

the applied arc pressure. Once the torch motion begins, the rim deposit in front migrates to the back of the melt-pool to form the arc initiation hump and part of the bead deposit. For the smooth bead deposits, shown in Figure 162, the crater traverses under the PTA torch until the arc is terminated. The final crater volume dictates the size of the autogenous bead deposit. Material removed along the side of the bead deposit through undercut also adds to the bead deposit geometry.

The images in Figure 162, Figure 163 and Figure 164 show the arc and arc pressure applying shear stress across the bead humps, smoothing and shaping the bead geometry alongside the material surface tension.

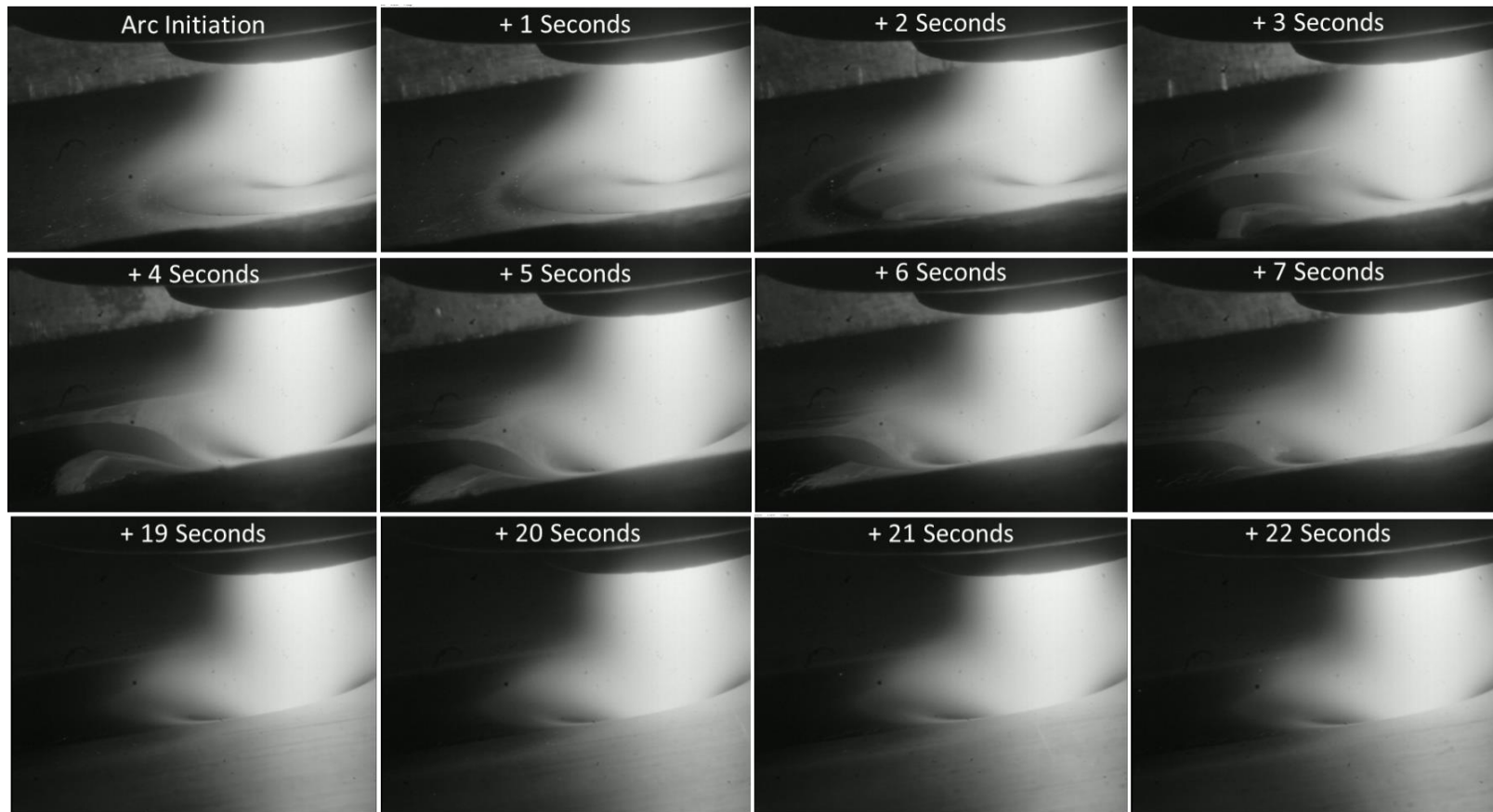


Figure 162 Smooth bead with no keyhole defect process video stills, shown at one second intervals from PTA arc ignition; PTA torch traversing left to right. Parameters: Heat input 0.64 kJ/mm, travel speed 3 mm/sec, 160 A, 0.8 l/min PGFR, 6.4 mm arc length, deposited on a cold titanium substrate. Measured arc pressure 1646.87 N/m².

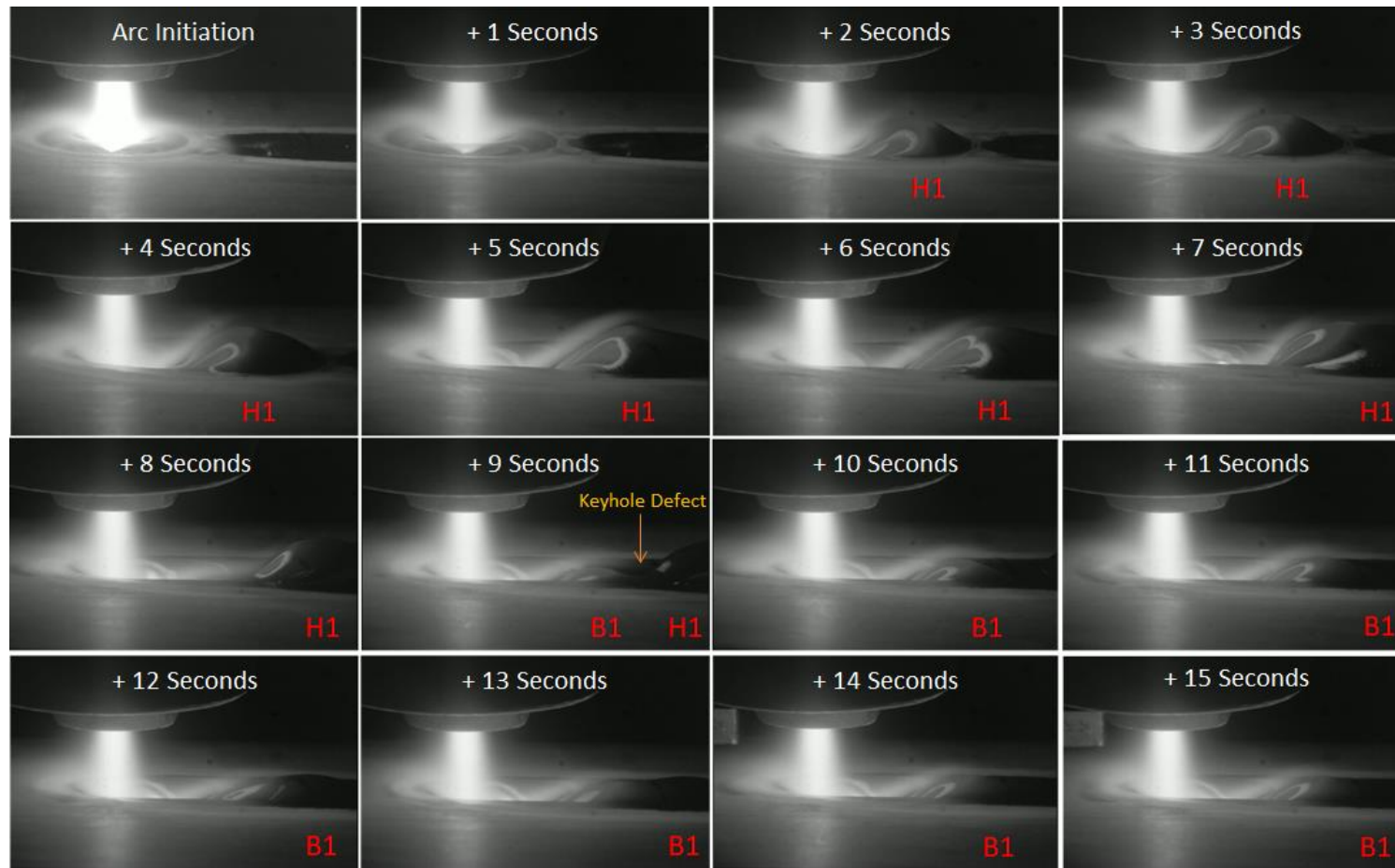


Figure 163 Keyhole defect type 1 (Open) video stills, shown at one second intervals from PTA arc ignition. PTA torch traversing right to left. H1 = Bead hump 1, B1 = Bead deposit. Parameters: Heat input 0.54 kJ/mm, travel speed 3 mm/sec, 140 A, 4 l/min PGFR, 6.4 mm arc length, deposited on a cold titanium substrate. Measured arc pressure 3239.17 N/m².

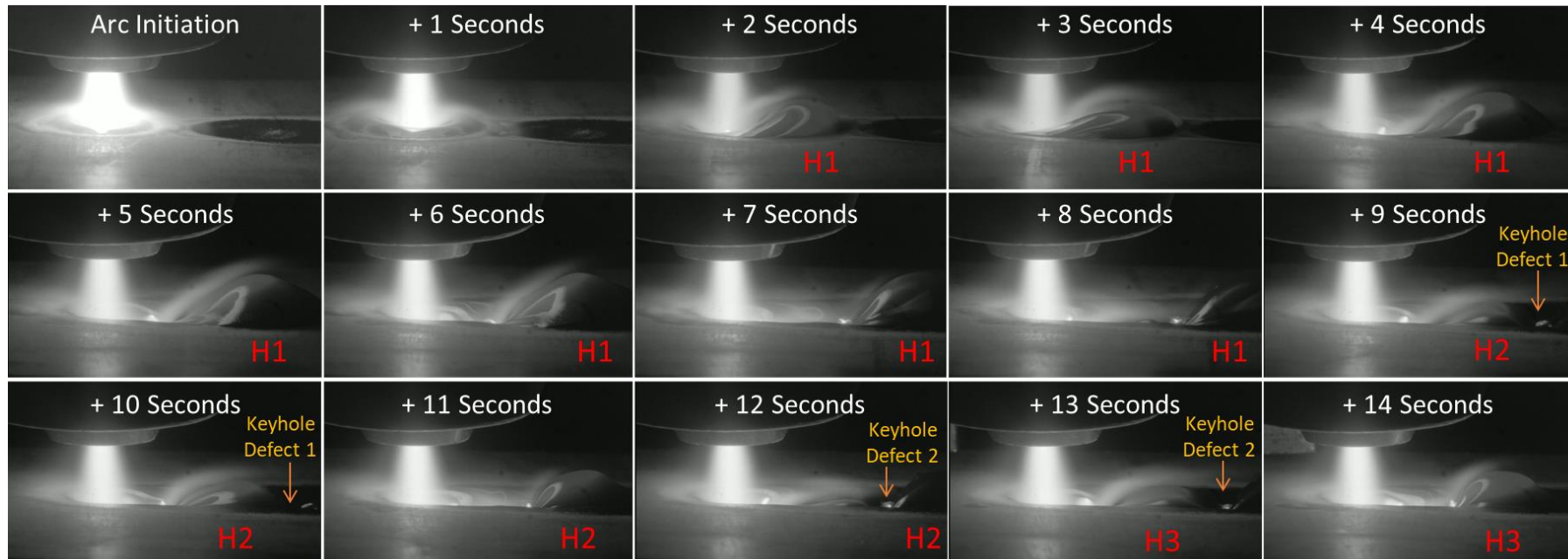
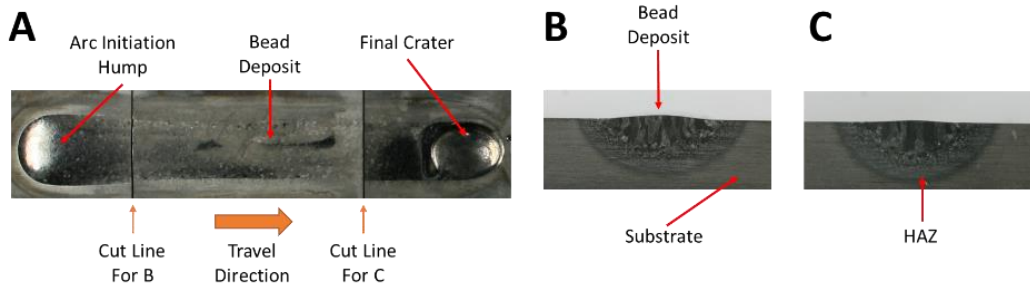


Figure 164 Keyhole defect type 2 (Open) video stills, shown at one second intervals from PTA arc ignition. PTA torch traversing right to left. H1 = Bead hump 1, H2 = Bead hump 2, H3 = Bead hump 3, Parameters: Heat input 0.54 kJ/mm, travel speed 3 mm/sec, 140 A, 6 l/min PGFR, 6.4 mm arc length, deposited on a cold titanium substrate. Measured arc pressure 3985.8 N/m².

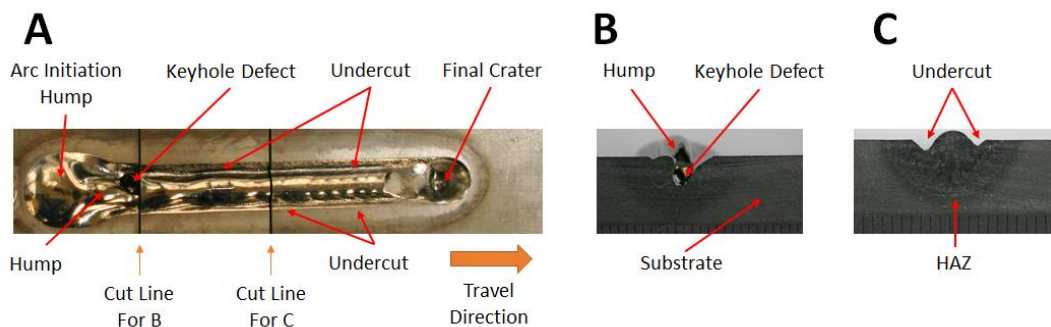
An example of a smooth deposit (smooth bead, no undercut, no keyhole defect and a small bead-height) formed autogenously with a low arc pressure is illustrated in Figure 165, with its features annotated. There is a shallow end crater as a result of the low arc pressure, and minimal bead-height, shown in Figure 165 ‘B’ and ‘C’.



Parameters: Heat input 0.64 kJ/mm, travel speed 3 mm/sec, 160 A, 0.8 l/min PGFR, arc length 6.4 mm, nozzle diameter 3.9 mm, deposited on a cold titanium substrate. Measured arc pressure 1646.87 N/m²

Figure 165 An example of a smooth bead, with no undercut or keyhole defects and a small bead-height – type 1. Torch traversing left to right.

An example of a type 1 open keyhole defect, as in Table 38, is illustrated in Figure 166, with its features annotated – formed autogenously with an increased arc pressure to the smooth bead of Figure 165. The end crater volume has increased as a result of the raised arc pressure, significant undercut is visible and a small bead-height is evident, shown in Figure 166 ‘C’.

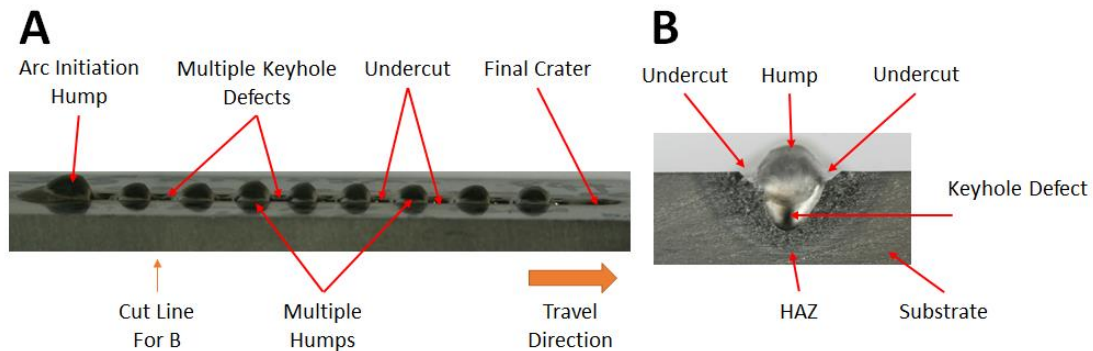


Parameters: Heat input 0.54 kJ/mm, travel speed 3 mm/sec, 140 A, 4 l/min PGFR, arc length 6.4 mm, nozzle diameter 3.9 mm, deposited on a cold titanium substrate. Measured arc pressure 3239.17 N/m²

Figure 166 An example of a type 1 open keyhole defect. Torch traversing left to right.

The single deep keyhole near to the start of the bead is a likely result of a combination of increased arc pressure and unstable melt-pool at the start of torch motion, causing the initiated gouged region to collapse partially. As a result of the higher thermal gradient, thermal losses to the cold substrate at the start of deposition enable accelerated solidification of the initial gouged region. This additionally hinders molten metal fluid flow into the keyhole defect, which would ordinarily fill the hole and mitigate the defect. After this point, the plate has sufficiently heated to reduce the thermal gradient and enable a smooth bead deposit. Changes to heat input and travel speed mitigate this type of keyhole defect.

An example of a type 2 open keyhole defect, shown in Table 38, is illustrated in Figure 167 with its features annotated – formed autogenously with an increased arc pressure to the smooth bead in Figure 165 and the type 1 open keyhole defect in Figure 166. The end crater volume has further grown as a result of the raised arc pressure and several keyhole defects with pursuing humps are evident. A significant undercut is also visible, alongside an increased bead/hump height, shown in Figure 167. Each keyhole defect is preceded by a bead hump, under which the subsequent keyhole partially extends, resulting in void formation, shown in Figure 168 ‘D’.



Parameters: Heat input 0.54 kJ/mm, travel speed 3 mm/sec, 140 A, 6 l/min PGFR, arc length 6.4 mm, nozzle diameter 3.9 mm, deposited on a cold titanium substrate. Measured arc pressure 3985.8 N/m²

Figure 167 An example of a type 2 open keyhole defect. Torch traversing left to right.

GTA bead humping is explained in the literature review and Figure 34. The mechanisms are similar for PTA. However, the primary differences observed by this study for type 2 open keyhole defect involve the increased depth of the depressions because of the higher

arc pressure of PTA, and void formation below the humps. The steps illustrated in Figure 164 show the formation of type 2 open keyhole defects and the deposition of Figure 167.

After arc ignition, initial crater formation and rim breach, as the torch starts to traverse and the raised rim is deposited, with molten metal in front, it traverses to the back of the melt-pool and starts to create the first bead hump, 'H1', shown in Figure 164, after two seconds. As the torch continues to traverse, the partial penetrating keyhole defect increases in length, with the excavated material migrating to the back of the melt-pool, increasing the size of the first bead hump, 'H1'. The distance between the PTA arc column and the first bead hump 'H1' increases with duration. The gouged region of the keyhole defect is forced down and backwards under and into the molten metal bead hump 'H1' as the torch traverses, creating a void, the plate and a depressed surface shape deflecting and distorting the arc pressure distribution, as in Figure 35. As the substrate material ahead is solid and the material behind is molten, the majority of arc pressure deflects in a rearward direction, resulting in backwards-facing voids. This continues until seven seconds after arc ignition (21 mm at a travel speed of 3 mm/sec). At this point, the distance between the PTA arc column and the first bead hump 'H1' is too long and the temperature has reduced sufficiently to enable the bead hump 'H1' to freeze, generating the first solidified bead hump.

At eight seconds the process restarts with a second partial penetrating keyhole defect being produced and the excavated molten metal traversing to the back of the melt-pool to generate the start of the second bead hump 'H2', and the partial penetrating keyhole defect and the void below hump 'H2'. This process continues, creating bead hump 'H3', the third partial penetrating keyhole defect and the void below hump 'H3' at 13 seconds after arc ignition.

The initial bead hump is always more extensive as a result of the increased molten metal gouged region below the static arc before the start of torch motion, and subsequent humps exhibit a reduced height. The PTA hump height is more significant as a result of the higher arc pressure, which generates voids and extracts material below the humps.

The PTA bead hump with void formation is based on Mendez et al.'s (1999) premature freezing of the gouging region concept, outlined in the literature review (Figure 34) and illustrated in Figure 168.

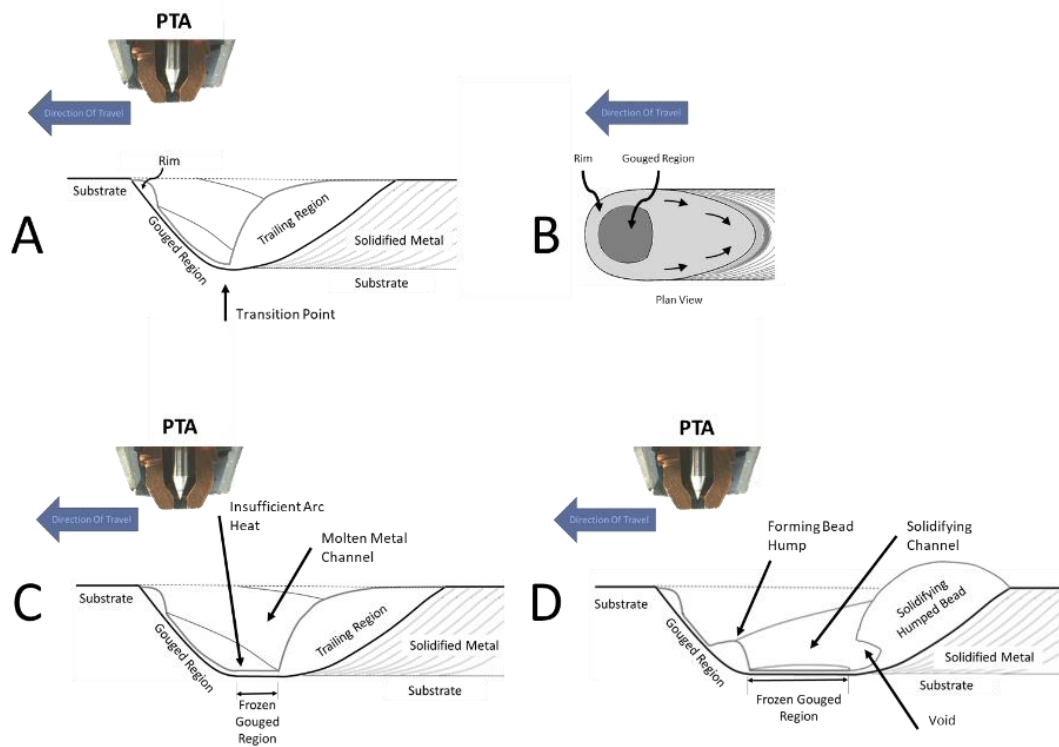


Figure 168 PTA Formation of a bead hump and hump void. A] Small distance between arc and gouging region, B] Plan view of the rim, gouging region and fluid flow, C] Increased distance of the trailing region from the arc, D] Bead hump formation with incorporated void.

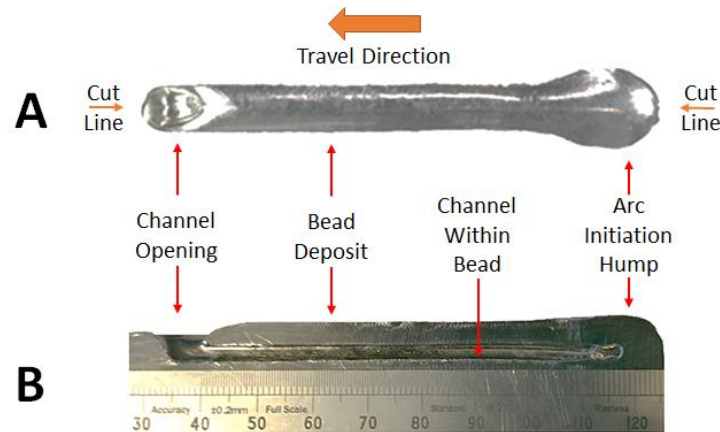
An example of a type 3 closed keyhole defect, as in Table 38, is illustrated in Figure 169, with its features annotated. It is formed autogenously with an increased arc pressure to the smooth bead in Figure 165, and the type 1 and 2 open keyhole defects in Figure 166 and Figure 167 respectively, but also at a higher heat input.

Mendez et al. (2003) and Soderstrom and Mendez (2006) found a similar phenomenon in GTA termed tunnel porosity. They established that the defect is similar to bead humping, shown in Figure 34.

In tunnel porosity, the gouging regions link up under the solidified molten metal to form a tunnel under the bead deposit. The channel is generated at the weld root and is unfilled by molten metal. It is formed when the side streams/rims increase in size to the extent

that they collapse and combine into one trailing region. The solidified gouged region below is prevented from the supply of molten metal by the overhead trailing region and turns into an enclosed channel the length of the bead (Mendez et al., 2003; Soderstrom and Mendez, 2006).

The autogenous produced sub-surface channel is straight with a smooth internal bore and no stress risers, continuing the full length of the deposited bead while maintaining its geometry, as in Figure 169.



Parameters: Heat input 0.74 kJ/mm, travel speed 3.48 mm/sec, 200 A, 2 l/min PGFR, arc length 6.4 mm, nozzle diameter 3.9 mm, deposited on a cold titanium substrate. Measured arc pressure 4138.9 N/m²

Figure 169 An example of a type 3 closed keyhole defect. Torch traversing right to left. A smooth bead with an internal keyhole channel within the bead. A] Plan view of deposit, B] Cross-section view of the sub-surface channel.

Of the parameters tested for the keyhole defect study, the sub-surface autogenous channel formation only occurred for titanium substrate, not stainless steel, and only at a specific travel speed of 3.48 mm/sec at two heat input values – 0.74 and 0.84 kJ/mm. Figure 170 illustrates the channel formation conditions required for it to form. Partial sub-surface channels, where the channel was not the full length of the bead, are also indicated. The conditions were repeated, and the channels were found to be repeatable.

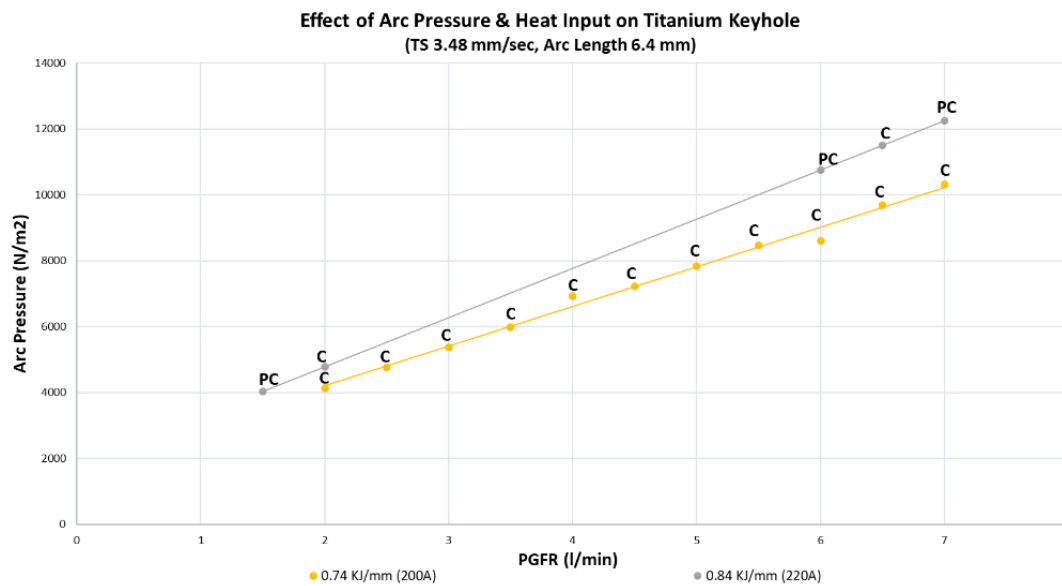


Figure 170 Titanium channel formation conditions. Bead shape indicated: PC= Partial sub-surface channel, and C= Sub-surface channel through bead.

5.3.3.2 Effect of Arc Pressure on Keyhole Formation

In order to study the role of arc pressure on keyhole formation, a study was made of the effect of arc pressure on keyhole formation, as shown in Figure 139. For two different nozzle diameters, 3 and 3.9 mm, the arc pressure was increased linearly by increasing the PGFR. A sharp transition between keyhole and no keyhole is apparent. A change of only 0.5 l/min in PGFR was needed, in both cases, in going from a situation without a keyhole defect to one with it. This corresponds to an arc pressure change of less than 226.2 N/m^2 for the 3.9 mm nozzle and 916.6 N/m^2 for the 3 mm nozzle. The difference was because of the trend gradients in Figure 140. This sharp transition corresponds to a type 2 keyhole defect formation.

Figure 140 also shows that the arc pressure needed to induce a keyhole defect is very similar – a difference of 7% (well within experimental and model error) – for the two different nozzle diameters. The PGFR for the larger nozzle to achieve this arc pressure was 4.5 l/min, while the smaller nozzle only required 1.5 l/min, confirming that the main parameter needed to control, and, in the case of WAAM, avoid keyhole formation is arc pressure.

The arc pressure empirical model developed utilising the measured arc pressure data from Chapter 3 is therefore integral for WAAM operations as it allows arc pressure to be predicted and controlled, consequently mitigating against keyhole defect formation. WAAM parameters can be selected, using the model, before WAAM operations, in the knowledge of their effect on arc pressure and keyhole defect formation. The correlation set out in Chapter 4 between arc pressure and arc voltage additionally allows the voltage signal to be used as a proxy for real-time arc pressure measurement. This can therefore be used to ensure that keyholes will not be formed during WAAM. This requires knowledge of the arc pressure keyhole defect transition threshold and how this threshold varies depending on the thermal conditions – covered in the remainder of this chapter.

5.3.3.3 Heat Input and PTA Arc Pressure Effect on Keyhole

Figure 142 and Figure 144 illustrate the threshold transition arc pressure values for stainless-steel and titanium respectively with increasing heat input and fixed travel speed. The gap between the keyhole and no keyhole boundary lines is a result of the limitations of allowable PGFR measurement. Taking an average of the keyhole/no keyhole defect threshold points for each heat input value for stainless-steel (Figure 142) and titanium (Figure 144), a comparison can be made of the effect of heat input and substrate material (Figure 171). Stainless-steel has a near linear trend.

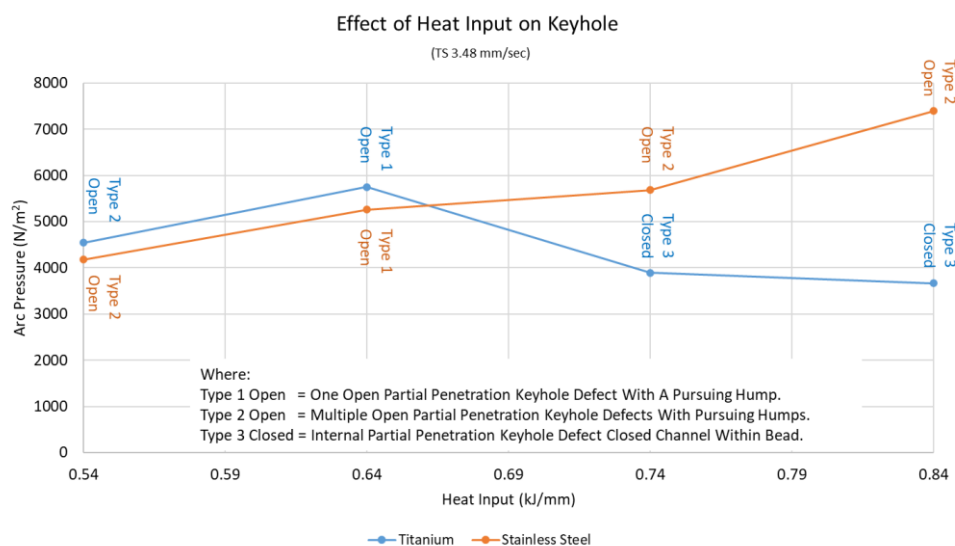


Figure 171 Comparison of average keyhole/no keyhole defect threshold with heat input for two materials. Solidified bead deposit shape type indicated. See Table 38 for full definitions.

It is apparent that initially the threshold arc pressures for titanium and stainless-steel are quite similar and that an initial increase takes place in keyhole threshold with increasing heat input. This continues for stainless steel, but the threshold reduces again for titanium. The increasing threshold with increasing heat input for stainless-steel is expected as the effect of this is to increase the amount of liquid metal significantly in the melt-pool and to generate a higher temperature, leading to increased fluidity. This means that the liquid metal has much more opportunity to fill the depression in the melt-pool, meaning that a higher arc pressure is needed to generate a deeper keyhole.

The change in keyhole deposit type is also shown in Figure 171. Of the three main keyhole defect types identified by this study, shown in Table 38, only two open types affect stainless steel. The third closed type sub-surface channel only occurs in titanium. Figure 171 indicates that, for titanium at the higher heat inputs of 0.74 and 0.84 kJ/mm, the keyhole defect type changes to the closed internal channel – type 3. This is probably because of the much greater keyhole depth of titanium compared to stainless steel. Figure 177 shows a comparison of the keyhole depth for various heat inputs, and the depth for titanium is nearly twice that of stainless steel, increasing significantly with arc pressure. It is also likely that melt-pool width and length are much greater for stainless-steel than titanium, shown in Table 39, because of the much higher thermal diffusivity (Table 26). The tunnel keyhole defect, type 3, in titanium may therefore result from the depth of the keyhole at these high arc pressures combined with a relatively narrow melt-pool (Table 39). When the material flows to the back of the melt-pool, it therefore begins to fill the depression but freezes before it can do so. For stainless steel, on the other hand, the depression is shallower, and the melt-pool is both wider (Table 39) and longer, meaning that the liquid metal has time to fill the depression before freezing.

Table 39 Comparison of stainless-steel and titanium beads for higher heat inputs in Figure 171. Titanium type 3 keyhole defect indicated.

Heat input 0.74 kJ/mm, travel speed 3.48 mm/sec, 200 A		
Material	No Keyhole Defect	Keyhole Defect
Stainless Steel	PGFR 3 l/min, AP 5374.89 N/m ² 	PGFR 3.5 l/min, AP 5992.8 N/m ² 
Titanium	PGFR 1.6 l/min, AP 3644.6 N/m ² 	PGFR 2 l/min, AP 4138.9 N/m ² 
Heat input 0.84 kJ/mm, travel speed 3.48 mm/sec, 220 A		
Material	No Keyhole Defect	Keyhole Defect
Stainless Steel	PGFR 3.5 l/min, AP 7022.700 N/m ² 	PGFR 4 l/min, AP 7768.642 N/m ² 
Titanium	PGFR 1 l/min, AP 3293 N/m ² 	PGFR 1.5 l/min, AP 4038.9 N/m ² 

The increased values of arc pressure required to initiate titanium keyhole defects are initially higher, compared with stainless steel, for the same defect type (Figure 171). This is a result of the smaller melt-pool of titanium because of its higher melting temperature and specific heat capacity, balanced by the material's thermal diffusivity, which is lower for titanium (Table 26). The increased surface tension also counteracts the arc pressure to a small degree. In addition, titanium has increased resistance to molten metal flow - higher kinematic viscosity compared to stainless-steel (Table 26), causing initiation and maintaining keyhole to be more difficult.

5.3.3.4 Travel Speed and PTA Arc Pressure Effect on Keyhole

Figure 148 and Figure 151 illustrate for stainless-steel and titanium respectively the threshold transition arc pressure values with increasing travel speed for fixed heat input.

The gap between the keyhole and no keyhole boundary lines is a result of the limitations of allowable PGFR measurement.

Figure 172 shows the comparison of the effect of travel speed at constant heat input on keyhole threshold for stainless-steel and titanium, generated from the average of the keyhole/no keyhole threshold points for each travel speed value for stainless-steel (Figure 148) and titanium (Figure 151). Keyhole defect types are also shown. A large increase threshold is apparent for both materials until it starts to reduce again. The increase up to the maximum can be explained in terms of the changing melting efficiency for the process. The overall melt-pool size and temperature are determined by the balance between the energy supplied by the arc and the thermal losses into the underlying material and the energy remaining to melt the metal. At constant heat input, the melting efficiency increases as travel speed increases and the thermal losses are reduced, leaving more energy available to melt more material (Fuerschbach and Knorovsky, 1991). The effect is similar to increasing heat input at constant travel speed and the melt-pool size increases, but it affects the shape differently. Increasing the heat input increases the melt-pool shape in all directions, with the width also increasing significantly. Increasing the travel speed at constant heat input has more effect on the length of the melt-pool. The longer the melt-pool, the more time there is for the molten material to fill the depression and avoid a keyhole defect forming. This is explained by the steep increase of threshold with travel speed, seen in Figure 172. Eventually, however, the threshold reduces again at higher travel speeds. These defects are always type 1 – partial penetration defects close to the beginning of the deposit. At higher travel speeds, longer initial dwell times may be needed to avoid this effect because of the longer times for thermal equilibrium to be reached. Dwell times were kept constant for the study.

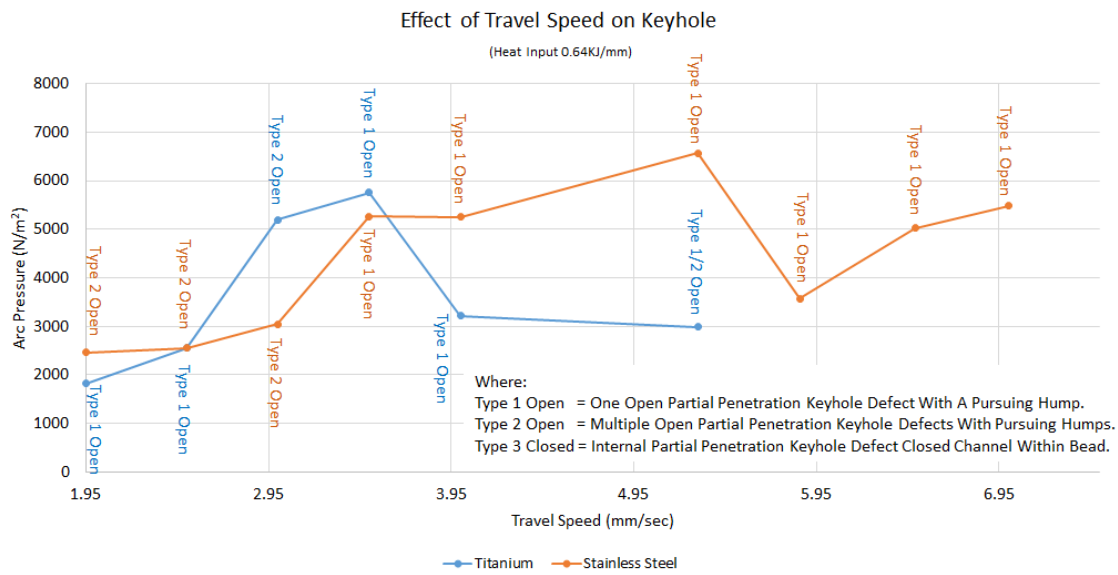


Figure 172 Comparison of average keyhole/no keyhole defect threshold with travel speed for two materials.

