

CRANFIELD UNIVERSITY

GUANGYU CHEN

BEAD SHAPE CONTROL USING MULTI-ENERGY SOURCE
(MES) FOR WIRE-BASED DIRECTED ENERGY DEPOSITION
(DED) PROCESS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
WELDING ENGINEERING AND LASER PROCESSING CENTRE

PhD

Academic Year: 2021 - 2022

Supervisor: Dr. Jialuo Ding
Associate Supervisor: Prof. Stewart Williams
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the degree of Doctor of Philosophy

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ABSTRACT

Independent control of layer width and height is essential to achieve a simultaneous high build rate with precision net shape and thermal control independent from deposition shape in the wire-based directed energy deposition (w-DED) process. Bead shape control using a multi-energy source (MES) method was studied to achieve independent control of layer width height of a bead for the w-DED process. This study was carried out in three stages:

First, a plasma transfer arc (PTA) energy density measurement was conducted. A split anode calorimeter (SAC) was applied for the measurement of PTA energy density. A laser beam with a well-defined energy profile was used to calibrate the calorimeter without the complications of arc instability. An optimised centred grounded SAC device was introduced to reduce arc distortion. More symmetric arc profiles were obtained.

The dynamic thermal characterisation of a scanning laser (SL) was then studied using both experimental and numerical approaches. SL experiments were conducted with different oscillation frequencies and laser beam sizes. An innovative solution dependent convection boundary (SDCB) method was introduced to reduce the element amount of the finite element (FE) model. Results show that the quasi-steady state SL can be applied as an equivalent stationary energy source.

Finally, an SL-PTA MES system was introduced to study the MES bead shape control, a PTA was employed in the front to create an initial melt pool and melt the feedstock wire, and an SL was used behind the PTA to reshape the melt pool and precisely control the bead width. A bead shape control strategy was proposed by using the wire feeding rate to control the layer height and the scanning width to control the layer width. The experiment results verified that the SL-PTA MES has independent control of layer width and height.

Keywords:

Wire-based additive manufacture; Directed energy deposition; Bead shape control; Finite element model; Multi-energy source.

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LIST OF ABBREVIATIONS

2D	two dimensional
3D	three dimensional
AM	additive manufacturing
CFD	computational fluid dynamics
CMT	cold metal transfer
CNC	computer numerical control
DED	directed energy deposition
EBM	electron beam melting
FE	finite element
GMA	gas metal arc
GS	Galvanometer-based scanner
GTA	gas tungsten arc
MES	multi-energy source
MIG	metal inert gas
Nd:YAG	neodymium yttrium aluminium garnet
PBF	power bed fusion
PTA	plasma transfer arc
SAC	split anode calorimetry
SDCB	solution dependent convection boundary
SL	scanning laser
SLM	selective laser melting
SLS	selective laser sintering
TIG	tungsten inert gas
WAAM	wire plus arc additive manufacturing
w-DED	wire-based directed energy deposition

LIST OF NOMENCLATURE

$A_{cross-section}$	area of the melt pool cross-section / (mm^2)
a_{input}	energy input efficiency
$a_{preserve}$	energy preserving coefficient
A_{sp}	area of the specific point / (mm^2)
$A_{surface}$	area of the melt pool top surface / (mm^2)
C	specific heat capacity / ($J/kg^{\circ}C$)
d	wire diameter / (mm)
D_L	laser beam size / (mm)
d_s	increment of the scanning pattern / (mm)
dt	time increment of the timestep / (s)
E_{sp}	specific point energy / (J)
F_s	scanning frequency / (Hz)
h	layer height / (mm)
I	current intensity / (A)
L	length of the computed element / (mm)
P_L	absorbed laser power / (W)
Q_{ad}	thermal energy of the adjacent material / (J)
Q_{cd}	energy that transfers during the thermal conduction / (J)
$Q_{current}$	received energy calculated from the current data / (J)
Q_{cv}	energy that transfers at the convection boundary / (J)
Q_{input}	energy transferred to the adjacent material / (J)
q_p	power density / (J/mm^2)
Q_{temp}	received energy calculated from the temperature data / (J)
R	deposition rate / (kg/s)
r	radius of the energy source / (mm)
$T_{1,2}$	temperature of the computed node and the adjacent node / ($^{\circ}C$)
T_b	node temperature at the boundary / ($^{\circ}C$)
T_f	bulk temperature of the fluid flow / ($^{\circ}C$)
t_i	interaction time / (s)
$T_{interface}$	temperature at the SDCB interface / ($^{\circ}C$)
$T_{out,in}$	water temperatures at the outlet and the inlet / ($^{\circ}C$)

U	voltage / (V)
v_a	advancing speed / (mm/s)
$V_{indicator}$	melt pool volume indicator / (mm ⁴)
v_s	scanning speed / (mm/s)
v_w	wire feeding rate / (mm/s)
W	overall width of the equivalent energy source / (mm)
w	layer width / (mm)
w_s	scanning width / (mm)
η	energy absorption efficiency
λ	thermal conductivity / (W/mK)
ρ	density / (kg/m ³)

1 Introduction

1.1 Research background

Additive manufacturing (AM) has developed rapidly in the last few decades and shows excellent advantages over traditional manufacturing methods. Compared to subtractive manufacturing methods, such as machining, AM can contribute to reducing material wastage and tremendously save the cost compared to formative manufacturing methods, such as forging and casting. Additionally, AM has shorter production lead-time and higher design flexibility, which is essential for rapid prototyping and flexible production. Today, AM has become a promising fabrication process for various engineering materials such as titanium, aluminium, nickel alloy and steel.

AM systems may be categorised in terms of material feedstock, energy source, build volume, etc. If classified by material feedstock, the AM process can be divided into two broad categories: powder-based processes and wire-based processes. If classified by how the feedstock material is delivered, the AM process can be divided into powder bed fusion (PBF) and directed energy deposition (DED) processes. The PBF process is suitable for relatively small-scale components with high geometry accuracy. Limitation of the PBF processes includes material integrity, high cost and low build rates. The wire-based DED (w-DED) AM process, however, has major inherent potential advantages, including very high build rates, 100% utilisation of material, high-quality feedstock and materials that can be deposited without defects, an unlimited build volume, and low cost.

Standard off-the-shelf equipment was used for conventional single energy source w-DED processes. Metal wire could be used as feedstock. Electron, laser, and electric arc can be applied as energy sources. When using an electric arc as an energy source, the process is also referred as the wire + arc additive manufacturing (WAAM) process. Standard welding equipment such as gas metal arc (GMA), gas tungsten arc (GTA), and plasma transferred arc (PTA) welding power source and torches can be utilised as ready-to-use equipment and directly

integrated into the AM system. However, these traditional axisymmetric energy sources are designed for welding or other applications. The energy distribution and dimension of these energy sources were not manipulatable. Therefore, the single energy source w-DED systems have a threefold function: generation of a melt pool in the substrate or previous layer of material, melting the feedstock material, and governing the overall temperature of the process. A great deal of empirical know-how and skill is required for applications.

Currently, using a conventional single energy source for w-DED, a high build rate is contradicted to a high build precision. A high build rate is possible, but accuracy is low, with significant extra material needing to be deposited and subsequently removed. Conversely, high accuracy net shape deposition is possible, but the build rate becomes very low and unsuitable for many applications. Therefore, new processes featuring independent control of layer height and width are needed to achieve a simultaneous high build rate with precision net-shape deposition with little or no finishing process required.

Homogeneous isotropic high-performance properties are also needed for the w-DED, which requires precise control of microstructure. This means that thermal conditions need to be controlled independently from deposited material shape. Currently, thermal conditions depend on deposition conditions, combined with local part geometry, leading to heterogeneous anisotropic microstructures and mechanical properties. Moreover, the range of thermal process regimes accessible is small, leading to a limited range of possible material properties. Therefore, thermal control independent from deposition shape is needed to achieve optimised material properties for different geometries.

To overcome the restriction of the conventional energy source and ensure independent control of geometry and thermal condition, a new energy source of which the energy distribution can be flexibly controlled needs to be introduced. Multi-energy source (MES) is the concept that combines the advantages of more than one energy source [1]. The energy distribution of the hybrid energy source can be designed by changing the arrangement of multiple energy sources. Benefiting from this, MES has the potential to achieve high flexibility bead shape

control for the w-DED process. Wang et al. [2] introduced a wire-based plasma transfer arc (PTA)-laser hybrid AM system and studied the bead shape control capability of the PTA-laser MES. The aspect ratio of the bead cross-section was improved. It also achieved independent control of the bead shape and the deposition rate. However, independent control on the layer width and layer height was not studied. The energy distribution was also restricted by combining multiple conventional sources. Apart from Wang's work, limited research has focused on using MES to control bead shape for w-DED AM.

The hypothesis of this thesis is that an MES featuring a quasi-steady-state scanning laser (SL) and a PTA can achieve full independent control of layer height and width for the DED AM process. When an SL reaches a quasi-steady state, it could be applied as an equivalent stationary energy source. The shape and energy distribution of this equivalent energy source can be designed and changed during the process. By using a quasi-steady-state SL as reshaping energy in an MES, the shape of the melt pool can be precisely controlled. A PTA could be employed in the front as a high-efficiency energy source to create an initial melt pool and melt the wire, and a quasi-steady-state SL could be used behind the PTA to precisely reshape the melt pool and control the layer width. The energy profile of the SL can be precisely designed to achieve the melt pool shape and thermal condition as required for different DED processes.

This study was carried out in three stages: Firstly, the energy distribution of a PTA was measured to investigate the properties and limitations of a PTA as a single energy source. Next, the melt pool dynamics of the SL process was studied using both experimental and numerical approaches to verify the capability of using a quasi-steady-state SL as a reshaping energy source. Lastly, a SL-PTA MES system was set up, and the bead shape control was studied to verify its capability of independent control of layer width and height. Walls were built using the MES system to show its potential for multi-layer deposition.

1.2 Aim and objectives

This research aims to study the mechanism of bead shape control using MES and achieve independent control of layer width and height. There are several individual objectives, which are listed below:

1. Investigate the energy distribution of each energy source involved in the MES, including PTA and laser. Understand the advantages and limitations of each energy source.
2. Investigate the melt pool dynamic of an SL. Verify the capability of using the quasi-steady-state SL as a reshaping energy source.
3. Develop an SL-PTA MES w-DED method for the MES bead shape control study. Show that MES can achieve independent control of layer width and height and multi-layer wall building.

1.3 Approaches.

The approaches in this thesis are outlined in Figure 1-1.

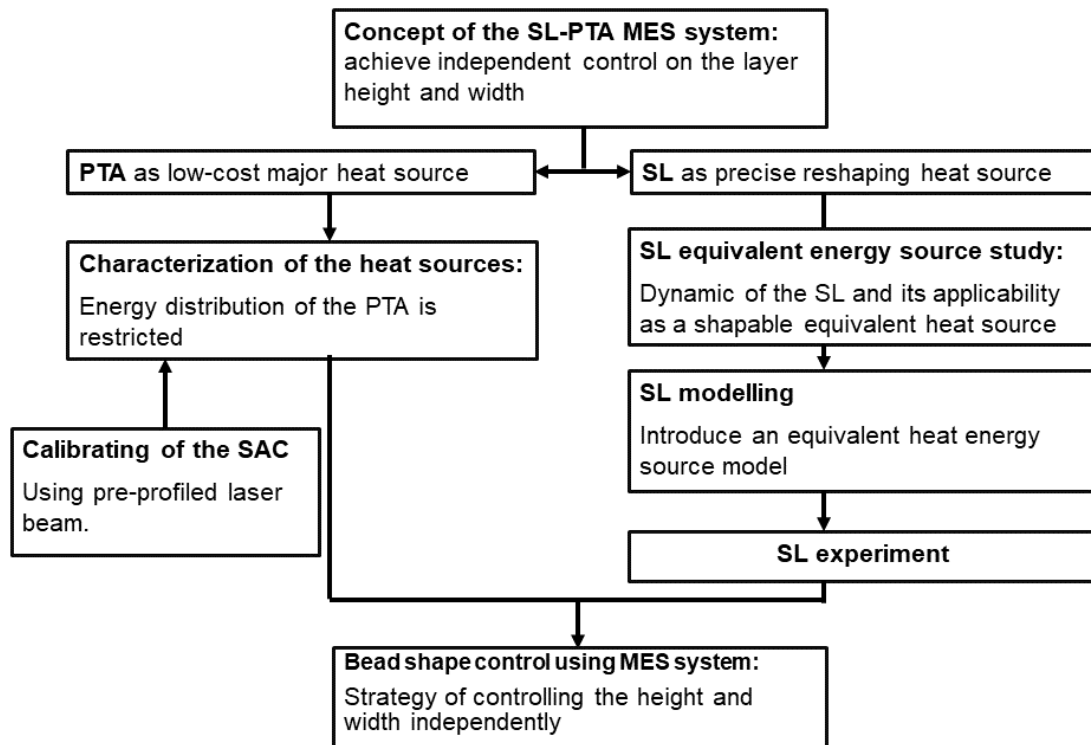


Figure 1-1 Approaches and methodologies of this thesis.

The MES method is a new concept, and no research has been conducted in the previous. Therefore, fundamental information of each individual energy source needs to be studied first to provide detailed knowledge for the MES study. Target on this, a split anode calorimetry (SAC) method was applied for the PTA profiling to reveal the limitations of a PTA as a single energy source and its advantages to be employed in an MES. A large-scale laser beam with a well-defined energy profile was first characterised using a commercial laser beam profiler and then was used to calibrate the calorimeter without the complications of arc instability to ensure the reliability of the SAC device.

As an innovative energy source to be integrated into the MES, the possibility of using a SL as a precise reshaping needs to be verified. This requires an understanding of the dynamic thermal characterisation of a SL. Therefore, both experimental and numerical approaches were conducted to investigate the SL. In the SL experiment, thermal images and highspeed images were captured to analyse the thermal dynamics and interaction mode of the SL. The finite element (FE) method was used to simulate the SL to provide a theoretical analysis on the thermal field. An equivalent bar-shaped energy source model was introduced for the quasi-steady-state SL modelling.

Finally, a SL-PTA MES system was developed to test the hypothesis of using a MES to achieve high flexibility bead shape control with independent control of layer width and height. A wide range of parameters can be adjusted in the MES. Therefore, a bead shape control strategy was demonstrated to coordinate those parameters and control the bead shape systematically.

1.4 Thesis structure

This thesis is presented in a paper-format structure based on three papers prepared for submission. It consists of six chapters altogether. The detailed introduction of each chapter is shown below.

Chapter 1 presents a general introduction of this thesis, which includes the research background, the approaches, the aim and objectives, and the thesis structure.

Chapter 2 presents the literature review, including an introduction of metal AM processes, bead shape control in w-DED AM processes and PTA and laser energy sources. Limitations of the conventional w-DED AM processes are highlighted.

Chapter 3 demonstrates the energy source characterisation using the SAC method. The SAC was calibrated by a laser beam which can be profiled by another well-developed and verified approach. A modified SAC was introduced to reduce the arc distortion issue during the PTA calorimetry. The energy profile of PTA was measured, and the limitation of PTA as a single energy source was revealed.

Chapter 4 studies the melt pool dynamic of the quasi-steady-state SL process using both experimental and numerical approaches. SL experiments were conducted with different oscillating frequencies and laser beam sizes. Thermal images and highspeed images were captured to analyse the thermal dynamics of the SL melt pool. An SDCB method was introduced to improve the computing efficiency of the SL transient modelling. Results show that a quasi-steady state melt pool can be created with a lower oscillating frequency of 13.6 Hz. A beam size of 4 mm can benefit the forming of a broad and thin melt pool with stabler conditions.