The travel speed investigation for stainless-steel (Figure 148) was continued further then titanium (Figure 151) to ascertain if, like titanium, the arc pressure plot would reach a maximum and reduce, which was found to be the case (Figure 172).

By manipulating PTA parameters to maximise melting efficiency, PTA process energy consumption can be reduced and HAZ and substrate distortion minimised. For a fixed arc power, if the travel speed is increased, the melting efficiency increases. However, at a critical rate, the travel speed will be too high to enable any substrate melting because of inadequate time for energy transfer. A drop therefore takes place in melting efficiency at higher travel speeds, as encountered for both materials, shown in Figure 172. Alternatively, the arc power can be increased at high travel speeds to mitigate the reduction of contact time (DuPont and Marder, 1995).

Figure 173 shows a comparison of two heat input keyhole transitions to illustrate the effect of heat input and travel speed on stainless-steel keyhole defect formation. The results indicate that the arc pressure required to initiate keyhole defects is higher at lower travel speeds with the higher heat input of 0.74 kJ/mm. As the heat input increases, the threshold transition arc pressure values required to initiate keyhole defects for the same

travel speeds also increase. This aligns with the increasing heat input plot in Figure 142, which shows a similar outcome.

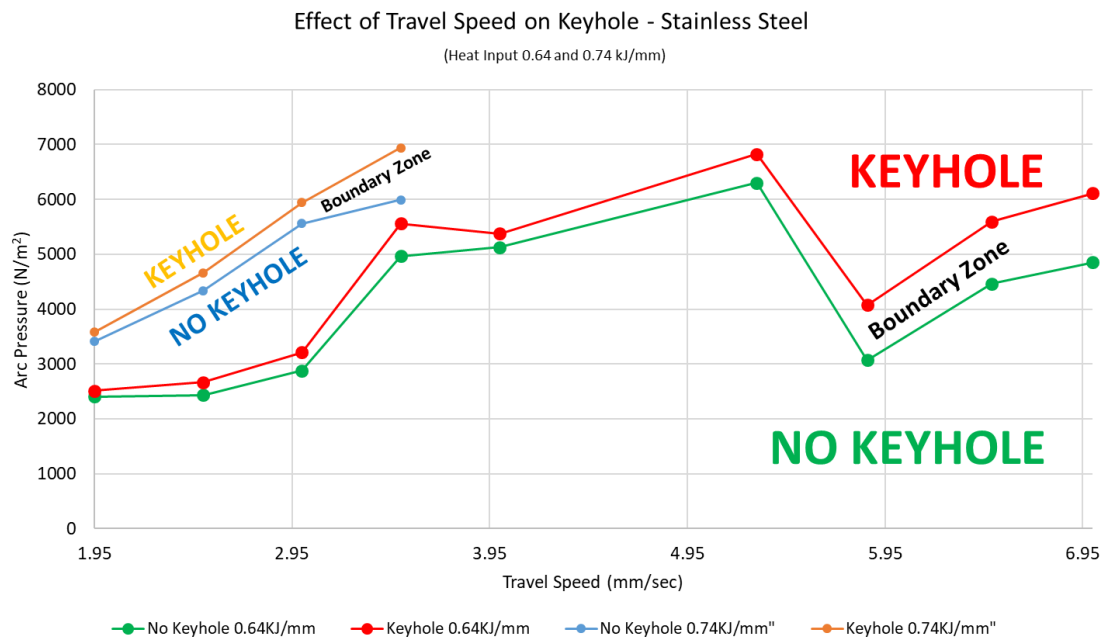


Figure 173 Effect of travel speed and heat input on keyhole formation in stainless-steel plate material. Keyhole transition for a heat input of 0.74 kJ/mm added to 0.64 kJ/mm for comparison.

5.3.3.5 Plate Thickness/Thermal Loss Effect on PTA Keyhole

The results in Table 35 can be split into two types: full and partial penetration keyhole defects. As outlined in the literature review and illustrated in , keyhole volume and depth are determined by the balance of material properties, melt-pool surface tension and gravitational pressure versus vapour pressure, recoil pressure and arc pressure.

Of the four titanium plate thicknesses, only the thinner, 5.6 mm thick plate achieved full keyhole penetration for the same parameters. The measured average bead-width of the 5.6 mm plate is 9 mm, 60.7% wider than the plate thickness. As a result, the surface tension acted to pull the molten metal back, as illustrated in Figure 32 'A', outweighing the forces attempting to close the keyhole altogether and resulting in plasma cutting (Lancaster, 1984), as seen in some of the experiment samples (Figure 174). As a result of the surrounding material acting as a heatsink, thermal loss is minimal because of the reduced volume of the thin plate and reduced depth of material under the melt-pool.

During full keyhole penetration, the thermal losses are only two dimensional. The diminished heatsink and ergo reduced melt-pool thermal loss enables a broad melt-pool and consequently a wide bead and reduced keyhole depth, in this case still through the thin plate (Figure 174).

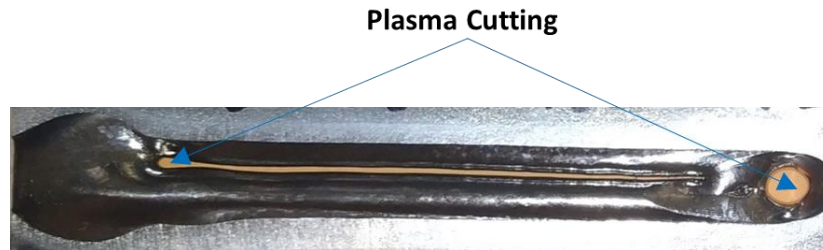


Figure 174 Example of full penetration keyhole in a 5.6 mm plate, high arc pressure and high PGFR (4.5 l/min). Orange colour below indicates full penetration.

For the other three plate thicknesses, only partial penetration keyhole defects are achieved, where the bead-width is smaller than the plate thickness. For greater thicknesses, thermal losses are three dimensional and the thermal gradient increased, resulting in an increase in melt-pool heat loss and consequently quicker solidification. As the energy to the fusion zone reduces and the energy lost to the base metal rises with more heatsink, the melting efficiency also drops for a fixed net heat input to the substrate.

Accordingly, more significant heatsink, with thicker plates, cause insufficient quantities of molten fluid to form and flow, with inadequate time to close the keyhole defects before solidification. A reduced arc pressure is therefore required to initiate a keyhole defect (Table 35). However, there is no explanation for the 9.5 mm thick plate, which requires further investigation.

5.3.3.6 Effect of Wire-feed on Keyhole Defects

Wire-feed and Wire position Effect on Titanium PTA Keyhole Defects

Before the experiment, it was theorised that the consumable wire, through the arc, would cause turbulence and shield the melt-pool below from the arc pressure (Figure 175), consequently affecting the keyhole defect transition.

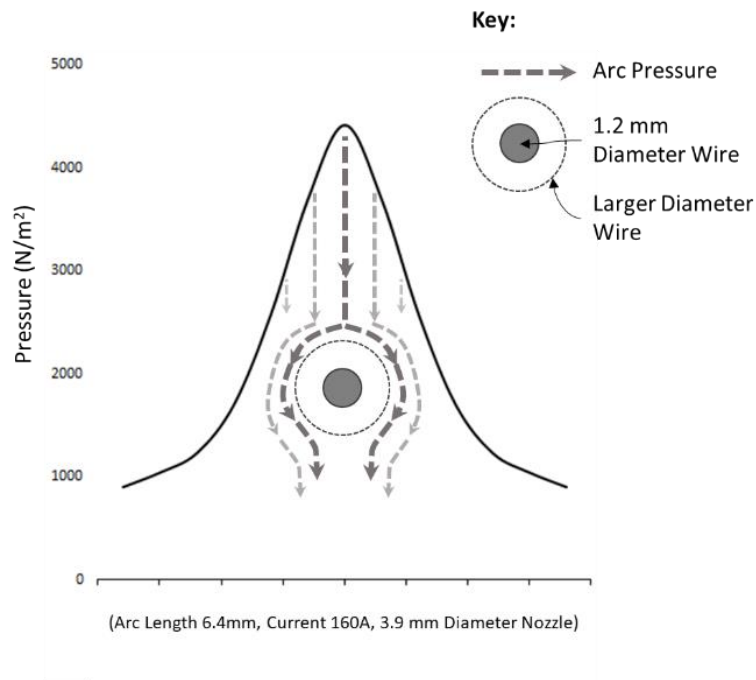


Figure 175 Effect of wire diameter on sheltering melt-pool from arc pressure.

However, the experimental results, shown in Figure 153, which compare no wire-feed and two wire-feed positions for titanium, indicate a small reduction in the required arc pressure to initiate keyhole defects with wire-feeding. However, the position of the 1.2 mm diameter wire does not affect the transition arc pressure. A possible explanation for the lack of effect from the wire position is that the 1.2 mm wire diameter is too small to shield the melt-pool. However, a larger diameter wire may have an effect, shown in Figure 175.

The small reduction in the required arc pressure to initiate keyhole defects with wire-feeding (Figure 153) at the same heat input is a result of the reduction in heat input experienced at the substrate because of the energy lost in the melting of the wire. The melt efficiency of the wire in the arc is significantly higher than the substrate, which is affected by thermal losses reducing the actual heat input to the substrate and hence the arc pressure required to initiate keyhole, in line with Figure 144.

The deposited beads illustrated in Table 37 indicate the number of keyhole defects for the same parameters, reducing with wire-feed and wire-feed position for the three transition points. This is a result of the increasing wire-feed rate and subsequently increased amount of molten metal, enabling defect closure.

Effect of Heat Input on Titanium Wire-feed Keyhole/No Keyhole Defect Transition

Figure 154 illustrates the effect of increasing heat input with wire-feed on the keyhole defect transition for titanium. The arc pressure values required to initiate keyhole defects are illustrated in Table 40 and show that, at lower heat inputs and with wire-feed, the keyhole defect transition arc pressure is reduced. The results align with the titanium heat input results of Figure 144 – reducing the heat input to the substrate and melting efficiency reduces the arc pressure value required to initiate keyhole defects.

Table 40 Effect of heat input on arc pressure required to initiate titanium keyhole whilst wire-feeding.

Arc pressure required to initiate titanium keyhole for different heat inputs and wire-feed rates.		
Heat Input (kJ/mm)	Wire-feed Rate (m/min)	Arc Pressure to initiate keyhole (N/m²)
0.54	None	4657.28
0.54	4	4431.08
0.64	None	5943.05
0.64	4	5558.25

By establishing the intersect of the keyhole defect transition at a heat input of 0.64 kJ/mm with 4 m/min wire-feed, shown in Table 40, with the no wire-feed heat input plot of Figure 144, an extrapolated heat input value can be determined (Figure 176). The

established heat input value at the substrate is 0.61 kJ/mm, a heat input reduction of 0.03 kJ/mm as a result of the heat diverted from the substrate to melt the wire-feed.

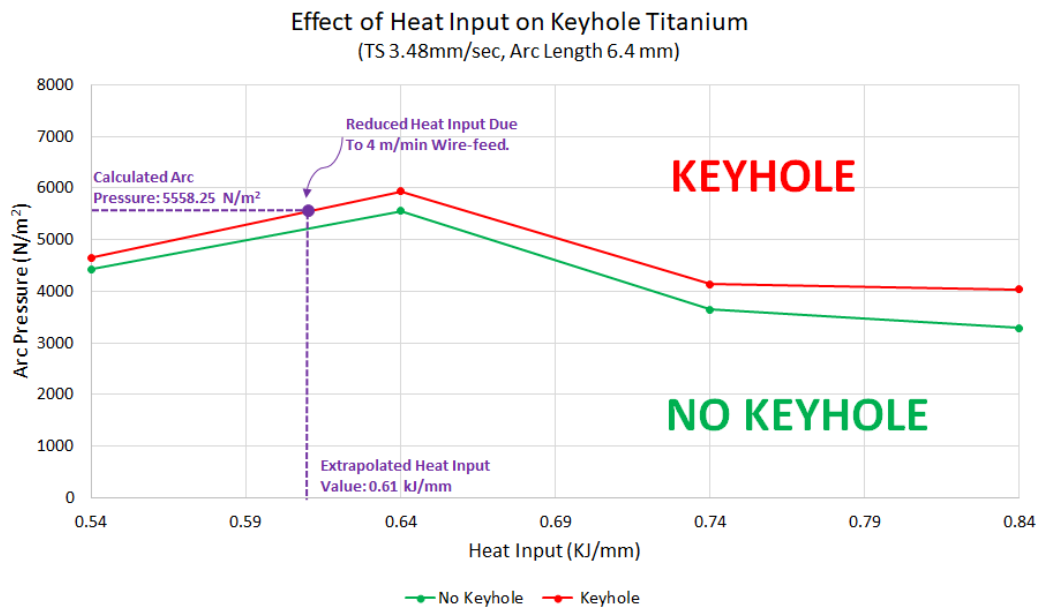


Figure 176 Reduced heat input because of wire-feed.

5.3.3.7 Keyhole Defect Depth

The variation in keyhole depth with heat input results (Figure 155 and Figure 156) for stainless-steel and titanium respectively shows that keyhole depth increases with arc pressure and generally with increasing heat input. However, this more or less follows the heat input/arc pressure plots of Figure 142 and Figure 144 for stainless-steel and titanium, which are not linear. The keyhole depths do not therefore fully follow a trend of increasing with heat input, affirming the affinity between keyhole depth and arc pressure.

The variation of keyhole depth with travel speed results (Figure 158 and Figure 159) for stainless-steel and titanium also shows that keyhole depth increases with arc pressure. However, keyhole depth does not align with travel speed, instead more or less following the travel speed/arc pressure plots of Figure 148 and Figure 151 for stainless-steel and titanium, which are not linear. The keyhole depths therefore do not fully follow a trend of increasing with travel speed, affirming the affinity between keyhole depth and arc pressure.

Figure 177 and Figure 178 show a comparison of keyhole depth for varying heat input and travel speed for stainless-steel and titanium, showing that the keyhole depths are significantly different for the same parameters. Titanium keyhole depth is deeper for varying heat input and travel speed. The increased depth for titanium is a result of the difference in physical and thermal properties of the two substrate materials (Table 26). The results suggest that keyhole is more easily formed for stainless steel: i.e. lower heat inputs, travel speeds and arc pressures are required than for titanium.

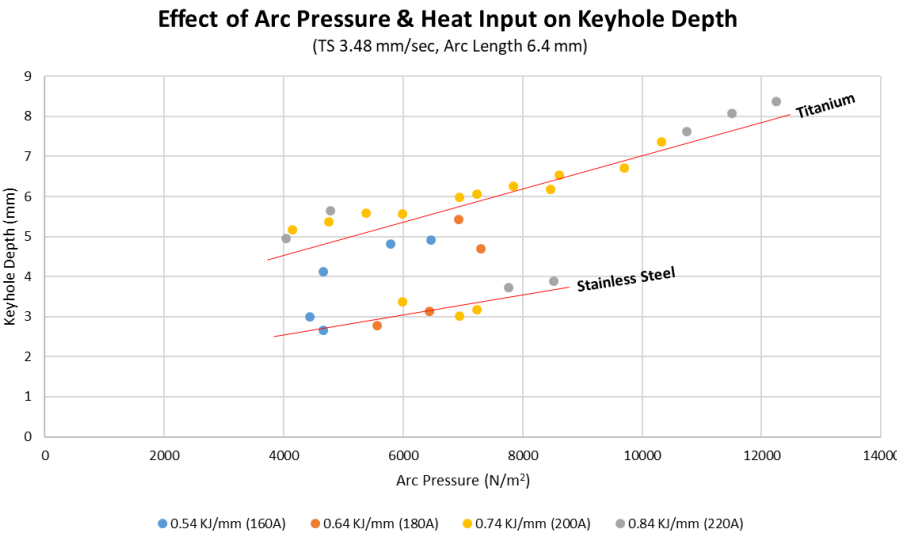


Figure 177 Comparison of the effect of arc pressure and heat input on keyhole depth for stainless-steel and titanium.

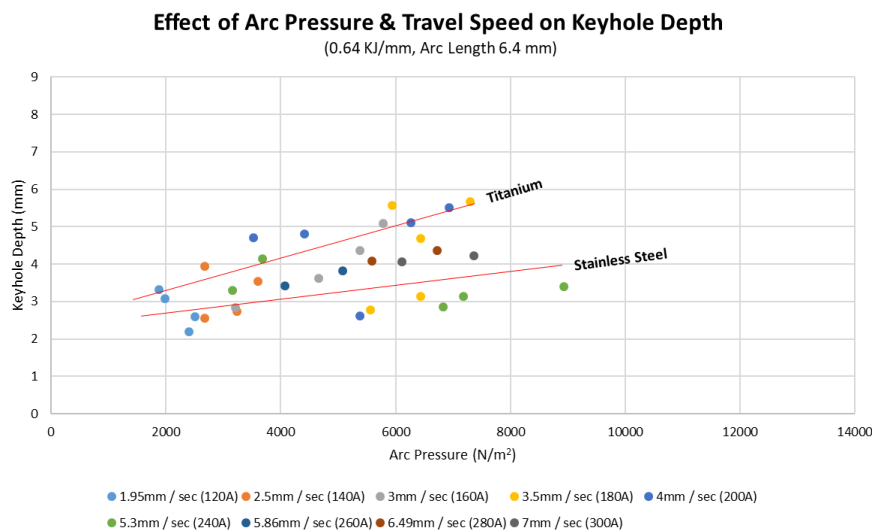


Figure 178 Comparison of the effect of arc pressure and travel speed on keyhole depth for stainless-steel and titanium.

Figure 160 shows a comparison of the reduced melt-pool depression as a result of a lower arc pressure for titanium (Figure 160 ‘A’) and an increased melt-pool depression with increased arc pressure (Figure 160 ‘B’) for a 5.6 mm thick plate. Compared with the increased arc pressure shown in Figure 157 ‘B’ for a 13.4 mm thick plate, the keyhole defect depth in Figure 160 ‘B’, for a 5.6 mm thick plate, appears to be more substantial – the start of full penetration keyhole (Figure 160).

The plot in Figure 161 also shows that partial penetration keyhole defect depth increases with arc pressure and generally with plate thickness. As the plate thickness enlarges, the thermal gradient increases, resulting in an increase in melt-pool heat loss, and consequently quicker solidification. The more significant heatsink causes insufficient quantities of molten fluid or time to close the keyhole defects. A reduced arc pressure is therefore required to initiate a keyhole defect (Table 35). However, there is no explanation for the 9.5 mm thick plate, which requires further investigation.

As outlined in the literature review, Adonyi, Richardson and Baeslack (1992) established arc force increases for titanium substrate compared with stainless-steel for GTA (Figure 38) – a novel finding. The PTA empirical model does not take into consideration substrate material effects on arc force as this data is not available for PTA. However, if we suppose that the PTA titanium arc force is higher than steel, similar to the GTA study, for the same

parameters, this may be partially accountable for the increases in keyhole defect depth of titanium (Figure 177 and Figure 178).

5.4 Conclusion

This study has confirmed that arc pressure is the controlling parameter in determining whether a keyhole defect is formed when using a PTA energy source for a given material and thermal conditions.

This is irrespective of how the arc pressure was varied. Utilising an empirical model developed from the data in Chapter 3, it was possible to control the arc pressure using a variety of parameters systematically and accurately. A sharp transition in going from no keyhole to keyhole defect situation was observed – a keyhole defect threshold. This means that, by using arc voltage as a proxy for arc pressure (Chapter 4), it is possible to set suitable conditions to avoid a keyhole defect and also to monitor real time if the arc pressure deviates near a regime where a defect could occur.

The PTA process, in terms of process parameters and torch design, is characterised using the derived model in terms of keyhole defect formation.

Using this control of the arc pressure, a systematic study revealed the dependence of the transition/threshold on the thermal conditions and material type with the following findings:

- The arc pressure transition goes up with heat input for stainless steel.
- The arc pressure transition initially goes up with heat input for titanium but reduces at higher heat inputs because of the appearance of a different defect type – a continuous keyhole defect: type 3 closed. This appears because of the very deep keyhole in titanium compared with stainless steel, combined with the smaller melt-pool size and different geometry.
- The arc pressure transition increases with travel speed at constant heat input up to maximum before dropping again. The increase results from increasing melting efficiency with travel speed. The decrease is a consequence of unstable initial conditions at the start of the deposit at very high travel speeds.

- The addition of wire-feed and its position does not have a significant effect on the transition value, leading to a small drop. However, a larger diameter wire might be more influential.
- Keyhole defect depth is proportional to the applied arc pressure. Keyhole can be achieved more readily for stainless steel. However, for the same parameters, titanium keyhole defect depth is deeper.

5.5 Implications for WAAM

- The stainless-steel and titanium keyhole defect threshold plots for travel speed and heat input, shown in Figure 171 and Figure 172, enable the optimisation of the WAAM process to avoid keyhole defects.
- High heat input is beneficial to WAAM as it corresponds to increased currents, which have the potential to enable higher WAAM deposition rates. However, there appears to be a limit for titanium (Figure 171) because of a change in keyhole defect type to type 3 closed, which requires a lower arc pressure to form. As a result, at higher heat inputs, the maximum arc pressure permitted before a keyhole defect forms is reduced. The heat input therefore limits the current used and potentially restricts the potential for increased titanium WAAM deposition rates. For stainless steel, which does not undergo type 3 closed keyhole defect formation, an increased arc pressure is required at higher heat inputs to instigate a keyhole defect, shown in Figure 171. Higher currents and correspondingly increased WAAM deposition rates are therefore possible for stainless-steel.
- Travel speed can be increased for both stainless-steel and titanium up to a point for each material, where the melting efficiency drops off (Figure 172). Operating in this region maximises the WAAM deposition rate and safeguards against keyhole initiation and keyhole defects to WAAM parts.
- Two examples of WAAM parts affected by surface keyhole defects are shown in Table 41, both requiring repair before completion of the next layer, or final machining, can be undertaken. Utilising the threshold data of this study, specific parameters can be selected to mitigate against keyhole defects while maximising the WAAM deposition

rate. This therefore maximises the WAAM process equipment availability and potentially reduces the build time of WAAM parts.

Table 41 Example of surface keyhole defects on titanium WAAM parts.

Example of arc pressure-induced surface keyhole defects on titanium WAAM Parts. Keyhole defect depth and geometry indicated.		
Keyhole Defect Examples	A	B
		
	Keyhole Defect Depth (mm)	2.08 up to 3.47
	Keyhole Defect Geometry (mm)	3.32 x 3.16 up to 5.19 x 3.55
		3.86
		3.16 x 2.83

- A possible application for the type 3 closed keyhole defect – autogenous sub-surface channel – is the incorporation of coolant or heating medium channels in a WAAM part. By spiralling the channel around a cylindrical item, the channel length can be maximised. Figure 179 illustrates a WAAM part – pressure vessel – that, when completed (Figure 179 ‘A’), if rotated while horizontal (Figure 179 ‘B’), an external spiral channel (Figure 179 ‘C’) can be added, with the PTA torch in the flat position. The channel would allow coolant or a heating medium to circulate the external of the pressure vessel. As this would be incorporated within the part, the thermal conduction to the contents of the pressure vessel would be maximised. At the same time, this would reduce manufacturing and installation/attachment issues and costs associated with incorporating an external separate heating/cooling system by means of a traditional method.

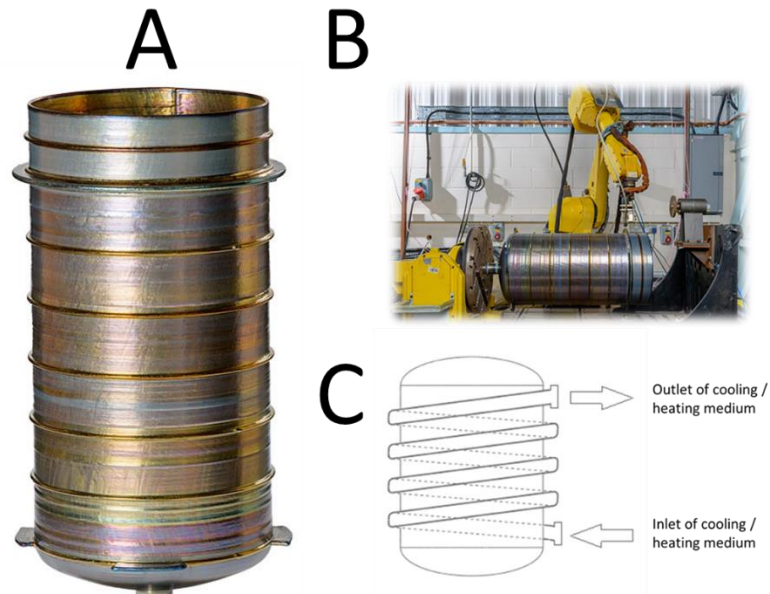


Figure 179 A] WAAM3D consortium project part – prototype titanium alloy (Ti-6Al-4V) pressure vessel for future manned missions of space exploration, B] The part is deposited using the WAAM process, C] Potential use for the sub-surface channel – cooling or heating channel.

Chapter 6

PTA Electrode TEAR Growth, Material Longevity and Wear Investigation

6.1 Introduction

Recent developments in the use of automated PTA for WAAM, which operates for extended duty cycles, require reliability and repeatable operation with maximum equipment availability. This has implications for standard available electrodes, which historically only run for short durations: relatively short weld lengths.

A feature of PTA is the higher velocity and temperature of the arc that the electrode must endure. WAAM requires a high PTA torch duty cycle, subjecting the non-consumable electrode to relatively high currents, argon gas and high temperatures for sustained periods to enable the continuous deposition required for the layer-by-layer build of WAAM components.

An understanding of PTA electrodes is important as awareness of the mechanisms and behaviours of PTA electrode wear during use and appreciation of the effect of electrode material and geometry on electrode longevity and wear could be used to optimise electrodes for WAAM operation and maximise electrode life.

Electrode wear in WAAM is important as the equipment must run for a maximum period while avoiding interruptions for the need to change electrodes – maximising equipment availability.

A small number of studies have been undertaken into GTA electrodes, with a smaller number undertaken for PTA electrodes – on doped electrode behaviour – but these have covered only short periods, and do not look within the electrode.

This study therefore aims to clarify what factors principally affect electrode lifespan and whether this can be maximised.

The objectives of this study are to:

- Quantify wear behaviour as a function of various factors, including electrode tip shape, material type, arc starting, environment, and operation type.
- Investigate what mechanism is behind the electrode wear behaviour.
- Identify factors limiting electrode lifespan.
- Determine if improvements can be made to optimise electrode lifespan.

6.2 Background

Electrodes are manufactured from tungsten because of its high melting temperature: 3410°C (Callister, 2010). The electrode material is typically a combination of tungsten and a small percentage (approximately 1–4%) of oxide, produced through powder metallurgy and fabricated from the sintered material. The oxide reduces the material work function and aids arc ignition. 2% thoriated electrodes were traditionally the material of choice for GTA applications, which transferred into PTA use. However, because of health and safety concerns over their use and exposure to low-level radioactive thorium, critically during grinding operations, other safer combinations have been developed, mainly for GTA use including: zirconiated, ceriated, rare earth and lanthanated.

The GTA melt-pool is susceptible to tungsten electrode contamination through contact or electrode tip detachment – less so with PTA because of the arc ignition method, longer arc lengths than GTA, improved electrode cooling and its encapsulation within the nozzle and torch body. As a result of the historical experience of manual GTA, tungsten inclusions in welding, reliable NDT methods and procedures have been developed to identify the inclusions. The intensity of tungsten, as a result of its high atomic number, also makes it straightforward to identify with X-ray NDT.

Nevertheless, failure or premature deterioration of the electrode requires its replacement, reducing equipment availability. Additionally, timely replacement of the electrode is needed to prevent electrode tip detachment, and consequently the likelihood of a tungsten inclusion in the melt-pool, which necessitates mechanical removal – e.g. grinding and consequent repair.

The longer durations of continual operation increase the electrode rate of wear and deterioration, which, unlike GTA electrodes, cannot always be sharpened and reused, rendering some PTA electrodes consumable with a finite life, as in the case of this study's PWP Viper MC PTA torch.

For WAAM applications an electrode with excellent tip retention, improved current-carrying capacity, a low wear-rate, stable arc characteristics, prolonged longevity, a high electrode erosion resistance for a range of arc powers and able to facilitate excellent arc ignition is therefore critical.

Through understanding different electrode compositions, the most appropriate combination can be selected, and a longer electrode life facilitated for PTA WAAM operations.

Another implication of electrode material relating to construction, geometry and its changes resulting from wear is the effect of the electrode on PTA arc pressure, covered in Chapter 3.

6.2.1 Associated PTA Torch Electrode Wear Terminology

Figure 180 illustrates the different stages of electrode transformation with use. The new electrode 'A' exhibits a polished as machined surface finish, while the used electrode 'B' shows a slight change in tip parallel length geometry and a mat coating across the shaft and bevel surfaces. The heavily used electrode 'C' indicates a change in length, a loss of the tip parallel length section and a change in tip geometry. A significant growth, referred to in this study as TEAR, has developed on the tip bevel, along with a heavily coated surface.

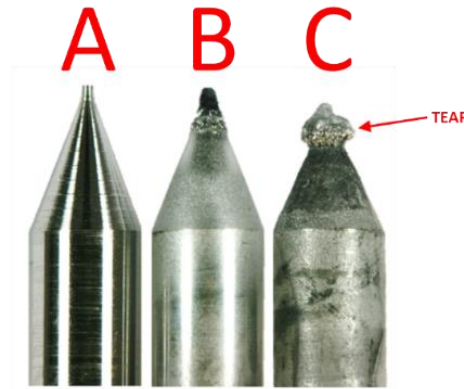


Figure 180 Stages of 2% thoriated electrode deterioration with use. A] New, B] After one hour at 180 A, C] After eight hours at 180 A, TEAR is indicated.

A micro image of the TEAR, which forms on the bevel section of the electrode tip with use, is shown in Figure 181. The changes in tip geometry, loss of material and necking are visible.

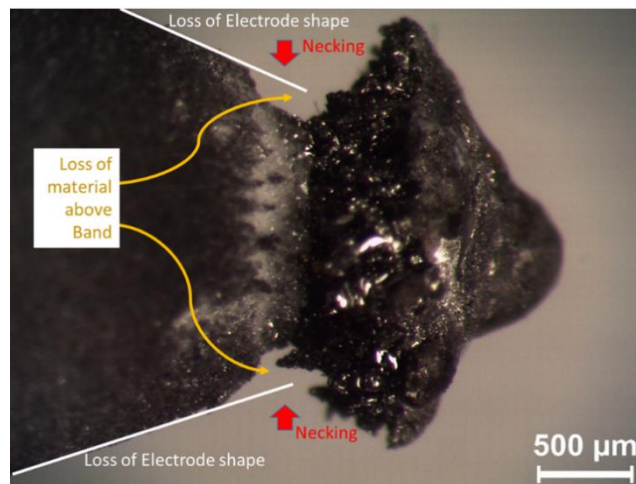


Figure 181 TEAR of a heavily used 2% thoriated electrode.

There is little published information about PTA electrodes, especially relating to WAAM, wear-rates, materials of construction, arc starting issues or the TEAR, including how it is formed, its composition and how it affects the PTA process or arc pressure. This chapter aims to address these unanswered questions and investigate, for various oxide/tungsten combinations, mechanisms of electrode deterioration, distinct wear-rates, tip retention and electrode geometries in an attempt to establish the best available electrode to meet specific WAAM electrode requirements. The effects of electrode material, geometry and wear on arc pressure are covered in Chapter 3.

6.3 Methodology

6.3.1 Equipment Setup and Parameters

An overview of the experimental setup is shown in Figure 182 and consists of a PTA torch, power supply with auxiliary coolant, gas (plasma and shielding) supply and process control, as well as an integrated six-axis industrial robotic arm for torch positioning, process measurement equipment and a water-cooled copper-block. The process parameters and equipment settings are listed in Table 42.

For information on measurement difficulties and errors, refer to Appendix C.

This setup allowed the investigation of TEAR growth, electrode wear and the effect of different tungsten oxide electrode compositions. The PTA arc was applied to a water-cooled copper-block, with no wire deposited, for a timed duration. All PTA electrodes were photographed, weighed and measured three times, and an average was calculated before and after their use to ascertain the wear-rate and TEAR growth with PTA operation. Macro and SEM images of new, heavily used electrodes and TEAR formations were produced in addition to the use of energy dispersive (EDS) detector counts to analyse TEAR and surface finish composition, as well as electrode dopant diffusion and depletion.

Off the shelf, PTA electrodes to suit this study's PWP Viper MC torch with compositions different to the standard 2% thoriated tungsten were not available. Specialist electrodes were therefore manufactured specifically for this study in various materials. These included pure tungsten (W), ceriated tungsten (W-CeO₂), lanthanated tungsten (W-La₂O₃), zirconiated tungsten (W-ZrO₂), rare earth doped tungsten and a mystery material named 'material X', supplied specifically for this investigation by tungsten manufacturer, Wolfram Industrie.

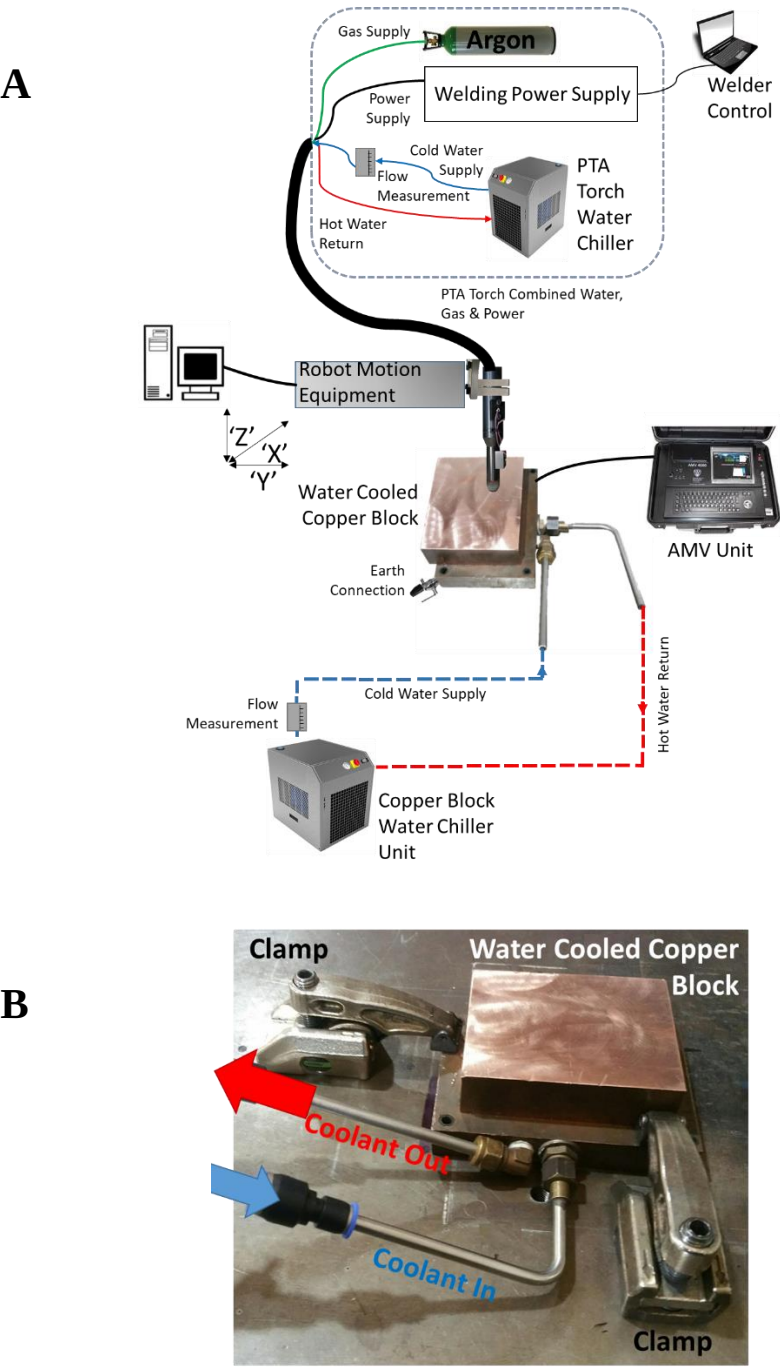


Figure 182 Equipment setup: A] Schematic (PTA), B] Enlargement of water-cooled copper-block.

Table 42 Process parameters and equipment settings – PTA electrode material longevity and wear study

Process Parameters and Equipment Settings	Values
Electrode Polarity	DCEN
Current	140, 160, 180, 200 A
Torch Angle to Substrate	90 ⁰
Shielding Gas Composition	99.998% Argon
Copper-block Chiller Flow-rate	13.6 l/min Approx.
Process Monitoring/Data logging Equipment	AMV 4000
Sample Rate of Data Logger	20,000 Samples Per Second – 20 kHz
Industrial Robotic Arc	KUKA KR 150 L110-2 F2000 6 Axis 150kg load
Arc Length	6.4 mm
Nozzle Standoff Distance	5 (See Note 2)
Straight-bore Nozzle Diameter	3.9 mm
Electrode Type:	
▪ PWP AC Electrodes	Two Tip Types: 1. Ball End, 2. Double Cone
▪ Standard PWP DC Electrode	(Geometry Below)
Electrode Diameter	4.0 mm
Electrode Length	29 mm
Electrode Setback	1.4 mm
Electrode Tip Angle	40 ⁰
Electrode Tip Diameter	0.36 mm, unless otherwise stated
Specialist Electrode Angle:	20 ⁰ and 60 ⁰
Electrode Material:	
▪ 2% (wt.) Thoriated Tungsten (Standard)	▪ 0.8% (wt.) Zirconiated
▪ 2% (wt.) Ceriated	▪ 2% (wt.) Rare Earth
▪ 2% (wt.) Pure Tungsten	▪ 2% (wt.) Material ‘X’
▪ 2% (wt.) Lanthanated	
PTA Torch	PWP Viper MC (Water-cooled)
Shielding Gas Flow-rate	15 l/min
Plasma Gas Composition	100% Argon
Plasma Gas Flow-rate	0.8 l/min
PTA Torch Coolant Flow-rate	3.1 l/min
PTA Torch Umbilical Cable Length	12.5 Foot/3.81 m
DC 550A Electrical Power Source Supply	EWM Tetrix 552 RC Plasma CW GR (electrode negative – DCEN and DCEP)

Note 1 – No welding wire was used in the experiment.

Note 2 – As a result of a PTA ESB of 1.4 mm, the PTA nozzle standoff distances/CTWD equates to an arc length of 6.4 mm.