Chapter 5 presents the results of the MES bead shape control study. An SL-PTA MES system was developed. A PTA was applied as an efficient energy source to initial the melt pool and melt the feedstock wire. An SL was employed behind the PTA as a programmable reshaping heat source to precisely control the melt pool shape. A bead shape control strategy was designed, and the independent control on the layer width and the layer height was achieved.

Chapter 6 is a summary of all findings presented in this thesis. In addition, suggestions for future development and how this research could be taken forward are proposed.

1.5 Reference

- [1] Williams, S.W. Suder, W.J. (2019). Additive manufacture, G.B. Patent No. 2569673. G.B. Intellectual Property Office.
- [2] Wang, C., Suder, W., Ding, J., & Williams, S. (2021). Wire based plasma arc and laser hybrid additive manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 293, 117080.

2 Literature review

2.1 Metal AM processes

2.1.1 Introduction

Additive manufacturing (AM) is the process that fabricates objects by joining materials, as opposed to subtractive manufacturing processes. Usually, the material is added in layer upon layer manner based on 3D model data. AM was developed and studied in the early 1980s. In 1981, Kodama introduced an automatic AM method for 3D plastic models. [1]. In 1990, Hull patented the stereolithography (SLA) AM method. [2]. Crump [3] documented a fused deposition modelling (FDM) method. In this method, a computer-aided design (CAD) model was created and sliced into horizontal layers. Since then, AM has developed rapidly and contributed to a varied range of applications. In 1925, Baker [4] patented a method of using a fusible metal electrode to deposit various components. But it was not until the 1990s that systematic studies on the metal AM were started [5]. In the last three decades, metal AM has developed rapidly and attracted great attention from both manufacturing industries and researchers. A typical metal AM system consists of a combination of a motion system, energy source and feedstock. A computer numerical controlled (CNC) gantry system or a robot is usually applied as the motion system to operate the process. An energy source is employed to melt the feedstock and deposit components layer upon layer. AM can be used to deposit almost all commonly used metallic materials and is particularly beneficial to fabricate the materials that are expensive and difficult to process with traditional approaches [6].

Compared to subtractive manufacturing methods, such as machining, AM can contribute to reducing material wastage. Compared to formative manufacturing methods, such as forging and casting that involve the preparation of dies or moulds, which are costly and only suitable for massive production, AM can tremendously save the cost. Additionally, AM has a shorter production lead time and higher design flexibility, which is essential for rapid prototyping and flexible production. Today, metal AM has become a promising fabrication process for various engineering materials such as titanium, aluminium, nickel alloy and steel.

2.1.2 Categorisation of metal AM processes

Metal AM systems may be categorised in terms of feedstock material, energy source, build volume, etc. If classified by how the feedstock material is delivered, the AM process can be divided into two broad categories: powder bed fusion (PBF) and directed energy deposition (DED) processes, as shown in Figure 2-1. Figure 2-2 illustrates the principle of the PBF and the DED processes. In the PBF process, the feedstock material is pre-placed by raking the power across the working area before the procedure. An energy source is programmed to melt or sinter the powder into the desired shape. Advantages of the PBF include its ability to produce high-resolution features, internal structures and precise dimensional control. Technologies that can be designated as PBF include selective laser melting (SLM), selective laser sintering (SLS), electron beam melting (EBM), etc. [6]. In the DED process, the feedstock material is directly fed onto the component during the process. Advantages of this type of system include its higher deposition rate and larger build volumes. This type of process includes wire + arc additive manufacturing (WAAM), wire + laser additive manufacturing (WLAM), electron beam direct manufacturing (EBDM), direct metal deposition (DMD), etc. [7]. Depending on the type of feedstock material, the DED processes can be divided into power-based and wire-based processes. The primary advantage of the wire-based processes is that the deposition rate can be dramatically increased, and with almost unlimited build volume compared to the powder-based processes [8]. In addition to that, the wire-based processes produce less contamination and are easier to control, while the power-based processes might bring more pollution and require powder recycling.

Category	Energy source	Feedstock
PBF	Laser beam	Powder
	Electron beam	Powder
	Laser beam	Wire/powder
	Electron beam	Wire
DED	Electric arc	GMA
		GTA
		PTA
	WAAM	Wire/powder

Figure 2-1 Classification of the metal additive manufacturing processes.

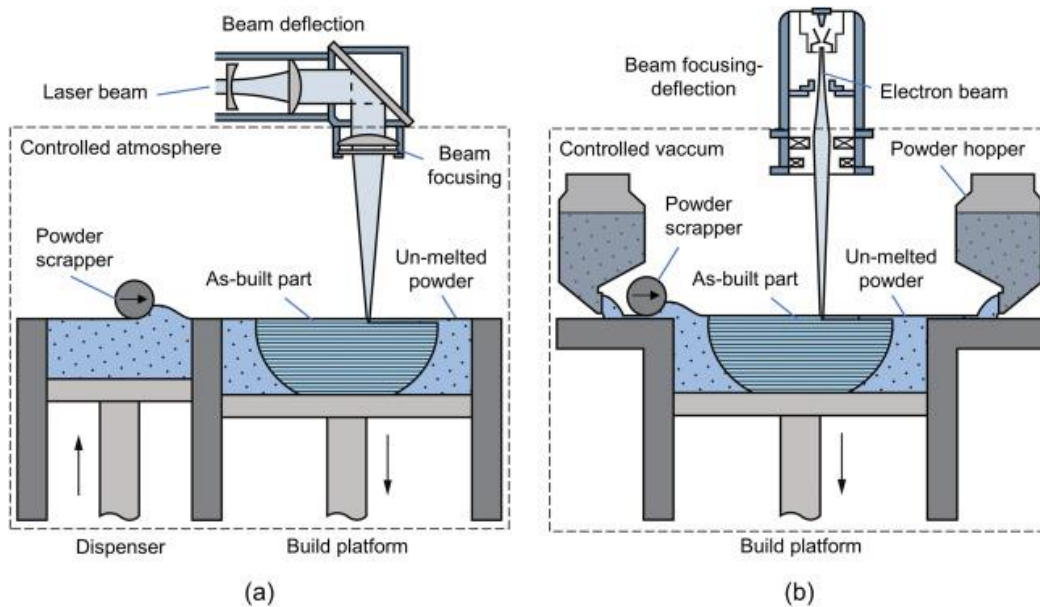


Figure 2-2 Schematic diagrams of the PBF-based processes [9]: (a) Laser powder bed fusion (LPBF), and (b) Electron beam powder bed fusion (EBPBF).

There are mainly three types of energy sources that can be used for metal AM: laser beam, electron beam, and electric arc (as illustrated in Figure 2-3). The geometry accuracy of a laser beam and electron beam is essentially satisfactory, making these two energy sources competent to fabricate parts with considerable

geometrical complexity. However, sophisticated and expensive facilities are required for the processes based on these two energy sources, and the energy efficiency was relatively lower compared to electric arc. It is also noteworthy that due to the lack of convective cooling in a vacuum environment, the cooling rates of the electron beam process upon solidification of material are typically lower than with other processes. An electric arc, including gas metal arc (GMA), gas tungsten arc (GTA), and plasma transferred arc (PTA), is mainly used for the DED process. Standard welding equipment such as welding power sources and torches can be directly utilised for the AM system. Compared to the laser and the electron beam processes, the electric arc processes have higher efficiency and relatively lower equipment cost [10].

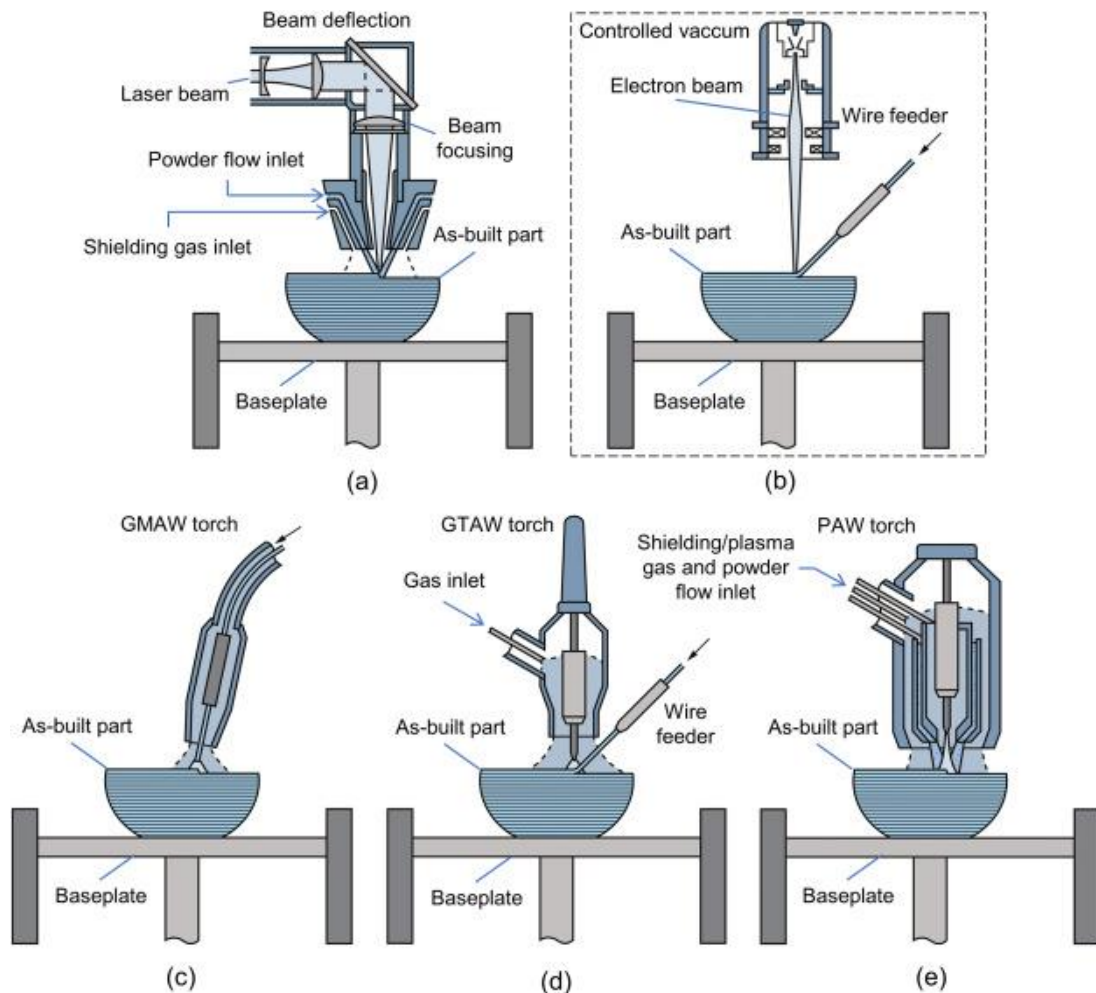


Figure 2-3 Schematic diagrams of the DED processes based on different energy sources: (a) laser, (b) electron beam, (c) GMA, (d) GTA, and (e) PTA. [9]

2.1.3 Wire-based DED AM

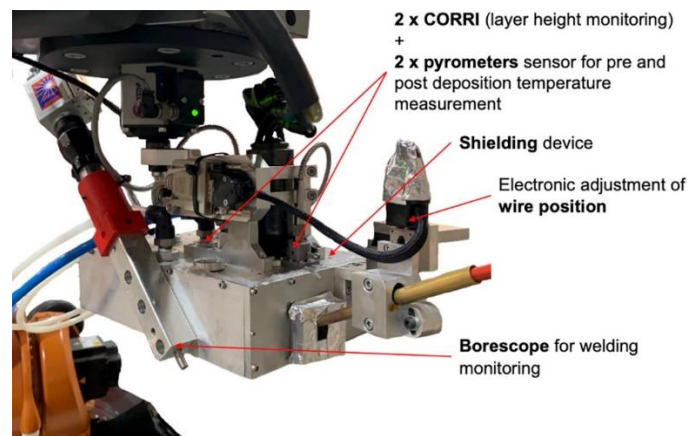
Among the many types of metal AM processes, the wire-based DED (w-DED) is the most cost-effective process for the deposition of parts with large volumes. GMA was one of the most widely used energy sources for the w-DED process. Figure 2-4 shows a classic GMA-based w-DED setup for the deposition of a large-scale component. The consumable wire electrode of GMA is coaxial with the welding torch, which makes it convenient to operate and path. An arc wandering issue would occur when using titanium as feedstock and affect the bead quality [10, 12]. Compared to consumable electrode processes, non-consumable electrode processes like GTA and PTA have better arc stability. Consequently, these techniques are mostly selected for titanium deposition. Unlike the consumable wire electrode, the feedstock wire needs to be delivered to the arc from the side of the torch, which increases the complexity of the system.



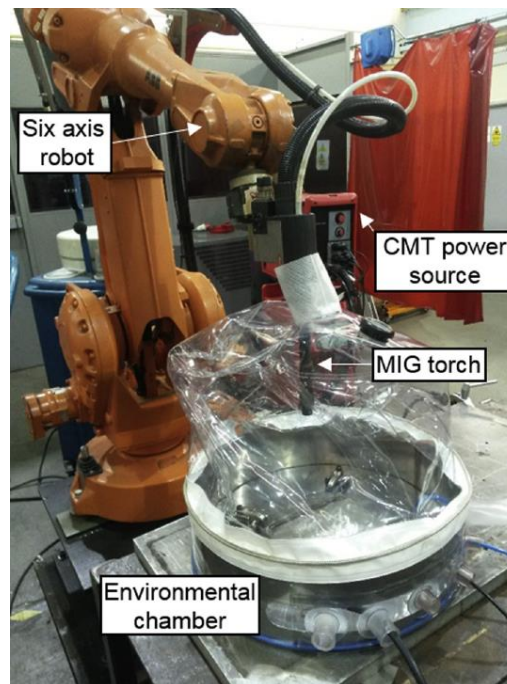
Figure 2-4 A GMA-based WAAM set-up for a complex large part [10].

An inert shielding atmosphere is required for the w-DED process to protect the melt pool from oxidation and contamination. Two types of inert gas shielding can be applied, global shielding and local shielding. The local shielding uses a semi-

enclosure attached to the torch to provide a positive pressure around the melt pool to expel ambient air. Figure 2-5 shows the examples of a local shielding device and a global shielding chamber developed by Cranfield University [13]. On the contrary, a global shielding encloses the whole system and fills with an inert gas atmosphere.



(a)



(b)

Figure 2-5 (a) A integrated local shielding device, and (b) an enclosed chamber for global shielding atmosphere. [13].

Compared to traditional subtractive manufacturing, the w-DED system can reduce fabrication time by 40–60% and post-machining time by 15–20%, depending on the component size [15]. For example, an aeroplane external landing gear assembly manufactured by the WAAM in Cranfield University saved approximately 78% of material compared to the traditional subtractive machining process [10]. On the other hand, contrary to the high deposition rate, the geometry accuracy of the w-DED is lower than other AM techniques. In addition, the melt pool size of an electric arc is relatively larger, leading to a more inadequate process resolution [14]. As a result, the w-DED is not suitable for producing small and complex parts.

In the w-DED process, a single bead is the fundamental unit of a built part and determines the final surface waviness of the component. The deposition efficiency can be defined as the ratio of the final part material to the deposited material. With low surface quality, significant material needs to be machined off, which means a low deposition efficiency. Figure 2-6 demonstrate how different layer width to height ratio affects surface weariness. In the conventional w-DED process, high deposition efficiency can only be achieved with narrow width and low deposition rate due to the positive correlation between layer width and layer height. Therefore, independent control on the layer and the layer height is essential to achieve high geometry accuracy and high deposition rate simultaneously. Also, with independent control of layer width and layer height, bead shape can be dynamically changed during the process. This would enable more flexibility for the AM system to build more complex parts.