6.3.2 Investigation of the Mechanisms and Behaviours of PTA 2% thoriated electrode wear

Electrode Wear Measurement

To investigate electrode wear with use, calculate a wear-rate and examine changes to electrode tip geometry and TEAR growth of standard 2% thoriated tungsten electrodes, new electrodes were subjected to a moving PTA arc, shown in Figure 182, with fixed parameters of 180 A, as in Table 42:

- For a 60-minute duty cycle with continuous movement – one arc start and one arc termination.
- For a 60-minute duty cycle with continuous movement, stopping at five-minute intervals to be photographed and for length and weight measurement changes to be recorded – 13 arc starts, 13 arc terminations and time to cool on each occasion to enable handling for measurement.

Both electrodes were then compared with a heavily used electrode, which had been subjected to similar parameters during WAAM part building operations, but for a long duration.

Geometry measurements of the TEAR and electrode tip changes were undertaken post-experiment using AxioVision microscope software and scaled electrode photographs.

For a consistent wear determination, each electrode, before and after use, was:

- Weighed to three decimal places three times and an average calculated, shown in Figure 183.
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

On completion of each 60-minute electrode trial (Table 42), the above procedure was repeated with a new electrode.

Using the following equations, the electrode wear-rates for both length and weight were calculated:

$$\text{Electrode Wear (Change in Length): } E_{L\Delta} = E_L \text{ Initial} - E_L \text{ Final} \quad \text{Equation 15}$$

$$\text{Electrode Wear (Change in Weight): } E_{W\Delta} = E_W \text{ Initial} - E_W \text{ Final} \quad \text{Equation 16}$$

$$\text{Electrode Wear-rate (Weight): } E_{WRW} = \frac{E_W \text{ Initial} - E_W \text{ Final}}{T_W} \quad \text{Equation 17}$$

$$\text{Electrode Wear-rate (Length): } E_{WRL} = \frac{E_L \text{ Initial} - E_L \text{ Final}}{T_W} \quad \text{Equation 18}$$

Where:

E_L = Electrode Length (mm)

E_{WRL} = Electrode Wear-rate - Length (mm/min)

E_W = Electrode Weight (g)

E_{WRW} = Electrode Wear-rate - Weight (g /min)

$E_{L\Delta}$ = Change in Electrode Length (mm)

T_W = Deposition Duration (Minutes)

$E_{W\Delta}$ = Change in Electrode Weight (g)

To prevent electrode identity mix-up, each electrode was labelled and stored separately, shown in Figure 183.

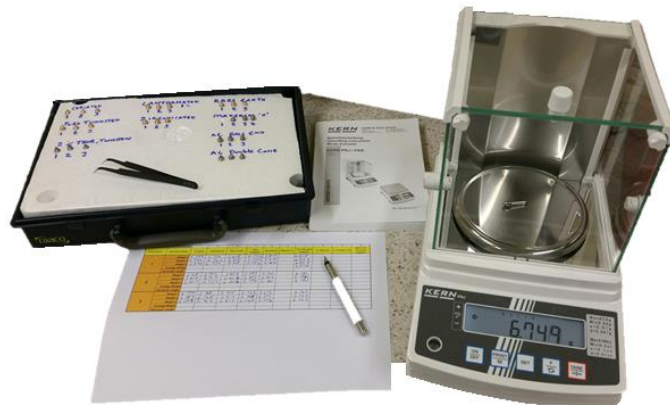


Figure 183 Weighing of each electrode, strict material isolation and traceability.

The calculated electrode wear-rates for both length and weight were compared with a heavily used electrode, which had been subjected to similar parameters during WAAM part building operations, but for six hours and eight minutes – 368 minutes.

Effect of Pilot Arc Voltage on TEAR Growth

PTA utilises a non-transferred arc, pilot arc, to initiate the main arc, and during torch moves through robot arm manipulation. When the main arc is not initiated, the pilot arc may remain operating. Welding equipment suppliers confirmed that, during normal main arc operation, the pilot arc remains initiated. It is therefore possible that the non-transferred arc continues to be in service while the main transferred arc is also in operation. The PTA pilot arc is a characteristic that is different from GTA, and therefore may be responsible for PTA TEAR growth. To establish the effect of pilot arc on TEAR growth, the voltage was minimised, and the results compared.

Effect of the Number of Arc Initiations on TEAR Growth

To determine if the number of arc initiations and arc terminations affects the TEAR growth of a 2% thoriated electrode, 13 arc starts were undertaken over a 60-minute duration – i.e. torch stopped and restarted 13 times over one hour. The electrode changes in weight, length, tip geometry and TEAR growth were compared with an electrode subjected to the same 13 arc starts but over a 120-second duration and fixed parameters of 180 A, set out in Table 42. This compares the effect of the number of arc starts against the duration in which they were applied.

For consistency, each electrode before and after use were:

- Weighed to three decimal places three times and an average calculated (Figure 183).
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

The results and final tip geometries were compared with a new 2% thoriated tungsten electrode.

Effect of Electrode Contamination

During normal operations over a long duration, a black residue is occasionally generated. To determine whether this is a result of electrode contamination, all electrodes were dipped in acetone before use. One electrode was purposely contaminated for comparison to establish not only if the residue formed but also whether surface contaminants affected arc initiation. An EDS detector count was used to analyse the surface black residue composition.

Examination of Change in Electrode Surface Finish and Surface Deposit with Use

To investigate the change in electrode surface finish with use for a 2% thoriated electrode (Figure 180 'B' and 'C'), macro and SEM images of used electrodes were produced in addition to using an EDS detector count to analyse the surface finish/deposit composition.

Comparison of 2% Thoriated Tungsten Electrodes Subjected to Different PTA Applications

Used 2% thoriated tungsten electrodes were photographed and compared to investigate the visible effect of their surface finish and tip geometry after being subjected to various applications, including duty cycle duration, plasma gas compositions and AC/DC parameters and applications.

6.3.3 Investigation of Electrode Material and Geometry and their Effect on Longevity and Wear

6.3.3.1 Electrode Material

Effect of Electrode Material Composition

To determine the effect of electrode material composition on the retention of tip geometry and wear-rate, seven electrodes with identical geometry but different material compositions, shown in Table 42, were subjected to a 60-minute cycle of operation, with fixed parameters of 180 A (Table 42).

After inspection, photography and measurement, the electrodes were then subjected to a further 60 minutes of operation – 120 minutes in total.

For consistency, before and after use, each electrode was:

- Weighed to three decimal places three times and an average calculated (Figure 183).
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

The results and final tip geometry after 60 and 120 minutes were compared with a new 2% thoriated tungsten electrode.

The electrode wear-rates for both length and weight were also calculated.

6.3.3.2 Electrode Geometry

Effect of Reduced Electrode Length and Nozzle Length on Cooling, Longevity and Wear

To ascertain if improved cooling of the copper nozzle and electrode increase their longevity and reduce their wear, a specialist short nozzle and 2% thoriated tungsten electrode were manufactured for this study, shown in Figure 184. The electrode and nozzle were subjected to a 60-minute cycle of operation with fixed parameters of 180 A, set out in Table 42.

Figure 184 shows the specialist short copper nozzle ‘A’ and short electrode ‘C’, both intended to increase the effect of torch cooling. For comparison, a standard nozzle and electrode are shown as ‘B’ and ‘D’ respectively.

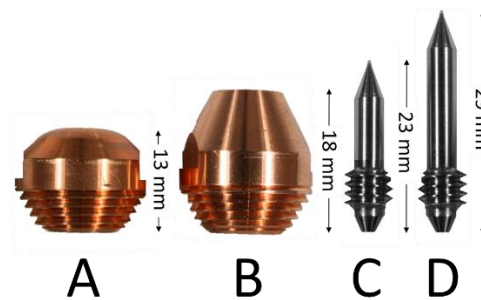


Figure 184 Specialist PTA nozzle and electrode length to increased PTA torch cooling effect: A] Short copper nozzle, B] Standard nozzle, C] Short electrode, D] Standard electrode.

The nozzle diameter, ESB, electrode tip geometry and all other electrode to nozzle geometries of the shorter nozzle and electrode remain the same as the standard nozzle and 2% thoriated tungsten used by this study, allowing a fair comparison.

After inspection, photography and measurement, the electrodes were then subjected to a further 60 minutes of operation – 120 minutes in total.

For consistency, before and after use, each electrode was:

- Weighed to three decimal places three times and an average calculated (Figure 183).
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

The results and final tip geometry after 60 and 120 minutes were compared with a new standard length 2% thoriated tungsten electrode and a standard-length nozzle, which were also subjected to the same parameters and duration of operation.

The electrode wear-rates for both length and weight were also calculated.

Effect of Electrode Length and Flat Tip Diameter

By subjecting four 2% thoriated tungsten electrodes with different lengths and flat tip diameters (Figure 62) to a PTA arc during the arc pressure measurements set out in Chapter 3, a comparison of the loss in weight and length, TEAR shape and electrode tip geometry changes with use was possible, with fixed parameters of 180 A (Table 42).

For consistency, before and after use, each electrode was:

- Weighed to three decimal places three times and an average calculated (Figure 183).
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

The electrodes were compared with a heavily used standard 2% thoriated tungsten electrode, which had been subjected to similar parameters during WAAM part building operations but for 10 hours of uninterrupted operation.

Investigation of the Effect of Electrode Length and Flat Tip Shape on Arc Initiation

To determine whether the length of an electrode or a flat tip diameter affect the ability of an electrode to initiate an arc, a 2% thoriated electrode was subjected to numerous arc

starts within a standard 3.9 mm nozzle between 19 reductions in length, up to the point of failure of arc initiation. For each iteration, the electrode was weighed to three decimal places three times and an average weight calculated. The length was also measured three times with a calibrated micrometre and an average length calculated.

The final electrode and cathode spot was photographed with a macro lens and compared with a new electrode.

Effect of Electrode Tip Angle

By subjecting three 2% thoriated tungsten electrodes with tip angles of 20° , 40° and 60° (Figure 61) to 20 minutes of operation, a comparison of the calculated electrode wear-rates of loss in length and weight with use was possible, with fixed parameters of 180 A (Table 42).

For consistency, before and after use, each electrode was:

- Weighed to three decimal places three times and an average calculated (Figure 183).
- Photographed with a macro lens.
- Measured with a calibrated micrometre three times and an average calculated.

The electrode wear-rates for both length and weight were also calculated.

Three further 2% thoriated tungsten electrodes with tip angles of 20° , 40° and 60° (Figure 61) underwent 12 minutes of operation at 140 and 200 A, shown in Table 42. This allowed a comparison of TEAR shape, TEAR location and electrode tip geometry with use. To allow a comparison, each electrode was photographed with a macro lens before and after use. Macro and SEM images of the angled electrodes (20° , 40° , and 60°) were also generated and compared.

6.4 Results

The results are divided into two distinct sections: mechanisms and behaviours of PTA electrode wear and the effect of material and geometry on electrode longevity and wear.

6.4.1 Mechanisms and Behaviours of PTA 2% Thoriated Electrode Wear

Electrode Wear and TEAR Growth

Time-lapse photography (Figure 185) illustrates, for a new 2% thoriated tungsten electrode at set parameters of 180 A (Table 42), the change in electrode tip geometry, electrode length through wear, TEAR growth and surface residue deposits at five-minute intervals. For comparison, an electrode run for a duration of seven hours and 45 minutes with the same parameters is also shown.

The deterioration of the electrode tip geometry and loss of the tip parallel length (Figure 43) is clearly visible. The electrode surface turns from a machined polish to a dull finish with time. The gradual growth of the TEAR is also visible, culminating in a large TEAR after seven hours and 45 minutes.

Figure 186 illustrates the measured average electrode length wear (change in length) for different conditions for 2% thoriated tungsten electrodes, using Equation 15. The calibrated micrometre used has an accuracy of ± 0.0003 mm and resolution of 0.001 mm. As all measurements were undertaken three times and an average measured, the values, however small, are therefore considered real.

The results indicate a minimal change in length over the first 60 minutes, which increases significantly during the second 60 minutes. The effect of 13 arc starts, 13 arc terminations, 12 cooling periods and 60 minutes of arc interaction has increased the change in length, compared to one arc start and one arc termination over 60 minutes of operation. The minor increase in electrode length as a result of 13 arc starts and 13 arc terminations undertaken over a 120-second duration probably results from electrode tip melting and corresponding tip geometry changes. Unsurprisingly, the 2% thoriated tungsten electrode subjected to the same parameters for six hours and approximately eight minutes during WAAM operations has suffered the most significant change in length, though even this is minimal.

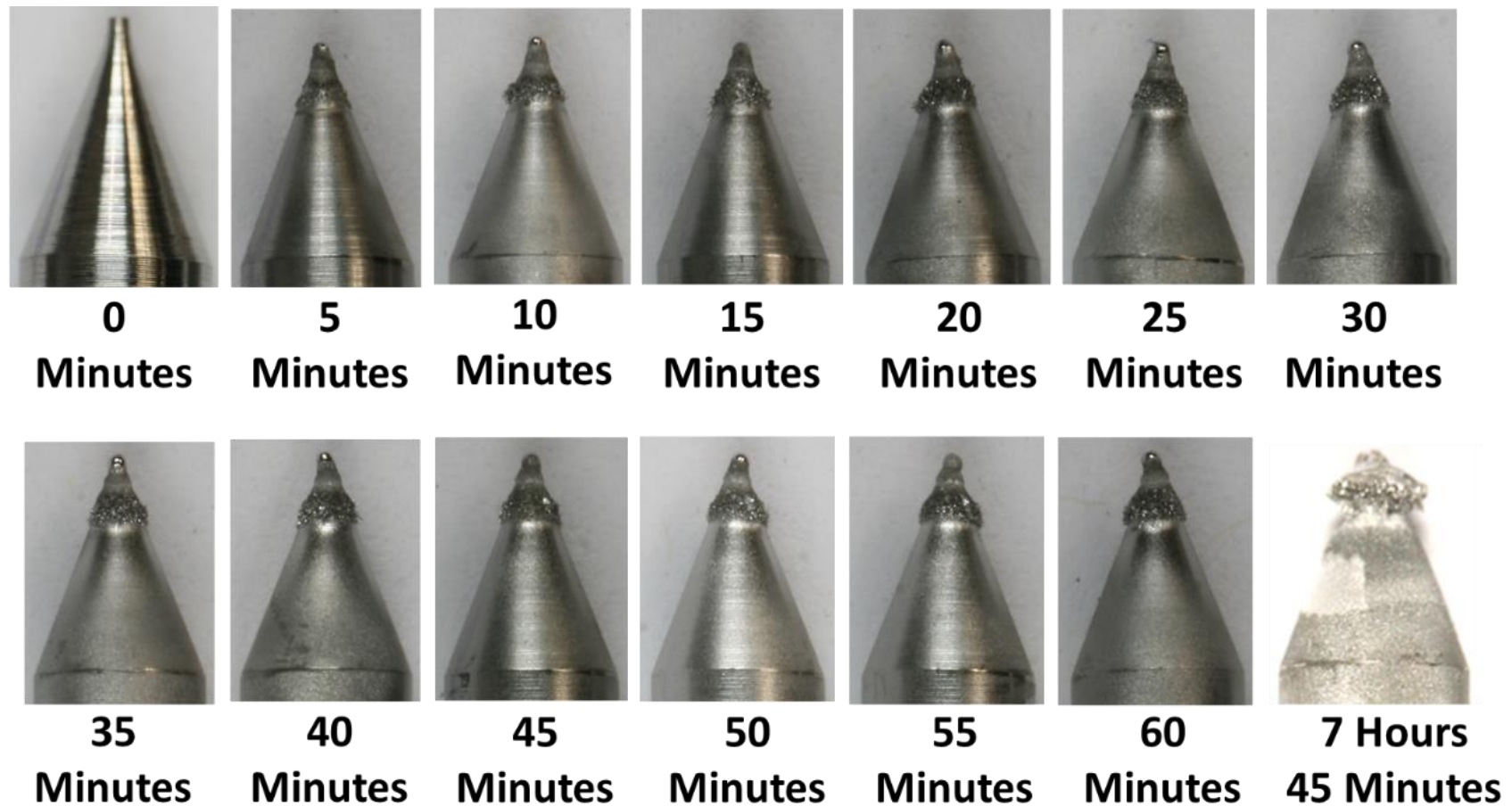


Figure 185 TEAR growth, PTA 2% thoriated tungsten electrode run for a duration of 60 minutes, photographed at five-minute intervals. For comparison, an electrode used during WAAM for the same parameters, but 7 hours 45 minutes (465 minutes) is added.

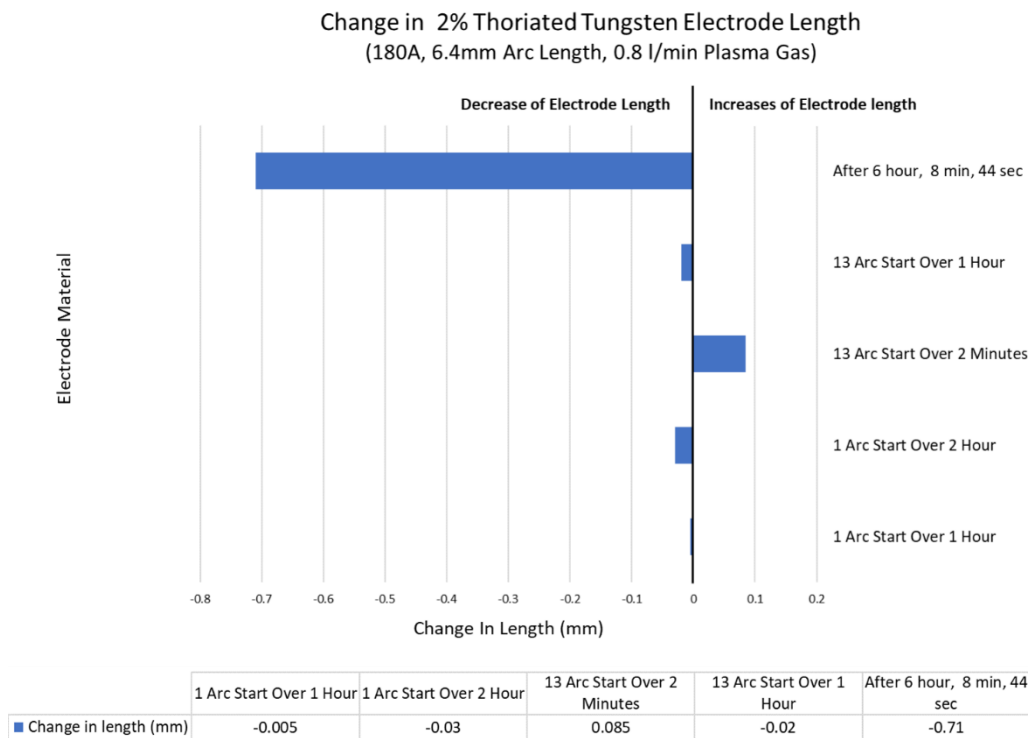


Figure 186 Measured length wear-rate for 2% thoriated tungsten electrodes under different conditions.

This indicates that arc voltage could be utilised as a means of measuring electrode length and electrode wear because of the changes in arc length.

Figure 187 illustrates the measured average electrode weight wear (change in weight) for different conditions with time for 2% thoriated tungsten electrodes, using Equation 16. The calibrated precision balance used has an accuracy of ± 0.001 g and resolution of 0.001 g. As all measurements were undertaken three times and an average calculated, the values, however small, are therefore genuine.

The results indicate a change in weight over the first 60 minutes, which increases at a reduced rate in the second 60 minutes. The effect of 13 arc starts, 13 arc terminations, 12 cooling periods and 60 minutes of arc interaction has significantly increased the change in weight, compared to one arc start and one arc termination over 60 minutes of operation, higher than 120 minutes of arc interaction. The 13 arc starts, and 13 arc terminations undertaken in a 120-second duration had zero measurable effect on the weight. The 2% thoriated tungsten electrode subjected to the same parameters for six hours and approximately eight minutes during WAAM operations has suffered the most significant

change in weight, though even this is still small, indicating no loss of electrode tip in normal service, up to 6 hours, and consequently no possibility of tungsten inclusions.

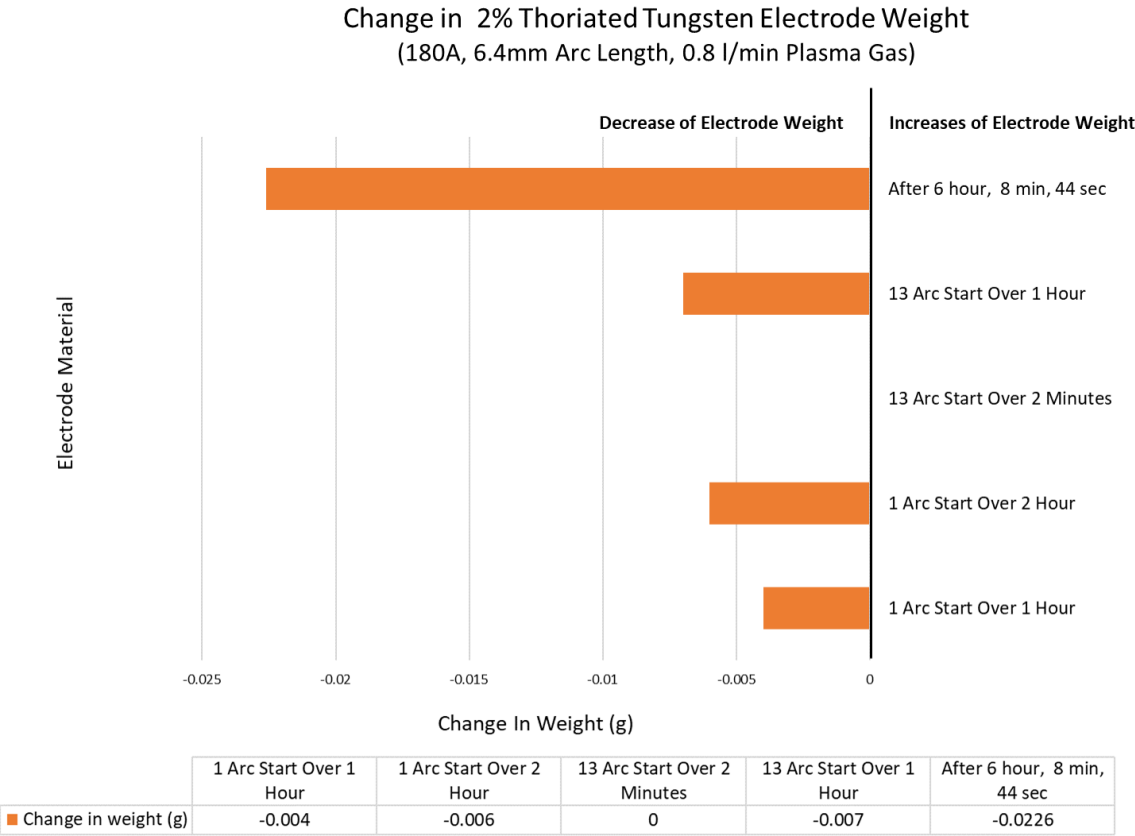


Figure 187 Measured weight wear-rate for 2% thoriated tungsten electrodes under different conditions.

Figure 188 shows the measured TEAR growth over 60 minutes, taken at five-minute intervals, for the 2% thoriated tungsten electrode shown in Figure 185, illustrated in both height and diameter gain. The results indicate a steady increase in TEAR height gain over the first 15 minutes, which continued at a reduced rate for the remaining duration. The increase in TEAR diameter also shows an initial increase in the first five minutes, while the TEAR is established. However, the remaining growth is at a low but steady rate, increasing with duration up to the dashed line (Figure 188 ‘A’ and ‘B’), indicating the TEAR height and diameter after 465 minutes (Figure 188 ‘C’).

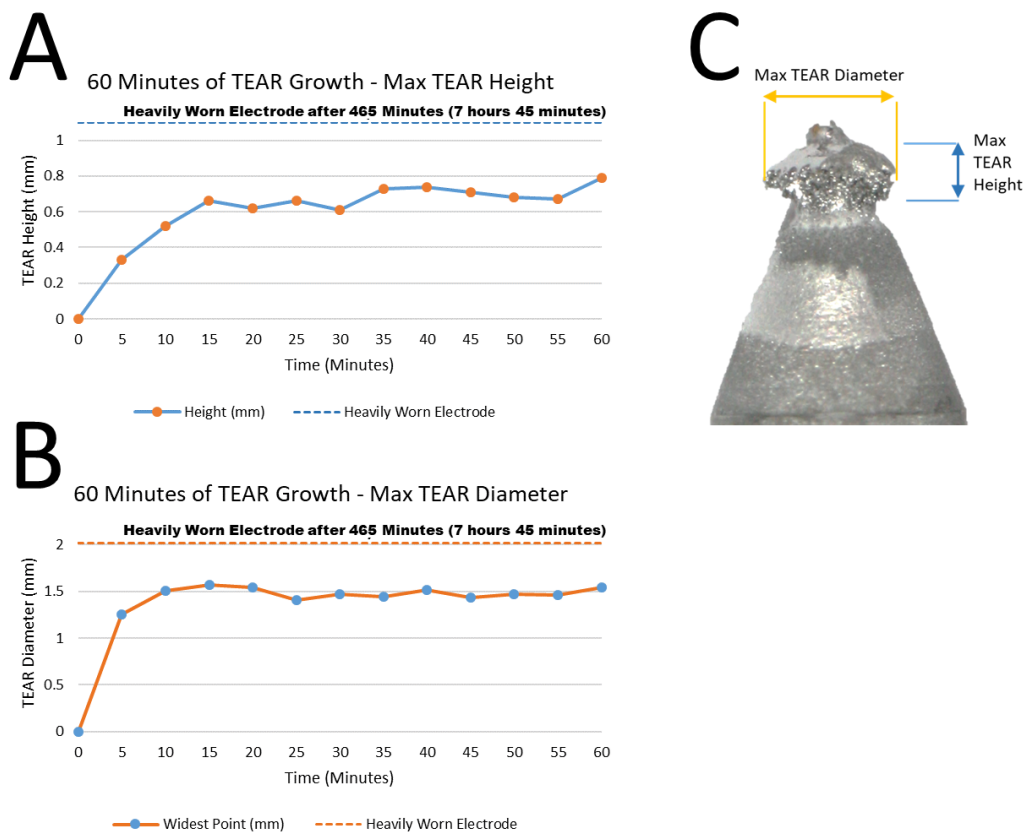


Figure 188 TEAR growth over 60 minutes at five-minute intervals. A] Maximum TEAR height gain, B] Maximum TEAR diameter gain, C] TEAR measurement locations. Heavily worn electrode values after 465 minutes of use indicated.

Figure 189 illustrates a comparison of the TEAR growth with the number of arc starts, arc terminations and associated cooling periods for the same operating conditions, at 180 A (Table 42) over a 60-minute duration. It is clear that the number of arc starts considerably impacts TEAR growth, along with the length of the operation. As the TEAR develops it initially appears jagged and porous, shown in Figure 189 ‘C’, with the appearance of iron filings on a magnet. However, with duration, the TEAR density increases, and the deposits consolidate (Figure 189 ‘D’).

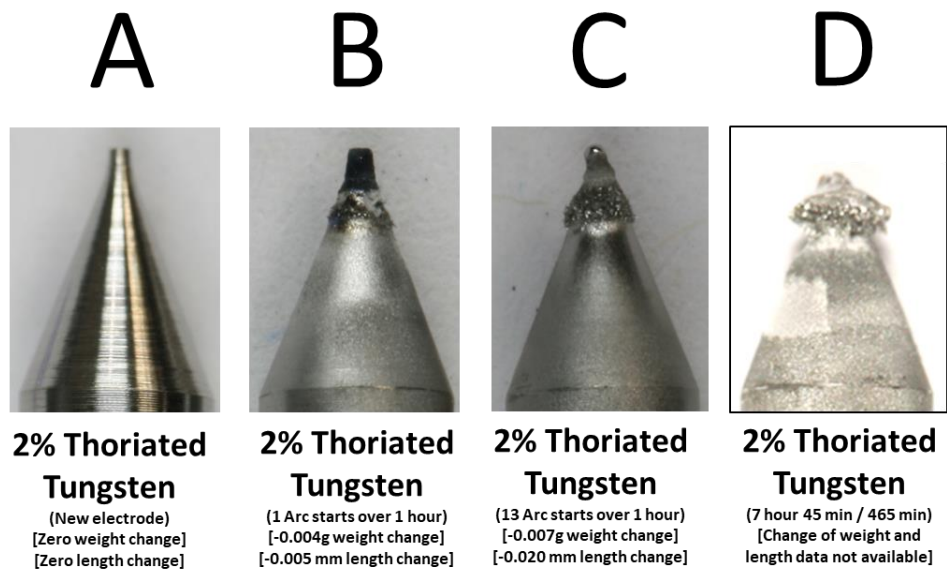


Figure 189 TEAR comparison photographs of PTA 2% thoriated tungsten electrode after 60 minutes. A] New electrode, B] One arc start and termination, C] 13 arc starts, terminations and cooling periods, D] Heavily used electrode up to 465 minutes.

Effect of Pilot Arc Voltage and Number of Arc Initiations on TEAR Growth

Figure 190 presents a comparison of the change in weight, length, tip geometry and TEAR growth for electrode operation duration and the number of arc initiations.

The photographs show that, for the same parameters, the TEAR is more significant and the change in weight and length greater for higher number of arc initiations over a one-hour duration, shown in Figure 190 ‘B’. However, also apparent from the photographs is that, separately, operation duration and the number of arc initiations do not have the same effect as when combined.

Changes to pilot arc voltage did not appear to improve arc initiation or have a measurable effect on the TEAR, weight or length of the electrode.

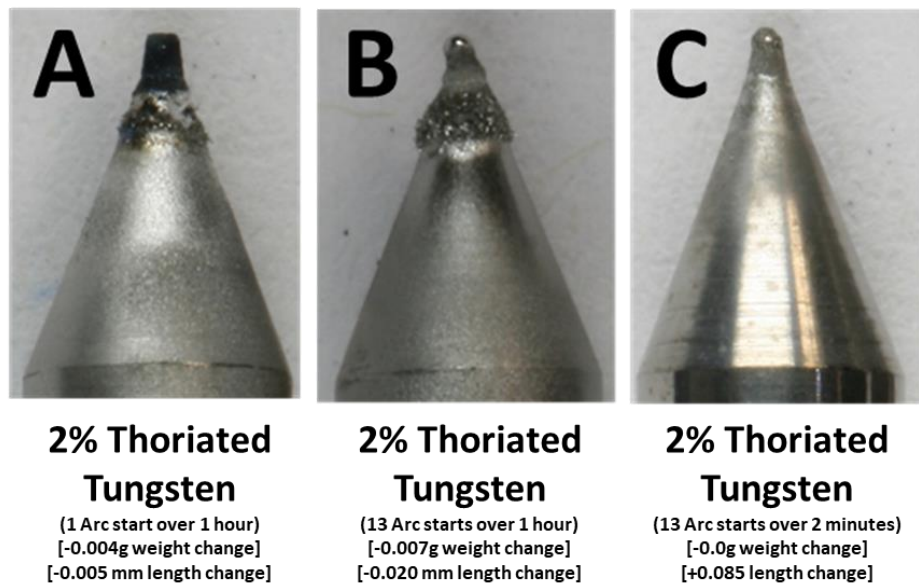


Figure 190 Effect of number of arc initiations of a standard 2% thoriated tungsten electrode on TEAR growth and wear: A] After one arc start over 60 minutes, for comparison, B] After 13 arc starts over 60 minutes, C] After 13 arc starts over two minutes.

Electrode TEAR Analysis

Figure 191 shows SEM images of a 2% thoriated tungsten electrode and indicates the brittleness of used electrodes – cracking, brittle fracture, and tip detachment – as a result of tungsten being brittle at room temperature (Paschen, 1996). A TEAR analysis using an EDS detector count (Figure 191 ‘D’, ‘F’ and ‘G’) indicates that the cubic shapes of the TEAR band are pure tungsten material. The irregular organic shapes of Figure 191 ‘D’ are pure thorium (Figure 191 ‘E’), precipitated out of the 2% thoriated tungsten material matrix.

The SEM images of Figure 192 show, with increasing magnification, the TEAR shape and crystal structure generated with electrode use, with cube-faceted crystals strongly in evidence. Figure 192 ‘F’ suggests electrode surface material elimination.

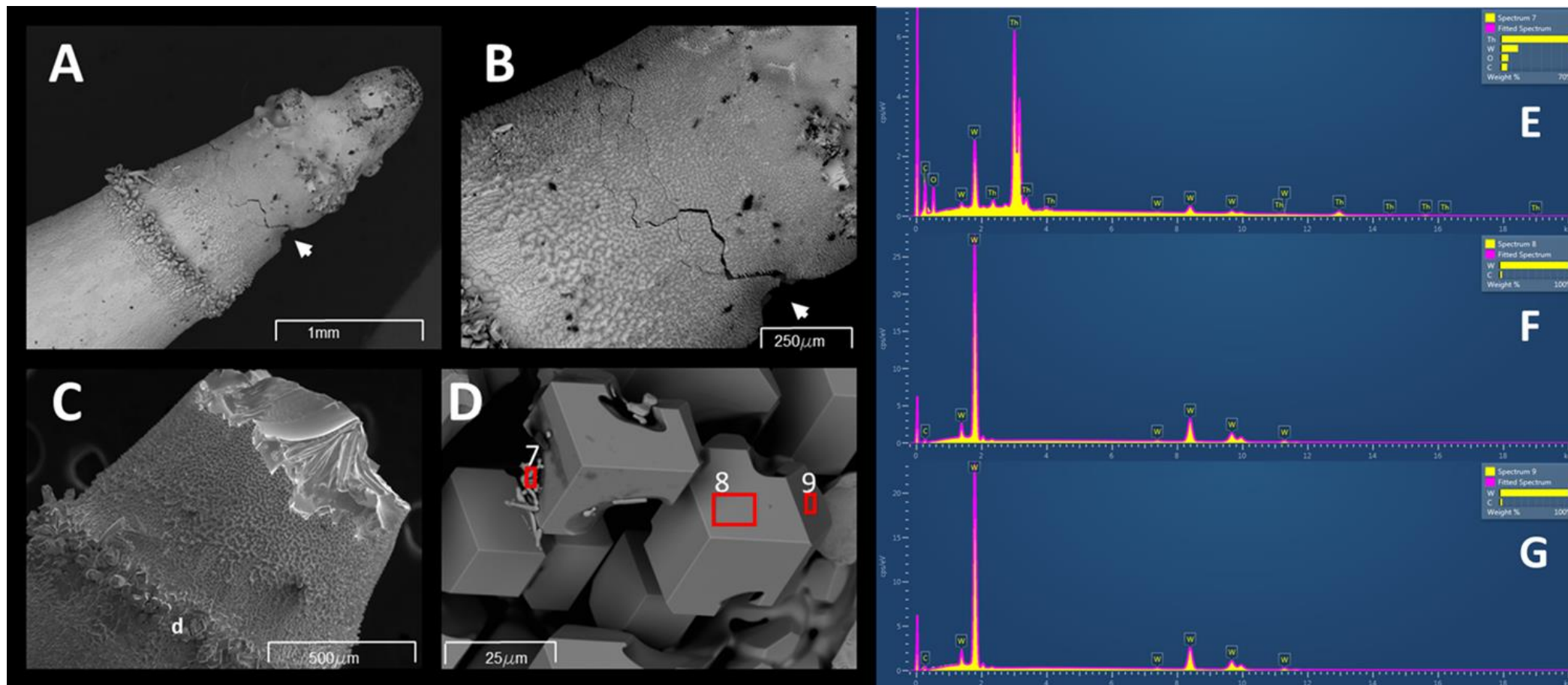


Figure 191 SEM images of a 2% thoriated tungsten electrode. A] Overall image of 20° electrode tip shape with two TEAR bands visible, B] Enlargement of crack running across electrode, arrow shown in same position, C] Brittle fracture of tip, TEAR location indicated on electrode – 'd', D] Enlargement of TEAR at point 'd', cube-faceted crystal structure shown, areas of EDS detector count analysis identified, E] TEAR composition region: Area marked '7' in 'D' – irregular organic shapes – precipitated thorium, F] TEAR composition region: Area marked '8' in 'D' – regular cubic shapes – pure tungsten, G] TEAR composition region: Area marked '9' in 'D' – regular cubic shapes – pure tungsten.

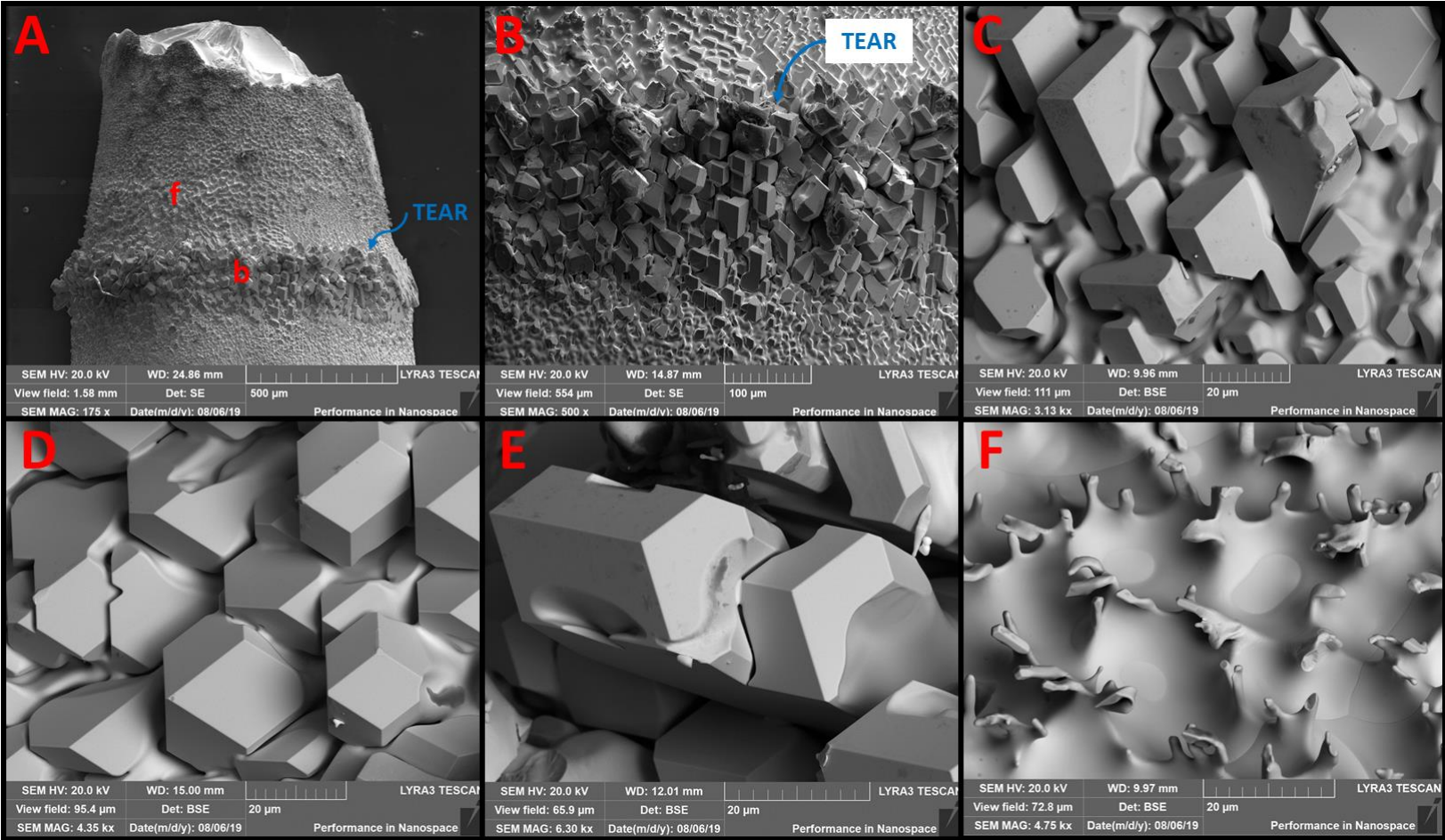


Figure 192 SEM images of a 2% thoriated tungsten electrode TEAR. A] Electrode at 175 x magnification. Brittle fracture of tip visible. TEAR band labelled, B] TEAR band at 500 x magnification, location indicated on electrode – ‘b’, C] Enlargement of TEAR, 3.13K x magnification, D] Enlargement of TEAR, 4.35K x magnification, E] Enlargement of TEAR, 6.30K x magnification, F] Electrode surface at 4.75K x magnification, tip side of the TEAR, approximate location indicated on electrode – ‘f’.