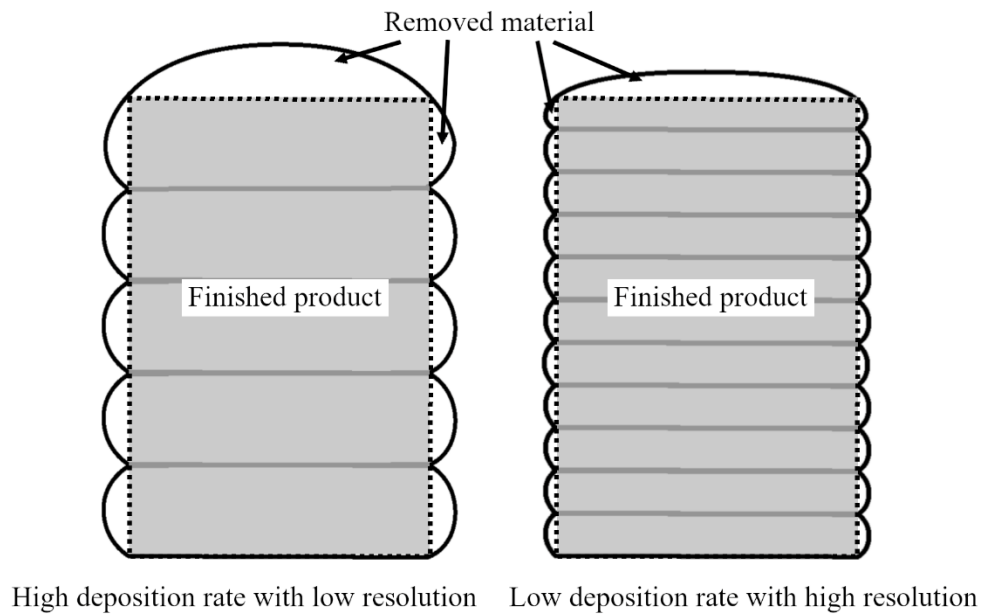


Figure 2-6 Different surface weaving with different layer aspect ratios.

2.1.4 PTA-based w-DED

PTA has better arc stability, higher energy density and higher energy efficiency than conventional welding techniques [13]. Therefore, PTA can be applied in the w-DED AM process to ensure a higher deposition rate and better deposition quality. A more concentrated arc spot and a lower heat input made the deposition for small and complex components possible by using PTA [16]. Consequently, the application of the PTA w-DED AM process has grown rapidly in recent years.

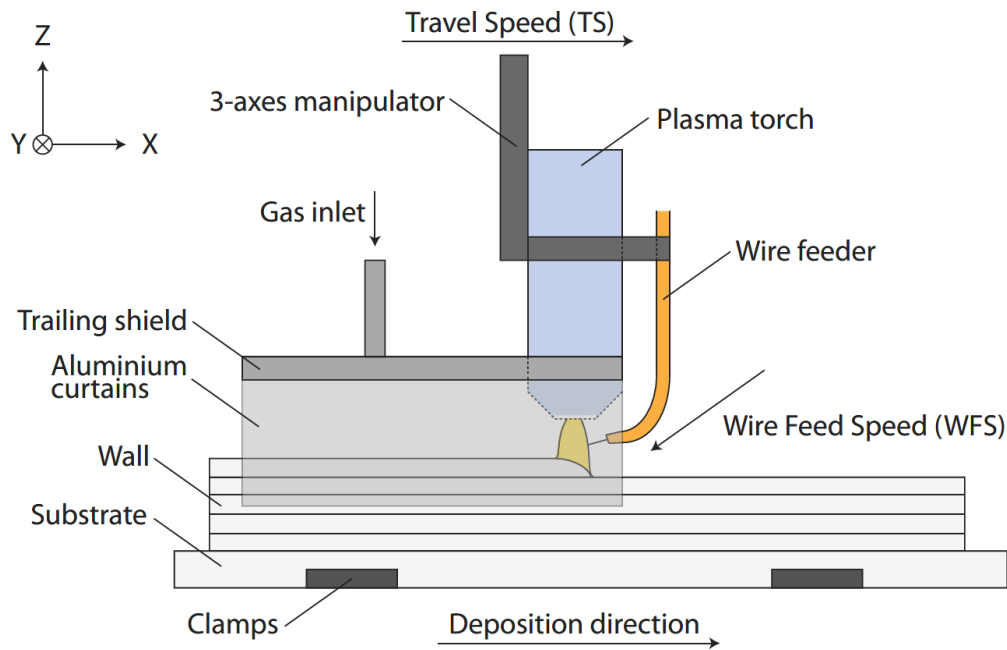


Figure 2-7 Schematic diagram of the PTA-based WAAM experimental equipment [8].

Martina et al. [8] introduced a PTA WAAM method for the deposition of Ti-6Al-4V. Figure 2-7 shows the schematic of the PTA WAAM experimental setup. The process window for PTA WAAM was demonstrated, and the unfeasible parameters combination and possible defects were explained. A model was proposed for the prediction of the deposited geometry, including total wall width, effective wall width and layer height. Compared to the competing wire-based AM process with cold metal transfer (CMT) and GMA, the process employed with PTA can achieve a higher deposition rate and a higher deposition efficiency with lower layer height to layer width rate. Wang et al. [17] studied the correlation between the wire diameter and deposition rate of the PTA AM process for Ti-6Al-4V deposition. The results show that with the same heat input, the deposition rate increases linearly with the wire size due to the increasing melting efficiency. The bead geometry obtained with a thinner wire has a higher aspect ratio, which can be attributed to the difference in the distribution of the energy between wire and workpiece. These researches show that deposition rate is highly related to the bead geometry in the conventional PTA-based w-DED.

2.1.5 Electron beam-based AM

An electron beam (EB) is a type of energy source in which a beam of high-velocity electrons is applied to the substrate. Substrate material melt as the kinetic energy of the electrons is transformed into heat upon impact. EB is often performed under vacuum conditions to prevent dissipation of the EB. Although the technology itself has been known for over 60 years, in the last decade, there has been growing interest on the part of individuals in science and industry. EB has been utilised as an energy source for many years in welding, repairing and AM. In contrast to conventionally processed systems, electron beam processed components feature a deposit overlay that is close to final contours. This reduces the cost of finishing [18]. The deposition welding for roller bearing seat shafts, turbine blades, die blocks, and splines can be adopted. The EB-based AM process has several advantages compared to other AM processes, such as better build part integrity because of the vacuum environment; several materials, including reflective materials, such as copper and aluminium, can be used; cost of the EB source is less compared to laser; control of the EB power; and diameter is better compared to laser. Till now, the EB based AM process has been established for powder-bed and wire deposition technologies. Both the processes have shown their capabilities and are still being explored.

The Electron Beam Melting (EBM) is the commercial process by Arcam, Sweden, which is based on powder-bed technology. In this process, a layer of powder is spread on the build plate and pre-heated. After pre-heating, helium is dispersed to avoid electrostatic charging of the powder. Subsequently, the powder melts on the required path for material consolidation. Both pre-heating and melting are done by the same EB energy source. For pre-heating, the beam is defocused with a high scanning speed. After completion of the process, the build part is cooled down by helium purging [19] (Körner, 2016; Additive Manufacturing, 2019). The computer-controlled electron beam scans over the powder layer in a predefined pattern and consolidates the desired areas into solid and dense metals. The beam has to first scan at high speed (order of 2 m/s) in multiple passes to pre-heat powders to a sintered state, while a beam scan on the order of ~ 0.5 m/s is used during the melting cycle. Then, a new powder layer is laid on

top, and the scanning process is repeated until all layers are completed [20]. EBM is one of the 3D printing techniques which can be used for high-stress aerospace applications and medical-grade implants. Different titanium alloys and cobalt chrome are used primarily in EBM services. Electron beam melting equipment is different from other laser or heat-based sintering processes. In general, EBM does not require any additional thermal heat treatment to achieve the full mechanical properties of the part. EBM prototype services produce parts with lower solid densities and no internal stresses due to the high temperature of electron beam melting. Therefore it allows companies to use EBM prototyping services to produce both prototypes and low cost, high-quality parts [20]. A wire-based EB process has been commercialised by an EB-based welding system-provider company Sciaky as EBAM. The first wire with an EB-based system was produced by Dave et al. in MIT in around 1995, and the name was given EB solid freeform fabrication (EBSFF) [23]. Later on, NASA produced again a similar system in around 2003 and called the process EB freeform fabrication (EBF3) [24]. Apart from this, an EB welding system is also utilised by various institutes for research work, AMRC uses the Pro-beam machine for AM [25]. In the EBAM process, a wire is melted in the melt pool created by the EB source on the substrate.

Modern devices enable the conduction of electron beam process with one beam or with many beams almost at the same time (a beam of a high frequency, higher than the human eye can spot, is activated and deflected, which in consequence creates the “presence” of many beams). The multiple-beam process is used, among others, in welding and AM with pre-heating (e.g. when cold crack avoidance is important) (Figure 2-8a) or in post-heating treatment processes (in order to eliminate brittle quenched microstructures such as martensite) (Figure 2-8b) or for welding “accompanied by” pre-heating or post-weld heat treatment (Figure 2-8c) [20].

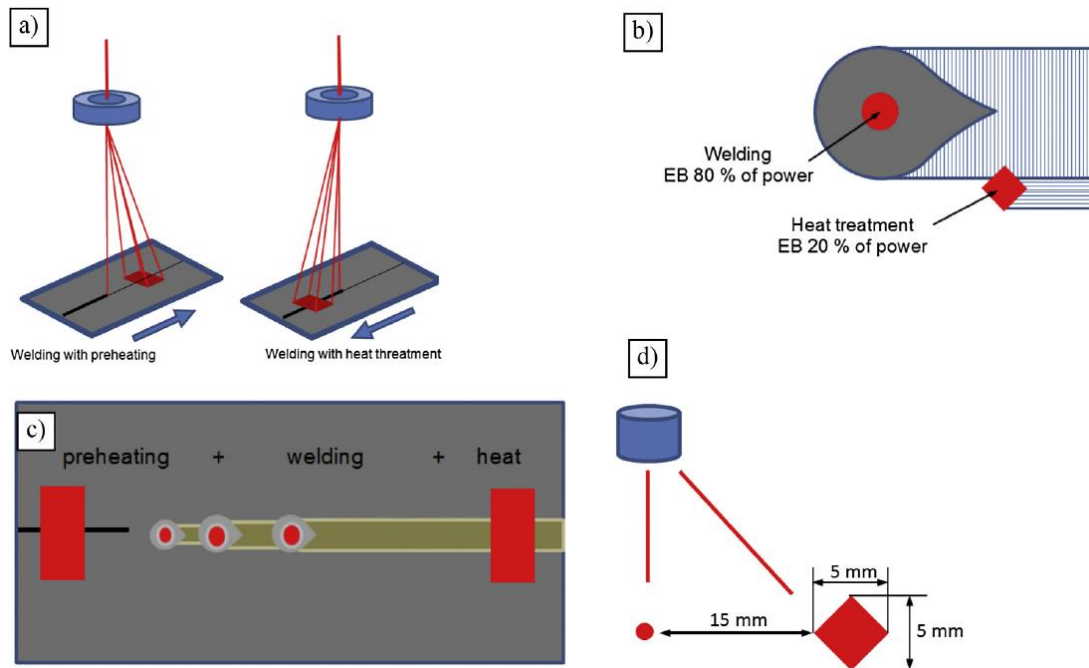


Figure 2-8 EB process: (a)with pre-heating or post-heating treatment, (b) with pre-heating and post-heating treatment, (c) with heat treatment conducted outside the weld axis, and (d) exemplary geometrical dimensions of the additional beam [20].

2.1.6 Bead shape control of the w-DED AM

In w-DED AM processes, a single layer is the smallest and most fundamental element of a product. The characteristics of the single-layer determine the final quality of the product. There are mainly three deposition tool paths when building parts: single pass, oscillated pass, and parallel pass. Wang et al. [17] studied the effect of the bead shape on the surface finish of the part. He reported that a flatter layer shape would lead to a high surface quality of final parts, and the deposition rate can be improved. In oscillated and parallel deposition pass strategies, layer shape also determines the overlapping of two adjacent layers, which will further affect the bead quality and dimensional accuracy of the final parts [26, 27].

Material per unit length is an essential factor that determines the cross-sectional area of a single layer. Material per unit length can be determined by wire feed speed to travel speed ratio. Deposition rate is another significant aspect that determines the lead-time for building parts and is determined by wire feed speed

when given constant wire diameter. Wire feed speed needs to be increased while maintaining a constant wire feed speed to travel speed ratio to increase the deposition rate without changing the layer cross-sectional area. However, effective wall width decreases with increasing wire feed speed when keeping a constant wire feed speed to travel speed ratio, resulting in a narrower and taller wall [28]. Consequently, deposition rate is restricted by bead shape.

Another limitation is that the thermal conditions during the deposition process vary with the bead shape. Yehorov et al. [29] proposed a strategy to assess the potential reduction of the production cost during wire+arc additive manufacturing (WAAM) based on the combination of wire feed speed (related to deposition rate) and travel speed (related to deposition time). They reported that a higher wire feed speed to travel speed ratio could achieve a larger cross-sectional area, but it will increase the heat input of the process for GMA based processes. Su et al. [30] studied the Al-Mg alloy components with different heat input by adjusting wire feed speed and travel speed using a CMT-based WAAM system. They concluded that the effective wall width under different heat input showed an increasing trend (with dimensions ranging from 26.6 mm to 31.7 mm) with an increase in wire feed speed. The effective wall width also showed an increasing trend (with dimensions ranging from 27.2 mm to 28.4 mm) with the decrease in travel speed. These papers show that thermal conditions depend on deposition conditions, combined with local part geometry, leading to heterogeneous anisotropic microstructures and affecting mechanical properties. Thus, independent bead shape control is also essential to achieve optimised thermal conditions for different geometries.

A vast collection of studies have focused on the variation in the layer shape as a function of different process parameters in a single power source deposition process. Dinovitzer et al. [31] discussed the effects of varying process parameters, including travel speed, wire feed rate, current, and gas flow rate in the GTA-based WAAM on layer shape, surface quality, oxidation, penetration and microstructure with a current range between 50 to 59 A. They reported that increasing travel speed or decreasing current would lead to higher penetration and rougher surface finish. Layer width decreased whilst layer height increased

with an increase of wire feed speed. Layer width increased with increasing current. Travel speed had a significant effect on layer width but a minor effect on layer height. Decreasing travel speed and increasing current contributes to higher heat input. Shielding gas flow rate has a minor impact on layer width, layer height, contact angle, penetration and surface quality. Martina et al. [8] investigated the PTA deposition of titanium for a much wider range of parameters (e.g. current ranged from 120 to 300 A). They found that effective wall width increased with increasing current and decreasing travel speed, and layer height increased with increasing wire feed speed and decreasing current. An analysis of variance (ANOVA) was performed to determine the relationship between the bead geometry and the parameters. Response models for the total wall width, effective wall width and layer height were established. The linear term of wire feed speed has statistical relevance in the total wall width model but not in the effective wall width. These studies achieved bead shape control within a limited range of forms. However, layer width and height, bead shape accuracy and deposition rate are highly correlated.

A laser beam was also used in single energy source deposition. Schulz et al. [32] achieved process maps using a semi-analytical approach to study the bead width as a function of wire feed rate, laser power, and laser intensity distribution in a laser wire deposition process. Thermal optimisation, wire feeding configuration, layer buildup, and the effect of different thermal treatments were studied. Results showed that laser beam size should be selected according to the estimated melt pool size. A small laser beam size can avoid a large melt pool. The energy distribution on the wire is important to achieve a high deposition rate with a stable process. Thermal treatments were suggested for turbomachinery components. Abioye et al. [33] developed a process map to predict process characteristics and bead geometry in the laser wire deposition process. They studied the relationship between the input parameters (wire feed speed, travel speed, and laser power) and the resulting bead properties (contact angle, width-height aspect ratio, and dilution ratio) of Inconel 625 wire deposition using surface profilometry and optical microscopy. Material per unit length and energy per unit length were reported as critical parameters that influence process stability and bead geometry. Aspect

ratio showed a positive correlation to dilution ratio and a negative correlation to material per unit length. Contact angle decreased with increasing energy per unit length and decreasing material per unit length. Optimised bead geometry for overlapped layers with good surface finish, minimal dilution and free of inter-run porosity were analysed. Mok et al. [34] studied the bead shape of deposition using a bar-shaped stationary laser beam. Independent control of layer height and layer width was achieved in specific ranges by correspondingly adjusting wire feeding rate and laser power. However, due to the limitation of the fixed laser beam shape, the bead shape range was restricted. Because the power intensity of the laser beam can be independently controlled without changing the dimension, layer height can be controlled with higher independence compared to the arc-based process. But the layer width control was limited by laser beam dimension and cannot be changed dynamically. Also, compared to electric arc processes, laser processes are expensive and with lower energy efficiency.

2.1.7 MES-based w-DED

Multi-energy source (MES) is the concept that combines the advantages of multiple energy sources to overcome the limitations of a conventional single energy source. For welding applications, MES methods such as laser-GTA, laser-GMA, laser-PTA, double-electrode GTA, double-electrode GMA, GTA-GMA, etc., were widely utilised. Among these hybrid combinations, the laser-electric arc hybrid method is one of the most investigated techniques. A laser beam has a high energy density and concentrated focus but low energy efficiency and poor gap tolerance. Electric arc has a good gap bridging ability and high energy efficiency, but low energy density that results in a slower process, which might lead to a higher heat input [35]. Combining these two energy sources can compensate for the drawbacks, and the advantages are complemented [36-38]. GMA welding process has good efficiency and a high deposition rate. However, instability of GMA would lead to spatter, oxidation, and a lower bead geometry quality. On the other hand, GTA arc is relatively stable and can achieve a better bead surface but with a lower speed and deposition rate [39]. By adopting a hybrid GTA-GMA, the cathode spots of the GMA arc can be stabilised and

achieve a welding process that combines both high quality and high efficiency [39, 40].

The feasibility of applying MES on the metal AM process has also been studied in recent decades to improve the deposition rate and product quality. Qian et al. [41] developed a PTA-laser hybrid technology to improve the accuracy and metallurgical performance of the deposition. Results showed that the laser beam stabilised the PTA, improved the bead surface quality, and diminished the porosity. Liang et al. [42] proposed a GTA-CMT hybrid welding process. In their study, two energy sources were separated without interaction. They concluded that GTA improved the wettability of the melt pool. Bead shape was achieved with decreased contact angle and better dilution. Yang et al. [43] compared the parts built by regular GMA and double-electrode GMA (DE-GMAW). The results showed that the dimensions of the melt pool were reduced by about 30% by the bypass arc of the DE-GMAW. A lower heat input was achieved while maintaining the same deposition rate. Zhang et al. [44] introduced a hybrid plasma-laser deposition manufacturing (PLDM) for a thick coating. A laser beam was employed to interact with the PTA as an additional energy source. The PTA was more concentrated with a smaller diameter and deeper penetration and was easier to be ignited. The mechanical properties of the coated layer were improved. Wu et al. [45] used a laser-GTA hybrid additive manufacturing to fabricate Al–Cu alloy parts. The microstructure of the Al-Cu alloy was improved with smaller grain size and more uniform distributed Cu. As a result, the mechanical properties of the laser-GTA deposited specimen were better than TIG, CMT, and SLM deposited specimens. Zhang et al. [46] used a low-power pulsed laser-assisted MIG arc welding (L-M) for metal AM and studied how laser affected layer width and height. Within a specific range of laser power, a higher laser power contributed to a narrower and taller layer cross-section. Compared to the conventional GMA AM process, the L-M AM method showed the potential to fabricate thin-wall components with better surface quality, higher stability, and higher deposition efficiency. Liu et al. [47] studied the improvement of the addition laser energy source in a laser-arc hybrid Al alloy thin-wall AM process. The microstructure of the hybrid AM process showed a reduced heat-affected zone with refinement

grains. Sr was found more uniform in hybrid additive manufactured samples with better mechanical performance. Li et al. [48] investigated the single bead and intersections deposited by a laser-CMT hybrid AM method. A surface quality metric for intersection builds was proposed based on the volume deviation between the ideal CAD model and the scanned shape of the part to optimise a set of parameters. The validation experiment showed that the optimised parameters significantly improved the geometry quality of the bead. Gong et al. [49] proposed an oscillating laser-arc hybrid additive manufacturing (O-LHAM) method to balance the surface accuracy, deposition efficiency, and mechanical properties of the deposited parts. The sample properties of the wire-arc additive manufacturing (WAAM), laser-arc hybrid additive manufacturing (LHAM), and O-LHAM processes were compared. It was found that both the surface roughness and minimum processing margin of the O-LHAM sample were improved. The non-destructive X-ray test suggested that the visible porosity within the O-LHAM sample was suppressed by beam oscillation. The O-LHAM almost eliminated the anisotropy of tensile strength and improved the elongation due to the microstructure changes and the porosity suppression.

Previous research using hybrid processes mainly focused on improving the process stability and bead geometry. Limited research has focused on bead shape control using the MES process. Wang et al. [38] developed a wire-based PTA-laser hybrid AM method for large-scale components with a high deposition rate and deposition efficiency. In this system, two laser beams were added at two sides of a PTA. Compared to the conventional single PTA AM process, the PTA-laser hybrid process had a broader energy distribution and a larger melt pool size that allowed more wire to be melted and fed into the melt pool. Keyhole mode can be effectively avoided in the hybrid process. The bead shape control using the PTA-laser hybrid was also investigated. The results showed that the optimum operating regime was that the wire was melted by the PTA, and the melt pool size was controlled by the laser. The bead width was mainly determined by the laser power and travel speed, whereas the laser beam size had a minor effect on the bead shape. This method increased the deposition rate with a higher process tolerance. It also achieved independent control of the bead shape and the

deposition rate. However, this work did not further study the independent control of the layer height and the layer width. Also, the energy distribution of the hybrid energy source can be altered but with limited flexibility of combining multiple conventional energy sources. An innovative energy source whose energy profile can be precisely designed and dynamically changed is needed to achieve full control of layer width and height for the MES.

2.2 PTA and laser energy sources

2.2.1 PTA

Plasma is one of the four fundamental states of matter. It consists of a gas of ions, atoms or molecules and becomes electrically conductive [50]. In the PTA process, a non-transferred arc was initiated between a non-consumable tungsten electrode and a water-cooled copper nozzle. A transferred arc was formed between the electrode and the workpiece when the high-velocity plasma gas flowed through the copper nozzle. Figure 2-9 illustrates the schematic diagram of a PTA welding process. Typically, the non-transferred arc is used to initiate the PTA and will be switched off once the PTA is ignited. A large volume of shielding gas flows through an outer nozzle to protect the melt pool. Due to the constriction effect of the plasma gas, PTA has higher arc pressure, temperature and power density and is more concentrated and stable than GTA [51]. There were three types of different interaction modes for the PTA process: micro-plasma arc mode, melt-in mode and keyhole mode [52]. When the current is less than 15 A, it is known as micro-plasma welding. It is suitable for thin sheets and produces low energy density and low plasma velocity. When the current varies between 15 and 400 Amp, it is called the melt-in mode plasma arc welding process. It is usually used to weld up to 2.4 mm thickness sheets. For more than 2.5 mm thickness of the material, the keyhole mode plasma arc welding process is used where the current works in more than 400 A [53]. With a higher current, deeper penetration and higher energy input can be achieved by forming a keyhole, which is capable of joining thick components with high tolerance. With a lower current, a conduction mode can be maintained, and a stabler melt pool can be generated, which is suitable for applications such as metal AM [54, 55].

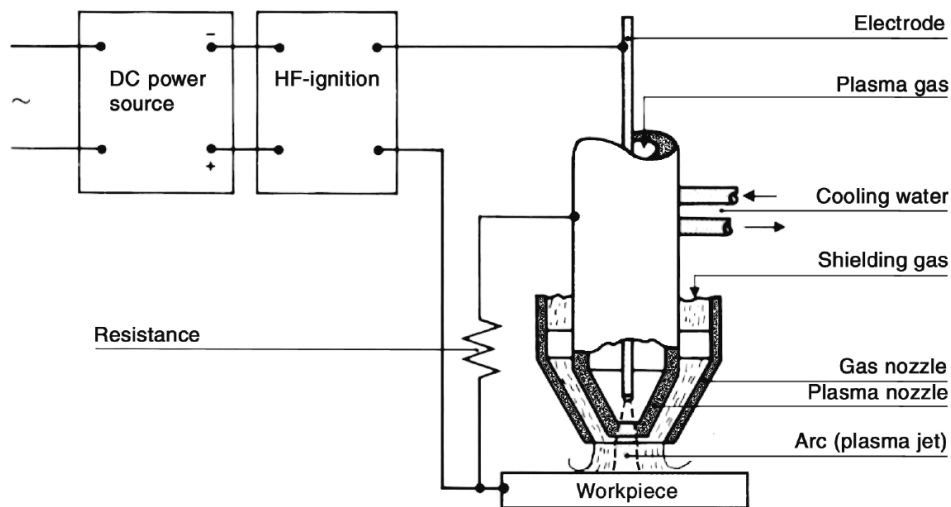


Figure 2-9 Schematic diagram of PTA welding. [50].

Modified PTA variants were proposed and studied to meet the varied requirement of different applications. Voropai et al. [56] developed a pulsed micro-plasma arc welding (MPAW) to weld the butt joints of the Aluminium asbestos-metal gaskets shells. MPAW used current intensities lower than 15 A. The process can be done with steady arc burning and requires no after-weld reworking. Sepokurov et al. [57] developed a power for the MPAW that ensured a smooth current control for welding thin components and hard facing small components. Variable polarity plasma arc welding (VPPAW) is another variant of the PTA welding technique. VPPAW was designed by Boeing Company in the 1920s for aluminium alloy welding to remove surface oxide layer by cathode atomisation effect without damaging the tungsten tip [58]. VPPAW uses alternating-current (AC) square wave current, and the amplitude and duty cycle of the current waveform can be freely adjusted. During the electrode-positive duration, the oxide film on the substrate surface can be cleaned up. Zhang et al. [59] analysed the performance of the VPPAW for AZ-based Mg alloys. Welding parameters, fusion-zone characteristics, mechanical properties, welding temperature fields and behaviour of PTA were studied. Zheng et al. [60] investigated the front image sensing of the keyhole puddle invariable polarity plasma arc welding for aluminium alloys. Ganguly et al. [61] measured the residual stress fields of the VPPAW process using neutron and synchrotron X-ray diffraction. A strong tensile residual stress

field was detected in the longitudinal direction, parallel to the weld in both the as-welded and the skimmed specimens. Zhang et al. [62] introduced a double-sided PTA welding method to increase the penetration ability of the PTA process. An additional GTAW torch was employed to the back of the workpiece opposite to the upper sided PTA torch, the two torches connected separately to the positive and negative polarities of the welding power source. By using this method, the plasma column of PTA can be further concentrated, and therefore the penetration capability was enhanced. This method requires a setup with higher complexity and accuracy.

The advantages of the PTA process include reliable arc stability with different current intensity and arc length, reliable arc ignition, deep penetration, lower heat input and better metallurgical quality, which benefit a faster process, better bead quality and wider application availability. To date, PTA techniques are one of the most interested welding techniques that draw the attention of researchers all around the world.

2.2.2 Arc profiling

The energy density profile of an electric arc typically has an axial symmetric bell-shaped distribution. This profile needs to be quantified for many reasons, for example, in the simulation of a welding process. The measured energy profile will allow more accurate modelling compared to reverse engineering. In addition, process control and understanding could also be improved if the arc energy density profile was determined as a function of different system designs and process parameters, with the best energy profiles selected for specific applications. Many researchers have studied the energy distribution of an electric arc with various kinds of methodologies being developed. Some non-invasive spectroscopic measuring methods were introduced due to the hostile condition inside an arc plasma body. Haddad et al. [63] measured the temperature distribution in a free-burning arc in pure argon at atmospheric pressure using spectroscopic techniques. Farmer et al. [64] used Rayleigh scattering of argon-ion laser radiation to obtain the number densities in the outer regions ($T < 9000$ K) of a free-burning arc. Thornton [65] used the normalised spectroscopic method

to measure the temperature distribution of a tungsten inert gas (TIG) arc with a number of different spectral lines. These spectroscopic methods are based on an essential assumption of local thermodynamic equilibrium (LTE) [65]. LTE requires that within a given (small) volume, element electron, ion and neutral temperatures are (approximately) equal and thermodynamic properties (such as density, heat conductivity, etc.) are virtually constant [66]. However, the validity of LTE is questionable for complex arcing conditions. Some researchers argued that LTE is not valid for all arc regions and conditions. Bott [67] implied that the electron kinetic temperature might exceed the heavy-particle kinetic temperature in low current arcs. Cram [68] provided strong evidence for significant departures from LTE in high-current (>100 A), free-burning arcs. Farmer et al. [64] reported that excited-state densities are not in equilibrium with ground-state densities. Some invasive methodologies were also introduced to directly detect an arc from the inside of its plasma body, e.g., the Langmuir probe [69] and the split anode calorimetry (SAC) [70]. The Langmuir probe method uses an electrostatic probe to measure an arc plasma body directly. It is fast and relatively easy to apply and has been shown to be viable even at high pressures where the plasma temperatures considerably exceed the melting temperature of the probe. Unfortunately, interpretation of the data produced is fraught with difficulties because no simple, comprehensive underlying theory exists [71]. The SAC method was first proposed by Nestor [70] and has been widely used to measure different kinds of heat sources, including gas tungsten arc and plasma transfer arc (PTA). A verification experiment was introduced by Schoeck [72] to test the reliability of the SAC method. In his work, he used a point anode probe method, which consisted of a water-cooled copper probe surrounded by an insulated water-cooled copper holder to measure electric arcs and compared it with the SAC results. However, this calibration method of his device is not definitive as he used a similar unverified invasive procedure. In the previous SAC measuring works, axial asymmetric distortion was found when an arc travelled across the interface, with its shape altering during the measuring process [73]. Vilarinho et al. [74] also reported the arc bending issue during the SAC arc measurement. However, the mechanism of this phenomenon was not fully revealed. Some

researchers stated that oxidation that occurred on the surface of the copper plates during the calorimetry influenced the location of an arc root [73], whereas other researchers concluded that oxide might have an influence on the current distribution but not on the arc stability [74]. A magnetic field was used to restrict the arc column from wandering [70]. But in the author's opinion, a magnetic field might change the character of an arc. The influence of grounding on arc shape, however, has not yet been analysed.