Electrode Dopant Analysis

A comparison between used and new electrode tip cross-section macro photographs is provided in Figure 193. Image ‘A’ shows uniform voids throughout the new electrode from the sintering process. There are longitudinal pores as a result of extrusion of the material, and the flat 0.36 mm diameter tip is also visible. Image ‘B’ is a used electrode showing longitudinal voids away from the tip and rounder voids at the tip. The tip melt area is also discernible. Image ‘C’, an enlargement of ‘B’, shows the rounding of the electrode tip and coalescence of the voids: larger and rounder. A void-free zone is also evident to the right of the boundary. Image ‘D’, an enlargement of ‘C’, shows coalesced voids sub-surface of the tip and a surface band of voids at the tip. The surface cavities and voids are from evaporation, erosion and vaporisation.

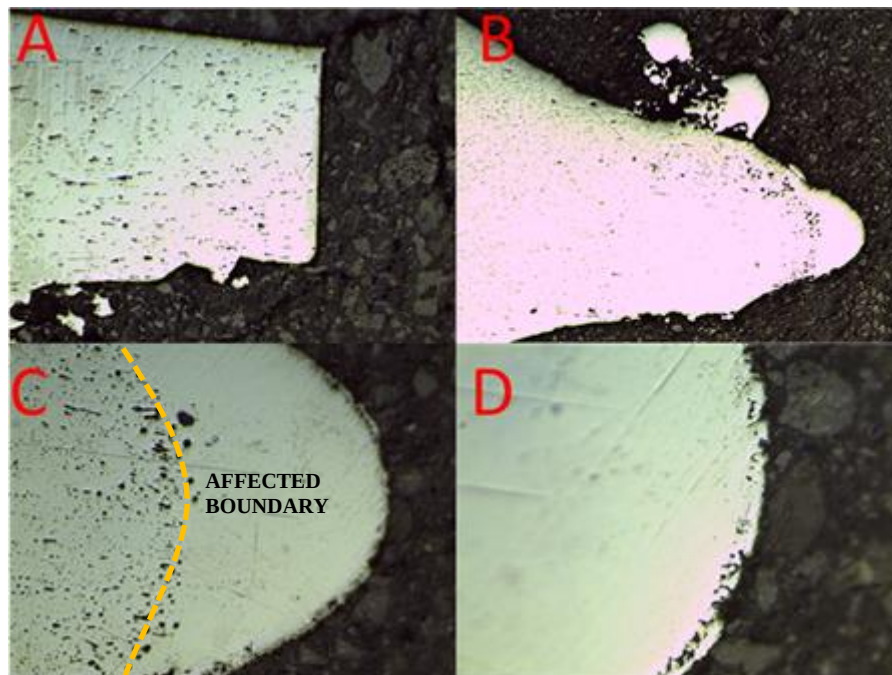


Figure 193 Comparison of new and used 2% thoriated tungsten electrode tips – cross-section macro images. A] New electrode, B] Used electrode, C] Enlargement of ‘B’, affected boundary indicated, D] Enlargement of ‘C’, melt-tip zone, with a distinct irregular void band around the tip.

Cross-section SEM images of a new 2% thoriated electrode are shown in Figure 194, demonstrating the elongated thorium phases within the tungsten. Image ‘B’ shows an EDS layered image, illustrating the concentrations and distributions of the thorium,

including the tip. The percentage thorium is on average 3.28%, higher than required (British Standards Institution, 2015).

Figure 195 shows, for a heavily used 2% thoriated electrode, cross-section SEM images, indicating that, in ‘A’, at a distance from the electrode tip, the thorium phases remain elongated and unaffected. Images ‘B’ and ‘C’ of the tip illustrate a boundary to the left of the line for the thorium phase, where the voids have each coalesced and become rounder. To the right, the thorium phase and voids are missing. The EDS layered image ‘D’ illustrates the drop in thorium concentrations to the right of the boundary.

The SEM image and EDS composition, shown in Figure 196, across the used tip cross-section, indicate a trend of decreasing thorium with reduced distance from the tip: see Table 43 for values.

Table 43 Used 2% thoriated electrode EDS compositions from Figure 196

Dispersive X-ray Spectrometry (EDS) Detector Count Analysis Identify Compositions		
Location	Percentage Thorium % wt.	Percentage Tungsten % wt.
A	3.42	96.58
B	5.02	94.98
C	0.34	99.66
D	0	100

Figure 197 illustrates the surface and sub-surface band of voids around the used electrode tip, and, through ‘EDS’ analysis, the low percentage of thorium at the tip.

A further SEM enlargement of the surface and sub-surface band is shown in Figure 198, and illustrates a hairline crack and a stress concentration initiation point. The surface cavities and voids are from evaporation, erosion and vaporisation. The EDS composition analysis shown in Figure 198 ‘B’ and ‘C’, indicates the depletion of the thorium at the tip: see Table 44 for values.

Table 44 Used 2% thoriated electrode EDS compositions from Figure 198

Dispersive X-ray Spectrometry (EDS) Detector Count Analysis Identify Compositions		
Location	Percentage Thorium % wt.	Percentage Tungsten % wt.
Spectrum 13	0	87.32
Spectrum 14	0	90.10

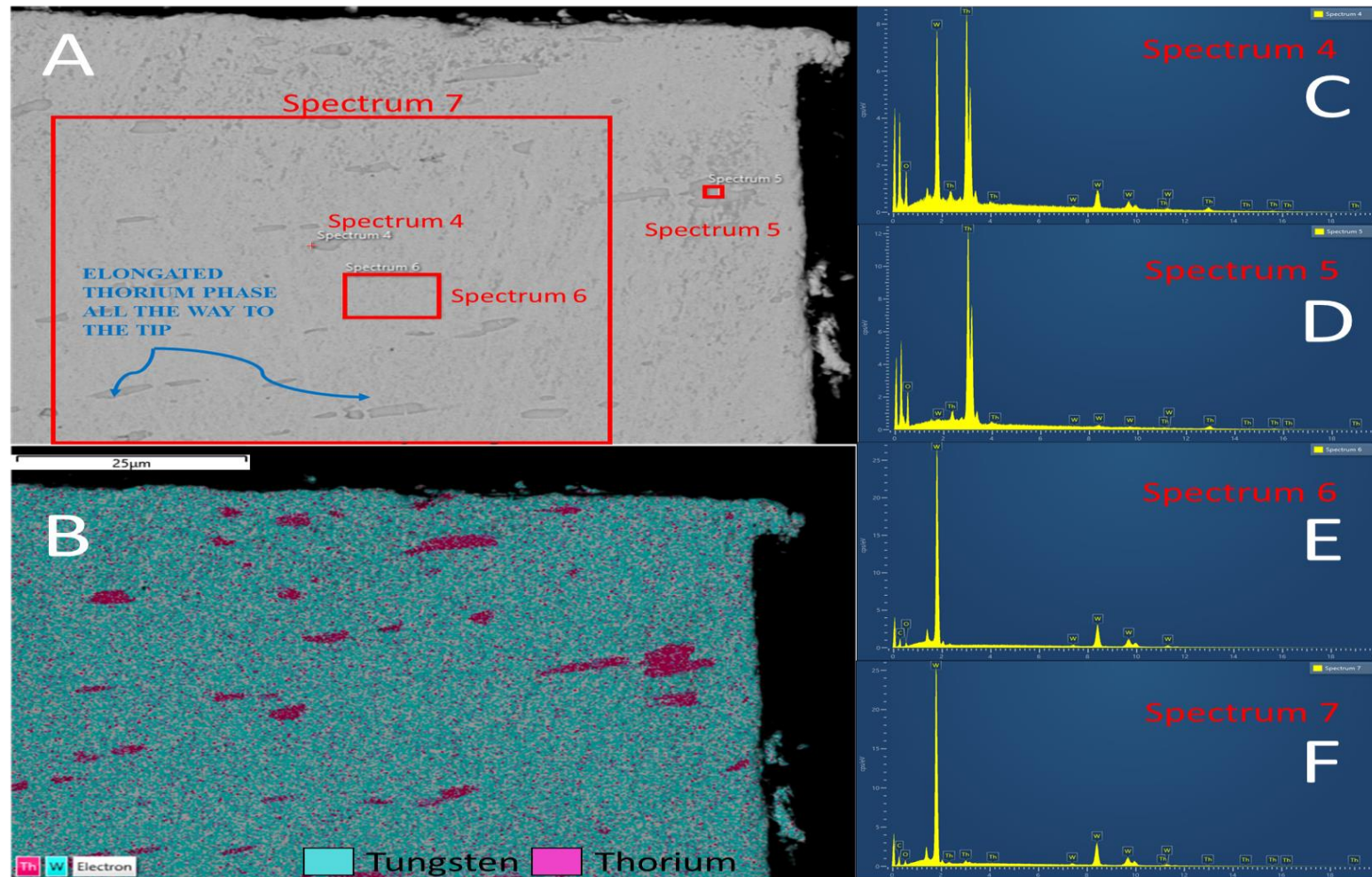


Figure 194 New 2% thoriated tungsten electrode cross-section. A] SEM image of Figure 193 image 'A', B] Layered EDS image showing tungsten and thorium concentrations. ['C' to 'F'] 'EDS' composition of the spectrum number locations identified in image 'A'.

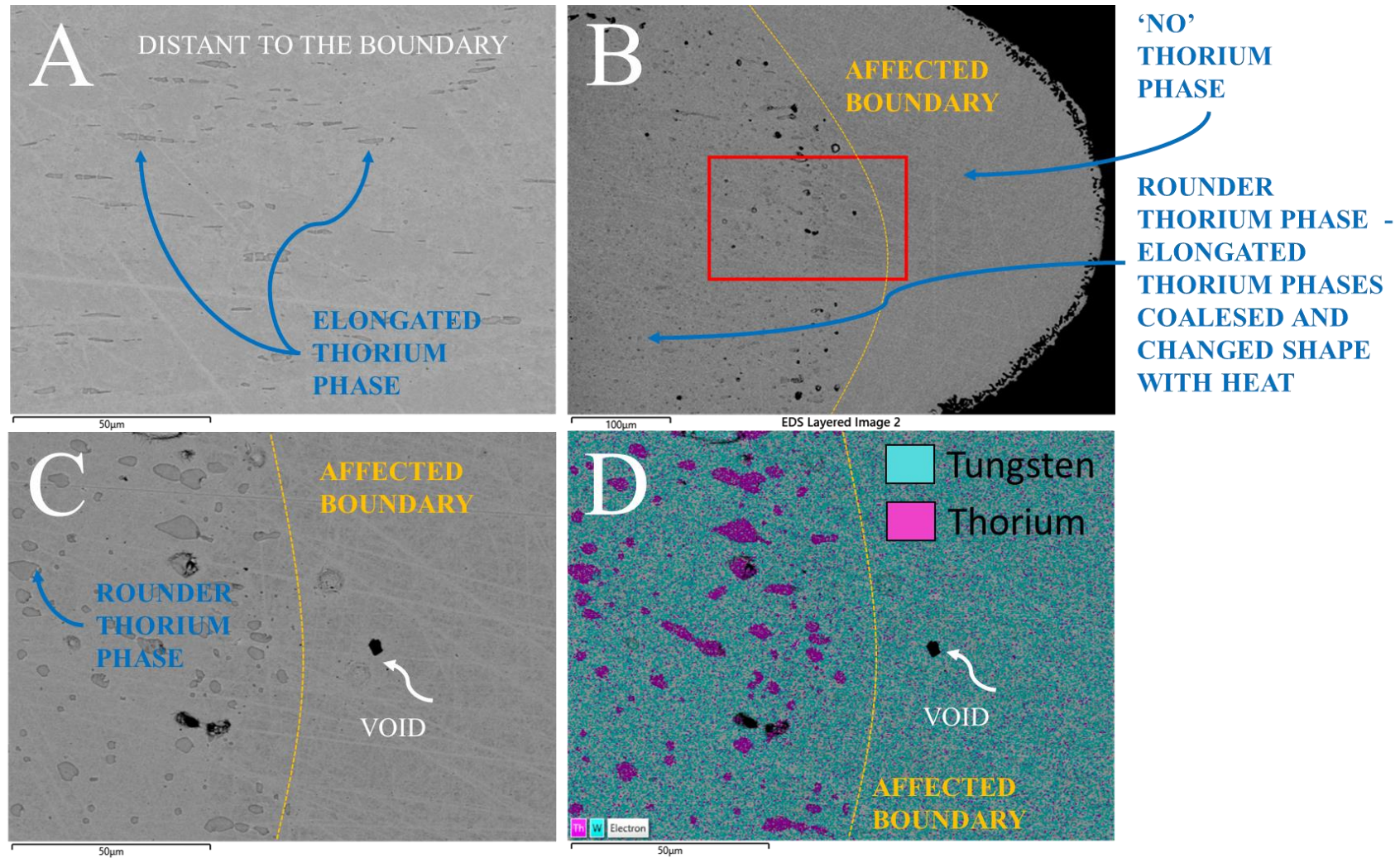


Figure 195 Heavily used 2% thoriated tungsten electrode cross-section. A) Location distant from the electrode tip, B) SEM image of Figure 193 image ‘C’, C) Enlargement of area identified in image ‘B’, D) Layered EDS image showing tungsten and thorium concentrations.

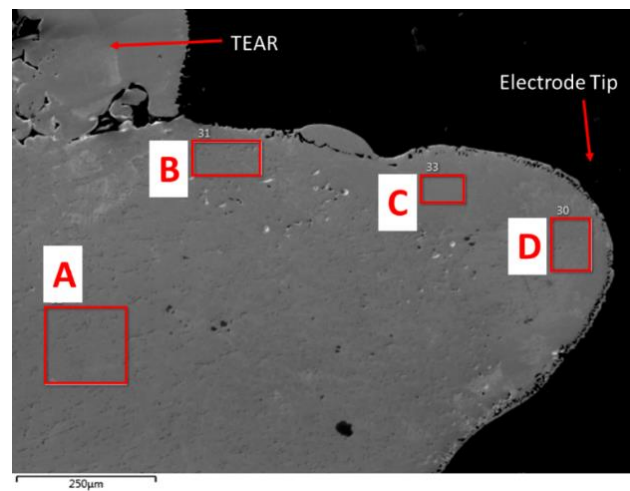


Figure 196 SEM enlargement of used electrode tip cross-section in Figure 193. ‘EDS’ composition locations identified: see Table 43 for values.

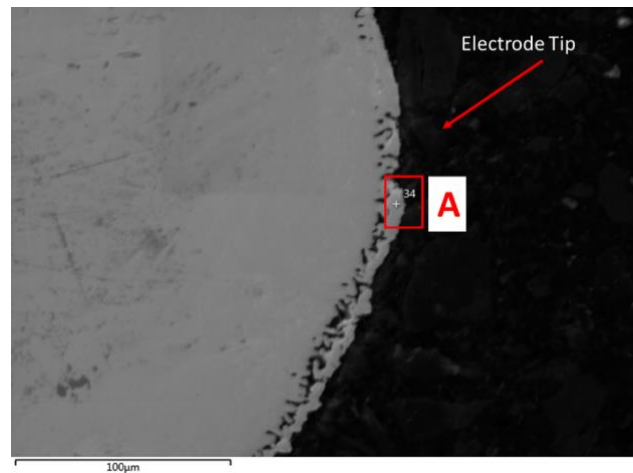


Figure 197 SEM further enlargement of Figure 196 electrode tip, a distinct irregular void band around the tip on the surface and sub-surface evident. ‘EDS’ composition at location ‘A’ 99.81% tungsten/0.19% thorium.

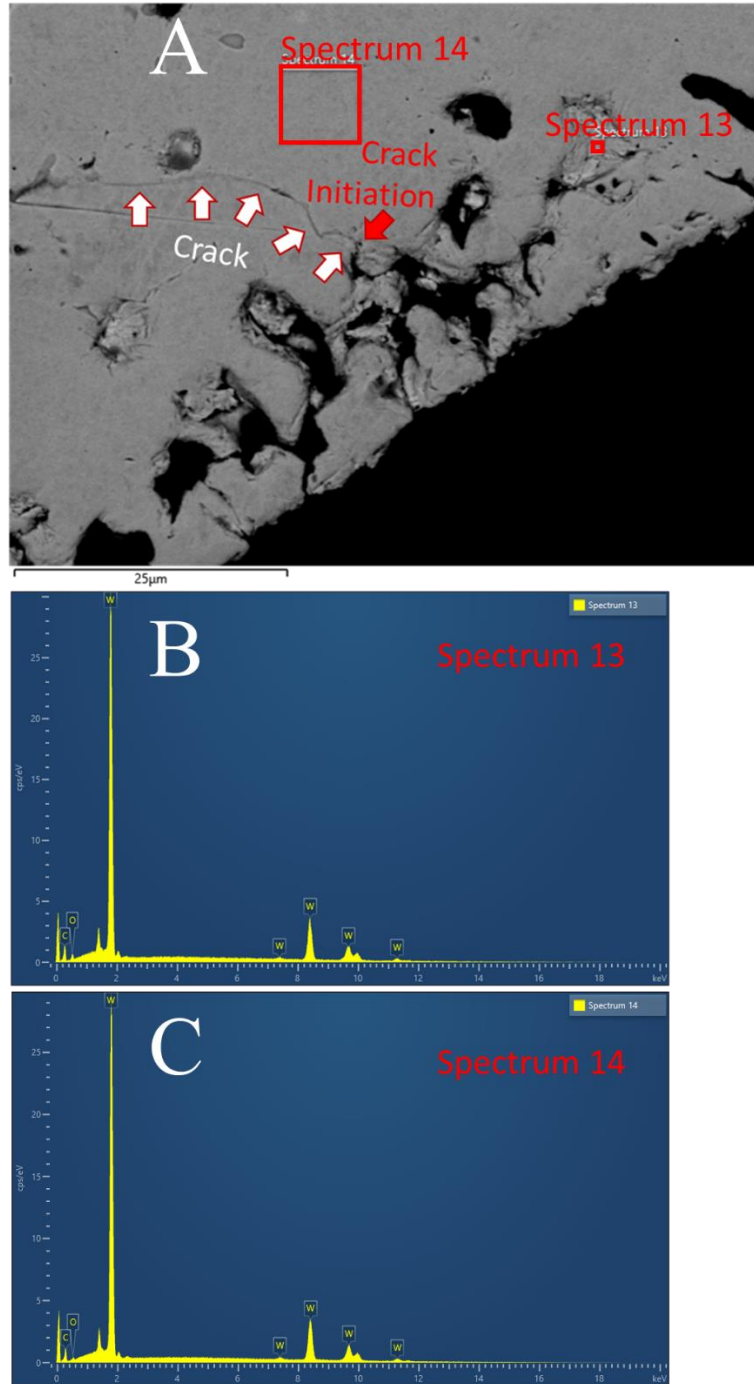


Figure 198 SEM further enlargement of Figure 196 electrode tip, distinct irregular void band around the tip on the surface and sub-surface evident. Crack and crack initiation location identified. [‘B’ and ‘C’] ‘EDS’ composition of the spectrum number locations identified in image ‘A’: see Table 44 for values.

Electrode Surface Deposit

Figure 199 ‘A’ and ‘B’ compare the difference between a new, with machined (reflective) finish, and used 2% thoriated tungsten electrode, with a mat finish and TEAR visible. In

addition to the change of tip shape, loss of length and TEAR formation, there is also a change in surface finish – an electrode surface deposit.

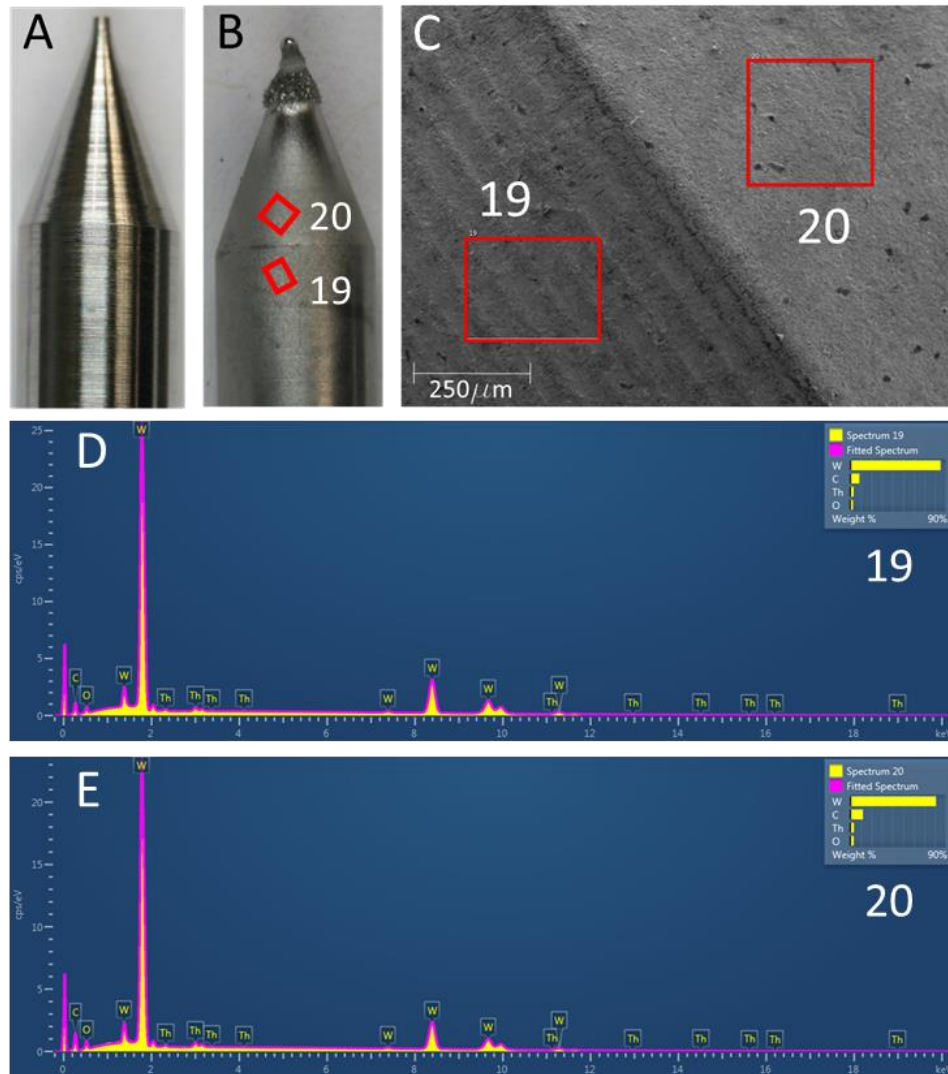


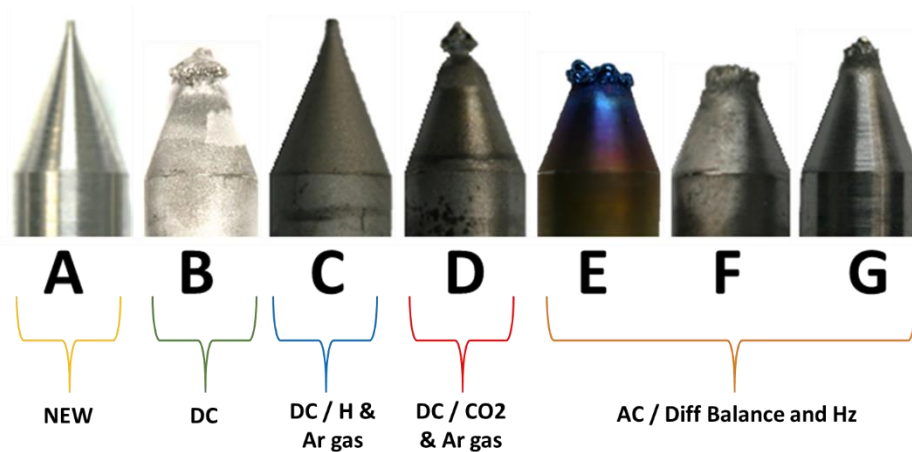
Figure 199 Standard used 2% thoriated tungsten electrode surface deposit material composition: A] New electrode, B] Used electrode, C] SEM enlargement of the surface of the used electrode 'B', electrode shaft to the left and electrode bevel to the right, D] EDS detector count for area '19' – electrode shaft, E] EDS count for area '20' – electrode bevel. Highlighted surface deposit confirmed as tungsten with minimal thorium.

Using an EDS detector count, the surface deposited powdered coating composition above and below the electrode bevel interface in areas labelled 19 and 20 of Figure 199 'B' and 'C', confirmed as pure tungsten particulate. The EDS spectrum composition of locations

19 and 20 are shown in Figure 199 'D' and 'E' respectively. The powder deposit observed is pure tungsten.

Effect of Different PTA Applications on Electrodes

Figure 200 compares 2% thoriated tungsten electrodes subjected to different PTA applications in relation to the effect on electrode life. It is clear that extended DCEN use in argon, shown in Figure 200 'B', changes electrode tip geometry, electrode length, surface finish and TEAR formation. Subjecting an electrode to a 1.5% hydrogen/89.5% argon plasma gas mix at 200 A DCEN, electrode 'C', resulted in its premature failure to arc start after 30 minutes. While the electrode and tip geometry are unchanged, however, the electrode surface texture has uniformly changed. After six minutes at 140 A DCEN with 2.5% CO₂/97.5% argon plasma gas mix, the electrode 'D' failed to arc start, leading to significant necking around the tip and a change to the electrode surface finish – a surface deposit. Electrodes 'E', 'F' and 'G' endured AC PTA at different values of current, frequency and balance, and all lost significant electrode tip shape within a very short duration. For AC PTA applications, a 5 mm diameter nozzle was utilised. Nozzles smaller than 4.4 mm only last a few minutes with AC before failure, probably because of double-arcing. Changes to the electrode surface in habited arc ignition because of changes in the surface work function and severe changes to tip geometry also suppressed arc ignition.



A] New electrode for comparison.

B] Heavily used (7 hours 45 minutes / 465 minutes) DC plasma electrode with 100% argon.

C] DC plasma for 30 minutes at 200 A before failure of arc ignition with 1.5% hydrogen/89.5% argon plasma gas mix.

D] DC plasma for six minutes at 140 A before failure with 2.5% CO₂/97.5% argon plasma gas mix.

E] AC plasma with 100% argon at 200 A, 50 Hz, balance 70/30.

F] AC plasma for 17 minutes with 100% argon at 200 – 100 A, 100 Hz, balance 70/30.

G] AC plasma for less than two minutes with 100% argon at 130 A, 200Hz, balance 85/15.

Figure 200 Effect of PTA process and plasma gas composition on 2% thoriated tungsten electrode tips.

6.4.2 Effect of Electrode Material and Geometry on its Longevity and Wear

6.4.2.1 Material Effect on Electrode Longevity and Wear

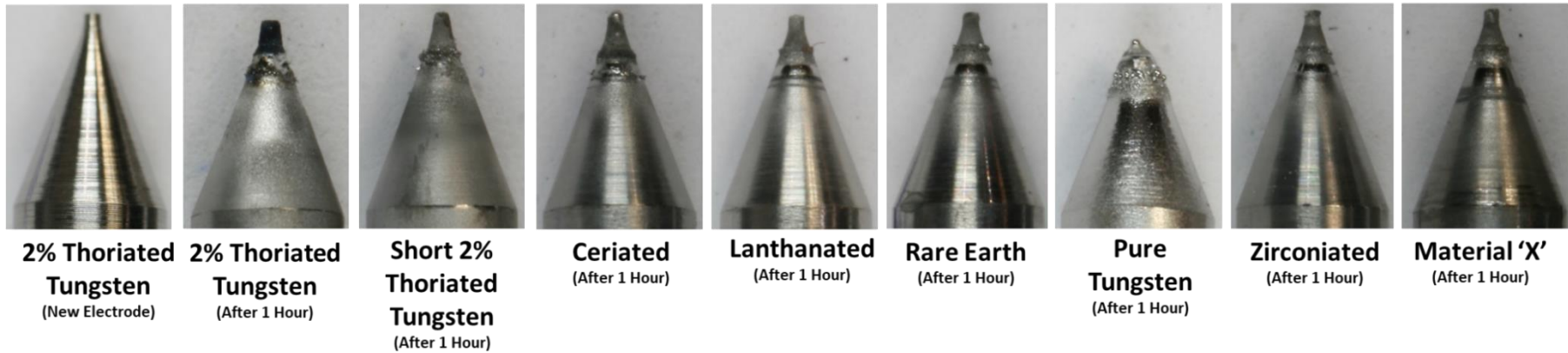
The impact of electrode material, different dopant and tungsten material combinations on electrode longevity, tip geometry retention, TEAR shape and wear-rates is shown in Figure 201 for a standard 2% thoriated tungsten electrode, a special (increased cooling) short electrode and six different materials: ceriated, lanthanated, rare earth, pure tungsten, zirconiated and material 'X'. Each electrode was photographed after a duration of one hour (top row), and two hours (bottom row). A new electrode is shown for comparison, with parameters of 180 A, shown in Table 42.

Within the first hour of use (Figure 201 top row), only the pure tungsten electrode significantly changed. However, after a further hour (Figure 201 bottom row), the rare earth electrode also substantially changed. To a lesser extent, the rest of the electrodes showed changes to tip geometry and surface finish, as well as changes to surface deposit, length and TEAR growth.

Figure 202 shows a comparison of the calculated wear-rate of weight loss for each of the seven electrode materials. Comparing the average wear-rates calculated, it is clear that the pure tungsten electrode demonstrates the highest wear-rate of weight loss, followed closely by the standard 2% thoriaated tungsten electrode. However, all the weight losses are relatively small.

A comparison of the calculated wear-rate of length loss for each of the seven electrode materials is shown in Figure 203. Comparing the average wear-rates of length loss calculated shows that the pure tungsten followed by rare earth tungsten electrodes exhibit the highest length wear-rates, with significant electrode length lost with use.

After one hour:



After two hours:



Figure 201 PTA electrode wear and TEAR shape for a standard 2% thoriated tungsten electrode, a special short electrode and seven different materials. Photographed after one hour (top row) and after two hours (bottom row).

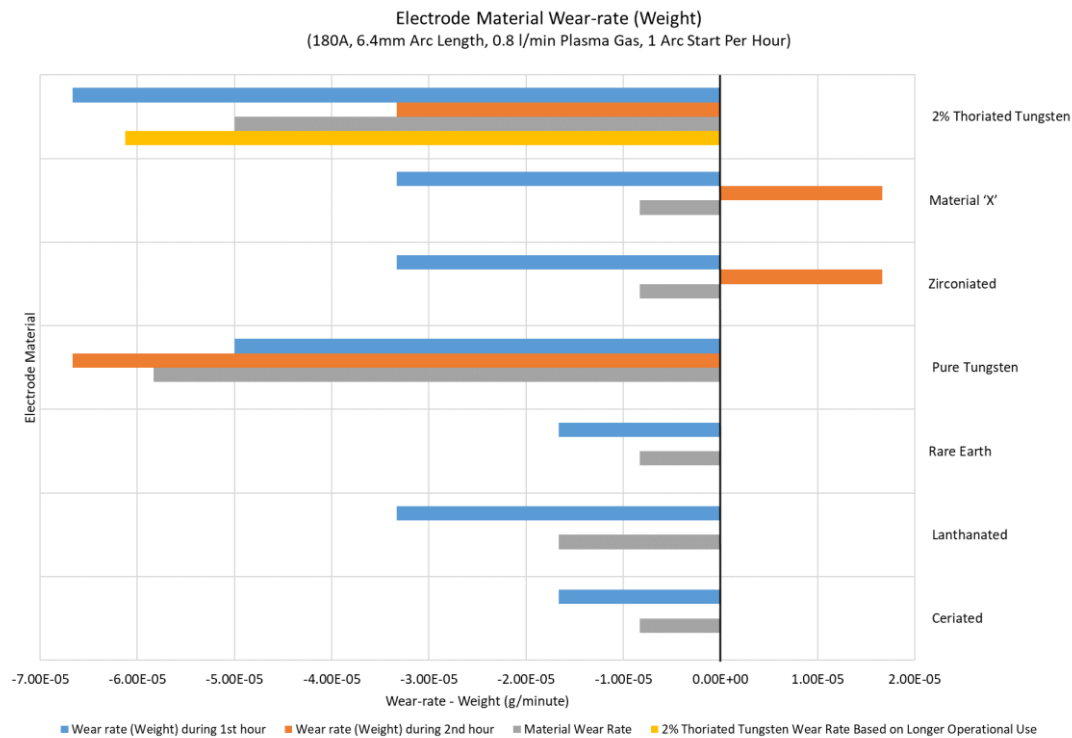


Figure 202 Calculated weight wear-rate for seven electrode materials over one and two hours, and for 2% thoriated tungsten material over a longer period. The average wear-rate over the measured duration (120 minutes) is also shown.

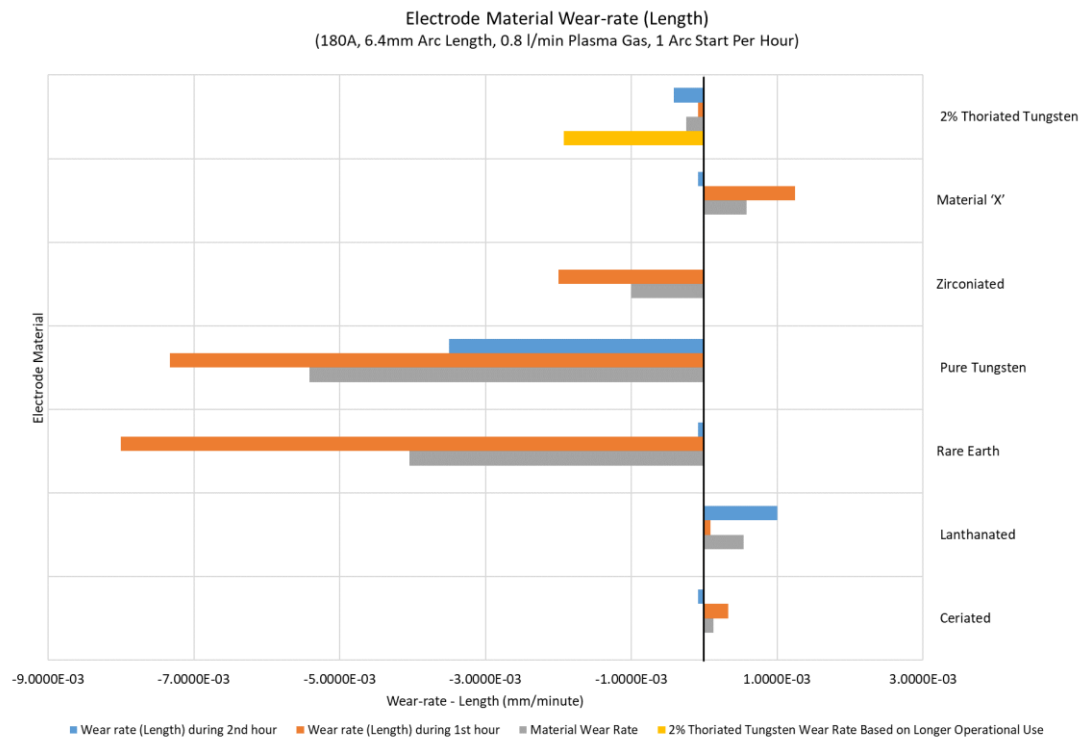


Figure 203 Calculated length wear-rate for seven electrode materials over one and two hours, and for 2% thoriated tungsten material over a longer period. The average wear-rate over the measured duration (120 minutes) is also shown.

6.4.2.2 Geometry Effect on Electrode Longevity and Wear

Effect of Reduced Electrode Length and Nozzle on Electrode Cooling, Longevity and Wear

Figure 204 shows a comparison of the changes in weight, length, tip geometry and TEAR growth versus electrode operation duration for two lengths of 2% thoriated tungsten electrode, with parameters of 180 A, shown in Table 42. The short electrode is identical in tip geometry and diameter, but the straight shaft length is 6 mm shorter (Figure 184).

The photographs show that, for the same parameters, the TEAR is slightly larger, with the change in length relatively higher for the shorter electrode over the first hour (Figure 204‘C’). Over the second hour, however, the TEAR reduces for the shorter electrode (Figure 204 ‘D’).

However, the loss in the electrode length of the shorter electrode is higher than the standard-length electrode over the two-hour operation duration.

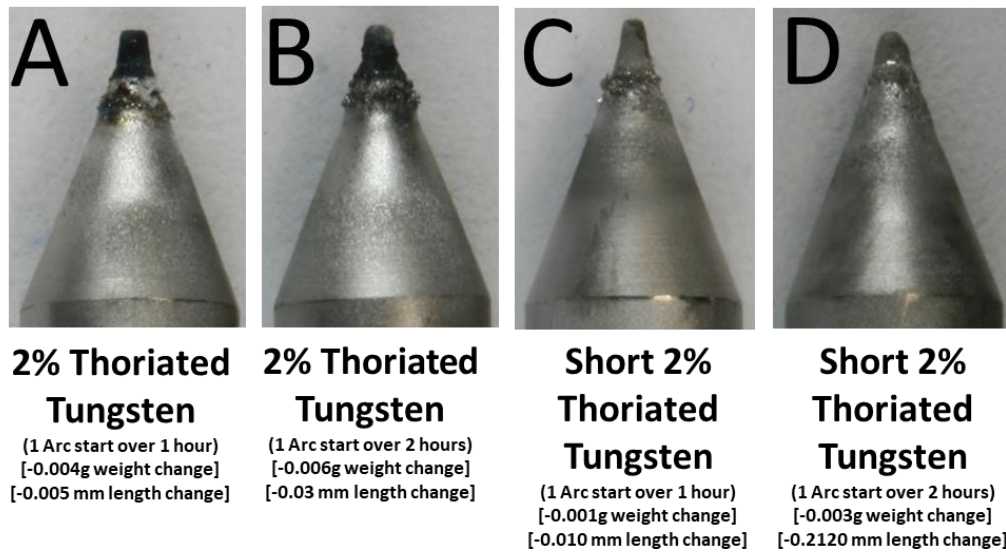


Figure 204 Effect of electrode and nozzle length on 2% thoriated tungsten electrode TEAR growth and wear: A] Standard electrode, 60 minutes of operation, B] Standard electrode, 120 minutes of operation, C] Shortened electrode, 60 minutes of operation, D] Shortened electrode, 120 minutes of operation.