2.2.3 Laser

Laser welding is a relatively new technology compared to conventional electric arc welding methods. Compared to an electric arc energy source, the energy distribution of a laser beam is essentially stable and can be manipulated with great flexibility, allowing a laser beam to be employed as a precise energy source with high versatility [75]. With a high energy density and a narrow concentration, laser processes can achieve deep penetration with low heat input, ensuring high productivity, a smaller heat-affected zone, and lower distortion. Another incompatible advantage compared to the conventional electric arc energy source is that the energy distribution of a laser beam can be manipulated with high flexibility. One of the approaches to alter the laser energy is varying the optical magnification. With different distances to the laser head lens, the laser beam can be highly focused to tens of microns and also can be enlarged to tens of millimetres, allowing a wide range of power densities and interaction times. Besides, by designing the optical setups, the laser energy profile can be shaped into different forms, such as Gaussian, top-hat, doughnut, and higher-order modes. Such flexibility in the energy distribution control enables the laser process to meet the requirements for various applications. Common issues of the laser welding process include porosity and spatter, which were mainly caused by the keyhole. Another disadvantage of the laser process is that higher accuracy is required for the preparation of workpieces and laser positioning due to a small laser beam diameter. A lower heat input led to a high cooling rate, which might hinder the degassing and increase the possibility of pore formation [76]. A higher power density is required for industrial applications. This level of power density

can be provided by carbon dioxide (CO₂) gas laser (with a wavelength of the order of 10 μm) and neodymium-ytterbium-aluminium-garnet (Nd:YAG) solid-state lasers (with wavelengths of the order of 1 μm).

Depending upon the interaction between laser and substrate, there are two main interaction modes in laser processes: conduction mode and keyhole mode [77]. These two modes are well recognised by many researchers. A transition mode between the conduction mode and the keyhole mode was also widely reported by many researchers. For example, Zhang et al. [78] studied the transition between the different welding modes with different laser power, focal position and travel speed. Three welding mode regimes: heat conduction welding, stable deep penetration welding and unstable mode welding were identified. Buvanashakaran et al. [79] studied the finite-element model that involved three laser welding modes, namely conduction, conduction–penetration, and keyhole welding of thickness 1.6, 2, and 2.5 mm AISI304 stainless steel sheets. Assuncao et al. [80] studied the transition from conduction to keyhole mode by increasing power density and using different beam diameters and interaction times. He concluded that there was no sharp transition between conduction mode and keyhole mode in laser welding but a transition mode where the rate of increase of the penetration depth with power density was reduced (Figure 2-10).

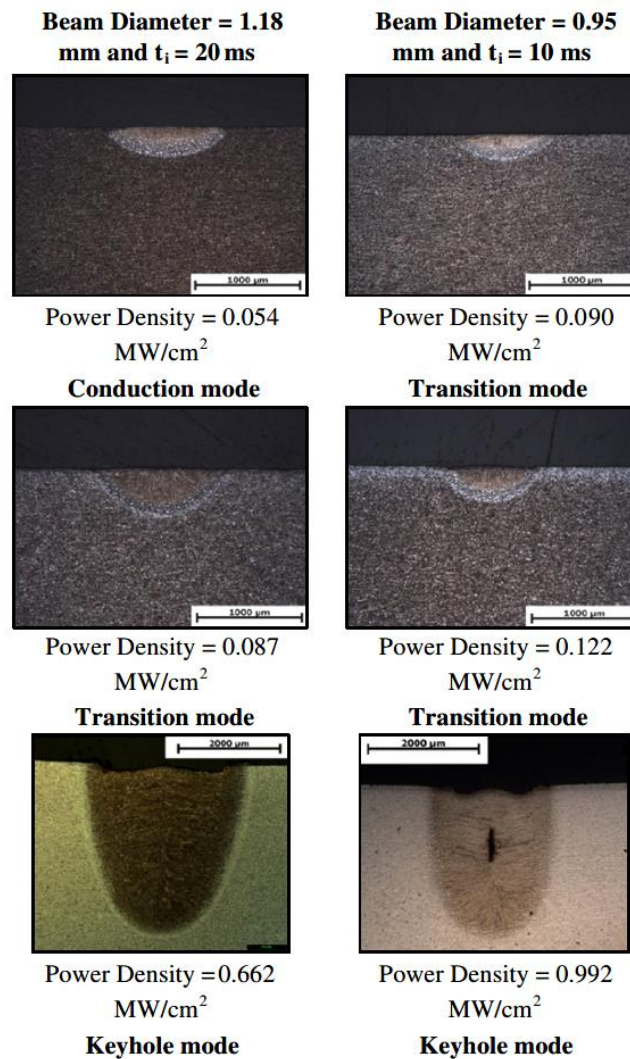


Figure 2-10 Macrographs of welds done in conduction mode, transition mode, and keyhole mode [76].

2.2.4 Scanning laser

In the laser beam welding process, edge preparation and positioning are critical for the whole process due to the small spot size. By oscillating the laser beam at a high frequency with a given amplitude, the welding zone can be significantly enlarged. Rubben et al. [81] first developed a scanning laser (SL) welding method to improve the gap tolerance and welding quality. In his work, a laser beam with a beam size of about 0.1 mm was used oscillating across the weld while advancing with a maximum frequency of 200 Hz. Since then, SL has been widely used in welding applications. Choi et al. [82] applied a low-frequency scanning

laser on the 6K21 Al alloy and found that the solidification crack was minimised at an oscillation frequency of 5 Hz. Schedewy et al. [83] studied the quasi-steady-state of the 200 μ m and 250 μ m beam size SL processes for the welding of slot-tab joints and found that the overlapping of adjacent beam paths should be closely controlled. Yamazaki et al. [84] found that increasing beam oscillation frequency would make the weld wider but shallower. However, the spatter would be greater with higher oscillation frequencies [85]. Hao et al. [86] studied the effects of oscillating beam parameters on weld morphologies with a 0.4 mm-diameter laser beam. The results showed that the weld cross-section became more homogeneous with the increase of oscillating frequency ranging from 20 Hz to 1000 Hz because of the forming of a quasi-steady-state melt pool. These previous works mainly focused on small laser beam sizes (less than 1 mm) to achieve deep penetration welding. Other studies have also been conducted on the SL with a larger beam size, which can be used for applications that require a thinner and broader melt pool, e.g., cladding and coating. Cheng et al. [87] used an SL with 1000-1300 W of power and 2 mm of beam size to melt NiTi wire and coated on AISI 316 stainless steel to obtain a clad track. The scanning speed was between 8 to 25 mm/s. In comparison with TIG clad, the laser double-clad track was much less defective, free of cracks and pores, with higher microstructural homogeneity and higher Vickers hardness. Cui et al. [88] studied the deposition of Co-based power feeding cladding on tool steel using an SL with a beam diameter of 4 mm, power of 1.7 kW and scanning speed of 5 mm/s. An analysis of surface modification was discussed, showing that the process produces thin surface layers of high microhardness and fine microstructure. Jiao et al. [89] deposited a layer of T15M high-speed steel alloy powder on the Q235 substrate surface by SL with a beam diameter of 3 mm and power of 600 W. Microstructure of different scanning speeds of 100 mm/min, 200 mm/min, 300 mm/min were compared and studied. The results showed that coating with a scanning speed of 200 mm/min has relatively fewer defects. However, limited research has focused on the dynamic thermal characteristics and the quasi-steady state of an SL with a larger beam size.

2.2.5 Laser scanner

Depending on the configuration, laser scanners can be categorised as pre-objective, objective, and post-objective [90, 91], as illustrated in Figure 2-11. In the objective scanning configuration, the objective, laser source, image plane, or combination is moved transversely or rotated about a remote axis. This type of configuration is the least commonly used for optical scanning due to the complexity of the setup. On the contrary, the post-objective is one of the most straightforward configurations. The rotating axis of the post-objective scanner is either coaxial or normal to the optical axis. Unlike the objective scanning configuration that has a flat focal plane, the focal plane of the post objective setup is curved. The pre-objective configuration is the most widely applied for the scanning system. In the pre-objective system, the beam is first scanned into an angular field and then usually imaged onto a flat surface by multielement flat-field lenses [92].

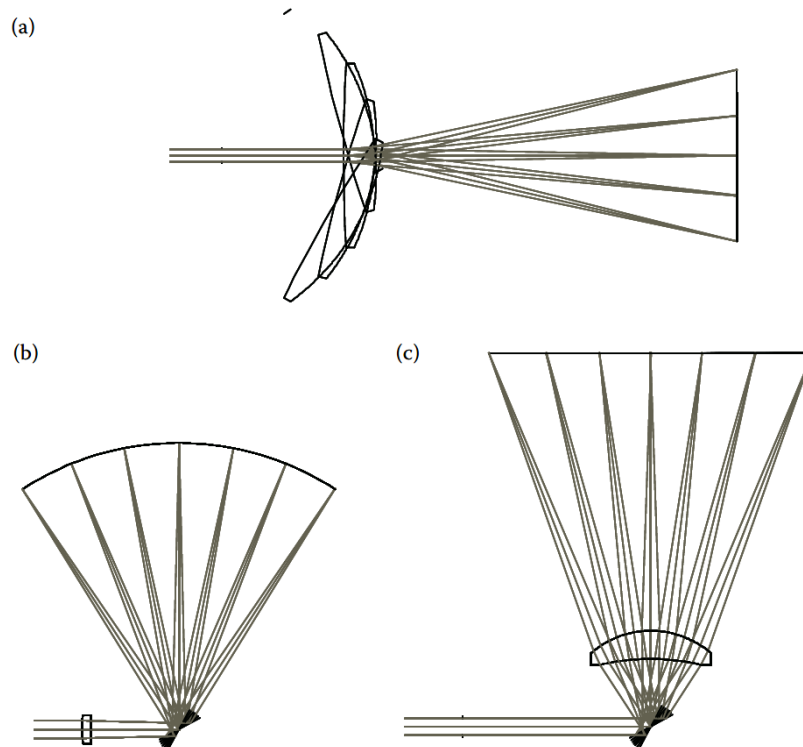


Figure 2-11 Three basic scanning configurations: (a) objective scanning, (b) post-objective scanning, and (c) pre-objective scanning [91].

Among various scanners, the Galvanometer scanner (GS) is one of the most widely used scanning devices due to its high positioning accuracy, satisfactory resolution, and good feasibility [93]. Since the 1970s, one dimensional (1D) GS devices have been developed and improved [92, 95] and are widely used for laser scanning. A GS system usually consists of torque motors, bearings, mirrors, position transducers and computer control. Figure 2-12 illustrates the schematic diagram of a two-mirror, two-axis flat-field GS. A relatively simple setup makes it one of the most straightforward approaches for flat-field scanning. The focal point will approximately paint a sphere after being reflected by two mirrors. When scanning with a small angle, the focus surface can approximately intersect as a plane. However, when a large operating angle is required, distortion becomes nonnegligible and needs to be corrected. Usually, an objective lens is placed between the mirrors and the working area to convert the focal surface from a sphere to a flat plane. Because the two mirrors need to be separated with a considerable distance, which leads to distortions, a system demanding both a large aperture and large field angle will have different degrees of distortion correction for the two directions of scanning. Distortion can be corrected by both optical and electronic approaches but considerably increases the complexity of the system.

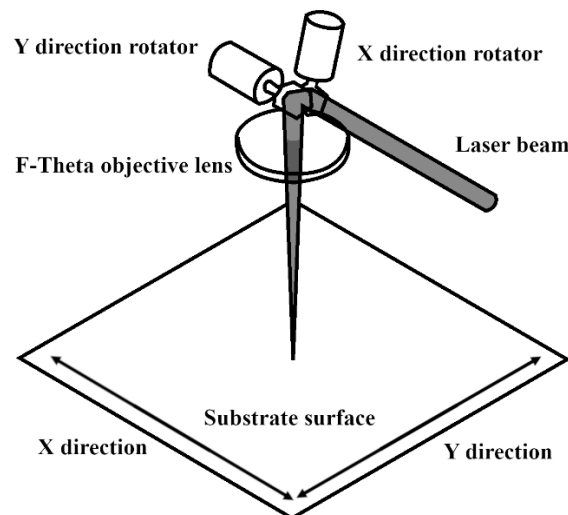


Figure 2-12 Schematic diagram of a GS.

The polygonal scanner is the type of scanner that uses a rotating optical component with multi reflective facets to achieve 1D line scanning. Figure 2-13 shows the schematic diagram of a polygonal scanner. The advantages of the polygonal scanners include high scanning speed, good velocity stability and wide scan angles. The optical component is usually rotated continuously in one direction with a fixed speed and provides a stable scanning speed on the scan field. AC rotators can be used to provide a rotating speed of up to 120000 rpm. Gas turbines can be applied to further extend the rotating speed to 90000 to 1000000 rpm for the requirement of a higher scanning speed but only with a short duty time. The focal line of the polygonal scanner is a curved line and usually requires the correction of a flat-field objective lens [96].

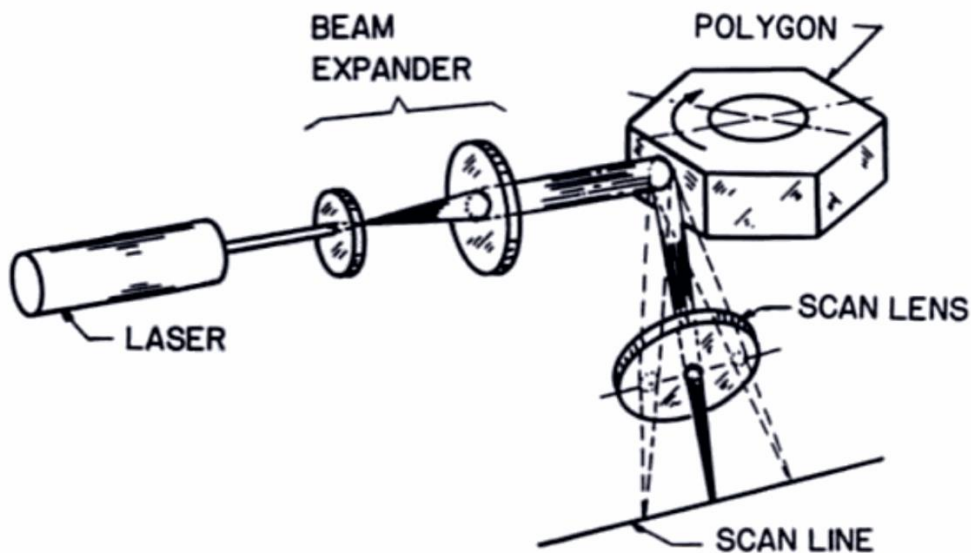


Figure 2-13 Schematic diagram of polygonal scanner [96].

2.3 Research gap

Based on the literature review, the research gap of this study can be concluded as follows:

- Conventional w-DED AM cannot achieve independent control of layer width and height. An innovative energy source is needed to control the melt pool and thermal field precisely.

- The reshaping availability and the dynamic energy profile of the SL have not been investigated. An equivalent model is needed for the SL study.
- The energy distribution of a PTA has not been fully understood.
- The SAC method has not been fully validated, and the arc distortion issue has not been fully studied
- The melt pool dynamic and the deposition quality of the MES method need to be studied. A bead shape control strategy was required to control the bead shape by adjusting these parameters systematically.

2.4 Reference

- [1] Kodama, H. (1981). Automatic method for fabricating a three - dimensional plastic model with photo - hardening polymer. Review of scientific instruments, 52(11), 1770-1773.
- [2] Hull, C. W. (1990). U.S. Patent No. 4,929,402. Washington, DC: U.S. Patent and Trademark Office.
- [3] Crump, S. S. (1991). Fast, precise, safe prototypes with FDM. ASME, PED, 50, 53-60.
- [4] Ralph, B. (1925). U.S. Patent No. 1,533,300. U.S. Patent and Trademark Office.
- [5] Acheson, R. (1990). U.S. Patent No. 4,952,769. U.S. Patent and Trademark Office.
- [6] Lewandowski, J. J., & Seifi, M. (2016). Metal additive manufacturing: a review of mechanical properties. Annual review of materials research, 46, 151-186.
- [7] Wu, B., Pan, Z., Ding, D., Cuiuri, D., Li, H., Xu, J., & Norrish, J. (2018). A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement. Journal of Manufacturing Processes, 35, 127-139.
- [8] Martina, F., Mehnen, J., Williams, S. W., Colegrove, P., & Wang, F. (2012). Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. Journal of Materials Processing Technology, 212(6), 1377-1386.

- [9] Pragana, J. P. M., Sampaio, R. F. V., Bragança, I. M. F., Silva, C. M. A., & Martins, P. A. F. (2021). Hybrid metal additive manufacturing: A state-of-the-art review. *Advances in Industrial and Manufacturing Engineering*, 100032.
- [10] Williams, S. W., Martina, F., Addison, A. C., Ding, J., Pardal, G., & Colegrove, P. (2016). Wire+ arc additive manufacturing. *Materials Science and Technology*, 32(7), 641-647.
- [11] Selvi, S., Vishvaksenan, A., & Rajasekar, E. (2018). Cold metal transfer (CMT) technology-An overview. *Defence technology*, 14(1), 28-44.
- [12] Shinn, B. W., Farson, D. F., & Denney, P. E. (2005). Laser stabilisation of arc cathode spots in titanium welding. *Science and Technology of welding and Joining*, 10(4), 475-481.
- [13] Ding, J., Colegrove, P., Martina, F., Williams, S., Wiktorowicz, R., & Palt, M. R. (2015). Development of a laminar flow local shielding device for wire+ arc additive manufacture. *Journal of Materials Processing Technology*, 226, 99-105.
- [14] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, 81(1), 465-481.
- [15] <https://ewi.org/wp-content/uploads/2017/03/Uziel-Reducing-Manufacturing-Costs-with-Robotic-Welding.pdf>
- [16] Aiyiti, W., Zhao, W., Lu, B., & Tang, Y. (2006). Investigation of the overlapping parameters of MPAW-based rapid prototyping. *Rapid Prototyping Journal*.
- [17] Wang, C., Suder, W., Ding, J., & Williams, S. (2021). The effect of wire size on high deposition rate wire and plasma arc additive manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 288, 116842.
- [18] Richter, A., Krüssel, T., & Just, C. (2012). Deposition welding with the electron beam as repair technology. In *International electron Beam Welding Conference*, Aachen.
- [19] Körner, C. (2016). Additive manufacturing of metallic components by selective electron beam melting—a review. *International Materials Reviews*, 61(5), 361-377.

- [20] Węglowski, M. S., Błacha, S., & Phillips, A. (2016). Electron beam welding—techniques and trends—review. *Vacuum*, 130, 72-92.
- [21] Gong, X., Anderson, T., & Chou, K. (2012, June). Review on powder-based electron beam additive manufacturing technology. In *International Symposium on Flexible Automation* (Vol. 45110, pp. 507-515). American Society of Mechanical Engineers.
- [22] Worldwide Leaders in Industrial Metal 3D Printing Technology and EB Welding Solutions (2019), available at: www.sciaky.com/
- [23] Dave, V. R., Matz, J. E., & Eagar, T. W. (1995). Electron beam solid freeform fabrication of metal parts. In *1995 International Solid Freeform Fabrication Symposium*.
- [24] Tamingier, K., & Hafley, R. A. (2003, July). Electron beam freeform fabrication: a rapid metal deposition process. In *3rd annual automotive composites conference*.
- [25] Baufeld, B., Widdison, R., Dutilleul, T., & Bridger, K. (2016). Electron beam additive manufacturing at the nuclear AMRC. *Elektronika ir Elektrotechnika*, 51, 25-30.
- [26] Xiong, J., Zhang, G., Gao, H., & Wu, L. (2013). Modeling of bead section profile and overlapping beads with experimental validation for robotic GMAW-based rapid manufacturing. *Robotics and Computer-Integrated Manufacturing*, 29(2), 417-423.
- [27] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). A multi-bead overlapping model for robotic wire and arc additive manufacturing (WAAM). *Robotics and Computer-Integrated Manufacturing*, 31, 101-110.
- [28] Almeida, P. M., & Williams, S. (2010). Innovative process model of Ti-6Al-4V additive layer manufacturing using cold metal transfer (CMT). In *2010 International Solid Freeform Fabrication Symposium*. University of Texas at Austin.
- [29] Yehorov, Y., da Silva, L. J., & Scotti, A. (2019). Balancing WAAM production costs and wall surface quality through parameter selection: A case study of an Al-Mg5 alloy multilayer-non-oscillated single pass wall. *Journal of Manufacturing and Materials Processing*, 3(2), 32.

- [30]Su, C., Chen, X., Gao, C., & Wang, Y. (2019). Effect of heat input on microstructure and mechanical properties of Al-Mg alloys fabricated by WAAM. *Applied Surface Science*, 486, 431-440.
- [31]M. Dinovitzer, X. Chen, J. Laliberte, X. Huang, H. Frei, Effect of wire and arc additive manufacturing (WAAM) process parameters on bead geometry and microstructure, *Addit. Manuf.* 26 (2019) 138–146.
- [32]M. Schulz, F. Klocke, J. Riepe, N. Klingbeil, K. Arntz, Process optimization of wire-based laser metal deposition of titanium, *J. Eng. Gas Turbines Power.* 141 (2019) 052102.
- [33]T.E. Abioye, J. Folkes, A.T. Clare, A parametric study of Inconel 625 wire laser deposition, *J. Mater. Process. Technol.* 213 (2013) 2145–2151.
- [34]S.H. Mok, G. Bi, J. Folkes, I. Pashby, Deposition of Ti-6Al-4V using a high power diode laser and wire, Part I: Investigation on the process characteristics, *Surf. Coatings Technol.* 202 (2008) 3933–3939.
- [35]Acherjee, B. (2018). Hybrid laser arc welding: State-of-art review. *Optics & Laser Technology*, 99, 60-71.
- [36]Mahrle, A., Rose, S., Schnick, M., Beyer, E., & Füßel, U. (2013). Laser-assisted plasma arc welding of stainless steel. *Journal of Laser Applications*, 25(3), 032006.
- [37]Liu, L. , & Chen, M. . (2011). Interactions between laser and arc plasma during laser–arc hybrid welding of magnesium alloy. *Optics & Lasers in Engineering*, 49(9-10), 1224-1231.
- [38]Wang, C., Suder, W., Ding, J., & Williams, S. (2021). Wire based plasma arc and laser hybrid additive manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 293, 117080.
- [39]Casalino, G. , Mortello, M. , Leo, P. , Benyounis, K. Y. , & Olabi, A. G. . (2014). Study on arc and laser powers in the hybrid welding of aa5754 al-alloy. *Materials & Design*, 61, 191-198.
- [40]Kanemaru, S., Sasaki, T., Sato, T., Mishima, H., Tashiro, S., & Tanaka, M. (2014). Study for TIG–MIG hybrid welding process. *Welding in the World*, 58(1), 11-18.

- [41] Qian, Y. P., Huang, J. H., Zhang, H. O., & Wang, G. L. (2008). Direct rapid high-temperature alloy prototyping by hybrid plasma-laser technology. *Journal of materials processing technology*, 208(1-3), 99-104.
- [42] Liang, Y., Hu, S., Shen, J., Zhang, H., & Wang, P. (2017). Geometrical and microstructural characteristics of the TIG-CMT hybrid welding in 6061 aluminum alloy cladding. *Journal of materials processing technology*, 239, 18-30.
- [43] Yang, D., Wang, G., & Zhang, G. (2017). A comparative study of GMAW-and DE-GMAW-based additive manufacturing techniques: thermal behavior of the deposition process for thin-walled parts. *The International Journal of Advanced Manufacturing Technology*, 91(5), 2175-2184.
- [44] Zhang, Hai-ou, Ying-ping Qian, Gui-lan Wang, Study of rapid and direct thick coating deposition by hybrid plasma-laser manufacturing, *Surface and Coatings Technology* 201.3-4 (2006) 1739-1744.
- [45] Wu, D., Liu, D., Niu, F., Miao, Q., Zhao, K., Tang, B., Bi, G., Ma, G. (2020). Al-Cu alloy fabricated by novel laser-tungsten inert gas hybrid additive manufacturing. *Additive Manufacturing*, 32, 100954.
- [46] Zhang, Z., Sun, C., Xu, X., Liu, L, Surface quality and forming characteristics of thin-wall aluminium alloy parts manufactured by laser assisted MIG arc additive manufacturing, *International Journal of Lightweight Materials and Manufacture* 1.2 (2018) 89-95.
- [47] Liu, M., Ma, G., Liu, D., Yu, J., Niu, F., & Wu, D. (2020). Microstructure and mechanical properties of aluminum alloy prepared by laser-arc hybrid additive manufacturing. *Journal of Laser Applications*, 32(2), 022052
- [48] Li, R., Wang, G., Ding, Y., Tang, S., Chen, X., Dai, F., ... & Zhang, H. (2020). Optimisation of the geometry for the end lateral extension path strategy to fabricate intersections using laser and cold metal transfer hybrid additive manufacturing. *Additive Manufacturing*, 36, 101546.
- [49] Gong, M., Meng, Y., Zhang, S., Zhang, Y., Zeng, X., & Gao, M. (2020). Laser-arc hybrid additive manufacturing of stainless steel with beam oscillation. *Additive Manufacturing*, 33, 101180.

- [50]Gurnett, D. A., & Bhattacharjee, A. (2005). Introduction to plasma physics: with space and laboratory applications. Cambridge university press.
- [51]Wu, C. S., Wang, L., Ren, W. J., & Zhang, X. Y. (2014). Plasma arc welding: Process, sensing, control and modeling. Journal of manufacturing processes, 16(1), 74-85.
- [52]DebRoy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., Beese, A.M., Wilson-Heid, A., De, A., & Zhang, W. (2018). Additive manufacturing of metallic components–process, structure and properties. Progress in Materials Science, 92, 112-224.
- [53]Sahoo, A., & Tripathy, S. (2020). Development in plasma arc welding process: a review. Materials Today: Proceedings.
- [54]Beth, E., Carroll, Todd, A., & Palmer, et al. (2015). Anisotropic tensile behavior of ti–6al–4v components fabricated with directed energy deposition additive manufacturing. Acta Materialia.
- [55]B.A. Szost, S. Terzi, F. Martina, D. Boisselier, A. Prytuliak, T. Pirling, M.Hofmann, D.J. Jarvis, (2016). A comparative study of additive manufacturing techniques: Residual stress and microstructural analysis of CLAD and WAAM printed Ti–6Al–4V components. Materials & Design, 89, 559-567.
- [56]Voropai, N. M., Shcherbak, V. V., & Grigor'ev, A. A. (1971). Pulsed Microplasma welding of thin Aluminum gaskets. Chemical and Petroleum Engineering, 7(11), 977-978.
- [57]Slepokurov, A. S., Sergatskii, G. I., & Alikin, A. P. (1971). Use of microplasma welding in component construction. Chemical and Petroleum Engineering, 7(11), 979-980.
- [58]Nunes, A., Bayless, E., Jones, C., Munafo, P., & Biddle, A. (1984). Variable polarity plasma arc welding on the space shuttle external tank. Welding journal, 63(9), 27-35.
- [59]Zhang, Z. D. (2010). Variable polarity plasma arc welding of magnesium alloys. In Welding and Joining of Magnesium Alloys (pp. 197-229e). Woodhead Publishing.

- [60]Zheng, B., Wang, H. J., & Wang, Q. L. (1998). Front image sensing of the keyhole puddle in the variable polarity PAW of aluminum alloys. *Journal of Materials Processing Technology*, 83(1-3), 286-298.
- [61]Ganguly, S., Fitzpatrick, M. E., & Edwards, L. (2006). Use of neutron and synchrotron X-ray diffraction for evaluation of residual stresses in a 2024-T351 aluminum alloy variable-polarity plasma-arc weld. *Metallurgical and Materials transactions A*, 37(2), 411-420.
- [62]Zhang, Y. M., & Zhang, S. B. (1998). Double-sided arc welding increases weld joint penetration. *Welding Journal-Including Welding Research Supplement*, 77(6), 57-62.
- [63]Haddad, G. N., & Farmer, A. J. D. (1984). Temperature determinations in a free-burning arc. I. Experimental techniques and results in argon. *Journal of Physics D: Applied Physics*, 17(6), 1189.
- [64]Farmer, A. J. D., & Haddad, G. N. (1988). Rayleigh scattering measurements in a free-burning argon arc. *Journal of Physics D: Applied Physics*, 21(3), 426.
- [65]Thornton, M. F. (1993). Spectroscopic determination of temperature distributions for a TIG arc. *Journal of Physics D: Applied Physics*, 26(9), 1432.
- [66]Richardson, & I., M. . (1991). Properties of the constricted gas tungsten (plasma) welding arc at elevated pressures. (Doctoral dissertation, Cranfield Institute of Technology).
- [67]Bott, J. F. (1966). Spectroscopic measurement of temperatures in an argon plasma arc. *The Physics of Fluids*, 9(8), 1540-1547.
- [68]Cram, L. E. (1985). Statistical evaluation of radiative power losses from thermal plasmas due to spectral lines. *Journal of Physics D: Applied Physics*, 18(3), 401.
- [69]Mott-Smith, H. M., & Langmuir, I. (1926). The theory of collectors in gaseous discharges. *Physical review*, 28(4), 727.
- [70]Nestor, O. H. (1962). Heat intensity and current density distributions at the anode of high current, inert gas arcs. *Journal of applied physics*, 33(5), 1638-1648.

- [71]Fanara, C., & Richardson, I. M. (2001). A Langmuir multi-probe system for the characterisation of atmospheric pressure arc plasmas. *Journal of Physics D: Applied Physics*, 34(18), 2715.
- [72]Schoeck, P. A. (1963). An investigation of the anode energy balance of high intensity arcs in argon. *Modern developments in heat transfer*, 353-400.
- [73]Egerland, S., Colegrove, P., & Williams, S. (2017). Investigation of low current gas tungsten arc welding using split anode calorimetry. *Science and Technology of Welding and joining*, 22(1), 71-78.
- [74]Vilarinho, L. O., & Fanara, C. (2003). A modified split-anode detector for the study of the anode region of atmospheric pressure arc plasmas. *Measurement Science and Technology*, 15(1), 67.
- [75]Suder, W. J. (2011). Study of fundamental parameters in hybrid laser welding (Doctoral dissertation, Cranfield University).
- [76]Goncalves Assuncao, E. (2012). Investigation of conduction to keyhole mode transition (Doctoral dissertation, Cranfield University).
- [77]Steen, W. M., & Mazumder, J. (2010). *Laser material processing*. Springer science & business media.
- [78]Zhang, X., Chen, W., Ren, J., Huang, G., & Zhang, H. (1996). Laser welding mode transition and influence of thermal focusing on mode transition. In *Laser Processing of Materials and Industrial Applications* (Vol. 2888, pp. 306-315). International Society for Optics and Photonics.
- [79]Buvanashakaran, G., Shanmugam, S. N., Sankaranarayananasamy, K., & Sabarikanth, R. (2009). A study of laser welding modes with varying beam energy levels. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 223(5), 1141-1156.
- [80]Assuncao, E. , Williams, S. , & Yapp, D. . (2012). Interaction time and beam diameter effects on the conduction mode limit. *Optics & Lasers in Engineering*, 50(6), 823-828.
- [81]Rubben, K., Mohrbacher, H., & Leirman, E. (1997, August). Advantages of using an oscillating laser beam for the production of tailored blanks. In *Lasers in Material Processing* (Vol. 3097, pp. 228-241). International Society for Optics and Photonics.