Effect of Electrode Length and Flat Tip Diameter Effect on Electrode Wear and TEAR Growth

The average change in length for the flat tip electrodes showed minimal change because of their short duration of use. However, the weight decrease, shown in Figure 205 and Table 45, is most significant for the 2.29 mm diameter flat tip electrode (Figure 205 ‘E’), with a loss of 0.023 g in 15 minutes of use. This indicates the loss of electrode material, confirmed by observation of tungsten particles on the copper-block surface.

The effect of electrode length and flat tip diameter on electrode TEAR shape is shown in Figure 205. The TEAR growth is on the electrode flat tip edge and as a broader flat band for the larger electrode tip diameters, ‘D’ and ‘E’. The electrode surface finish and surface deposit for the flat tip electrodes are less tungsten particle coated on the surface than a standard electrode geometry.

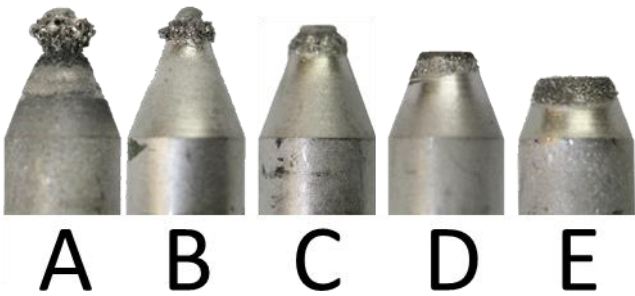


Figure 205 Flat tip electrode TEAR shape. A] For comparison, a standard 0.36 mm diameter flat tip after 10 hours uninterrupted operation at 180 A, B] 0.62 mm diameter flat tip electrode, C] 1.13 mm diameter flat tip electrode, D] 1.69 mm diameter flat tip electrode, and E] 2.29 mm diameter flat tip electrode.

Table 45 Effect of electrode length and flat tip diameter on wear-rate – loss in weight.

Electrode Flat Tip Diameter (mm)	0.62	1.13	1.69	2.29
Electrode Original Length (mm)	28.270	27.545	26.788	25.957
Weight Loss With Use (g)	0.016	0.006	0.006	0.023

The plan view of the flat tip electrodes is shown in Figure 206. It is clear that the TEAR band is around the whole edge of the electrode and that small pit marks and craters are evident on the flat electrode tip surfaces where tungsten particle emissions have occurred. The TEAR for the flat tip electrodes is less coarse and more uniformly distributed than that of a smaller diameter flat tip electrode, ‘A’.

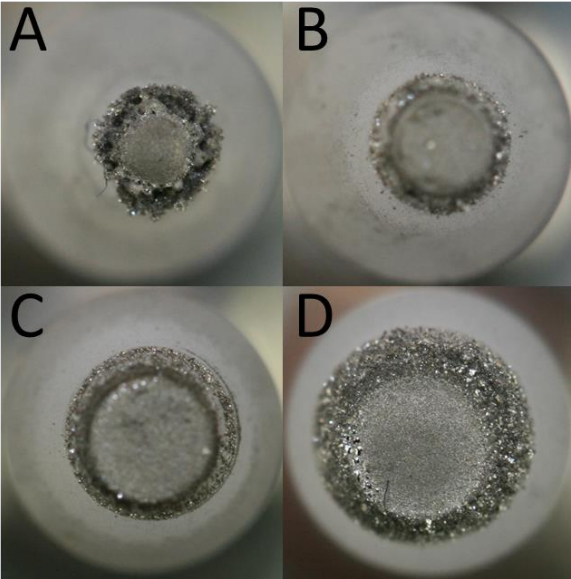


Figure 206 End view of flat tip electrode TEARs. A] 0.62 mm diameter, B] 1.13 mm diameter, C] 1.69 mm diameter, D] 2.29 mm diameter.

Effect of Electrode Length and Flat Shape on Arc Initiation

The effect of reducing the electrode weight and length of a 2% thoriated electrode on arc initiation is shown in Figure 207. The arc duration after each arc start was 60 seconds.

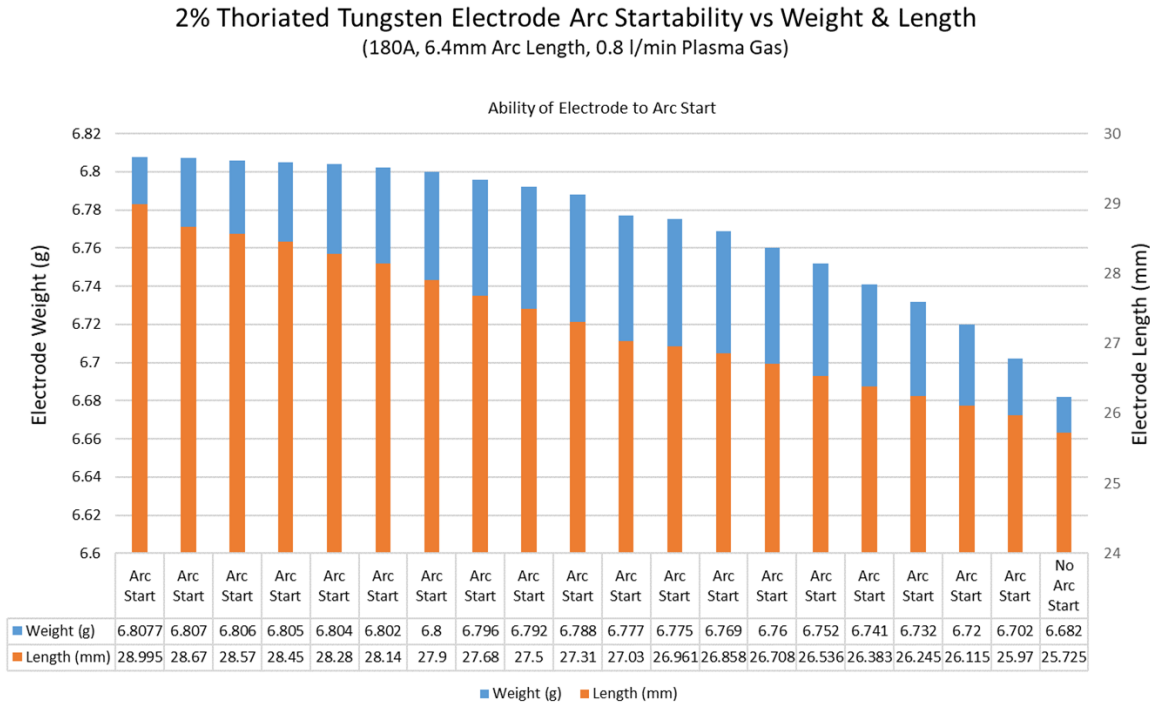


Figure 207 Electrode change in weight and length for a 2% thoriated tungsten electrode at each iteration up to failure to arc start.

The results show that an electrode can still initiate the arc even with a large flat tip (Figure 206), and a reduction in length of up to 3.025 mm and loss of weight of 0.1057 g (Figure 207). After a further loss of 0.245 mm and 0.02 g, the arc failed to initiate as a result of the minimum critical electrode length not being met.

Effect of Electrode Tip Angle on Wear and TEAR Growth

Figure 208 and Figure 209 illustrate a comparison of the calculated electrode loss in length and weight, with use for three 2% thoriated tungsten electrodes with different electrode tip angles: 20°, 40° and 60°.

The results indicate that loss of electrode length is more significant than weight and that the standard electrode tip angle of 40° has a considerably increased loss of length but a reduced loss of weight over the 20 minutes than non-standard angles.

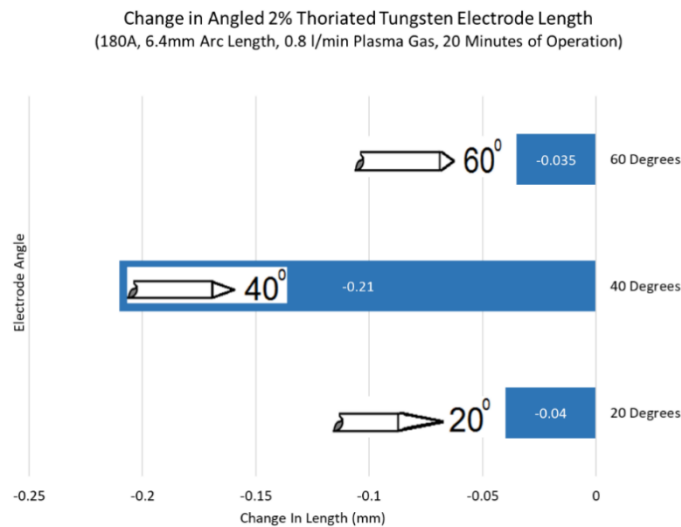


Figure 208 Comparison of electrode length loss with use for three-angled electrode tips: 20°, 40°, and 60°.

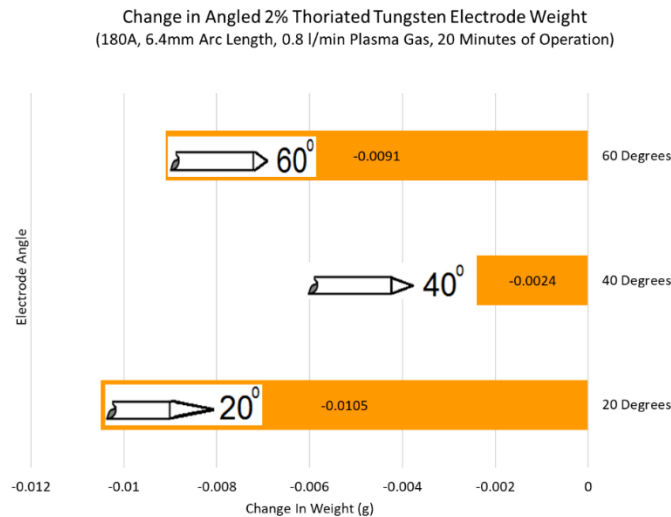


Figure 209 Comparison of electrode weight loss with use for three-angled electrode tips: 20°, 40° and 60°.

Figure 210 shows macro images of angled electrodes – 20°, 40° and 60° – subjected to 140 A followed by 200 A. A 40° electrode angle is standard. The TEARs are visible, with both ‘A’ and ‘C’ having two distinct bands. The location of each current band appears to be in a different location for each electrode angle, probably because of the variation in temperature as a result of the different electrode cross-section areas.

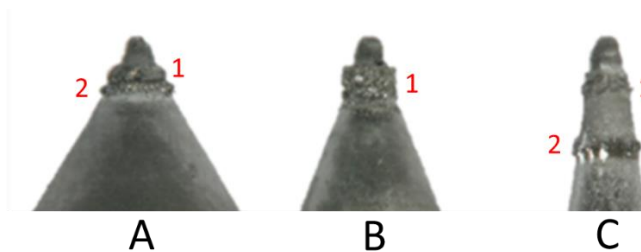


Figure 210 Macro TEAR images of 2% thoriated tungsten angled electrodes, with TEARs numbered; A] 60° electrode, with two separate bands visible, B] 40° electrode, with only one large band visible, C] 20° electrode, with two clearly separated bands.

The SEM images of the same angled electrodes are shown in Figure 211. In these close-up images, it is possible to see the difference in electrode angle, tip geometry and TEAR shape. The TEAR bands labelled as ‘1’ for each electrode were formed after electrode use at 140 A, while the ‘2’ labelled band is from use at 200 A. The two distinctive bands for each electrode are clearly visible in the close-up images. The 200 A arcs were initiated after the formation of the 140 A bands. As a result, the initial TEAR bands were eroded

and appear less clearly defined. The distance between the bands appears to increase inversely to the electrode tip angle. The used electrode tip shape is different for each angle, with material necking in front of the TEAR visible.

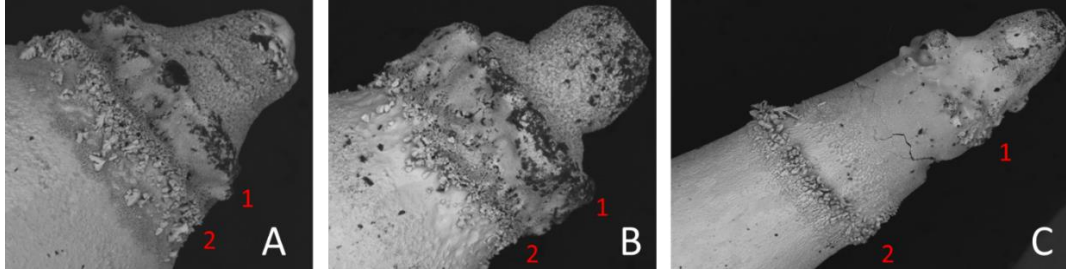


Figure 211 SEM images of the same 2% thoriated tungsten angled electrodes, with two TEAR bands (numbered) clearly visible on each electrode, A] 60° electrode, B] 40° electrode, C] 20° electrode.

6.5 Discussion

WAAM operating conditions are predicted to change to increase the deposition rate, thus reducing WAAM part build times with currents of approximately 300 A (higher than the rating of the PWP Viper MC torch). This significantly affects electrode wear and, consequently, electrode lifespan.

A difference between this study and previous studies is the duration for which the electrode is subjected to the arc. This study is therefore more realistic for WAAM applications.

6.5.1 PTA 2% Thoriated Electrode Wear Mechanisms and Behaviour

Wear of 2% Thoriated Tungsten Electrodes

The results of the study show that a PTA DCEN thoriated tungsten electrode (cathode) loses a small amount of length with use, shown in Figure 185 and Figure 186, but loses insignificant mass, shown in Figure 187. The surface of used electrodes also becomes coated in a tungsten particle deposit, confirmed through an EDS detector count (Figure 199).

Increases to arc current focus the current and increase the current density where the temperature is highest, subsequently raising the temperature and thermal flux of the electrode tip cathode spot (Sillero, Ortega, Muñoz-Serrano and Casado, 2010), resulting in higher levels of tip evaporation, vaporisation and erosion, in agreement with similar findings from Zhou and Heberlein (1998).

The thermionic emission is aided by the lowering of the material work function and required surface area for thermionic emission through the inclusion of thorium or other oxides, shown in Table 2.

TEAR Growth Mechanisms

This study has shown that a PTA TEAR develops on electrodes with a combination of operational use (Figure 189) and to a lesser extent with the number of arc ignitions and terminations (Figure 190). The shape of the electrode tip is largely retained after just one

arc start and a short duration of use. Rapid growth of the TEAR stabilises after a few minutes (Figure 188), but continues at a diminished rate with time at temperature.

Figure 212 shows the transition from a new electrode (left) to TEAR growth and potential electrode tip loss (right). Necking behind the TEAR is visible, and Zhou, Ding and Heberlein (1996) assert that the neck erosion is caused by ion bombardment in this colder zone. As a result of the low temperature in this zone, thermionic emission is replaced by an increased electric field and consequently field emission, resulting in vigorous ion bombardment erosion (Zhou, Ding and Heberlein, 1996).

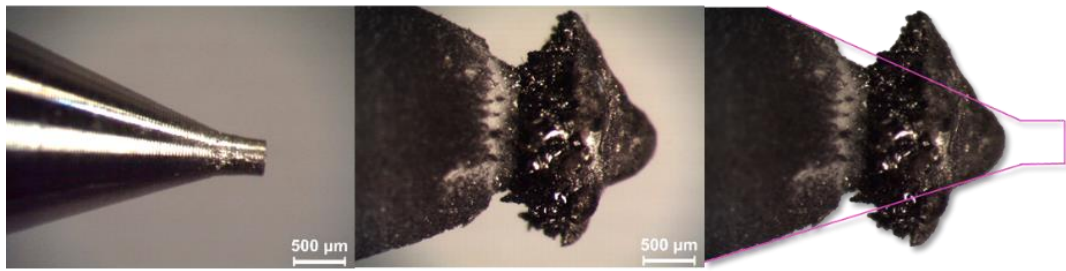


Figure 212 TEAR growth. A] New 2% thoriated tungsten, B] Heavily used electrode with TEAR, C] Indication of original electrode tip loss.

Tungsten is a refractory metal with a very high melting point – 3410°C – which exhibits metallic bonding. In metallic bonding, the atoms of the metal remain bonded within a sea or cloud of valence electrons that came from the outer shells of the atoms (Callister, 2010). Thermionic emission of the electrons, outlined in the literature review, is principally dependent on temperature and material surface work function value, in line with the factors in the Richardson Dushman Equation 19, (Cachard, Cadoret, Martinez, Veillet and Millot, 2001; Paschen, 1996). The surface area and critical current density, which depends on the work function, affect the temperature.

$$J_s = A_0 \times T^2 \times \exp(-\Phi_s / k T) \quad \text{Equation 19}$$

Where:

J_s = Emission current density (A/cm²), A_0 = Richardson constant (A/cm²/k²), Φ_s = Work function (Joules), k_{BC} = Boltzmann constant, T_K = Temperature (Kelvin)

For a specific current, the current density inside the electrode depends on the cross-sectional area, and the narrow electrode tip region reaching the threshold temperature first, before starting to emit electrons – thermionic emission. Both the tungsten and oxide particles are evaporated from the tip and electrode surface. However, because of the lower boiling and melting points of the oxides, shown in Table 3, these are emitted preferentially. Once the dopant is depleted, the arc can be sustained through the thermionic emission of the tungsten. However, once the arc is terminated, arc re-ignition is no longer possible.

The continuation of the electrode tip loss results in electrode length reduction, shown in Figure 212.

A proportion of the evaporated tungsten and dopant re-condenses to form vapour deposits on the electrode surface and becomes loosely bonded in the region just above the thermionic emission zone where the temperature is lower and ions may achieve ground status, initially creating a powder-like surface coating over the electrode with operation duration forming an annular ring, TEAR, just above the thermionic emission zone.

With exposure to high temperature over time, and during cooling periods where the main arc is temporarily terminated to the pilot arc, TEAR crystal growth occurs. The TEAR increases in diameter, while the electrode tip length reduces because of evaporation, vaporisation and erosion from impinging metallic ions from the substrate, shown in Figure 181 and Figure 212. The TEAR forms just above the region of thermionic emission where the temperature is below the threshold temperature for thermionic emission – an isotherm where the thermally affected area stops, and the TEAR starts. Increasing the arc current increases the electrode temperature through increased resistive heating, so that the area of thermionic emission increases. There is a thermal gradient from the isotherm temperature at the TEAR down to the electrode tip, where the cross-section is smallest, the temperature highest and the internal current density greatest. Zhou, Ding and Heberlein (1996) undertook pyrometry temperature readings along an initiated PTA electrode and observed approximately 1000⁰ Kelvin reduction in 2.5 mm from the electrode tip.

Unlike in Sillero, Ortega, Muñoz-Serrano and Casado's (2010) investigation, distinct bands of thorium and tungsten surface crystals were not observed. The TEAR comprised both crystal formations. The difference probably results from the longer duration for which the electrodes were subjected to a PTA arc – hours rather than their 10 minutes – thus approximating WAAM operations more closely.

Figure 191 and Figure 192 show the SEM images of the TEAR structure and its cube-faceted crystals, confirming through EDS that the crystals are pure tungsten, the thorium having segregated and deposited on top of the crystals separately. Figure 192 'F' shows the electrode below the arc and, potentially, the surface material elimination.

The front of the TEAR is smooth because of emissions and melting as a result of the arc. Past the TEAR edge is the TEAR crystallisation zone, followed by the necking zone, where there is a loss of material. This is a typical site for stress concentration, with potential for tip detachment: see Figure 181 and Figure 212.

Figure 188 shows the TEAR growth over time and indicates that the growth steadily increases with use, in line with electrode length loss. Figure 190 shows that the number of arc ignitions and terminations does affect TEAR growth but only when combined with durations of initiated arc. Separately, they have less effect on TEAR growth.

TEAR growth not only results in electrode failure and potential for tip detachment but also impedes the flow of laminar plasma gas flow, resulting in turbulent flow and reduced gas ionisation (Pan et al., 2002). The relationship between worn electrodes and reduced arc pressure has also been established in Chapter 3.

Reducing the pilot arc voltage was investigated to ascertain its effect on TEAR growth. Unfortunately, no improvement or change was found over a standard electrode after the same duration at the standard pilot arc voltage.

Electrode Dopant – Thorium Oxide Transition within the Tungsten

This study's analysis of thorium oxide transition within the polycrystalline structure of the PTA tungsten electrode is consistent with the mechanisms identified within the literature review for GTA electrodes (Sadek, Ushio and Matsuda, 1990; Nemchinsky,

2014; Lancaster, 1984; Sadek, Ushio and Matsuda, 1990; Lowke et al. (1997). The initial electrode tip has an even distribution of elongated thorium, shown in Figure 194.

The macro cross-section images of a used 2% thoriated electrode, shown in Figure 193, clearly show a surface band of cavities around the electrode tip resulting from evaporation, vaporisation and erosion by metallic ions from the substrate. An area has also become void-free, right of the boundary: see Figure 193 'C', compared to 'A'. The voids within the electrode material, initially elongated by extrusion, coalesce to form larger and rounder voids. These are probably responsible for the sub-surface band of cavities at the tip, shown in Figure 197 and Figure 198.

Figure 197 and Figure 198 show SEM images of the tip region and indicate a loss of thorium – a hairline crack and an initiation site within the region. The cracks in the tip probably result from thermal stress. However, there may also be a metallurgical reason: grain boundary segregation or contamination within the tungsten matrix. The thorium, with its lower work function (Table 2) and lower melting point (Table 3) and vaporisation point, will be removed from the electrode tip surface first. A reaction at temperature causes the thorium oxide with tungsten to form pure tungsten and pure thorium (Ushio, Sadek and Matsuda, 1991). The pure thorium can more readily diffuse through the electrode to the surface, where it can evaporate (Matsuda and Ushio, 1988), and, as seen in Figure 191, condense separately in the TEAR.

The lost thorium oxide is replaced by diffused thorium particles distributed within the boundaries of the polycrystalline tungsten structure, moving across the thermal gradient towards the hot electrode tip through the longitudinal grain boundaries.

As the electrode continues to be used at temperature, the tungsten crystals, no longer pinned by the oxide particles, continue to grow, further reducing the number of boundaries and dislocations, and, consequently, paths for the oxide to migrate through, creating a barrier for oxide, shown in Figure 193 'C'. Figure 195 illustrates the reduction in thorium as a result of the boundary preventing migration.

The fully dense electrode tip section, shown in Figure 193 'C' and 'D', illustrates the tungsten crystal growth. The oxide evaporation rate reaches a critical juncture when the

backfilling oxide starts to taper off and the oxide concentration at the tip begins to drop, increasing, locally, the electrode tip work function, returning to that of pure tungsten (Table 2) and higher temperature accordingly (Costa, 2014; Nemchinsky, 2014). This further intensifies the loss of the remaining oxide, resulting in tip geometry changes and reduced service life, which continues until the operator terminates the arc, at which point re-crystallisation occurs and subsequent arc starts on request are no longer possible. This is a consequence of the localised high work function of the remaining almost pure tungsten electrode tip as a result of the loss of oxide, requiring an unavailable ultra-high voltage to initiate the arc (Costa, 2014; Nemchinsky, 2014). Appraisal of the ability of electrode compositions to initiate an arc is considered by Paschen (1996) to involve the capability of initiating an arc with the lowest arc voltage, corresponding to the lowest work function of the tungsten alloys, shown in Table 2.

The SEM longitudinal cross-section image and dispersive EDS detector count analysis of the same used electrode, shown in Figure 196 and Table 43, further supports the concept by showing higher oxide concentrations with distance from the tip. Areas are evident of high levels of thorium oxide, but these are too distant to diffuse to the electrode tip and are potentially barred by a tungsten crystal growth region — barrier. At areas closer to the tip, shown in Figure 196 ‘C’ and ‘D’, the thorium oxide percentage is significantly reduced (Table 43), indicating oxide diffusion from this region. The enlarged SEM cross-section image and EDS value of the same heavily used electrode, shown in Figure 197, shows the depleted amount of oxide and high concentration of pure tungsten at the tip (Figure 197 ‘A’).

Arc starting issues mainly result from changes to electrode geometry rather than solely from dopant depletion, as Sillero, Ortega, Muñoz-Serrano and Casado, (2010) observed after 10 minutes 100% dopant depletion at the tip, and electrodes re-ignite well beyond this. This thesis research only measured dopant depletion for new and heavily used electrodes.

WAAM part building operations found that, in some cases, a heavily used electrode that is unable to arc start can obtain pilot arc ignition by directly applying emery paper to the electrode tip. This is undoubtedly a short-term measure and is only recommended away

from the melt-pool deposited material as it may result in contamination. An explanation for why this might work is that, in some cases, the insulating sub-surface void/cavity band is removed, shown in Figure 197 and Figure 198, which may impede current conduction and expose a fresh layer of oxide, reducing the localised work function and enabling arc ignition.

Heavily used/worn electrodes generally have the same shape, but the structure is different. In particular, a region utterly devoid of thorium at the tip end is present. This seems to be a primary reason for the failure of the arc to start at this point and the electrode's fundamental limit.

Effect of Electrode Contamination

Contamination from nozzle and electrode machining (i.e. coolants, cutting fluids, oils and oily water), usually removed by the manufacturer with solvents, was found during high frequency pilot ignition and use to contaminate the electrode surface. The contaminant increases the electrode surface work function and impedes pilot and main arc ignition. PTA electrodes and nozzles should therefore be cleaned by the operator at the work location – e.g. dipped in acetone – and contaminant free before use. Minimising their handling is also essential.

A black residue found to occur at the top of electrodes, below the connection thread, shown in Figure 213, typically only after long durations of operation and sometimes at high current values, was identified through EDS detector count analysis as carbon. It was established that the deposit could easily be removed from the electrode surface and does not appear to be detrimental to PTA operation.

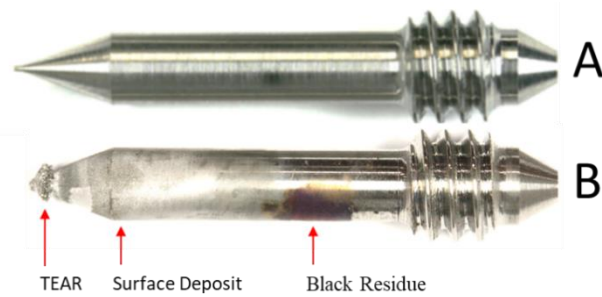


Figure 213 Residue comparison photographs of PTA 2% thoriated tungsten electrodes. A] New electrode, B] Heavily used electrode, up to 465 minutes, black residue in evidence.

How and why the black residue forms at this location is only conjecture. However, it may be as a result of the electric current reacting with electrode contamination. During electrode installation within the PTA torch, a specialist tool is utilised. Initial insertion of the electrode into the device necessitates handling the top of electrodes below the connection thread. Contamination from finger grease and oil through electrode handling is therefore probably the cause and can be easily mitigated through electrode cleaning and use of protective gloves.

Electrode Surface Deposit

The electrode surface coating of pure tungsten confirmed via an EDS detector count (Figure 199) is probably related to the evaporated and vaporised or eroded tungsten from the electrode tip and surface, outlined in the literature review. The redistribution of this deposit is responsible for the change in electrode length but minimal change in electrode weight. It was observed before the TEAR formation (Figure 199 'B') that the deposit was along the electrode shaft (Figure 43 'A'), with the concentration increasing towards the tip.

Different PTA Applications and Their Effect on the 2% Thoriated Tungsten Electrode

When different plasma gas compositions are being considered for PTA applications, the reaction between the gas and the 2% thoriated tungsten electrode material must be considered. Though this study used argon, helium and argon/helium mixes successfully, attempts with 1.5% hydrogen/98.5% argon resulted in an unexpected reaction with the electrode surface and prevented further arc ignitions, probably as a result of the semi-

inert/active gas reacting on the surface of the electrode, increasing the electrodes' work function and subsequently the ability of the electrode to arc start, significantly reducing electrode life. A plasma gas of 2.5% CO₂/97.5% argon composition – a semi-inert/active gas – also reacted with tungsten at temperature, resulting in heavy oxidation and aggressive erosion of the electrode tip, shown in Figure 200. Both these gas compositions should therefore be avoided for PTA WAAM operations.

For active materials such as aluminium, an oxide coating forms that upsets molten metal flow. DCEP can therefore be utilised to harness cathode cleaning to remove the oxide. However, DCEP reduces the amount of power to the substrate and increases the power to the electrode, resulting in electrode contamination and reduced electrode life. To benefit from both electrode polarities, variable polarity is used – AC PTA (McClure and Weldability, 1993). This study has predominantly examined DCEN PTA, as AC PTA destructively affected the arc pressure experimental setup. However, the initial research has shown, as set out in Figure 200 'E', 'F' and 'G', that AC PTA has a drastic initial effect on 2% thoriated tungsten electrodes, with the tip geometry outlined in Figure 43.

The operating current and frequency balance, decreasing the heat balance by reducing the electrode positive cycle, are the critical parameters. The AC PTA process initially attempts to change the electrode tip into a ball shape, better suited to AC operations. The change is achieved through evaporation/vaporisation of the tip material, which does not appear to form the same TEAR as DCEN PTA, meaning that the evaporated material is lost, potentially to the work-piece.

To ascertain the effect of electrode tip design on its wear and longevity during AC PTA operations, two tip designs, shown in Figure 214, were developed and manufactured. Figure 214 'A' and 'B' already incorporate the initial tip loss and rounding effects in their design. It was proposed that each design should be trialled, and the results compared with that of a standard electrode – 60 minutes at 200 A, frequency 200Hz and balance 70/30 – and their length, weight and TEAR growth compared. However, because of the coronavirus (COVID-19), this study has been pushed into future work.

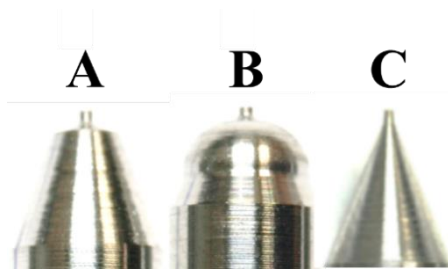


Figure 214 AC electrode tip designs: A] Double cone, B] Ball end, C] Standard

Loss of PTA Electrode Tip during Operation

The minimal loss of weight, 0.34% of the original PTA electrode weight, after 368 minutes of WAAM operations, shown in Figure 187, alleviates any concerns relating to constant electrode material contamination of the melt-pool from ongoing electrode wear during normal operating conditions. Experimental observations have shown that it is more likely that failure of the arc to start, as a result of depleted oxide at the electrode tip and gradual loss of electrode tip geometry, will prevent further electrode use, well before the point of tip detachment. However, exceptional upset operating conditions – e.g. extreme thermal shock – may have the potential to result in a sudden catastrophic electrode failure and electrode tip detachment.

Figure 215 illustrates the full lifecycle of a 2% thoriated tungsten electrode:

B] A new electrode with tip parallel length.

C] An electrode after a duration of use where the tip parallel length is missing, the surface dulls, and a large TEAR grows within the straight section of the nozzle.

D] Catastrophic electrode failure with tip detachment, in this case above the TEAR. At this point, the torch exhibits an inability to initiate the arc but continues to maintain the main arc if already initiated before tip loss.

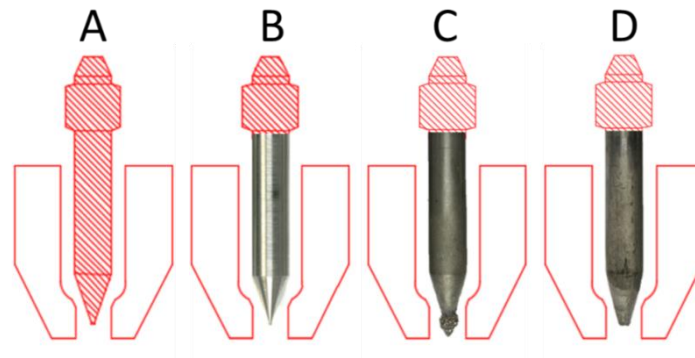


Figure 215 2% thoriated tungsten electrodes in different stages of the lifecycle, shown within a 3.9 mm straight-bore nozzle; A] CAD sketch of electrode to nozzle geometry, B] New electrode with tip parallel length, C] Electrode after use, with TEAR growth visible, D] Electrode tip loss.

As outlined in Figure 212, necking behind the TEAR occurs after long durations of use, and reduces the electrode cross-section with arc duration. This effect has the potential to detach the electrode tip behind the TEAR, shown in Figure 215 ‘D’.

A tungsten electrode tip detachment and consequential inclusion in the melt-pool during WAAM part building operations is a defect requiring costly removal and re-working, and is therefore of critical concern. This study found that tip detachment, as illustrated in Figure 215, is uncommon and mostly avoidable. Electrode tip separation is typical as a result of thermal stresses on a heavily used electrode – i.e. eight hours of near continuous use – as a result of countless arc initiations and terminations at a high current. Loss of dopant reduces electrode resistance to thermal shock. The majority of the rare electrode tip losses during the study occurred during electrode changeovers, where handling, tool use and associated stresses on the heavily used electrode resulted in the tip breaking off. Tungsten is brittle at room temperature, with increased ductility and strength at elevated temperatures (Paschen, 1996).

Though a tungsten electrode tip detachment during the WAAM part building operation is very rare, it is recommended that operators are trained, and electrodes are replaced after eight hours of use or sooner if used in more aggressive applications. Their integrity should be checked regularly during this period where access permits, and always at the end of operations. If a tip detachment is suspected, radiographic non-destructive testing of the WAAM part should be undertaken prior to machining.

6.5.2 Electrode Material and Geometry Effect on Longevity and Wear

6.5.2.1 Wear-rate and Selection of PTA Electrode Materials

The studies outlined in the literature review undertook GTA electrode wear experiments but only for single-digit durations. To reflect PTA and the longer durations of WAAM operations, each material was therefore trialled for 120 minutes, as shown in Figure 201. The rationale is that the outstanding electrodes from this test are further trialled, as part of future work, for WAAM part building operations, with durations of approximately eight hours.

Figure 216 and Figure 217 show the calculated average wear-rates for weight and length, from Figure 202 and Figure 203, of the seven materials over 120 minutes.

Zhou and Heberlein (1998) suggest that evaluating electrode wear solely via changes to electrode weight can be misleading because of material redistribution – i.e. TEAR growth. This study takes a different view and considers not only the weight wear-rate, acknowledging the issue of redistribution, but also the length wear-rate and visual changes to the tip geometry.

A comparison of the estimated expected weight loss, based on loss of electrode tip geometry, against the measured weight loss indicates that more evaporated, vaporised and eroded electrode material is lost than re-condenses on the electrode surface and TEAR. This can be explained by the actuality that the measured change in electrode length does not take into account changes to the electrode bevel. Lost material is not just from the tip but also from the electrode surfaces (Matsuda and Ushio, 1988) at sufficient temperatures, as observed in Figure 212 ‘C’, where necking has occurred. It is likely that the lost material partly condenses on the colder PTA nozzle internal wall, with the rest flushed out by the PGFR and away by the shielding gas.

It is apparent in Figure 216 that pure tungsten, followed by 2% thoriated tungsten, has the highest weight wear-rate. For pure tungsten, the predominant mechanism of erosion is the ejection from the cathode spot of liquid droplets – a method of significant material loss (Zhou and Heberlein, 1998). The 2% thoriated tungsten rate of erosion is partly influenced by the electrode geometry, cathode spot size and temperature (Zhou and Heberlein, 1998).

For the 2% thoriated tungsten electrode only, extra data is available from more extended WAAM operational use – six hours and eight minutes. The wear-rate increases over the longer duration by a further percentage of 22.4% to a weight wear-rate of 6.125×10^{-5} g/minute (Figure 202). All electrode materials, except pure tungsten, suffered a relatively higher weight wear-rate during the first hour, which reduced during the second hour, in some cases to zero, shown in Figure 202. The initial high wear is probably as a result of bedding in, with an initial burst of electrode consumption when the oxide concentration and contamination on the surface is initially high, and while subjected to the pilot and primary arc ignition.

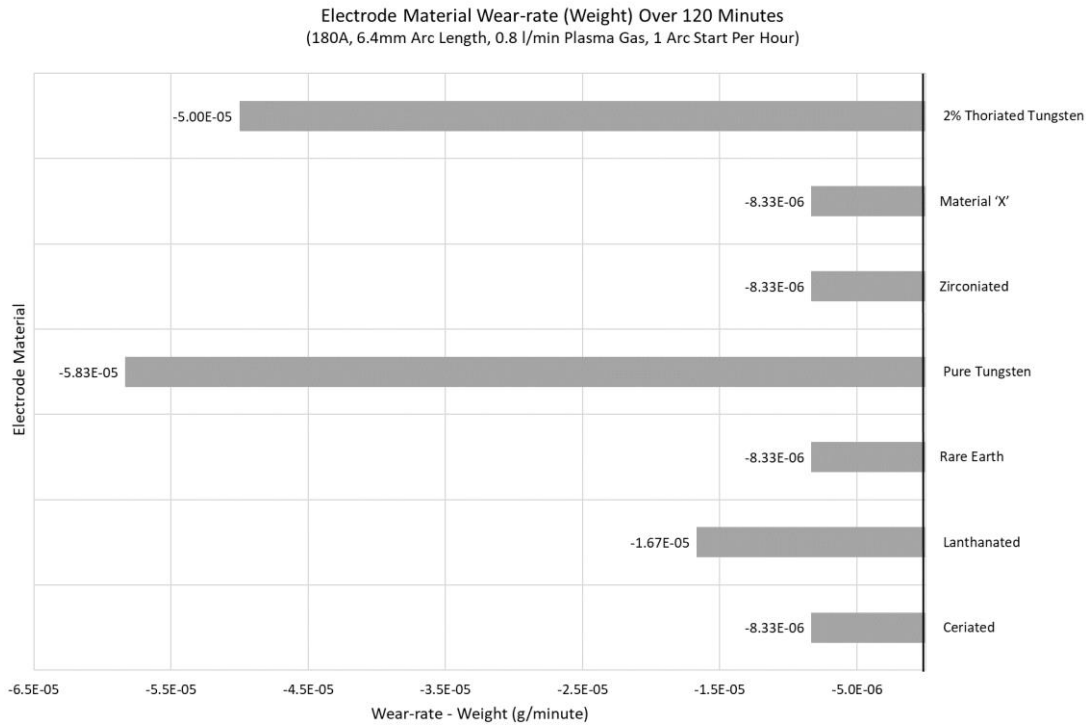


Figure 216 Calculated average weight wear-rate for seven electrode materials over 120 minutes.

With the exception of the lanthanated tungsten, shown in Figure 216, which has a slightly higher rate, the average weight wear-rates of the other materials over 120 minutes – ‘X’, zirconiated, rare earth and ceriated – were the same, at 8.33×10^{-6} g/minute, which is remarkable given the different material characteristics and the different start and end weights.