- [82]Choi, K. D., Ahn, Y. N., & Kim, C. (2010). Weld strength improvement for Al alloy by using laser weaving method. *Journal of Laser Applications*, 22(3), 116-119.
- [83]Schedewy, R. , Dittrich, D. , Standfu, J. , & Brenner, B. . (2008). LBW of high stiffness light weight structures generated by scanned fiber laser beams. *ICALEO 2008: 27th International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing*.
- [84]Yamazaki, Y. , Abe, Y. , Kitagawa, A. , & Nakata, K. . (2013). Fundamental study on the laser welding phenomena with high-frequency laser beam oscillation. *prep.nat.meet.jws*.
- [85]Yamazaki, Y., Abe, Y., Hioki, Y., Nakatani, M., Kitagawa, A., & Nakata, K. (2016). Fundamental study of narrow-gap welding with oscillation laser beam. *Welding International*, 30(9), 699-707.
- [86]Hao, K., Li, G., Gao, M., & Zeng, X. (2015). Weld formation mechanism of fiber laser oscillating welding of austenitic stainless steel. *Journal of Materials Processing Technology*, 225, 77-83.
- [87]Cheng, F. T., Lo, K. H., & Man, H. C. (2004). A preliminary study of laser cladding of AISI 316 stainless steel using preplaced NiTi wire. *Materials Science and Engineering: A*, 380(1-2), 20-29.
- [88]Cui, C., Guo, Z., Liu, Y., Xie, Q., Wang, Z., Hu, J., & Yao, Y. (2007). Characteristics of cobalt-based alloy coating on tool steel prepared by powder feeding laser cladding. *Optics & Laser Technology*, 39(8), 1544-1550.
- [89]Jiao, X., Wang, J., Wang, C., Gong, Z., Pang, X., & Xiong, S. M. (2018). Effect of laser scanning speed on microstructure and wear properties of T15M cladding coating fabricated by laser cladding technology. *Optics and Lasers in Engineering*, 110, 163-171.
- [90]Beiser, L. (1974), in M. Ross (Ed.), *Laser Applications*, Vol. 2. New York: Academic Press, pp. 53–159.
- [91]Beiser, L. (1992), *Laser Scanning Notebook*, Vol. PM13. Bellingham, WA: SPIE Opt. Engrg. Press.
- [92]Marshall, G. F., & Stutz, G. E. (2012). *Handbook of optical and laser scanning* (p. 788). Taylor & Francis.

- [93]Duma, V. F., Lee, K. S., Meemon, P., & Rolland, J. P. (2011). Experimental investigations of the scanning functions of galvanometer-based scanners with applications in OCT. *Applied Optics*, 50(29), 5735-5749.
- [94]Montagu, J. (2015). Scanners: galvanometric and resonant. In *Encyclopedia of Optical and Photonic Engineering*, Second Edition (pp. 1-22). CRC Press.
- [95]Beiser, L., & Johnson, R. (1995). Scanners, *Handbook of Optics*, vol. 2.
- [96]Marshall, G. F. (2017). *Laser beam scanning: opto-mechanical devices, systems, and data storage optics*. Routledge.

3 Energy source profiling.

3.1 Split anode calorimetry for plasma arc energy density measurement with laser calibration

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ABSTRACT

A split anode calorimeter (SAC) has been developed for the measurement of plasma transferred arc (PTA) energy density. A novel aspect is the use of a laser beam with a well-defined energy profile which was first measured using a commercial laser beam diagnosis system and was used to calibrate the SAC calorimeter. The SAC temperature profile showed the same profile measured by the laser diagnosis system. This confirmed the accuracy of the SAC method and its suitability for measuring the energy distribution of an electric arc if provided stably. The PTA energy profile was observed to be distorting when crossing over the split anode interface of the SAC. This was corrected by moving the ground wire from the side to the centre of the anode. Detailed analysis of a 130A PTA energy density profile with both the current density profile and the temperature distribution of the arc showed that the current profile is narrower than that of the temperature profile. This indicates that the effective energy distribution is wider than that of the width of the arc column due to other energy transfer processes such as convection and radiation. The energy absorption distribution matched well to a Gaussian distribution model with a radius of 6 mm. The arc energy absorption rate of the copper plate was measured and found to be about 56%.

Keywords: Arc profile; Split anode Calorimetry; Plasma arc

3.1.1 Introduction

An electrical arc is a discharge between two electrodes, with current conducted from an electrode to a workpiece through a heated and ionised gas, the plasma. The voltage and the current in the arc determine the amount of power released,

the heat from which melts the electrode and the joint faces when using the arc for welding [1]. The energy density profile of an electric arc typically has an axial symmetric bell-shaped distribution. This profile needs to be quantified for many reasons, for example, in the simulation of welding processes. The measured energy profile will allow more accurate modelling compared to reverse engineering. In addition, process control and understanding could also be improved if the arc energy density profile was determined as a function of different system designs and process parameters, with the best energy profiles selected for specific applications. Many researchers have studied the energy distribution of an electric arc with various kinds of methodologies being developed. Some non-invasive spectroscopic measuring methods were introduced due to the hostile condition inside an arc plasma body [2-5]. These spectroscopic methods are based on an essential assumption of local thermodynamic equilibrium (LTE) [5]. LTE requires that within a given (small) volume element electron, ion and neutral temperatures are (approximately) equal and thermodynamic properties (such as density, heat conductivity etc.) are virtually constant [6]. However, the validity of LTE is questionable for complex arcing conditions. Some researchers argued that LTE is not valid for all arc regions and conditions [7-10]. Some invasive methodologies were also introduced to directly detect an arc from the inside of its plasma body, e.g., the Langmuir probe [11, 12] and the split anode calorimetry (SAC) [6, 13-17]. The Langmuir probe method uses an electrostatic probe to measure an arc plasma body directly. It is fast and relatively easy to apply and has been shown to be viable even at high pressures where the plasma temperatures considerably exceed the melting temperature of the probe. Unfortunately, interpretation of the data produced is fraught with difficulties because no simple, comprehensive underlying theory exists [11]. The SAC method was first proposed by Nestor [13] and has been widely used to measure different kinds of heat sources, including gas tungsten arc and plasma transfer arc (PTA). A schematic diagram of a SAC is shown in Figure 3-1 [13]. Two separated non-ablating copper anodes are employed under a torch, with electrical and thermal insulation in between. Two separate cooling water circuits are placed under each of the copper plates. During the measurement, the electric

arc is traversed across the interface between the two anodes in equal increments. The energy of the arc plasma is then 'split' into two parts at the interface. The current going through each section of the anodes, and the mass flow rate and the temperature changes of both cooling water circuits are measured. In this way, the energy amounts that two plates absorbed can be calculated. Based on this, the energy distribution of the arc can be determined when the interface is scanned across the arc section.

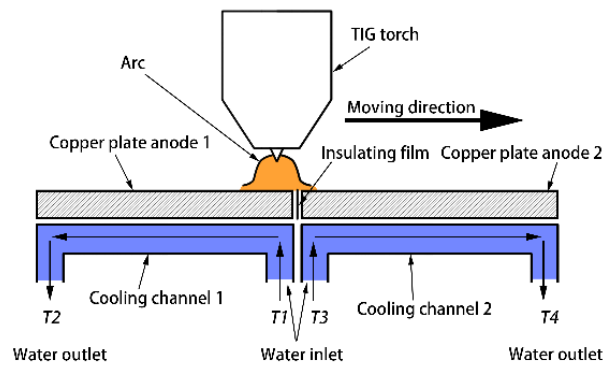


Figure 3-1 Schematic diagram of the SAC [13].

A verification experiment was introduced by Schoeck [14] to test the reliability of the SAC method. In his work, he used a point anode probe method, which consisted of a water-cooled copper probe surrounded by an insulated water-cooled copper holder to measure electric arcs and compared it with the SAC results. However, this calibration method of his device is not definitive as he used a similar unverified invasive procedure. Since then, the SAC method has been widely accepted but with limited studies investigating its accuracy and reliability. In this study, a laser beam measurement was introduced to calibrate this method. Unlike an electrical arc, a laser beam is inherently positionally stable and is not be affected by other ambient factors such as position changing during measurement. Another critical point is that the energy distribution of a laser beam can be measured by other fully developed and well-verified methods. There are several methods of acquiring the intensity profile of a laser beam, such as camera-based sensors, slit scanners, knife-edge scanners and pinhole scanners [18]. A rotating hollow needle laser beam diagnosis system is one of the most

versatile and effective methods. By comparing the profile generated by the SAC with the profile generated by the rotating hollow needle method, the SAC's capability of measuring an energy profile can be tested and verified. The diagnostic principle of the rotating hollow needle method is based on a small pinhole on the circumference of a hollow needle probing a laser beam. Part of the laser beam that passes the pinhole is reflected inside the needle and guided to the rotating centre. It is then reflected out of the needle and measured using a pyroelectric detector. With every rotation, a cutting line through the beam is measured. The completed system of a needle with a pinhole, motor and sensor is moved through the beam in such a way that the whole beam section is scanned (Figure 3-2) [19]. Although this method is limited by the damage threshold of the material [20], a rotating hollow needle is capable of analysing the energy distribution of a laser beam [21]. Calibration and qualification of the laser profiler can be made by analysing the beam propagation behind a pinhole and compared to a theoretical calculation [22].

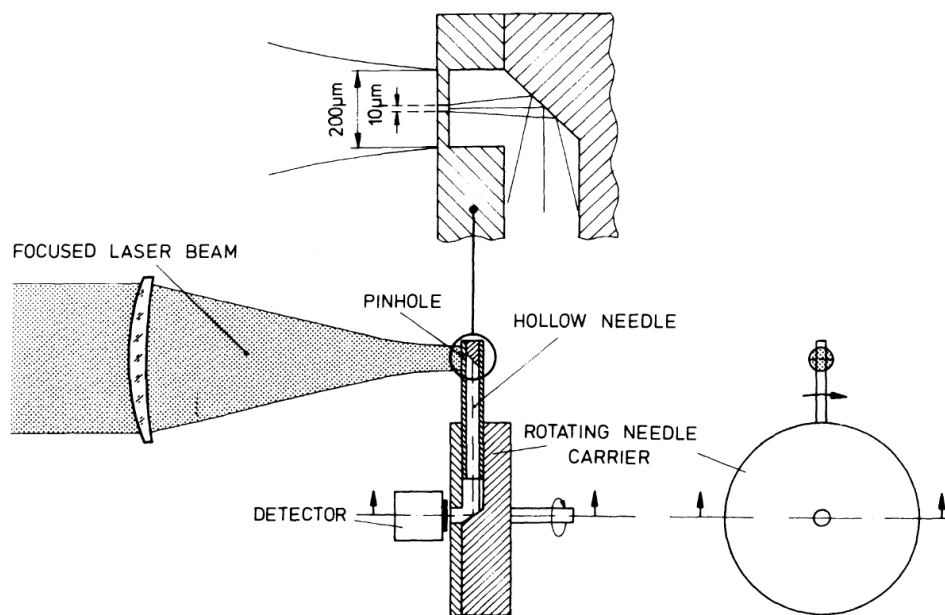


Figure 3-2 Schematic diagram of the hollow needle diagnosis system [19].

The results obtained by the SAC are not two-dimensional but an integrated one-dimensional profile along the moving direction of an electric arc. To convert a

one-dimensional profile to a two-dimensional profile using an Abel inversion, an assumption that the arc body is axial symmetrical needs to be made [13]. Therefore, arc stability is essential for the SAC measurement. In the previous SAC measuring works, axial asymmetric distortion was found when an arc travelled across the interface, with its shape altering during the measuring process [15, 16]. However, the mechanism of this phenomenon was not fully revealed. Some researchers stated that oxidation that occurred on the surface of the copper plates during the calorimetry influenced the location of an arc root [15], whereas other researchers concluded that oxide might have an influence on the current distribution but not on the arc stability [16]. A magnetic field was used to restrict the arc column from wandering [13]. But in the author's opinion, a magnetic field might change the characteristic of an arc. The influence of grounding on arc shape, however, has not yet been analysed. In this study, the shape and position variation of a PTA when crossing the interface was investigated. Different grounding arrangements were tested, and their effects on arc distortion were revealed. Based on that, a modified SAC setup was designed to reduce arc distortion. However, as the plasma body of an electric arc is not rigid [6, 15, 16], random distortion seems to be inevitable during the measurement. Repeated measurements still need to be applied when measuring a single arc heat source to get an averaged result.

Finally, a typical PTA with a current intensity of 130 A was measured. The measured result was compared with a widely used Gaussian distribution model. The verification of this critical empirical model that is used in most welding simulations is essential. It was shown in this study that a Gaussian profile can be used as an approximate substitution for the actual energy profile of a PTA.

3.1.2 Methodology

3.1.2.1 Initial and modified SAC setups

Two versions of the SAC setups, both initial and modified, were tested to investigate the effect of grounding on arc distortion. Figure 3-3 illustrates the initial SAC setup. Two separated cooling water slots were machined into a glass fibre reinforced polyamide holder as the lower halves of two cooling channels (Figure

3-3b). Two 99.95% oxygen-free copper anodes with dimensions of 95 mm × 90 mm × 10 mm were fixed onto a polyamide holder. Water slots were machined at the bottom of the copper plates as the upper halves of the two cooling channels. Two Viton® O-Ring seals were placed between the copper anodes and the polyamide holder to prevent water from leaking. Two separate cooling channels were formed when placing the copper anodes on the top of the polyamide holder. A set of brass screws were mounted in the copper slots to increase turbulence and mixing of water (Figure 3-4a). Without the turbulence induced by the brass screws in improving the stability of the thermocouples signal is shown in Figure 3-4b. A gap between those two anodes was set using a 75 µm thick heat and electrically resistant polyamide film (DuPont® KAPTON® HN'3mil'). Four K-Type thermocouples were attached to the inlets and the outlets to measure the temperature changes of the cooling water. Two turbine flow meters were placed within each circuit to monitor the flow rate of the cooling water. A chiller with refrigeration was used to pump and cool down the water and provide a total flow rate of 2.7 L/min for both cooling circuits. The inlets of the cooling water were placed closed to the anode interface to provide a lower water temperature for the arc section. In the initial design, two earth connectors were mounted to both the copper anodes on the opposite sides, as shown in Figure 3-3a, and connected to an arc power supply.

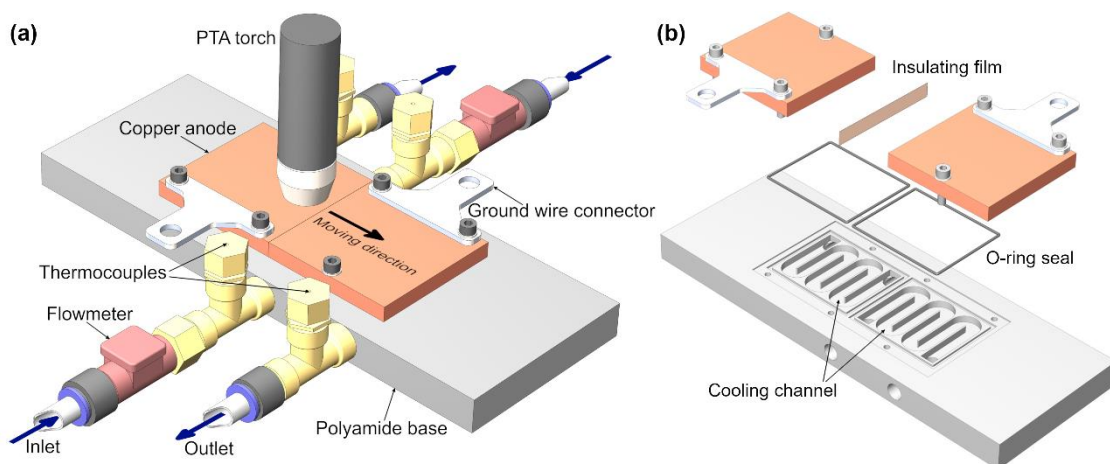


Figure 3-3 (a) Setup of the initial SAC device, and (b) cooling channels machined on the polyamide base.