The calculated average wear-rates for length, shown in Figure 217, indicate that pure tungsten, followed by rare earth tungsten electrodes, has the highest length wear-rate. The 2% thoriated tungsten electrode appears to have a relatively low length wear-rate. However, extra data is available from more extended WAAM operational use of this material – six hours and eight minutes. The wear-rate increases over the longer duration by a further percentage of 669.65% to a weight wear-rate of 1.924×10^{-3} mm/minute (Figure 203). The negative values of Figure 217 indicate loss of electrode length (left of the vertical line), while the positive numbers (right of the vertical line) indicate increases in electrode length.

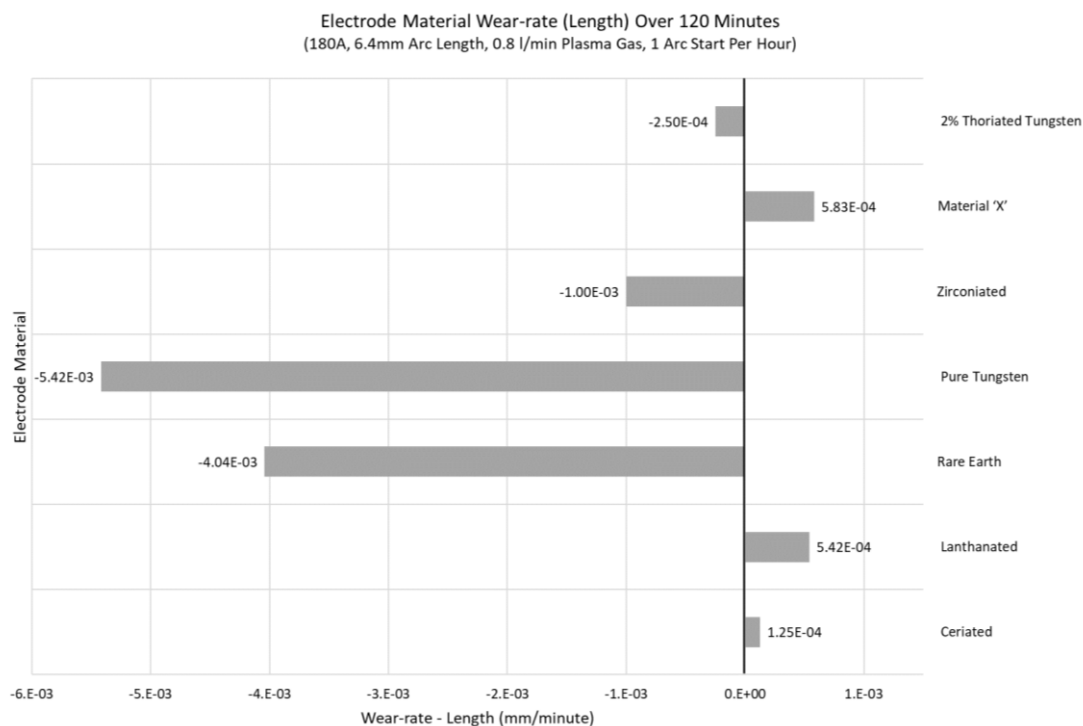


Figure 217 Calculated average length wear-rate for seven electrode materials over 120 minutes.

The increases in length of electrode materials 'X', ceriated, and lanthanated tungsten over 120 minutes are probably a result of material burn-off and tip material melting modifying the electrode tip geometry and resulting in a thinner but longer tip. The electrode tip photographs of Figure 201 show electrode tip retention with minimal rounding and possibly a very slight length build-up. It is likely that these materials, after longer arc durations, will start to lose length, like the other electrode materials.

Where there is a high loss of electrode length but a relatively low loss of weight – e.g. a rare earth electrode – the material has migrated from the electrode tip to the TEAR, maintaining the weight. However, the rare earth photographs of Figure 201 are misleading and do not reflect a large TEAR to compensate for the high loss of length but minor loss in weight. As pure tungsten electrodes have been shown to have a high loss of weight and length material and exhibit a shiny surface finish of the electrode, shown in Figure 201, it is evident that material from the electrode tip has been lost through vaporisation and ejection of liquid droplets, with minimal material redistribution.

Loss in electrode length is significant as it affects the arc length and electrode to nozzle geometries, and can therefore prevent arc ignition. Nevertheless, the loss of weight is critical as lost material through vaporisation could result in melt-pool contamination or harmful dust/vapour.

Figure 218 illustrates a nine-box electrode evaluation grid, combining both wear factors of calculated average wear-rates for weight and length, shown in Figure 216 and Figure 217, and the visual comparison of electrode materials, shown in Figure 201. The grid outlines the mechanisms of electrode wear and positions of each electrode material on the X–Y axis, based on their performance, to help to identify which electrode material has the highest potential, which may be acceptable, and which are best avoided for WAAM applications.

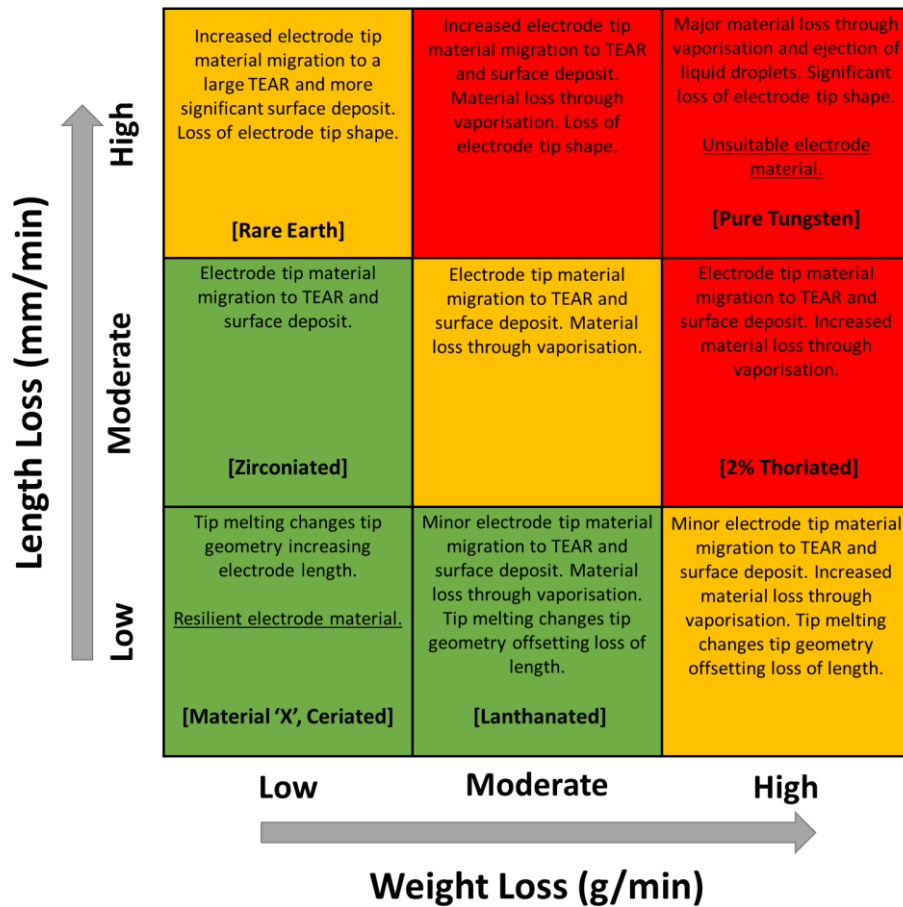


Figure 218 Electrode material nine-box evaluation grid.

Pure tungsten has the highest work function value, shown in Table 2, resulting in ignition issues and arc instability. The current carrying capacity (Diamond-Group, 2002) is lower than alloyed electrodes, and electrode temperature is also higher, resulting in poor tip retention, tip melting and high erosion, leading to a short service life, shown in Figure 201. The cathode spot is molten during arcing. Better alternative electrodes are available for WAAM (Lowke, Morrow and Haidar, 1997; Diamond-Group, 2002; O'Brien, 1991; Ushio, Sadek and Matsuda, 1991; Zhou, Ding and Heberlein, 1996).

2% thoriated tungsten has one of the highest work functions, shown in Table 2, and a vaporisation rate higher than the migration rate, leading to oxide depletion and arc ignition issues. The erosion rate is also high, shown in Figure 202. The cathode spot is more complex during arcing than for pure tungsten because of the thorium diffusion through and evaporation from the electrode (Ushio, Sadek and Matsuda, 1991; Sadek, Ushio and Matsuda, 1990; Zhou, Ding and Heberlein, 1996). The health and safety

concerns of the radioactive element should rule it out for future WAAM operations, as safer alternatives are available.

2% ceriated tungsten has a low work function, shown in Table 2, and a high migration rate, which together enable easy arc ignition, superior to 2% thorium tungsten (Wolfram Industrie, 2019). However, the increased migration rate leads to premature depletion of the oxide and therefore arc starting issues after extended use, making this electrode material better suited for shorter operations (Diamond-Group, 2002) not typical of WAAM operations. Cerium tungsten is best suited for lower current operations (O'Brien, 1991), which again are not usual for WAAM. However, the high consumption rate, as a result of a low melting temperature, outlined in the literature review, was not experienced by this study after two hours of use, shown in Figure 202.

2% lanthanated tungsten has one of the lowest work functions, shown in Table 2, allowing easy arc ignition, reduced tungsten grain growth and increased service life. However, the vaporisation rate is higher than the migration rate, leading to oxide depletion (Ushio, Sadek and Matsuda, 1991). This is thought to be the best option for GTA operations (Sadek, Ushio and Matsuda, 1990) and, given its results for PTA, a WAAM contender.

The ideal electrode for PTA WAAM operations requires the following characteristics:

- Ignition reliability.
- Ease of arc starting.
- Low burn-off rate – i.e. low length and weight wear-rate.
- Resistance to electric arc erosion (Paschen, 1996).
- High electrical conductivity.
- Good thermal conductivity.
- Dopant balance of migration/evaporation rates.
- Low work function value.
- Good electrode tip geometry retention.
- Long service life.
- Minimal TEAR formation, as this impedes laminar plasma gas flow.
- Ability to maintain high arc quality.

- No health concerns – i.e. no radioactive substances.

It is clear from Figure 201 that doped electrodes exhibit improved tip geometry retention compared to thoriated and pure tungsten. This aligns with the findings of Matsuda and Ushio (1988).

To compare the tested electrodes and aid selection for PTA WAAM operations, a colour-coded summary is shown in Table 46: ‘Green’ means good and ‘Red’ is less desirable. For surface deposit, electrode tip retention and TEAR formation, a rating scale of 1 to 5 has been assigned, shown in Table 46, based on observations (Figure 201) to allow comparison.

Table 46 Electrode summary and selection guidance.

Electrode Material	Surface Deposit See Figure 201 (Note 1)	Calculated Average		Tip Retention See Figure 201 (Note 2)	TEAR Formation See Figure 201 (Note 3)
		Weight Wear-rate See Figure 216 (g/min)	Length Wear-rate See Figure 217 (mm/min)		
Pure Tungsten	1	5.83×10^{-05}	5.42×10^{-03}	5	5
2% Thorium Oxide Tungsten	7	5.00×10^{-05}	2.5×10^{-04}	3	4
2% Cerium Oxide Tungsten	5	8.33×10^{-06}	Increase of 1.25×10^{-04}	2.5	2.5
2% Lanthanum Oxide Tungsten	2	1.67×10^{-05}	Increase of 5.42×10^{-04}	2	3
0.8% Zirconium Oxide Tungsten	4	8.33×10^{-06}	1×10^{-03}	2	2
2% Rare Earth Oxide Tungsten	3	8.33×10^{-06}	4.04×10^{-03}	4.5	2.5
2% Material ‘X’ Oxide Tungsten	6	8.33×10^{-06}	Increase of 5.83×10^{-04}	1.5	3

Note 1. Ranked in order from 1 to 7, 1 being the shiniest and 5 the dullist.

Note 2. Scale from 1 to 5, 1 being no change in tip geometry to 5 with tip missing.

Note 3. Scale from 1 to 5, 1 being no TEAR or the start of a TEAR to 5 being large TEAR formation.

Based on the summary in Table 46 and evaluation of Figure 218, the following materials are proposed to be taken forward for WAAM part building operation trials and future work: material 'X', 2% cerium oxide tungsten and % lanthanum oxide tungsten.

At the end of the study, Wolfram Industrie acknowledged the mystery material 'X' electrode material as their relatively new GTA electrode material, trade name Inostar. This study is the first trial for PTA applications. Inostar contains up to 2% by weight of a confidential blend of rare earth metals and tungsten alloy. The material was developed for sensitive materials, including titanium, and to improve arc ignition with reduced burn-off and increased service life.

6.5.2.2 Electrode Geometry Effect on Longevity and Wear

Electrode Length

The short nozzle and electrode combination, shown in Figure 184, should have resulted in less wear because of the increased cooling by the torch cooling system. Unfortunately, minimal improvement was in evidence when compared with the standard nozzle and electrode after the same duration of use, shown in Figure 201 and Figure 204 . Over the measured two-hour operation duration, the shorter electrode actually suffered a higher wear-rate. Nevertheless, the TEAR growth was reduced after 120 minutes compared to the standard-length electrode (Figure 201).

The increased wear may be attributed to the increased temperature gradient as a result of the improved cooling which, as reported by Zhou, Ding and Heberlein (1996) in their findings, increases ion bombardment and consequently vigorous erosion.

Effect of 2% Thoriated Tungsten Tip Geometry and Length on Arc Ignition

Initially, it was believed by the manufacturer, PWP, and the operators that the electrode tip parallel length, shown in Figure 43, was required for a reliable PTA arc initiation. This understanding is in line with literature, which outlines the relationship between higher resistive heating of the sharp electrode and easier arc ignition (da Cruz and Scotti, 2016).

However, in retrospect, with PTA operating experience, this is not always the case, as initial electrode wear removes this element in the first few minutes and arc ignition is still reliably possible at this time.

In addition, the electrode tip to nozzle geometries were also thought critical for arc ignition. Taking this to the extreme (Figure 207), the results reveal that this is not the case and that a considerable amount of the electrode length and tip can be removed – up to 3.025 mm – before arc ignition issues occur. Figure 219 ‘C’ suggests that the arc initiates from the edge of the tip flat (cathode spot), when the parallel length (Figure 43) or sharp tip of a new tip is missing. The change in the surface coating is also evident (Figure 219 ‘B’).



Figure 219 Effect of electrode length on arc starting: A] A new 2% thoriated electrode, B] Reduced electrode length at the point of failure to arc start. C] Close-up of electrode flat tip ‘B’, and evidence of an arc starting cathode spot on flat tip edge.

Arc ignition at the reduced electrode length was probably possible as a result of the edge, and possibly because of the associated charge concentration, in addition to the newly exposed thorium oxide reducing the work function of the electrode and the voltage required to initiate the pilot arc (Sadek et al., 1990). However, initial arc ignition from a cold electrode is more likely a field emission than a thermionic emission because of the temperature. Nevertheless, the finding demonstrates the electrode tip to nozzle geometries, and electrode tip shape is not always critical for initial PTA arc ignition.

However, removal of the electrode surface is not usually undertaken before every arc start in normal operations. To maintain a reliable arc ignition, the electrode cone shape and parallel length in Figure 43 should therefore still be retained for WAAM operations.

Electrode Geometry and Angle

The geometry of the PTA electrode, electrode angle and flat tip diameter and its wear have been shown within this study (Chapter 3) to affect arc pressure.

The diameter of the PWP Viper MC (water-cooled) PTA torch electrode is fixed at 4 mm, with a manufacturing tolerance of ± 0.1 mm in accordance with BS EN ISO 6848:2015. At this diameter, the approximate current range, following the standard, for an electrode with an oxide additive operating in both electrode negative and positive is illustrated in Table 47. The electrode is therefore higher current rated than this studies PTA torch.

Table 47 Approximate current range for a 4 mm diameter electrode (British Standards Institution, 2015).

Electrode Diameter (mm)	Direct Current (DC)		
	Electrode Negative (ve-)	Electrode Positive (ve+) (Note 1)	
	Tungsten with Oxide Additives (A)	Tungsten with Oxide Additives (A)	Pure Tungsten (A)
4	100 to 400	35 to 50	35 to 50

Note 1. The current rating is significantly lower for the DCEP because of the higher heat output at the electrode.

The cone shape of electrode tips allows control of the electrode area subjected to thermionic emission. Its geometry affects the plasma gas flow, arc stability, arc ignition, electrode service life, arc penetration and melt-pool geometry, making it critical for WAAM operations.

The diameter of the electrode dictates its current-carrying capacity. Larger diameters are rated for higher currents and exhibit longer service life. However, larger diameters used at low currents result in arc instability, while narrow diameter electrodes used at high currents result in excessive melting, reducing service life but enabling easier arc ignition. A balance therefore needs to be reached for each application and PTA torch design. The PWP Viper MC torch used in this study has an electrode diameter fixed at 4 mm, equating to a DCEN electrode range of 100 to 400 A, shown in Table 47.

The electrode design and geometry are PTA torch manufacturer specific but typically have the commonality of a smooth bevel and centralised pointed electrode tip.

Resistive heating of an electrode is proportional to the cross-section area of the electrode. A small electrode tip diameter (smaller angle) therefore has a smaller cross-section area and consequently greater resistance to current flow, so heats up. In contrast, a larger electrode tip diameter (larger angle) heats up less. Where the change in cross-section is increased, a higher thermal gradient is evident. It is therefore the case that the sharper and smaller angled the electrode tip, the higher the tip temperature from concentrated resistance heating, thus resulting in increased rate of wear.

It was observed that, initially, a pointed electrode tip suffers increased rate of wear. However, once the tip has rounded with use, the rate of wear decreases, aligning with the findings of Zhou and Heberlein (1998).

In addition, where the temperature is highest, and with a smaller angled electrode, the current becomes focused and the current density increases. Elevated temperature can result in electrode melting and consequent changes to the tip geometry. The sharper electrode also has a more significant concentration of surface oxide as a result of the increased cross-cut area of the bevel exposing the longitudinal sub-surface oxide regions. For larger angled electrodes, there is a change in the ratio of surface to volume, reducing the current density and temperature.

The smaller 20° angled electrode lost more material than the 60° electrode and significantly more than the 40° electrode, shown in Figure 209, aligning with the findings of Zhou and Heberlein (1998). The smaller cross-section increases the temperature, consequently initially resulting in high erosion and an increase in the electric field as well as higher ion bombardment and more sustained tip erosion.

This study shows that the TEAR location on the electrode changed with the current. This change in position is more evident on the 20° electrode, shown in Figure 211. This electrode tip was also found to become more brittle with use and be more likely to suffer from tip detachment, shown in Figure 191 'C'. This is probably as a result of the reduced cross-section area and increased current density and tip temperature. The measured wear-rates of the angled electrodes show that the standard 40° electrode loses the most significant length (Figure 208) but least weight (Figure 209), indicating that the tip material has migrated to the TEAR and as a surface deposit.

The PWP Viper MC torch electrode flat tip diameter (Figure 43) is 0.36 mm. However, to investigate if flat tip diameter increases arc wander and ignition issues, as outlined in the literature, this was increased in stages to 2.29 mm. The electrode tip diameter was increased by reducing the electrode length (Figure 205). The most significant material loss was measured for the largest tip diameter, aligning with the observation of tungsten particles on the copper-block surface. The likely cause of the weight loss and observation is that the thermionic emitted particles from the face of the electrode tip, facing the work-piece, are unable to cross the flat tip surface (Figure 206) and ascend the side of the electrode to the TEAR. They are forced to transition down to the substrate. Figure 205 illustrates the change in TEAR shape and location, as it grows along the surface and not axially as a result of the evaporated material path and material loss to the surface. The literature also suggests that a large flat electrode tip diameter results in a less stable arc. It is therefore recommended for WAAM operations that a standard electrode tip, shown in Figure 43, is utilised.

This study has shown (Figure 207) that arc ignition is still possible with the electrode tip parallel length removed (Figure 43), and with changes to the electrode to nozzle geometry, both previously thought to be critical for PTA arc ignition. However, this required the removal of electrode material for each iteration, removing oxide-depleted material and exposing fresh oxide material, aiding arc ignition. For normal operations, where material removal is not possible, the original electrode shape should therefore be utilised to assist PTA arc ignition.

6.6 Conclusion

In this chapter, electrodes were investigated for PTA. The mechanisms and behaviours of PTA electrode wear during their use and the effect of electrode material and geometry on electrode longevity and wear have been examined to maximise electrode life, optimise WAAM operations and maximise equipment availability.

The limit to electrode lifespan for PTA WAAM occurs with failure to reinitiate the arc. After extended use over eight hours of near continuous operation, PTA ignition is no longer possible. Operator intervention is required to replace the electrode, enabling commencement of WAAM. For a heavily used electrode, an initiated main arc does not involuntarily stop after a duration of use but will not re-ignite if terminated.

Reasons for non-arc starting involve a combination of three main factors: changes to the electrode tip geometry, depletion of the tungsten dopant and loss of electrode length through wear, which increases the distance between the PTA nozzle and electrode during pilot arc ignition. Arc ignition can be improved through electrode replacement, reducing the number of arc initiations and selection of a doped electrode material with a low work function and better tip retention properties. Re-igniting a used electrode can be achieved by means of removal of the tip surface, thus exposing fresh dopant.

Factors identified as affecting PTA electrode wear include:

- Duration of continuous use combined with the number of arc initiations increases the loss of electrode length, material and tip geometry, encouraging TEAR growth.
- Loss of electrode tip through evaporation, vaporisation and erosion through substrate ions results in length and material losses, as well as material migration from the electrode surface and tip in the form of a surface deposit and TEAR growth.
- High currents increase resistive heating, and the current becomes focused. Current density increases where the temperature is highest, and subsequently increases electrode tip and surface evaporation and vaporisation. The increased temperature and thermal gradient increase the depletion of the dopant at the tip.
- Electrode angle affects length and weight wear-rates – a smaller angle increases the wear-rate, and the 20° electrodes lose the maximum amount of material.

- Large diameter flat tip electrodes change the TEAR shape, exhibit tungsten particle loss to the substrate and associated contamination, and display increased material loss, so are not recommended for PTA WAAM.
- Electrode material selection:
 - An incorrect balance between dopant evaporation and dopant replacement through diffusion results in dopant depletion, causing a dopant-free pure tungsten tip with increased wear characteristics.
 - Pure tungsten experiences significant wear compared to doped electrodes.
 - Different doped tungsten materials affect the amount of material migration, electrode length and weight wear-rates, as well as tip geometry retention and TEAR growth.
 - Duration at temperature and number of stops increase tungsten grain growth, inhibiting dopant diffusion to the tip and resulting in a dopant-free pure tungsten tip.
- Electrode subjection to specific PTA applications increase electrode wear, including:
 - AC PTA at different values of current, frequency and balance.
 - Use of active gases – semi-inert plasma gas, including hydrogen and carbon dioxide/argon gas mixes.
- In the lower temperature region above the TEAR ion erosion has potential for the most rapid rate of material loss through catastrophic electrode tip loss. However, this study observed such loss to be rare, occurring only after over eight hours of continuous high current operation.

Methods of reducing electrode wear include:

- Minimising the diameter of the flat electrode tip.
- Electrode dopant increasing tip shape retention, reducing the length and weight wear-rates and lessening burn-off compared to pure tungsten by reducing the work function of the material.
- A new electrode material, Wolfram Industrie's 'Inostar', was identified, with its improved wear-rate, as an alternative to 2% thoriated tungsten to alleviate HSE safety concerns.

- Evaluation of seven PTA electrode materials regarding wear-rate, tip retention, TEAR growth and surface deposit has led to the recommendation of three materials for WAAM trials: material 'X', aka Inostar, 2% cerium and 2% lanthanum oxide tungsten.

Chapter 7

Thesis Conclusion

This study establishes the relationships between arc pressure and keyhole defect formation for a variety of thermal conditions found when using PTA for WAAM, and additionally concludes that electrode lifespan when using PTA, can be optimised for WAAM operations.

Returning to the research hypotheses posed in section 1, at the beginning of this study, it is now possible to state that:

1. The research identified WAAM PTA process variables and established, through arc pressure measurements, their adaptability to reduce arc pressure for WAAM, thus allowing higher currents to be utilised to increase the WAAM deposition rate and minimising the risk of keyhole defects.
2. Within this study, the PTA process has been characterised in terms of arc pressure and keyhole defect formation, utilising the arc pressure measurements for torch nozzle designs, electrode geometries and process variables, thus establishing the sensitivities of the process and variable ranking concerning the effects on the arc pressure (PGFR, current, nozzle diameter, and arc length). This also enables an empirical model to be developed, capable of predicting PTA arc pressure for a broad set of process conditions and torch geometries. Optimum WAAM variable selection is also enabled, at the same time as minimising arc pressure and associated defects.
3. This study confirmed that PTA arc pressure controls the development of keyhole defects with sharp arc pressure transitions occurring between keyhole and no keyhole defects – a specific arc pressure keyhole defect threshold. In addition, the transition dependence on the material type and thermal conditions was established.
4. Evidence from this study affirms that electrode tip geometry and material can be improved to minimise arc pressure, with alternative electrode materials exhibiting lower wear-rates, better tip retention, improved arc starting, and potentially longer

electrode life identified as having the potential to optimise WAAM operations and maximise equipment availability.

7.1 Addressing the Research Objectives

The objectives posed at the beginning of this study, in section 1.1, are addressed below:

1. Method of arc pressure measurement – the piezoelectric pressure transducer, located below a measurement orifice within a water-cooled copper-block, has proven to be a reliable and repeatable method for arc pressure measurement. The effect of orifice diameter has a minimal effect on arc pressure measurement accuracy. However, the arc needs to be larger than the orifice and it is necessary to make a static measurement.
2. Factors controlling/affecting arc pressure and empirical model development:
 - Critical parameters affecting PTA arc pressure have been identified as current, arc length, PGFR and plasma gas composition. The PTA restriction nozzle geometry and specialist nozzle designs also affect arc pressure. PTA electrode geometry and electrode material have, in addition to electrode wear, also been determined as influencing arc pressure.
 - The empirical model developed from the arc pressure measurement data represents the relationships between PTA variables, combinations of variables and arc pressure.
3. Keyhole initiation – arc pressure has been confirmed as initiating keyhole defects, irrespective of how it is realised: e.g. nozzle diameter or PGFR for a given material and thermal conditions when using a PTA energy source.
4. Effect of WAAM operation conditions on electrode lifespan and methods for prolonging longevity:
 - Subjecting a 2% thoriaated electrode to WAAM operation conditions over eight hours of near continuous use at high current results in significant wear of the electrode tip.
 - The limit to electrode lifespan for PTA WAAM occurs with failure to reinitiate the arc. Reasons for non-arc starting involve a combination of three main factors: changes to the electrode tip geometry, depletion of the tungsten dopant and loss of electrode length through wear.

- Arc ignition can be improved by means of electrode replacement, reducing the number of arc initiations, and selection of a doped electrode material with a low work function and better tip retention properties.

7.2 Summary of Other Research Findings

Arc Pressure Measurement

- PTA peak arc pressure is significantly higher than GTA and their arc pressure distributions both approximate Gaussian. PTA provides the advantage of more protracted standoffs, longer arc lengths, for WAAM.
- Peak pressure, and the area under arc pressure distributions, is representative of total arc force.
- PTA arc pressure reduction can be achieved by varying the plasma gas composition with higher percentages of helium, modifying torch geometry (specialist nozzle designs, nozzle diameter, nozzle length and DA), and increasing arc length, in addition to reducing PGFR and current.
- A PTA nozzle interaction time concept is proposed, where the nozzle geometry dictates the density of the plasma gas, velocity and duration of gas conditioning.

Arc Voltage

- The determined relationship between arc voltage and arc pressure could be used as a real-time monitoring proxy for arc pressure to avoid high arc pressure and its associated defects during WAAM operations.
- The increase of arc voltage with increased arc length as a result of electrode length changes could be used as a real-time monitor of electrode wear during WAAM operations.

Keyhole Defect Transition

- Keyhole defects depend on arc pressure for a given set of thermal conditions with a sharp arc pressure/keyhole defect transition, representing a balance between thermal melt-pool fluid flow and the size of the arc pressure-induced hole. The transition values therefore depend on material type, travel speed, heat input and plate thickness.
- Keyhole defect depth is proportional to applied arc pressure.

- The substrate material affects arc pressure/keyhole defect transition through its physical and thermal properties and distinct melting efficiencies.
- For stainless steel, the arc pressure transition goes up with heat input.
- The arc pressure transition initially increases with heat input for titanium but reduces at higher heat inputs as a consequence of the appearance of a different defect type. This is arguably because of the deeper keyhole in titanium, compared with stainless steel, combined with the smaller melt-pool size and different geometry.
- The arc pressure transition increases with travel speed at constant heat input up to a maximum before dropping again. The increase results from increasing melting efficiency with travel speed. The decrease is because of unstable initial conditions at the start of the deposit at very high travel speeds.

Electrode Wear and Longevity

- Electrode tip detachment, a concern for WAAM, was predominantly observed during operator removal, and not during PTA operations. However, at the lower temperature region above the TEAR, ion erosion causing necking has the potential, given time, to initiate a catastrophic electrode tip loss. Nevertheless, this study observed such loss to be rare, occurring only following over eight hours of continuous high current operation. There is therefore minimal potential for tungsten inclusions during WAAM operations on the proviso that operator intervention occurs before eight hours.
- Duration of continuous use combined with the number of arc initiations increases the loss of electrode length, material and tip geometry, and encourages TEAR growth.
- Loss of electrode tip takes place through evaporation, vaporisation and erosion by substrate ions, resulting in length and material losses, as well as material migration from the electrode surface and tip in the form of a surface deposit and TEAR growth.
- TEAR formation/growth and electrode wear are determined by a combination of both the number of arc ignitions and terminations, in addition to the duration of time at temperature. Only very small changes in electrode length and weight were observed, and the majority of electrode length lost results from electrode tip evaporation and material relocation to the TEAR and as a surface deposit.
- The main mechanisms that lead to electrode oxide depletion are a combination of oxide migration rate through the grain boundaries via diffusion to the electrode tip and its

loss from the tip through evaporation. Dopant increases tip shape retention, reducing burn-off and ease of arc starting by reducing the work function of the material.

- Used/worn electrodes generally have the same shape, but the structure is different – in particular, a region utterly devoid of thorium at the tip, which is a reason for failure to arc start.
- High currents increase resistive heating, and the current becomes focused. Current density increases where the temperature is highest and subsequently increases electrode tip and surface evaporation and vaporisation. The increased temperature and thermal gradient increase the depletion of the dopant at the tip.
- Electrode angle affects the resistive heating and consequently the length and weight wear-rates – smaller angles increase the wear-rate, and 20° electrodes lose the maximum material.
- Though large diameter flat tip electrodes decrease arc pressure, they also change the TEAR shape, exhibit tungsten particle loss to the substrate and associated contamination, and display an increased material loss. They are therefore not recommended for PTA WAAM.
- Electrode materials identified during the study that may have the potential for optimising WAAM are material are ‘X’, aka Inostar, 2% cerium and 2% lanthanum oxide tungsten.

7.3 Significance and Implications of the Study

The research gap and literature research gap identified at the beginning of this study, in sections 1.1 and 2.12, are addressed below:

- A detailed study has been undertaken into the effects of PTA arc pressure in the operational regime for WAAM, with its influence on melt-pool depression and subsequent keyhole defect generation established.
- Long duration electrode behaviour and wear was investigated for WAAM operational conditions, and the effect of different electrode materials and tip geometries on arc pressure and electrode longevity determined.
- An arc pressure empirical model was developed, utilising the measured arc pressure data, which is integral for future WAAM operations in allowing arc pressure to be

predicted and controlled and consequently mitigating against keyhole defect formation. WAAM parameters can be selected using the model before WAAM operations in the knowledge of their effect on arc pressure and keyhole defect formation. The correlation in the study between arc pressure and arc voltage also allows the voltage signal to be used as a proxy for real-time arc pressure measurement. It can therefore be used to ensure that keyholes are not formed during WAAM. This, of course, requires knowledge of the arc pressure keyhole defect transition threshold and how this threshold varies depending on thermal conditions.

- A correlation between PTA arc pressure and keyhole defect initiation was confirmed, and arc pressure keyhole defect transition thresholds were identified for a given substrate material and thermal conditions, maximising WAAM deposition while remaining free from keyhole defects.
- A comprehensive study of arc pressure measurement was undertaken for the identified PTA parameters, torch and electrode geometries and electrode materials.
- The thesis provides a more in-depth insight into the mechanisms and behaviours of PTA electrode wear, TEAR growth and dopant depletion. Prior to this study, evidence of these phenomena predominantly related to short durations or was anecdotal.
- The study established a comprehensive measurement of wear-rates for several PTA electrode materials, allowing prediction of how many, and at what time, electrode change out is required – valuable information for an automated process such as WAAM.
- The electrode wear evaluation provides an insight into the probability of PTA electrode tip detachment with extended use, which was found to be rare, alleviating concerns about tungsten inclusions in WAAM-produced parts.

7.4 Identified Study Limitations

- The study is specific to the PWP Viper MC torch, though the findings and trends are comparable to other torch studies identified in the literature.
- This study has established relationships between measured arc voltage, arc pressure and electrode wear, and a novel means is proposed of utilising arc voltage as a proxy to avoid high arc pressure and its associated defects and to monitor electrode wear

through increased arc voltage as the arc length increases. However, both concepts still need to be implemented and trialled for WAAM operations.

- Though electrode materials have been identified that improve electrode longevity and subsequently improve equipment availability, WAAM trials, where electrodes are subjected to actual long and arduous conditions, longer than the two hours of this study, still need to be undertaken.

Chapter 8

Future Work

As a result of the 2020 worldwide COVID-19 pandemic, further experimentation was not possible, meaning that the outstanding work is listed below as future work:

- Determination of keyhole transitions for both heat input and travel speed with wire-feed
- TEAR differential pressure measurement
Undertake differential pressure measurement of a PTA arc within a nozzle to ascertain the pressure drop across the TEAR and identify if backpressure is developed, and whether this rises with TEAR growth. A differential pressure transducer with the 0–25 mbar range has been procured and a special PTA nozzle machined, with pressure tapping points. The workshop drawings are illustrated in Figure 238 of Appendix J.
- Welding trial of most promising DC electrode material
Investigate, for electrodes from different construction materials outlined in this study, their effect on electrode longevity, wear and ease of arc starting during DC WAAM operations and long duty cycles, i.e. up to eight hours of operation.
- Establishing of number of main arc starts possible
Examine the maximum number of arc starts possible over a 30-minute period, noting failure to arc start. Investigate electrode wear and tip geometry changes. This data will limit the number of arc starts available to a WAAM operator to reduce the number of electrode replacements and maximise equipment availability.
- Establishing effects of plasma gas composition on WAAM deposited material
Utilise high percentage of helium/argon plasma gas mixes to investigate the effect on WAAM operations and parts.
- Confirmation that the thermionic emission area is related to current and TEAR location
- Consideration of effects of TEAR and electrode surface finish/machining mark direction on longevity and wear for DC applications

Use a highly polished electrode and compare to an electrode with machining marks, or a standard electrode subjected to the same operational conditions. All PWP electrodes are machined on a lathe, resulting in machining marks transverse to the electrode length, shown in Figure 220.

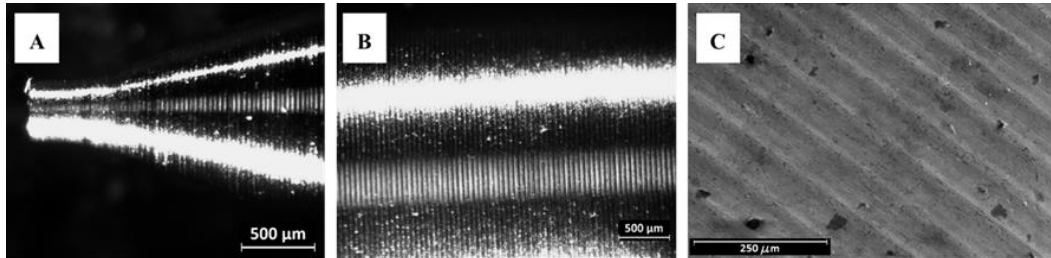


Figure 220 Electrode machining marks: A] Microscope image of electrode tip, B] Microscope image of electrode shaft, C] SEM image of electrode surface.

To establish whether the machining marks initiate necking and TEAR growth, increase resistance to arc flow and affect the wear or longevity of the electrode, an electrode with no machining marks should be trialled and the results compared with that of a standard electrode with machining marks.

- Identification of effects of electrode tip shape on longevity and wear for AC applications

Ascertain the effect of electrode tip design on its wear and longevity during AC PTA operations using the electrode tip designs in Figure 214. Each design should be trialled, and the results compared with those of a standard electrode – i.e. 60 minutes at 200 A, frequency 200Hz, Balance 70/30 – and their length, weight and TEAR growth compared.

- Establishing suitability of electrode materials for AC PTA applications
Investigate electrodes from different construction materials outlined in this study, including their effect on electrode longevity, wear and ease of arc starting during AC WAAM operations and long duty cycles.
- Relating arc pressure from torch design and operating parameters with energy density profile through calorimetry
- Investigating whether arc voltage is a suitable proxy for arc pressure for the purposes of avoiding too high an arc pressure (and therefore defects) during the building of a WAAM part

- Investigating whether electrode wear can be monitored through arc voltage as the arc length increases
- More detailed study of the effects of arc pressure and bead geometry
- Re-design of torch to minimise arc pressure and use better operating conditions to allow higher current operation and therefore higher build rates
- Study of similar effects in AC PTA and, specifically, attempts to minimise electrode wear

Chapter 9

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Chapter 10

Appendix A – Graph Extended Versions

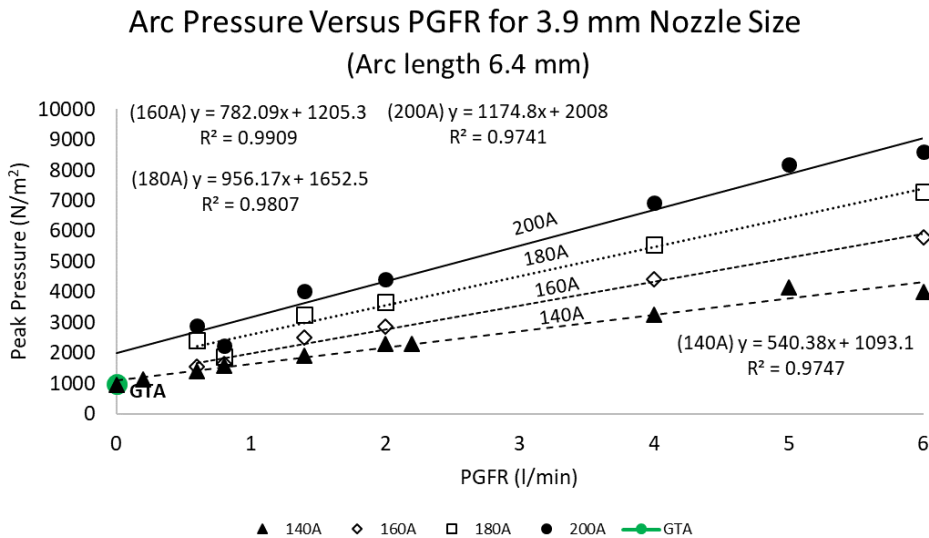


Figure 221 Effect of increasing PTA PGFR while keeping other parameters constant: 3.9 mm diameter nozzle, 6.4 mm arc length. The peak arc pressure for GTA, at 140 A and arc length of 6.4 mm, is shown for comparison. Extended version of Figure 76.

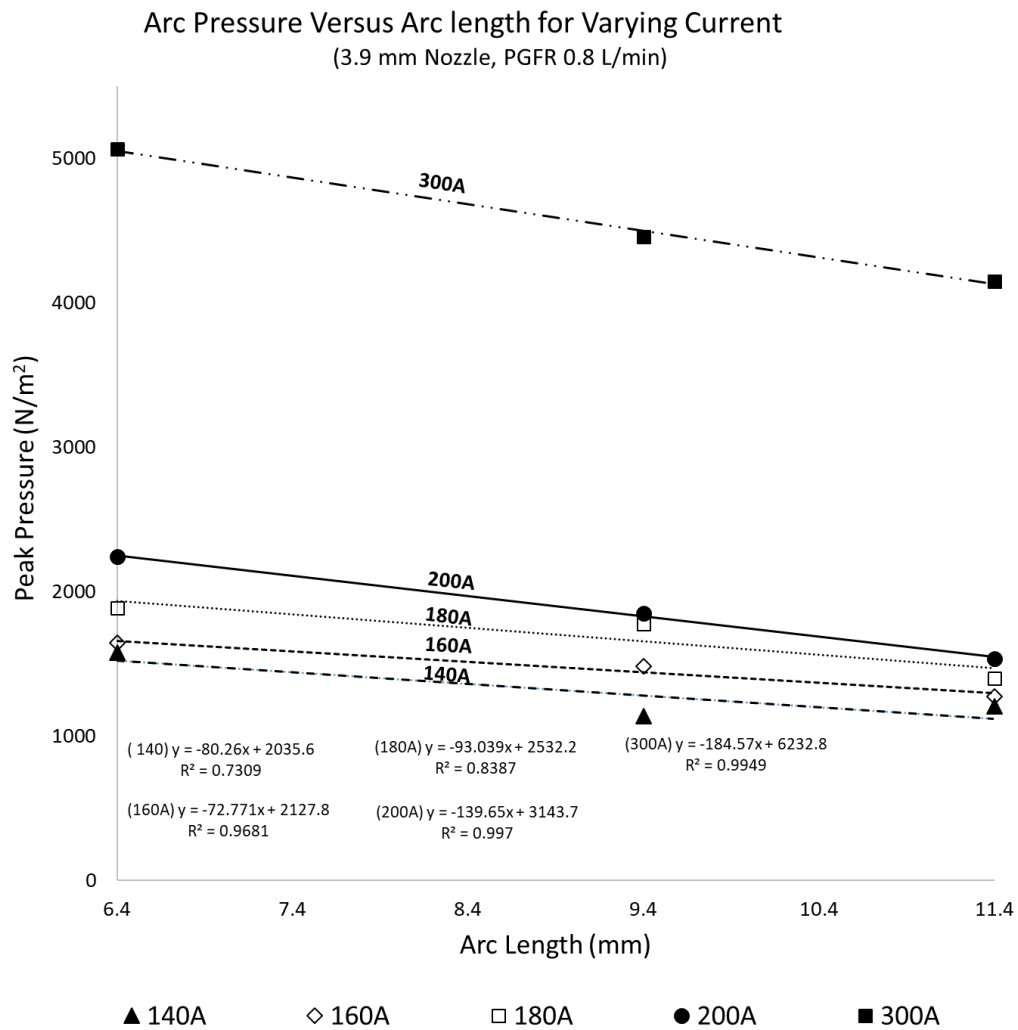


Figure 222 Comparison of arc pressure versus arc length for 140, 160, 180, 200 and 300 A and three arc lengths of 6.4, 9.4 and 11.4 mm for a straight-bore 3.9 mm nozzle. Extended version of Figure 80.

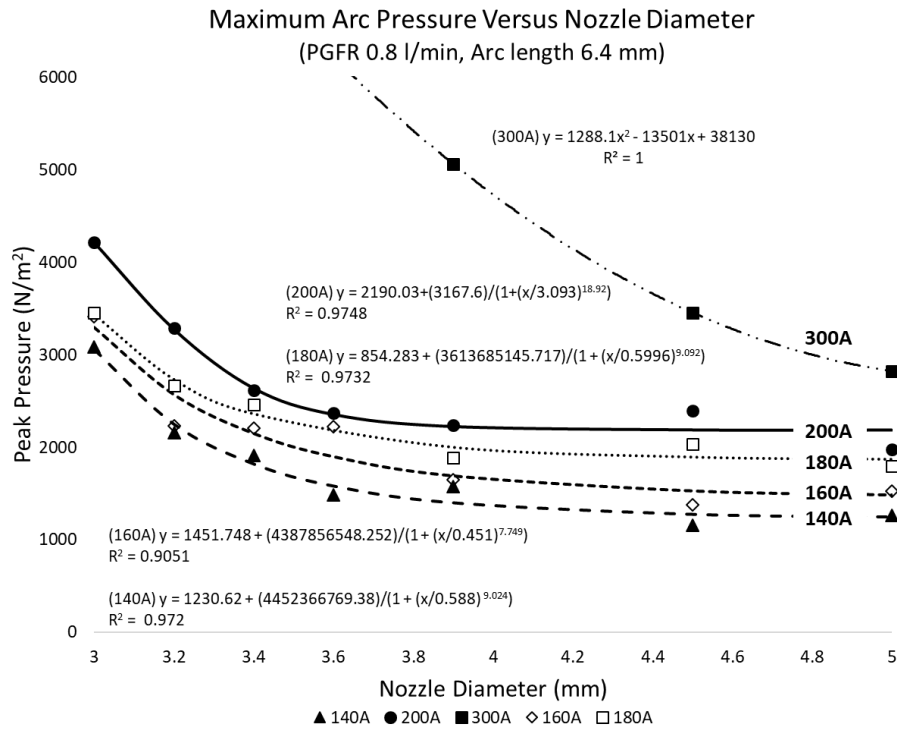


Figure 223 Peak arc pressure versus straight-bore nozzle diameter for seven geometries: 3, 3.2, 3.4, 3.6, 3.9, 4.5 and 5 mm, at an arc length of 6.4 mm. Extended version of Figure 88.

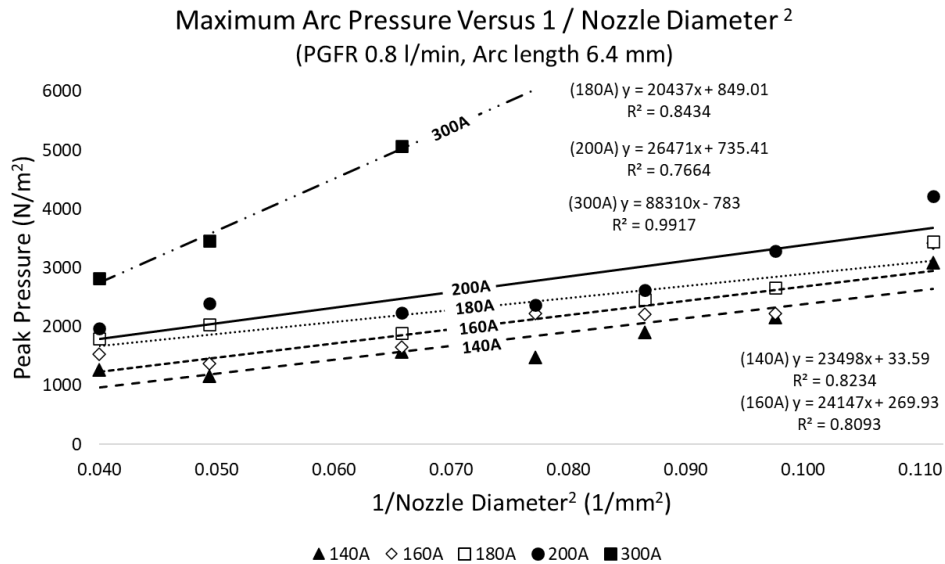


Figure 224 Peak arc pressure versus 1/square of nozzle diameter at an arc length of 6.4 mm. Extended version of Figure 89.

Appendix B – Arc Pressure Distributions

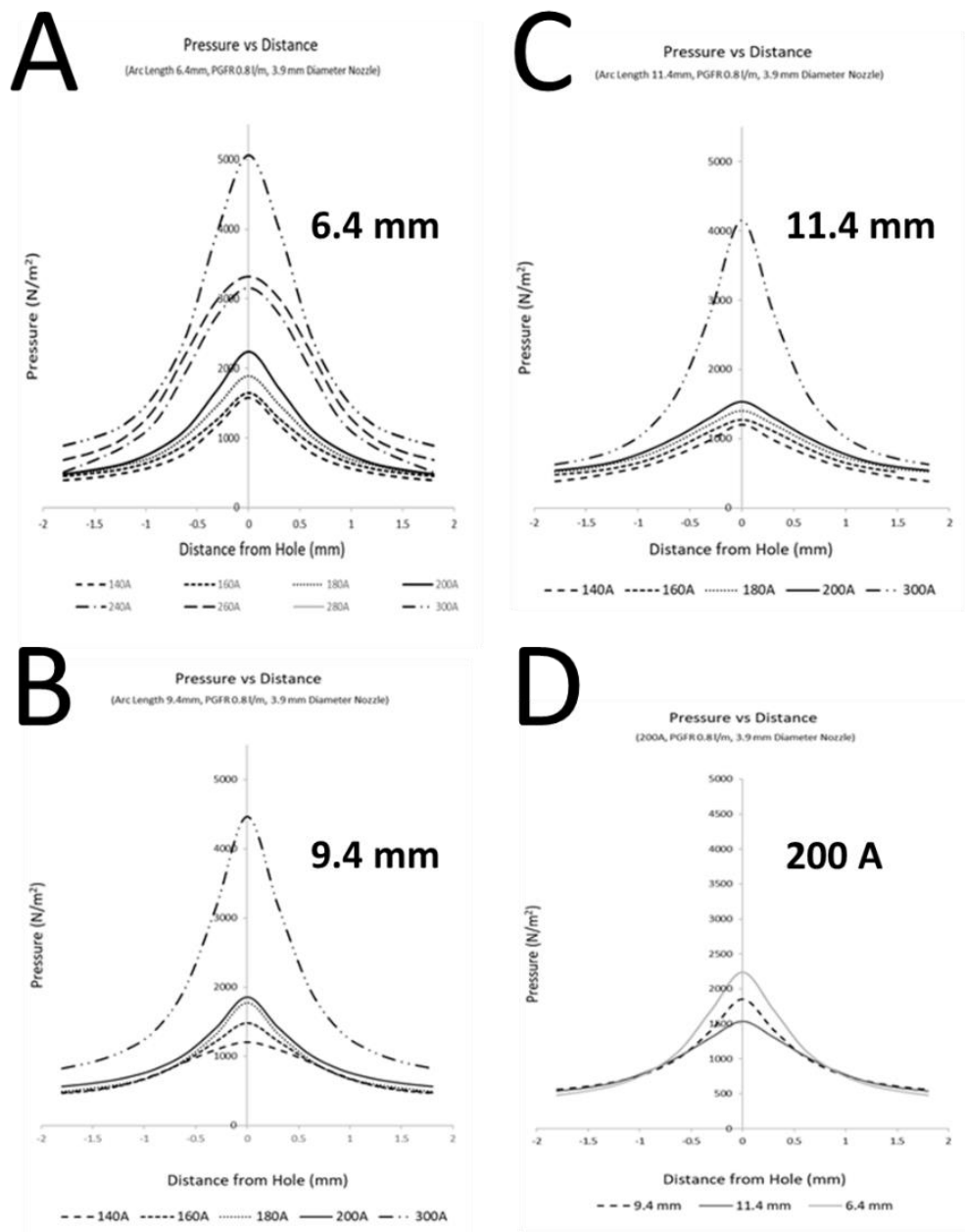


Figure 225 PTA pressure distributions for varying arc lengths. A] 6.4 mm, B] 9.4 mm, C] 11.4 mm, D] Comparison of the three arc lengths at 200 A.

Appendix C – Measurement Difficulties and Errors

A list of measurement equipment used in the study is set out in Table 48, along with details of their accuracy and resolution.

Table 48 Measurement equipment used and the manufacturers' stated accuracy and resolution.

Measurement Equipment	Manufacturers' Stated Accuracy and Resolution
Planton Direct-Reading Variable-Area Gas Flowmeter (Rotameter) – Graduation Marked Glass Tubes.	+/-1.25% Full Scale Deflection (FSD)
SPI Digital Caliper (12-527-8), Measurement Range 0–150 mm/0-6".	Accuracy +/- 0.3 mm, Resolution 0.01 mm
Moore & Wright MW192-20D – Digital Mini Height Gauge 192 Series, Measurement Range 0–150 mm/0-6".	Accuracy +/- 0.03 mm, Resolution 0.04 mm
Moore and Wright 0–75 mm Metric External Micrometre set MW215-01BL. Measurement Range 0–25 mm, 25–50 mm, 50–75 mm.	Accuracy +/- 0.0003 mm, Resolution 0.001 mm
Digital Weight Scales/Precision Balance Kern PNJ 620 g. Measurement Range 0.02 to 620 g.	Accuracy +/- 0.001 g, Resolution 0.001 g
AMV 4000 Weld Analyser and Data Logger	Amp Clamp Accuracy +/-10 A, Resolution 1 A Voltage: Accuracy +/- 1 V, Resolution 0.1 V Current: Accuracy +/- 10 A, Resolution 1 A Pressure: Resolution 0.1 mbar
Omega Pressure Transducer (PXM409-170HG10V), Measurement Range 0 to 170 mbar.	Accuracy +/- 0.08% of Full Scale
Omega Differential Pressure Transducer (PXM409-025HG10V), Measurement Range 0 to 25 mbar.	Accuracy +/- 0.08% of Full Scale
Moore & Wright Feeler Gauge Set – Safe & Sure Range (393M), Measurement Range 0.05 to 1 mm.	Tolerance +/- 0.003 to 0.016 mm dependent on thickness of gauge used (used for indication only)
Engineers Ruler	Accuracy +/- 0.2 mm, Resolution 0.5 mm (used for indication only)
Moore & Wright Workshop Combination Set 180°, 521 Series, 300 mm /12".	Ruler • Parallelism 0.03 mm • Straightness 0.03 mm • Flatness 0.2 mm (used for indication only)

Moore & Wright Traditional Engineers Square, Grade B, 6"/15 mm B.S. 939, No. 400.	(used for indication only)
Traditional Sprung Calipers & Dividers.	Used for indication only
Tend 'Digital Level Box', Inclinator.	Accuracy +/- 0.2°, Resolution 0.1°

Three main types of error affect this study: systematic, human and random.

The following potential errors have been identified and were possible to mitigate against:

Human Errors – unintended and undesired mistakes

<u>Error</u>	<u>Mitigation</u>
Untrained equipment use	Training and experience gained on measurement equipment before use to ensure correct usage within the designed range. Where appropriate, standard operating procedures and manufacturers’ instructions followed.
Misreading of scales	Training and experience gained on measurement equipment before use. Equipment scale checked before use.
Equipment affected: • Direct-reading variable-area gas flowmeter (rotameter) – graduation marked glass tubes. • Handheld digital meters. • Manual measurement equipment: micrometre, caliper, height gauge, digital weight scales and other measurement equipment, as listed in Table 48.	Each reading undertaken three times and an average calculated. Spurious high or low measurements checked and, where appropriate, repeated. Final average value sense checked to ensure within the anticipated region. To avoid parallax error flowmeter (rotameter) tube located in an accessible location and read parallel to the device. Measurements taken before, during and after each experiment to ensure correct reading.

Recording of wrong values	Each manual reading undertaken three times and an average calculated. Spurious high or low measurements checked and, where appropriate, repeated. Recording the value three times ensures the correct recorded value. Final average value sense checked to ensure within the anticipated region.
Equipment affected: • Direct-reading variable-area gas flowmeter (rotameter) – graduation marked glass tubes. • Handheld digital meters. • Manual measurement equipment – micrometre, caliper, height gauge, digital weight scales and other measurement equipment, as listed in Table 48.	
Fatigue	Appropriate breaks planned and undertaken.
Working speed	Sufficient measurement times during experiments planned and undertaken to allow for multiple repeat measurements.
Wrongly mixed plasma gas compositions	Ensure repeatability of experiments and use of premixed certified gas, supplied by BOC Ltd. Premixed gas used: 100% argon, 70% argon/30% helium, 50% argon/50% helium, 25% argon/75% helium, 100% helium, 98.5% argon/1.5% hydrogen, and 97.5% argon/2.5% CO ₂ .

Random Errors – data fluctuations, both positive and negative, in recorded data and manual measurement equipment.

<u>Error</u>	<u>Mitigation</u>
Fluctuations in recorded data and manual measurement equipment recordings	Multiple measurements undertaken and an average and standard deviation calculated for all measurements. Where appropriate, sample size increased and trend of values created and reviewed.

Signal noise	Instrumentation and power cables segregated to minimise signal noise. When signal noise experienced, average values and standard deviations calculated. Error bars of standard deviation utilised to indicate signal variance.
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Systematic Errors (Systematic Bias) – repeatable errors generally associated with faulty equipment or flawed experiment design: i.e. incorrectly calibrated or incorrectly used equipment.

<u>Error</u>	<u>Mitigation</u>
Calibration of equipment Equipment affected: • Direct-reading variable-area gas flowmeter (rotameter) – graduation marked glass tubes. • Handheld digital meters. • Manual measurement equipment – micrometre, caliper, height gauge, digital weight scales and other measurement equipment, as listed in Table 48. • AMV 4000 pressure, voltage and current measurement and data logging.	All measurement equipment calibrated by the manufacturer and checked to be in date. Manual measuring equipment calibrated prior to and post use with a calibration block. Un-calibrated handheld digital meters used for indication only – no values recorded. Motion equipment calibrated before use and re-checked at the end of the experiment for variation.
Power supply provided current The manually requested current and given current from the power supply are not always equal: e.g. 200 A may actually be as high as 204.5 A.	To minimise this error the arc current is recorded for each run, and, where arc current is deemed to deviate too far from the required arc current the required arc setting is manually changed $\pm$. The experiment is then repeated until the measured arc current is acceptable.
Zeroing of measurement equipment Equipment affected:	Before use, all equipment zeroed, and initial value checked.

- Direct-reading variable-area gas flowmeter (rotameter) – graduation marked glass tubes.
- Handheld digital meters.
- Manual measurement equipment – micrometre, caliper, height gauge, digital weight scales and other measurement equipment, as listed in Table 48.
- AMV 4000 pressure, voltage, current measurement and data logging.

Parallax error

Equipment affected:

- Direct-reading variable-area gas flowmeter (rotameter) – graduation marked glass tubes.

To prevent parallax error flowmeter (rotameter) tube located in an accessible location and read parallel to the device. Measurements taken before, during and after each experiment to ensure correct reading.

Incorrect measurement equipment used

During experiment design and setup advice sought from senior lab technician and supervisor to confirm selection of correct equipment within proper operating range.

Measurement equipment used incorrectly

Training and experience gained on measurement equipment before use to ensure correct usage within the designed range. All results recorded and sense checked to ensure within anticipated region. Results reviewed with the supervisors and unexpected results repeated.

Faulty equipment

Each reading was undertaken three times and an average calculated. Spurious high or low measurements checked and, where appropriate, repeated. Final average value sense checked to ensure within the anticipated region.

	Where readings are intermittent or spurious, measurement equipment checked and, where possible, calibrated, before measurement repeated.
Worn out instruments	Damaged, worn or un-calibrated equipment not used for data acquisition.
Signal noise	Instrumentation and power cables segregated to minimise signal noise. When signal noise was experienced, average values and standard deviations calculated. Error bars of standard deviation utilised to indicate signal variance.
PTA electrode and nozzle wear – resulting in inaccurate arc pressure measurements.	Electrodes and nozzles inspected and replaced regularly, results repeated, measurements undertaken and repeated in random order.
Equipment failure because of high temperature – resulting in spurious arc pressure readings.	Cooling intervals planned for and implemented, results from damaged equipment disregarded and repeated with new/repaired and recalibrated equipment.
Cleanliness of water-cooled anode copper-block – resulting in arc wandering and copper-block measurement orifice blockages.	Stringent cleaning routine between each run undertaken.
Poor PTA torch alignment – resulting in false arc pressure readings.	Meticulous electrode to copper-block orifice alignment and checks before use, and raw data reviews after each run to ensure accurate data capture.
Accuracy of copper-block measurement orifice diameter	Calibrated microscope used to measure exact size of precision-machined hole before and after use to ensure within machining tolerance. Experiment undertaken with multiple orifice diameters to ascertain the effect of diameter.

Plasma gas composition changeover delays	To allow for a lag in plasma gas through piping, an additional duration was planned and undertaken to enable gas flushing and ensure pressure measurements of actual plasma gas composition.
Pressure measurement lag	Copper measurement block mounted pressure transducer found to exhibit a measurement lag. By undertaking static torch measurements and allowing for a fixed measurement period to enable the measurement orifice, chamber and pressure sensor to fully pressurise and stabilise, the effects of the lag were mitigated.
High temperature effect on pressure sensor	To determine if the operating temperature of the water-cooled copper measuring block affects the pressure transducer measurements, an experiment was undertaken with high and low water flow-rates – minimal pressure difference recorded.
Repeatability of measurements	To ensure repeatability, measurements were undertaken in random order and repeated at different times of the day or on alternate days. Measurements compared and any variance investigated.
Voltage drops of instrumentation because of location of instruments and cable lengths	Measurement equipment located as close as was practical and cable lengths kept to a minimum. PTA torch umbilical minimised as far as possible to the torch to minimise voltage drop.
Change in ambient pressure	To account for different ambient pressures on different days, a means of accounting for ambient pressure was included within the methodology.
Wrongly mixed plasma gas compositions	To prevent incorrect mixing and correct plasma gas compositions and ensure repeatability of experiments, premixed certified gas was used, supplied by BOC Ltd. Premixed gas used: 100% argon, 70% argon/30% helium, 50% argon/50% helium, 25% argon/75% helium, 100% helium,

98.5% argon/1.5% hydrogen, and 97.5% argon/2.5% CO₂.

The parameters were chosen for the heat input study set out in Chapter 5 to maintain a heat input using Equation 13 and Equation 14, with arc voltage values measured during the arc pressure measurements on copper, shown in Figure 136. On completion of the study, the arc voltage values were found to change with constant parameters for different substrate materials, as in Figure 127. There is therefore a small difference in arc voltage – approximately a volt or less – between stainless-steel and titanium, and a corresponding minor effect on heat input. Figure 226 shows an example of the difference in heat input for the three materials. Please note that because the power supply provided current error – see above systematic errors – there is a further difference in heat input.

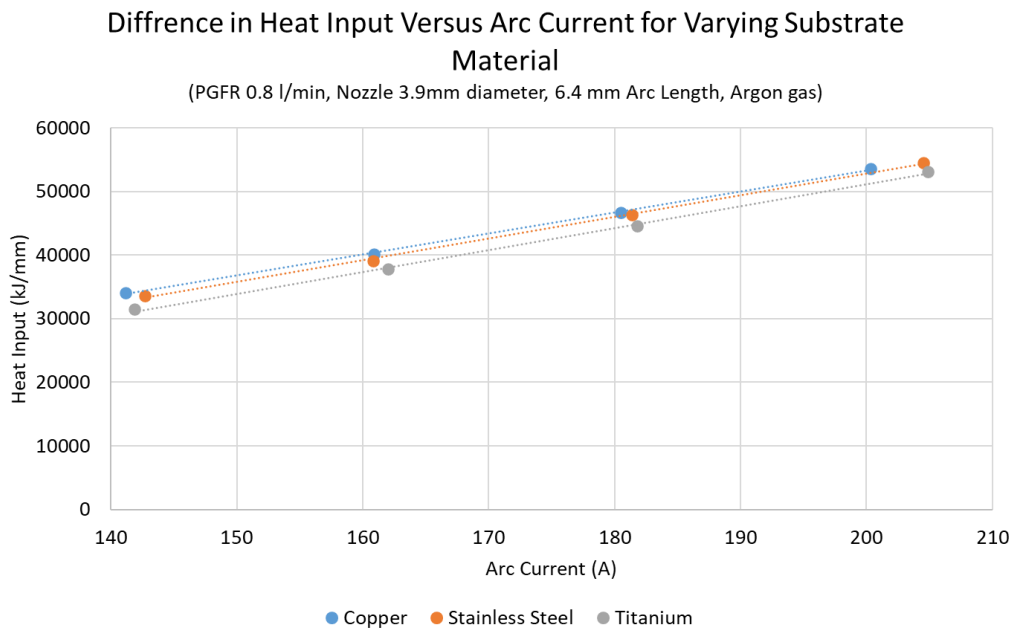


Figure 226 Example for the three materials of heat input difference resulting from arc voltage variance and power supply providing current error.

Error Examples

Hand measurement example:

Measurement	Procedure
Keyhole depth	
Electrode weight	Each measurement taken three times and an average calculated.
Electrode length	

Keyhole depth measurement error example

A minimum of three measurements was taken and an average calculated.

Number of keyhole depth measurements $N = 3$

Measurement	Depth (mm)
#1	2.07
#2	2.27
#3	2.23

Average = $(2.07+2.27+2.23)/3 = 2.19$ mm

Deviation:

Measurement	Depth (mm)	Deviation (mm)
#1	2.07	$-0.12 = 2.07 - 2.19$
#2	2.27	$+0.08 = 2.27 - 2.19$
#3	2.23	$+0.04 = 2.23 - 2.19$

The average deviation is 0.08 mm.

The standard deviation (S) is: =

$$\text{The standard deviation (S) is: } = \sqrt{\frac{(0.12)^2 + (0.08)^2 + (0.04)^2}{3 - 1}} = 0.10583 \text{ mm}$$

$$\text{The standard error (s}_x\text{)} = \frac{S}{\sqrt{N}} = 0.10583 / (\sqrt{3}) = 0.061101$$

Average keyhole depth = 2.19 ± 0.06 mm.

The accuracy of one keyhole depth measurement in this example is ± 0.06 mm.

Arc pressure measurement error example

Arc pressure measurements pressure transducer only:

Measurement	Procedure	Equipment	Equipment accuracy
Arc Pressure	Each location measurement is undertaken for 10 seconds per location. Typically, 14,335 measurements are taken within that 10 seconds. Average and standard deviation calculated.	Omega Pressure Transducer (PXM409-170HG10V), Measurement Range 0 to 170 mbar.	Accuracy +/- 0.08% of Full Scale

At the beginning of every arc pressure measurement session, a different previous measurement is repeated and compared to the original. These were typically found to be within 2.9% of one another. Subsequent measurements were undertaken once.

Each location measurement is undertaken for 10 seconds per location. Typically, 14,335 measurements are taken within that 10 seconds.

An average and deviation are calculated.

Number of arc pressure measurements $N = 14335$

Average = 16.581 mbar

Standard deviation = 0.151

Standard error = 0.00126

Average peak arc pressure = 16.58 ± 0.00126 mbar

The accuracy of the arc pressure measurement in this example is ± 0.00126 mbar

Arc pressure measurement – all instrumentation errors considered

Measurement	Procedure	Equipment		Equipment accuracy		
Setting PGFR	Manually set analogue gas flowmeter (rotameter), checked a minimum of three times to prevent parallax error.	Planton Reading Area Gas Flowmeter (Rotameter) Graduation Glass Tubes.	Direct-Variable- – Marked	+/-1.25% Full Scale Deflection (FSD)		
Arc current measurement data logger + current clamp	Continues sampling for full duration. Average and standard deviation calculated.	AMV 4000 Weld Analyser and Data Logger		Amp Clamp Accuracy +/- 10 A, Resolution 1 A Current: Accuracy +/- 10 A, Resolution 1 A		
Arc voltage measurement data logger	Continues sampling for the full duration. Average and standard deviation calculated.	AMV 4000 Weld Analyser and Data Logger		Voltage: Accuracy +/- 1 V, Resolution 0.1 V		
Arc pressure measurement pressure transducer	Each location measurement is undertaken for 10 seconds per location. Typically, 14,335 measurements are taken within that 10 seconds. Average and standard deviation calculated.	Omega Pressure Transducer (PXM409-170HG10V), Measurement Range 0 to 170 mbar.		Accuracy +/- 0.08% of Full Scale		
Arc pressure measurement data logger	Each location measurement is undertaken for 10 seconds per location. Typically, 14,335 measurements are taken within that 10 seconds. Average and standard deviation calculated.	AMV 4000 Weld Analyser and Data Logger		Pressure: Resolution 0.1 mbar		

Appendix D – Pressure Measurement Trigger Schematic

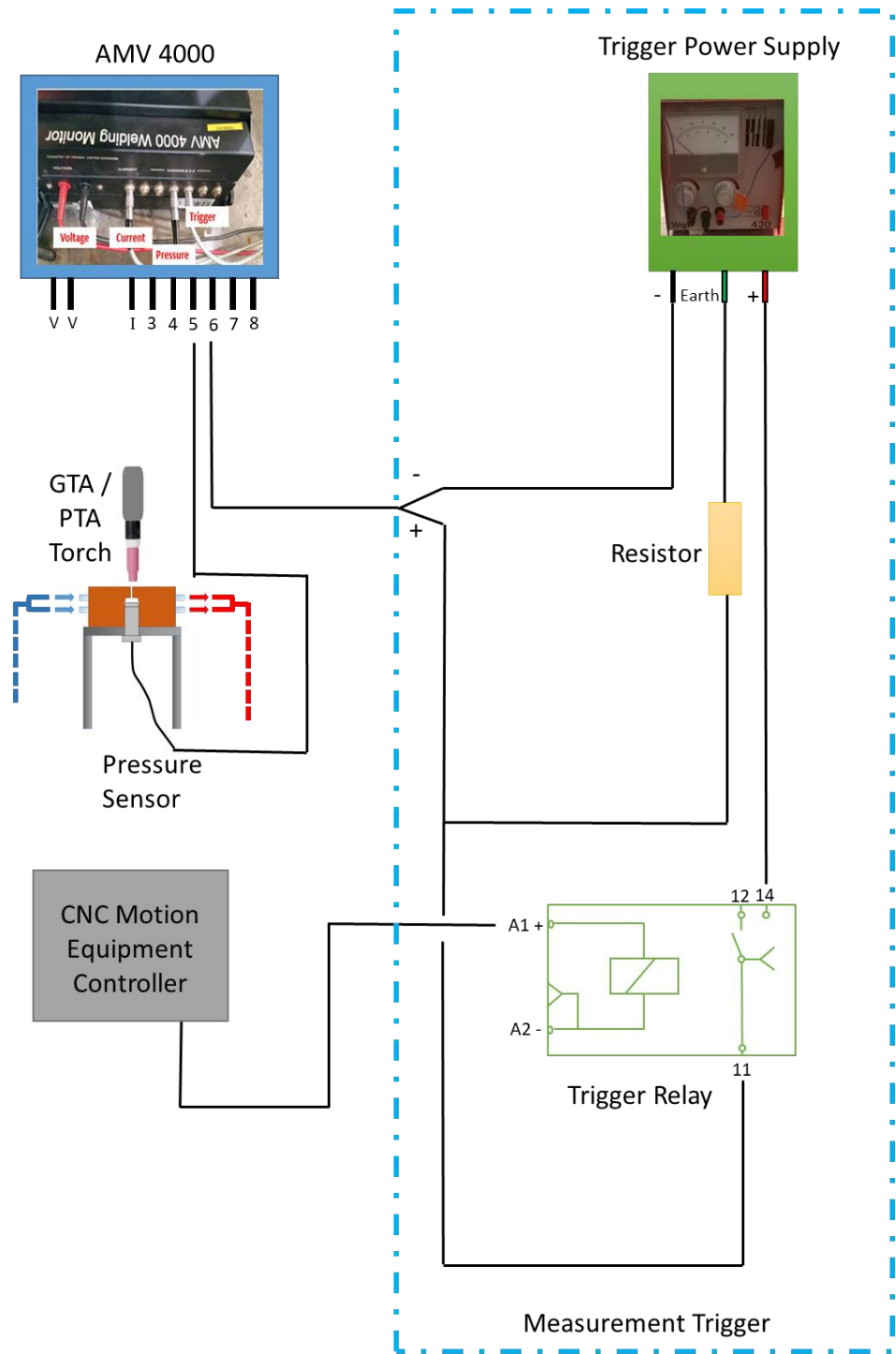


Figure 227 Pressure measurement trigger schematic. Detail within dotted box on equipment setup schematic (Figure 44).

Appendix E – Cost of Gas Compositions

The cost of helium continually fluctuates, but, for cost comparison, the prices in Table 49 were obtained from BOC UK in May 2020.

Table 49 Gas cost for argon, helium and argon/helium gas mixes.

BOC Trade Name	Gas Composition	Cylinder Size (m ³)	Cylinder Cost * (£)	Cost Per Litre # (£)	Cost % Increase Φ	Estimated Torch Gas Cost Ψ (£)
Pureshield Argon	99.9% Argon	11.01	127.19	0.01	-	74.86
Alushield Light	70% Argon /30% Helium	10.49	330.88	0.03	200	84.45
Alushield Universal	50% Argon /50% Helium	10.12	358.01	0.04	300	86.29
Alushield Heavy	25% Argon /75% Helium	9.94	405.56	0.04	300	88.90
Helium 'A' Grade	99.99% Helium	9.05	723.05	0.08	700	107.66

* Cost indicated is for gas and industrial BOC cylinder hire.

Cost per litre is used as cylinder size/volume is specific for each gas type.

Φ Percentage cost increase relative to argon.

Ψ Continuous 10-hour WAAM operation with a PGFR of 0.8 l/min of specified gas composition, and shielding gas flow-rate of 10 l/min of argon. This estimate does not include enclosure, or local shielding device, 'WAAM Shield', inert gas costs.

Appendix F – Arc Voltage

Figure 228 shows the arc voltage/arc current relationship for different plasma gas compositions. Though there are insufficient data points to show a trend, the linear upward trend does align with similar voltage/current trends for helium and argon within the AWS Welding Handbook (O’Brien, 1991). The trends show a voltage rise with increased current and with percentage of helium.

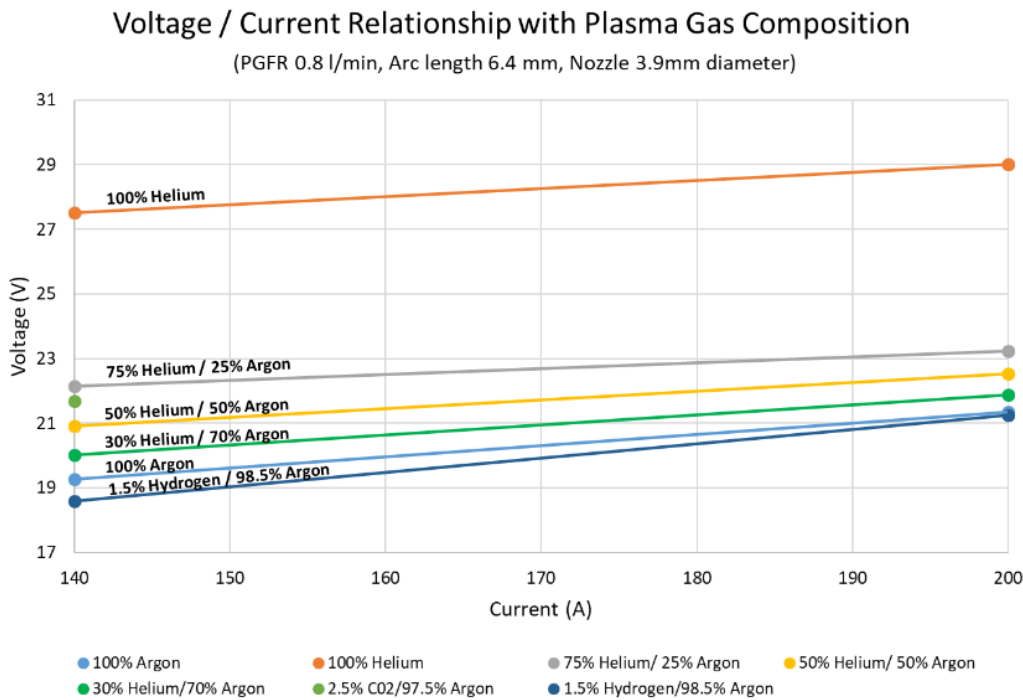


Figure 228 Arc voltage/arc current relationship for different plasma gas compositions.

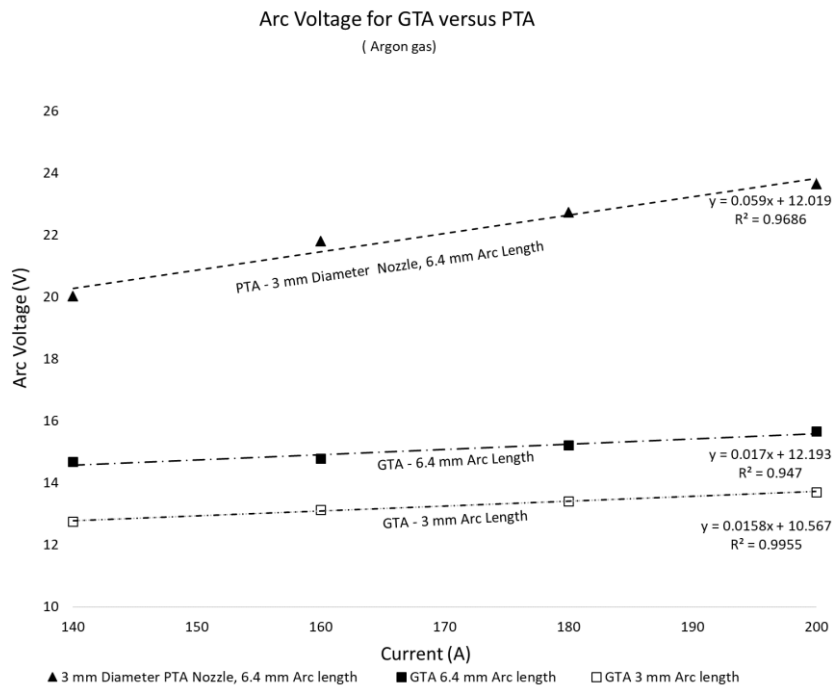


Figure 229 Arc voltage versus current for both PTA and GTA at 3 and 6.4 mm arc length.

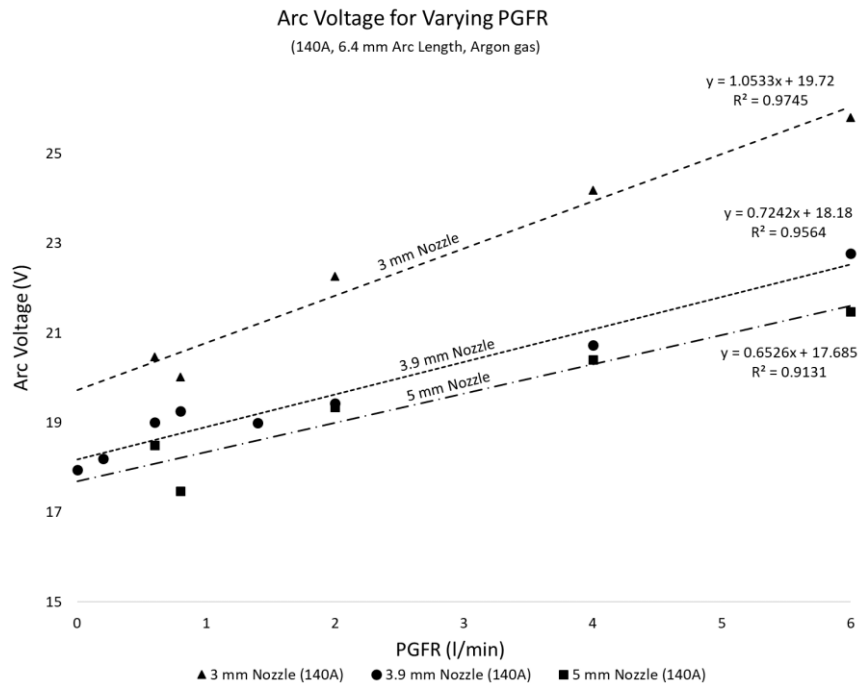


Figure 230 Arc voltage versus PGFR for three nozzle diameters, measured at 140 A.

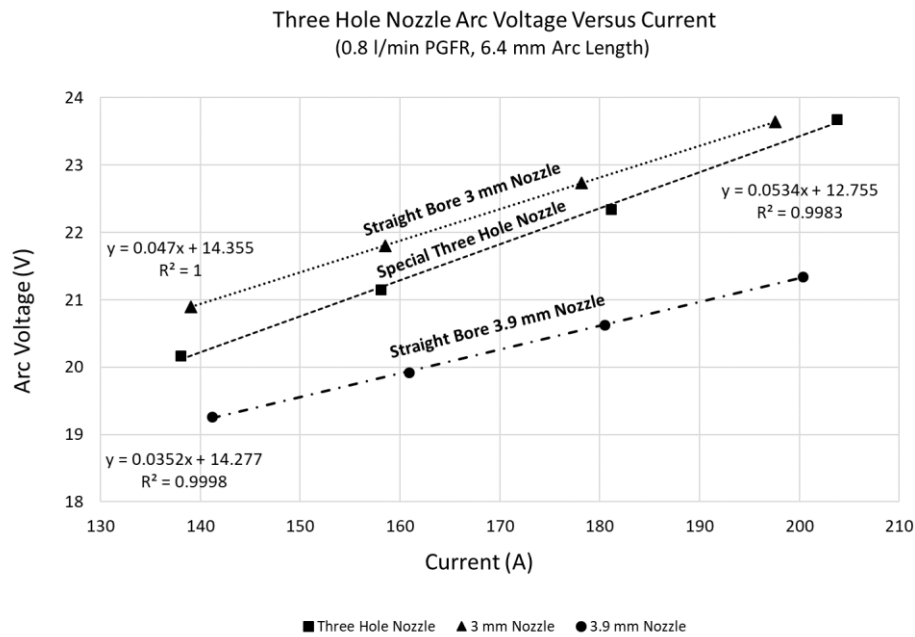


Figure 231 PTA arc voltage versus current for a special three-hole nozzle.

The arc voltage and, correspondingly, the electric field decreased with the three-hole nozzle, thought to be as a result of a reduction in resistance, resulting in an overall decrease in arc energy, electric field restriction and arc resistance for the three-hole nozzle (Zhang et al., 2014).

Figure 232 shows the arc voltage linear trend for the three-hole nozzle increasing with current and arc pressure. However, compared with a standard 3 mm nozzle, the arc voltage is reduced. Accordingly, the arc column resistance and arc energy, at constant current and arc length, is less than the standard nozzle. The three-hole nozzle therefore reduces arc pressure, arc energy, arc resistance, heat input to the substrate and potentially electromagnetic constriction strength (Zhang et al., 2014).

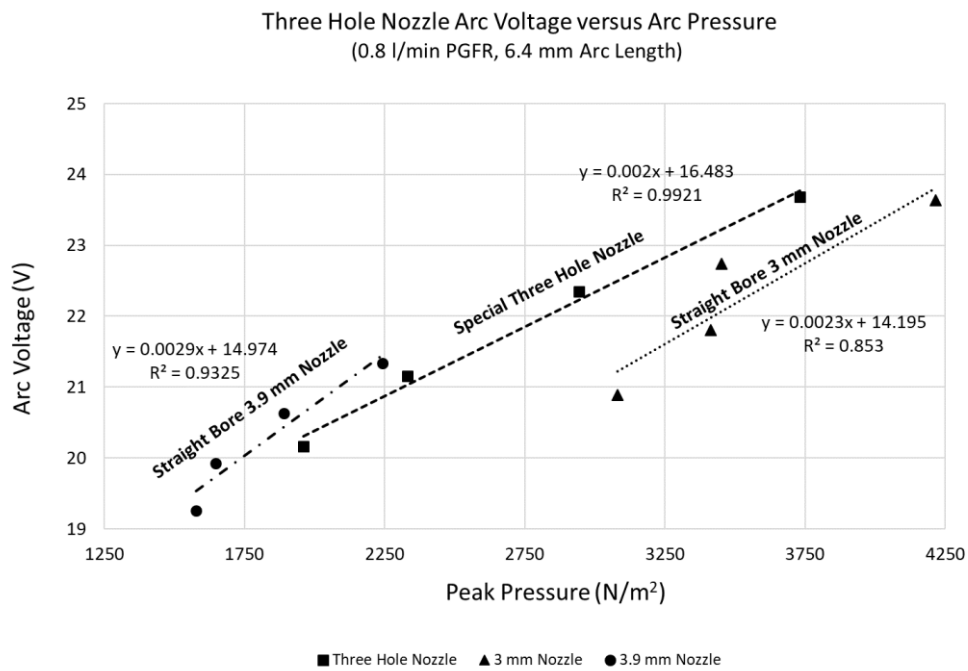


Figure 232 PTA arc voltage versus arc pressure for a special three-hole nozzle.

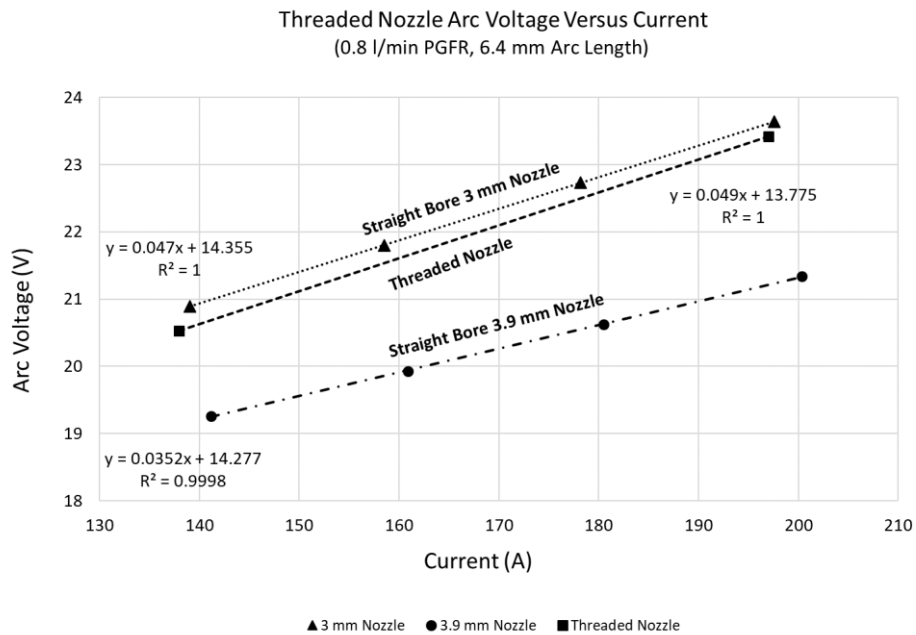


Figure 233 PTA arc voltage versus current for a threaded nozzle.

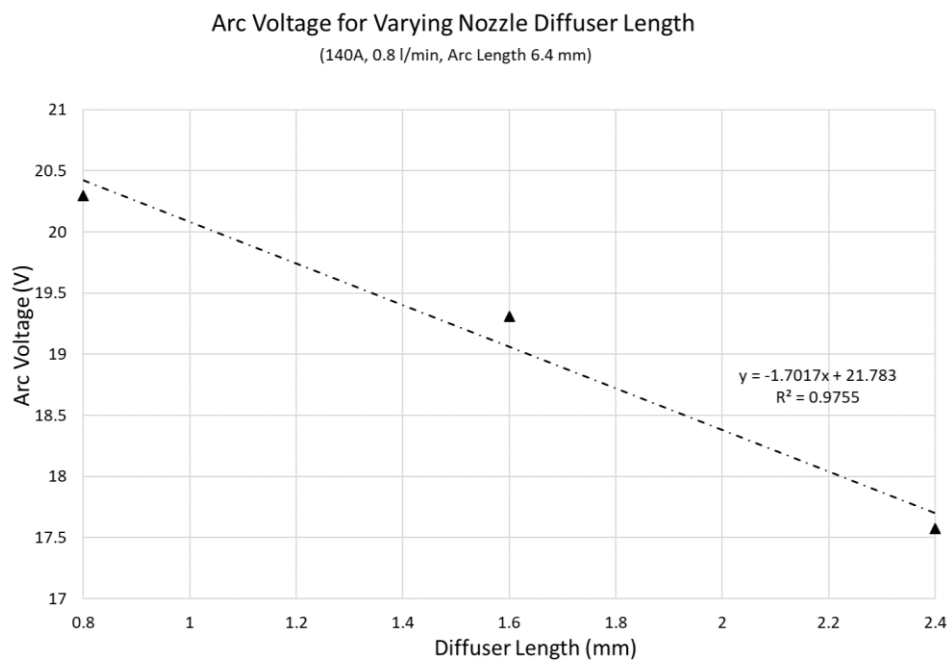


Figure 234 PTA arc voltage for diverging nozzles versus diffuser lengths.

Appendix G – Effect of Arc Pressure and Heat Input on Bead-width and Bead-height

Investigation Of Plasma Transferred Arc Dynamic Effects In Wire + Arc Additive Manufacturing

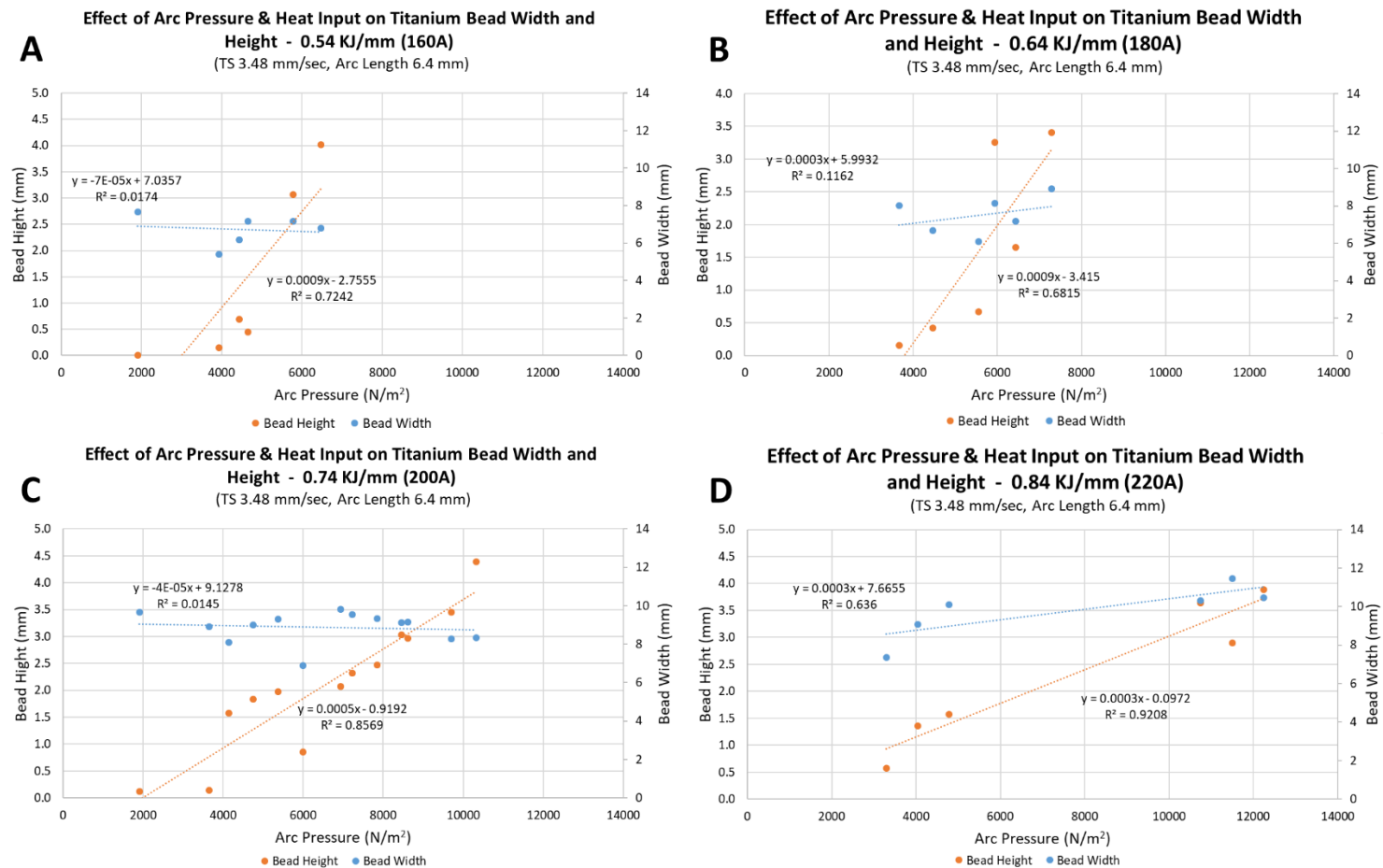


Figure 235 Effect of arc pressure and heat input on titanium bead-width and bead-height. A] Heat input 0.54 kJ/mm, B] Heat input 0.64 kJ/mm, C] Heat input 0.74 kJ/mm, D] Heat input 0.84 kJ/mm.

Investigation Of Plasma Transferred Arc Dynamic Effects In Wire + Arc Additive Manufacturing

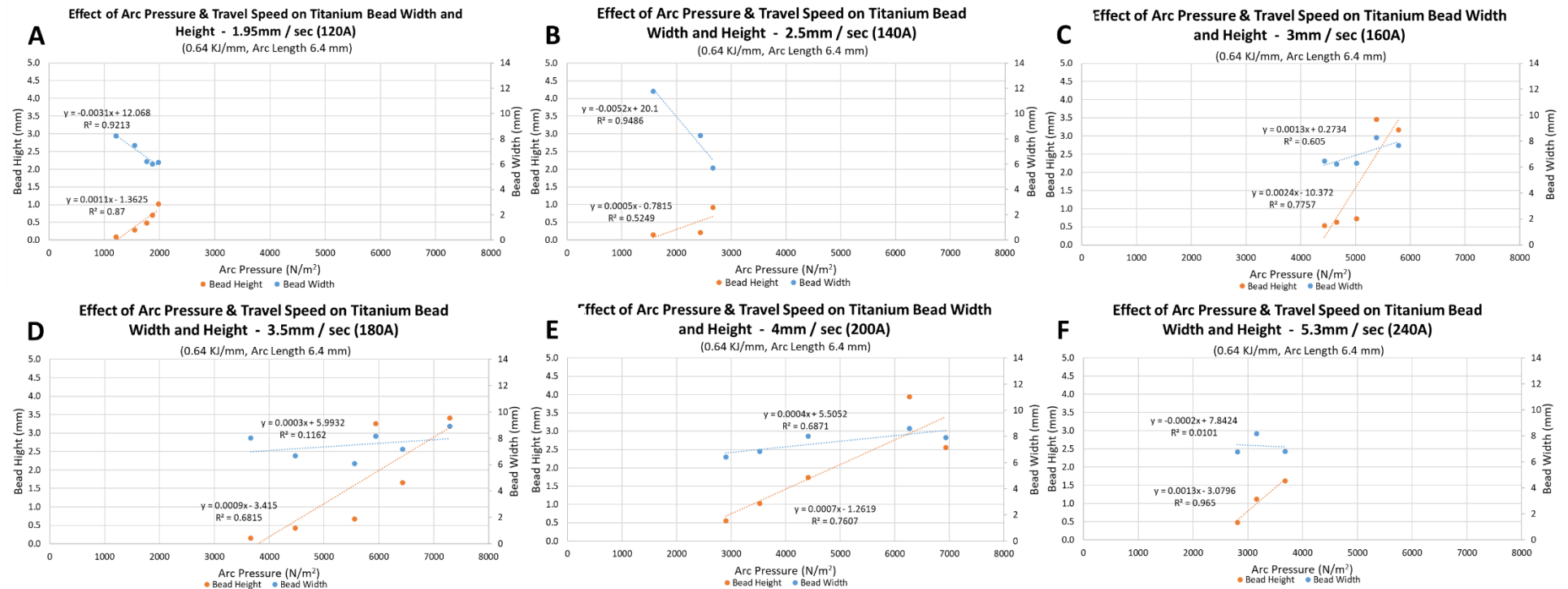


Figure 236 Effect of arc pressure and travel speed on titanium bead-width and bead-height. A] Travel speed 1.95 mm/sec, B] Travel speed 2.5 mm/sec, C] Travel speed 3 mm/sec, D] Travel speed 3.5 mm/sec, E] Travel speed 4 mm/sec, F] Travel speed 5.3 mm/sec.

Investigation Of Plasma Transferred Arc Dynamic Effects In Wire + Arc Additive Manufacturing

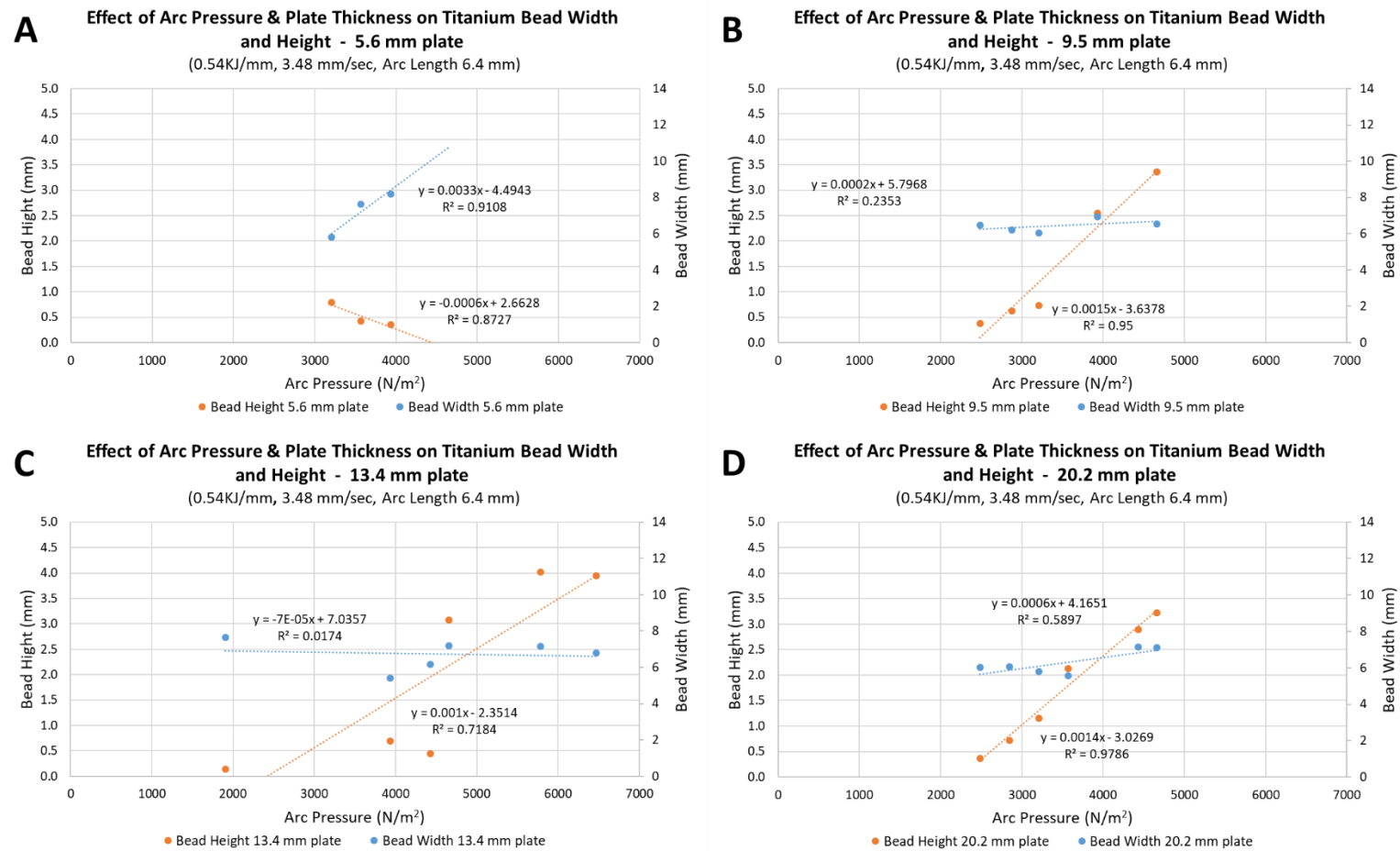


Figure 237 Effect of arc pressure and plate thickness on titanium bead-width and bead-height. A] 5.6 mm, B] 9.5 mm, C] 13.4 mm, D] 20.2 mm.

Appendix H – ANOVA

Analysis of variance (ANOVA) is a statistical technique used to test whether three or more data sets are significantly different with respect to one another and check the impact of one or more factors, determining if experiment results are significant. ANOVA is similar to a statistical t-test but is not limited to its two data sets and does not have the compounded error of multiple t-tests.

Typically, ANOVA is calculated using software because of the length and tediousness of the computation – for this study, Design-Expert version 11 was used. However, below is a high-level explanation of the calculations.

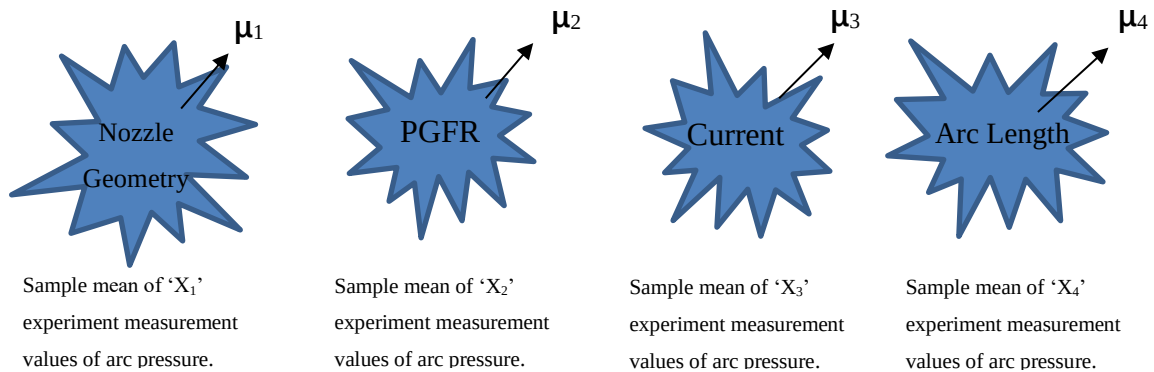
ANOVA

Null hypothesis (H_0) = $\mu_1 = \mu_2 = \mu_3 = \dots = \mu_k$.

Where ‘ μ ’ is a population mean and ‘k’ is number of populations.

Alternative test hypothesis (H_a) = At least one of the means differs from the others.

As it is not possible to experimentally measure every variation for each population ‘ μ_x ’, in this case PTA parameter – i.e. the population mean is not known – a sample of measurements is therefore taken for each population and a sample mean calculated: ‘ X_x ’.



Where X_1 , X_2 , X_3 and X_4 are average sample means of each population. The number within the sample does not need to be the same for each population, as ANOVA considers this in addition to the quality of the data.

All the data is combined and the variability among/between the sample means compared, and the variability around/within the distributions is also compared. ANOVA is the variability ratio therefore:

ANOVA = variability among/between the sample means/variability around/within the distribution = variance between/variance within, where variance between + variance within = total variance. If the calculated ANOVA variability ratio is greater than one, the samples are confirmed as coming from different populations, as in the case of this study.

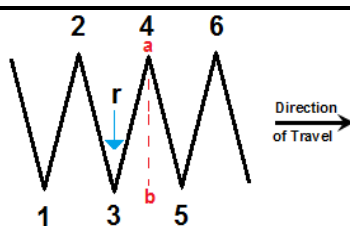
The sample means for each population are compared against the above null hypothesis (H_0) and alternative test hypothesis (H_a). For this study, the null hypothesis is unlikely as all the sample means are not equal, and the alternative test hypothesis is likely as at least one sample mean is different. The null hypothesis (H_0) is therefore rejected.

The level of significance for each sample mean is calculated and compared with all the populations.

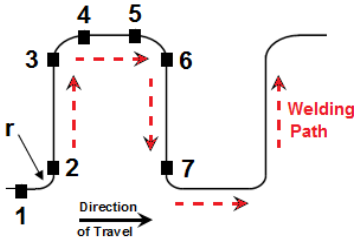
Appendix I – Definitions

Definitions of WAAM Terminology

In an attempt to standardise terminology, a ISO standard was created (ISO/DIS 17296-1, 2015). For ease of reference the following terminology is utilised for this project:

Additive Manufacturing System	Equipment and auxiliary equipment required to undertake AM.
Additive Shaping	The required component/part/shape is manufactured by the addition of material, normally in successive layers in AM.
AM Multi-Step Process	A process that in a single operation only meets the required geometry and a second operation is required to meet the material properties: i.e. a post-heat treatment.
Advancing Speed	The speed of motion equipment (longitudinal direction) for an advancing weave pattern.
Advancing Weave Pattern	 An oscillation pattern:
Advancing Weave Pattern Pitch	The distance between two similar points on advancing weave pattern – points 2 and 4 on above advancing weave pattern sketch.
AM Single Step Process	A process that in a single operation meets the required geometry and material properties.
Arc Efficiency	Net heat input into the WAAM part divided by net PTA energy output (Fuerschbach and Knorovsky, 1991)
Build Envelope	The largest external geometric size of space available in which to build parts/components for a given type of equipment and its auxiliary equipment, i.e. turntable positioners.
BTF Ratio	The ratio of the raw material and end component weights as an indicator of material wastage. $\text{Buy to fly ratio} = \frac{\text{Volume of initial forging}}{\text{Volume of final part}}$
Direction of Travel	The overall main direction in which the weld is deposited – normally perpendicular to the main oscillation or weaving direction. See sketches of advancing weave pattern above and square parallel rounded pattern below.

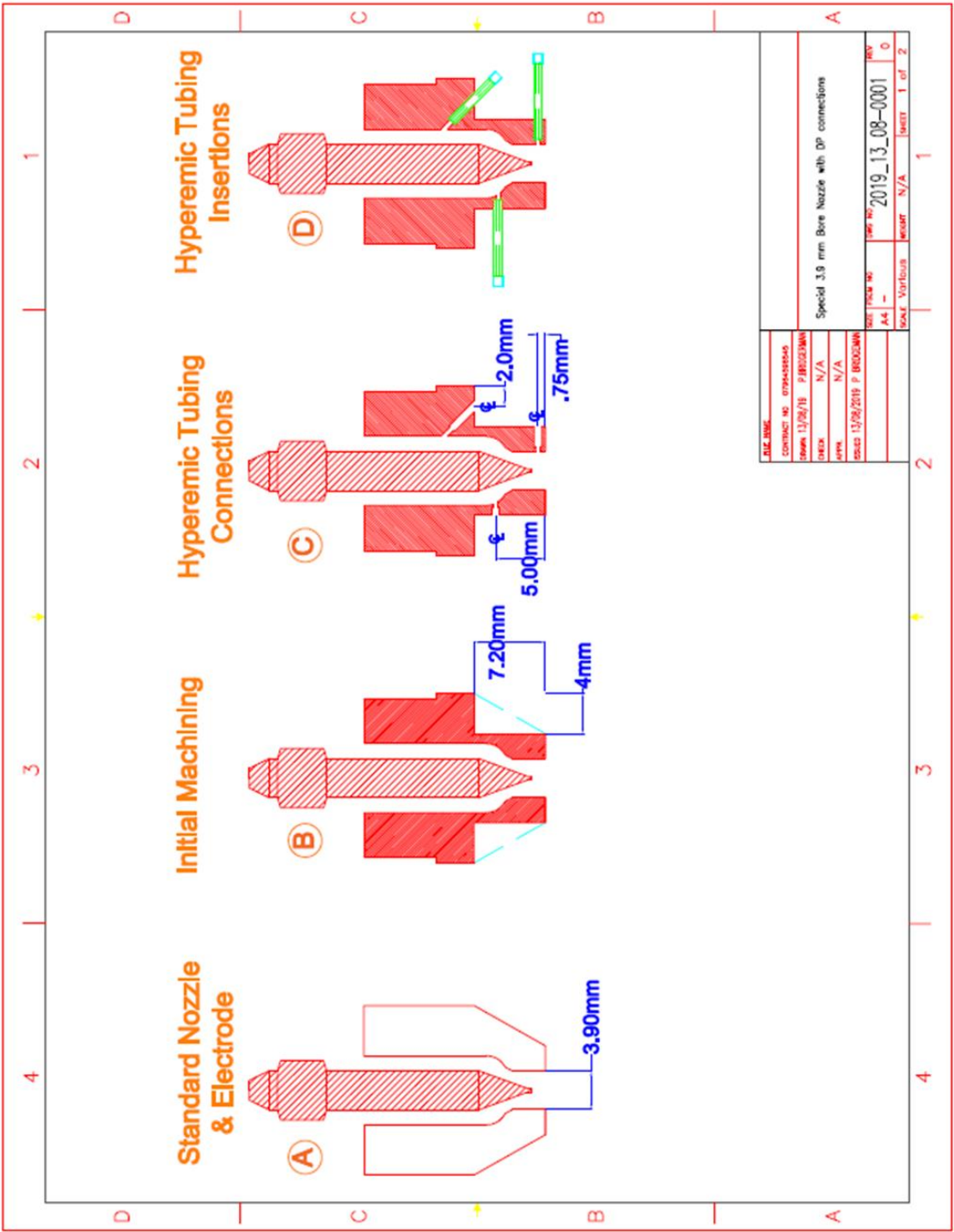
Effective Wall Width	Considering surface waviness (SW), effective wall width is the maximum remaining wall thickness after machining (removal of SW).
Feedstock	Raw bulk material used in the AM process as the construction material of the final component/part, normally for AM powder or welding wire consumable.
Layer	Normally a horizontally deposited stratum on to a surface, either on to a sub, straight or previously deposited stratum.
Layer Height	Measurable increase of deposited layer from the previous surface on which the layer was deposited.
Layer Surface	Visible outer surface of the deposited layer, exposed to the surrounding environment – normally the top but sides may also be included.
Melting Efficiency	Amount of heat required just to melt the fusion zone divided by the net heat input (Fuerschbach and Knorovsky, 1991).
Near Net Shape	Item produced only requires minor machining to meet the required shape and surface profile within specified tolerances.
Negative Material	Surplus material removed through subtractive shaping/machining: i.e. swarf/chips.
Oscillation Height	Layer height obtained after counting the preceding adjacent deposit.
Oscillation Width	Distance traversed in a lateral direction (perpendicular to direction of travel): i.e. 'a' to 'b' shown above for 'advancing weave pattern' and 'from point 2 to 3 + 2r' shown below for 'square parallel rounded pattern'.
Part	A near net shape item prior to machining, comprising walls and partitions that combine to make the part.
Part Geometry	Physical length, width and height of the three-dimensional solid object produced, bound by connecting surfaces.
Partition	Similar to walls but normally shorter in length and incorporating at least one interconnection with a wall.
Path Corner Radius	Motion equipment path corner radius to avoid sharp corners.
Programmed Wall Height Gain	Programmed height gain estimated and programmed into motion equipment to increase the welding torch by at the start of a layer to maintain the CTW distance as the number of layers increases.
Single Bead-height	Stable height of a single deposited layer of filler metal from a single welding pass, with a specific TS and WFS.
Single Bead-width	Stable width of a single deposited layer of filler metal from a single welding pass, with a specific TS and WFS.
Step Advancement	Distance between adjacent passes: i.e. distance between point 3 and 6 shown below for 'square parallel rounded pattern'. Only applicable to square oscillation pattern not weave because of its tapered width. Expressed as a percentage of single bead-width.

Square Parallel Rounded Pattern	 An oscillation pattern:
Substrate	Base plate material onto surface of which a wall is deposited (also known as Build Platform) – normally the same material specification as the AM feedstock, onto which the AM part is initially fused and onto which the component/part is manufactured. The substrate may become part of the final component.
Subtractive Shaping/ Machining	The required component/part/shape is produced using a manufacturing process – normally machining (metal lathe, CNC machining, milling, drilling etc.) – by means of the removal of specified material.
Surface Waviness	The maximum measured peak to trough along the part wall – an indication of maximum wall width after machining.
Wall	A continuous vertical upright structure comprising multiple layers. Wall may exhibit angles, overhangs, corners and varying thicknesses. Length of the wall depends on component geometry.
Wall Height	Total measured height from the substrate to the top of the uppermost layer surface.

Definitions of WAAM Variable Types

Control Variable (AKA Constant Variable)	An element that remains unchanged throughout the experiment, allowing its relationship with other variables to be further investigated.
Dependent Variable	A variable normally measured and observed during the WAAM process and the cause and effect of a change to affiliated independent variables.
Essential Variables	Variables with a severe impact on the integrity and outcome of the WAAM process, and critical to making acceptable WAAM parts.
Extraneous Variable	A variable that is uncontrollable/unmeasurable and preferably has little to no influence on the results of the WAAM part.
Fixed Variable	A variable that the operator can ensure remains constant throughout the WAAM operation – i.e. room temperature or gas composition.
Independent Variable	A variable that is manipulated or changed by the operator of the WAAM process. Several WAAM process variables are independent variables.
Random Variable	A variable that is the outcome of a statistical experimentation.
Non-Essential Variables	Variables with little significant impact/influence on the serviceability and mechanical properties of the WAAM part.
Manipulated Variables	Variables that may be changed during the WAAM process.
WAAM Process Variable	Parameters set at the beginning of the WAAM process and which may be manipulated during the process to allow control over the process and ensure the required outcome from the WAAM operation. Process variables need to be accurately measured and monitored to guarantee the accuracy of a WAAM process.

Appendix J – TEAR Differential Pressure Measurement



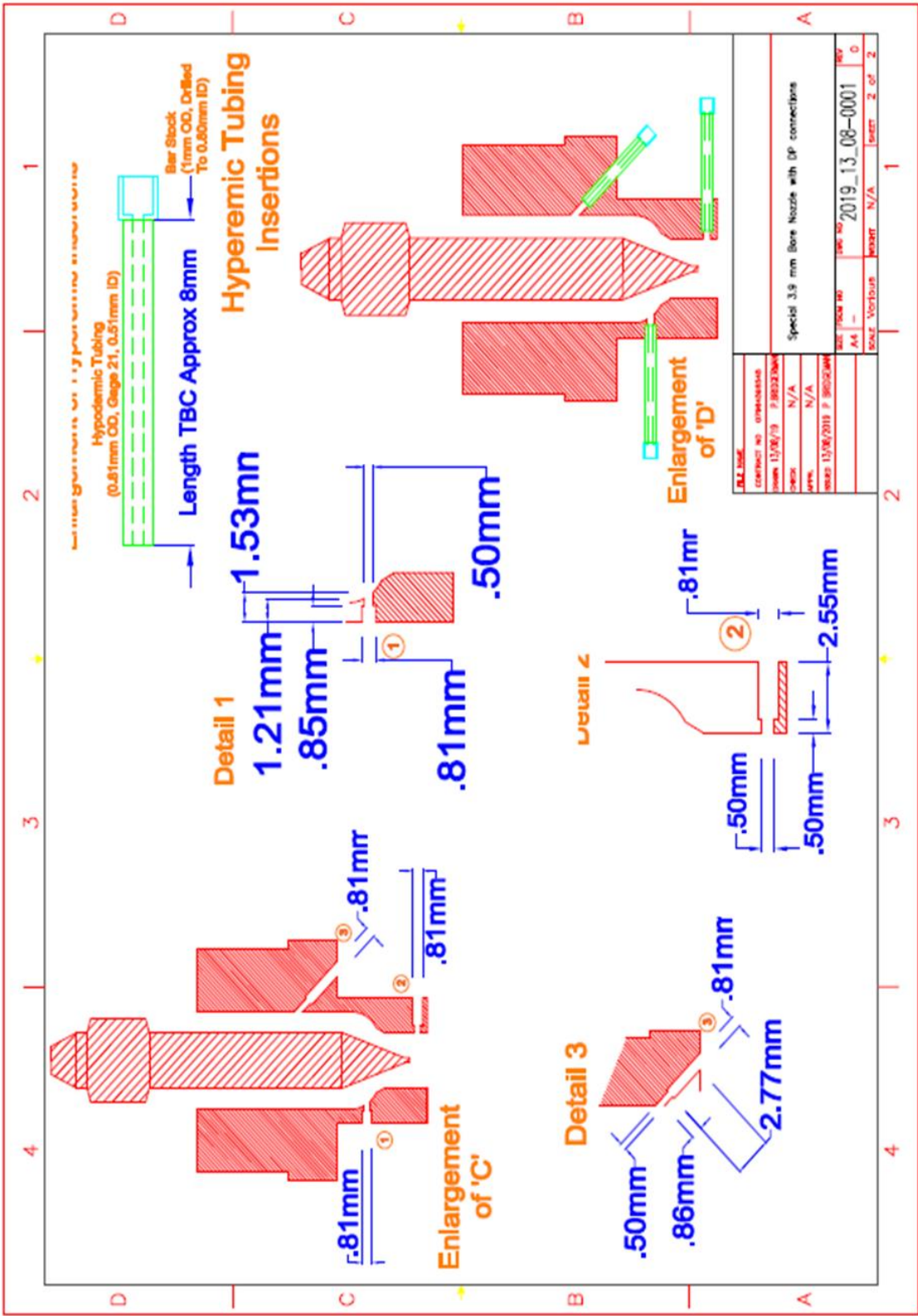


Figure 238 Workshop drawings – PTA nozzle differential pressure tapping.