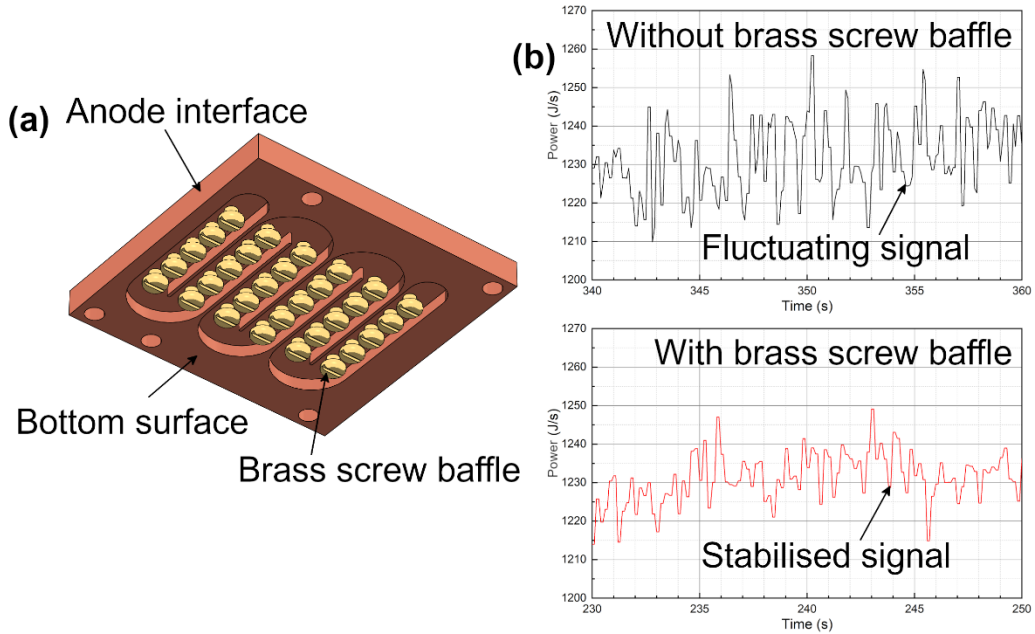


Figure 3-4 (a) Brass screw baffles implant inside the copper plate slot, and (b) temperature signals with and without brass screws.

Based on the initial SAC device, a modified SAC with centred grounding was designed. The setup of the centre grounded SAC device is demonstrated in Figure 3-5. Two ground wires were placed at the bottom of the plates right under the position of the arc instead of being placed at the sides of the copper plates. By using this configuration, the distance difference between the earth wires and the arc section was minimised. The electromagnetic force generated by the current flow was changed from horizontal direction to vertical direction that affected the arc root less. To allow the arc current to go through the copper anode from the upper surface to the ground connectors at the bottom, the copper plate holders need to be electrically conductive. Therefore, two separated aluminium holders instead of one polyamide holder were used to support the copper plates and enclose the water circuits.

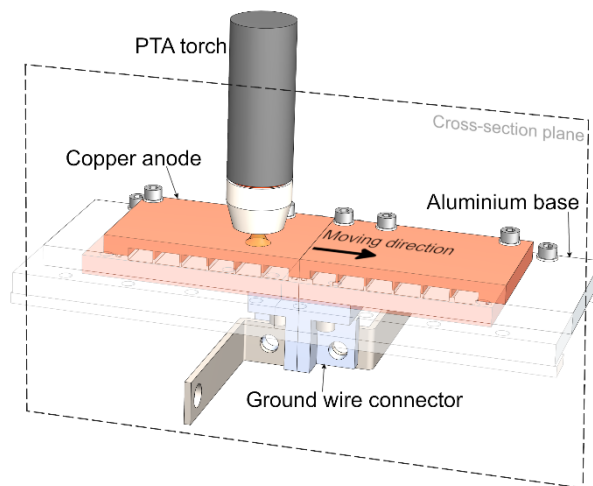
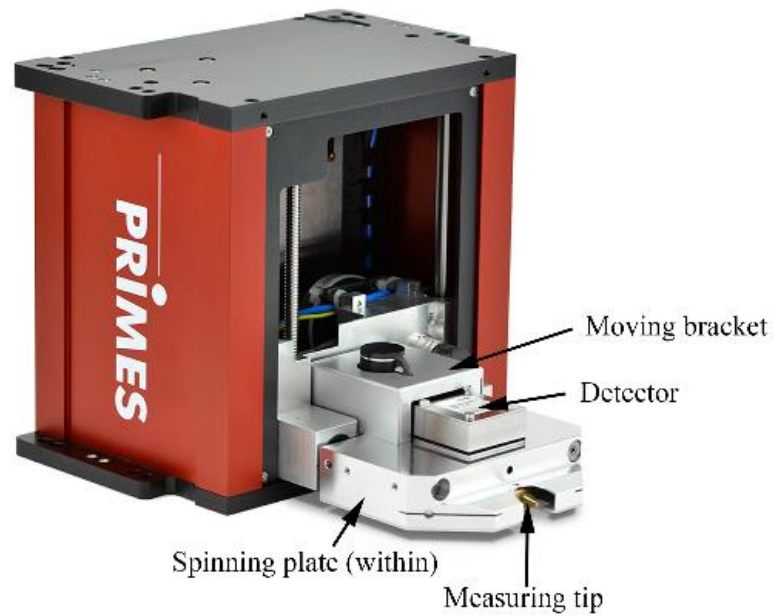


Figure 3-5 The modified SAC setup with ground wires placed under the copper plates.

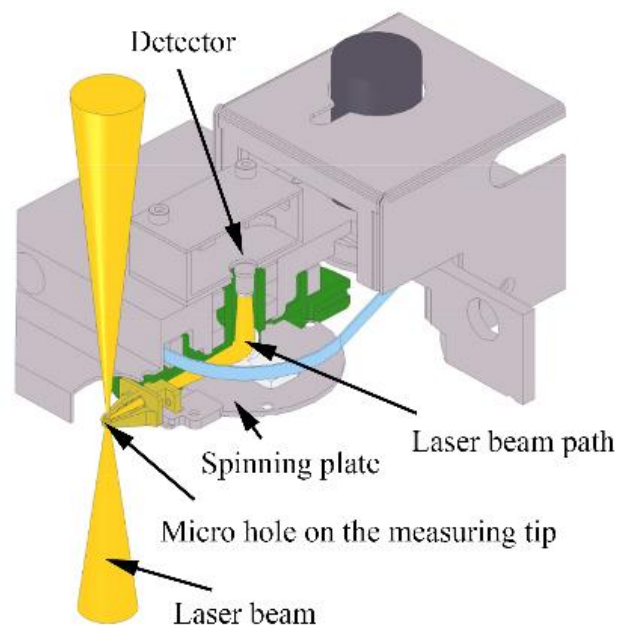
3.1.2.2 Laser calibration experiment

The laser calibration experiment was conducted using the initial SAC setup. An IPG YLR-8000 8 kW CW fibre laser was used to generate a 1.5 kW unfocused laser beam. The power of the output laser was measured using an OPHIR® LASERMETER laser power meter. A Fanuc RJ3iB robot system was used to hold and move the laser processing head. The copper plates were coated with graphite spay in this laser experiment to reduce the reflection of the laser and increase energy absorption. The graphite coating can also ensure that the measurement is stable and not affected by any surface oxidation. A PRIMES® FocusMonitor FM laser diagnosis was used to measure the laser beam energy profile as a reference. The FM is a commercially available hollow needle diagnosis system that complies with the requirements of the ISO 11146 standard [23]. Figure 3-6 shows a diagram of the FM and the beam path of the optical signal within the FM during measurement. A small pinhole (typical diameter 20 μm) in the measuring tip sampled a small part of a laser beam. The sampled part of the laser beam was guided onto a detector element, which was chosen according to the power and the wavelength of the laser radiation (Figure 3-6b) [24]. The setups of the laser measurements using both the FM and the SAC are explained in Figure 3-7. For the FM measurement, the laser beam was placed vertically and was absorbed by a laser beam dump to prevent accidental damage

(Figure 3-7a). For the SAC measurement, the laser processing head was set to an angle of 5 degrees to vertical to avoid reflection from the copper plate that might damage the processing head (Figure 3-7b).



(a)



(b)

Figure 3-6 (a) PRIMES FocusMonitor FM laser profiler, and (b) beam path of an optical signal within the FM. [24]

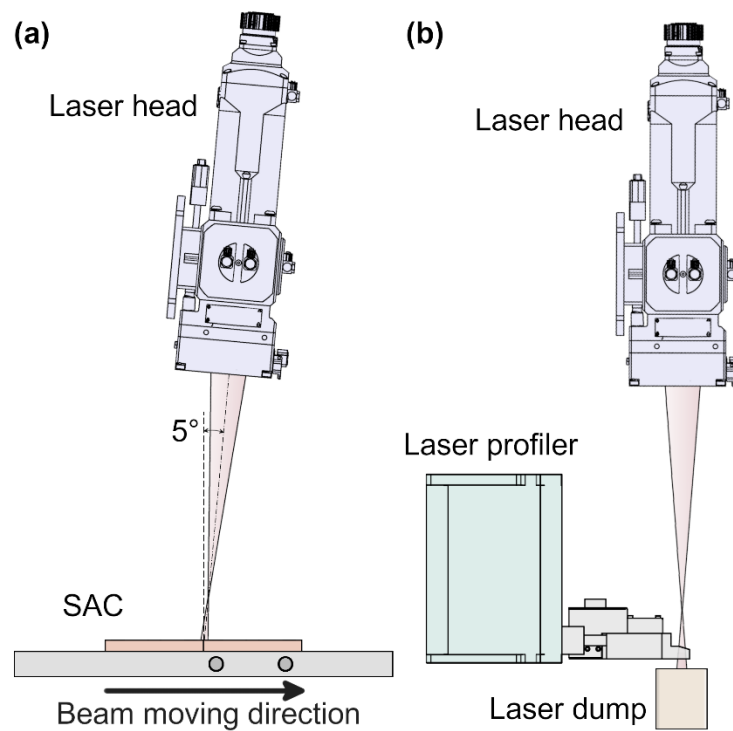


Figure 3-7 Laser measurement setup: (a) with the FM, and (b) with the SAC.

Parameters for the laser experiment are listed in Table 3-1.

Table 3-1 Parameters for the laser experiment.

Power / (W)	1500
Wavelength / (μm)	1.06
Focal length / (mm)	250
Distance between the laser head and the measuring plane / (mm)	305

3.1.2.3 PTA measurement and arc shape analysis

The whole setup was enclosed in a gas-tight tent filled with pure argon and purged until the oxygen level dropped below 300 ppm before the calorimetry process to avoid any possible influence of surface oxidation. The copper plate anodes were polished with 1000-grit abrasive paper to obtain a very fine upper surface. A Fronius® TransTig 5000 welding power source was used for the plasma arc calorimetry. A ZABER® A-LST0250D linear actuator was used with a repeating accuracy of 63 μm to move the torch in equal increments. Parameters used for the PTA measurement are listed in Table 3-2.

Table 3-2 Parameters for the PTA experiment

Current / (A)	130
Voltage / (V)	23.5
Plasma gas / (L/min)	0.8
Shielding gas / (L/min)	15
Distance between the torch and the anodes / (mm)	8
Orifice size / (mm)	3.9
Electrode diameter / (mm)	4
Electrode Tip Angle / (degree)	40
Electrode Tip Set-back / (mm)	2.4

Three different ground wire connections were arranged as indicated in Figure 3-8 to study the effect of grounding position on arc shape stability. The first arrangement is the initial arrangement used in the initial SAC setup (Figure 3-8a). The copper plates were insulated from each other and were both connected to earth wire connectors at the sides. In the second and third arrangements, the insulation between the anodes was removed to electrical connect them. Two separate ground wire connectors were replaced with one ground wire connector positioned at either the right or the left anode (Figure 3-8b and Figure 3-8c). A camera was placed at one side of the interface to capture the shape of the arc when it crossed the interface.

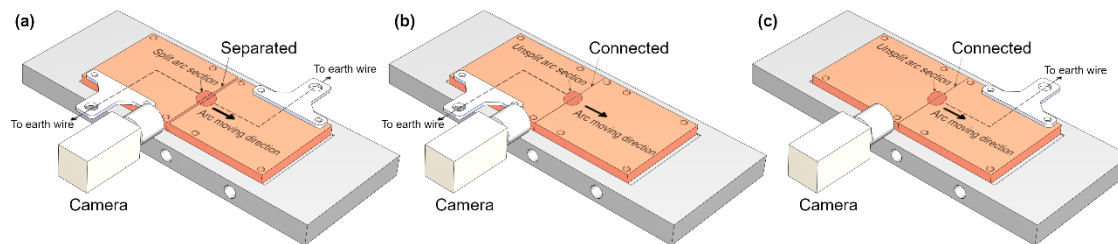


Figure 3-8 Three grounding arrangements for the arc stability study: (a) grounding at both sides with an insulated interface, (b) grounding at the right side with a connected interface, and (c) grounding at the left side with a connected interface.

3.1.2.4 Data acquiring and processing

Two National Instruments NI 9211 and NI 9361 data logger modules were used to acquire temperature and water flow rate data. A Triton P349 was used to collect current data. All experimental data were collected and recorded using Labview and processed using Excel and Origin softwares on a PC. During both the experiments, the laser head and the PTA torch were moved across the interface between the copper anodes at increments of 0.2mm. The whole interface traversing process was divided into 100 increments. A delay time of 30 seconds was applied between each increment keeping the laser head or the welding torch stationary and allowing stabilisation of water temperature before moving onto the next position.

The energy that each copper anode received can be calculated using either Equation 3-1 with the temperature data or Equation 3-2 with the current data:

$$Q_{temp} = (T_{out} - T_{in})C_{water}M_{water} \quad (3-1)$$

$$Q_{current} = IU \quad (3-2)$$

In Equation 3-1, Q_{temp} represents the received energy calculated from the temperature data, T_{out} and T_{in} are the water temperatures at the outlet position and the inlet position, C_{water} is the specific heat of water and M_{water} is the mass flow rate of the cooling water. In Equation 3-2, $Q_{current}$ represents the received energy calculated from the current data, I is the split current that flows through each of the copper anodes, U is the voltage of the arc.

The energy per increment ΔQ_i received at each 0.2mm interval was measured using Equation 3-3. Q_i represents the average energy that each of the copper anodes received calculated from Equation 3-1 or 3-2 in each increment.

$$\Delta Q_i = Q_{i-1} - Q_i \quad (3-3)$$

By associating each ΔQ_i with the position of the corresponding increment, the distribution of the energy source was generated. It is worth noting that this profile is a one-dimensional profile directly converted from the acquired data. This profile

represents the energy distribution along the arc advancing direction, and each point means the energy integrated along the split anode interface direction at each increment. In this study, only the directly converted one-dimensional profile will be discussed.

Later, the resemblance between the measured profile and the Gaussian model was analysed to test the reliability of the Gaussian model. Equation 3-3 is a typical Gaussian distribution formula used in welding simulation:

$$Q(x, y) = \frac{3\eta Q_{total}}{\pi r^2} \exp[-3(x^2 + y^2)/r^2] \quad (3-4)$$

where Q represents the energy density of the arc at a particular point, Q_{total} represents the total energy input of the heat source, x and y are the relative position coordinates to the centre of the arc, r is a parameter that determines the size of the heat source, η is the absorption rate. Since Q_{total} and η are determined in this experiment, r is the only adjustable variable to alter the Gaussian profile shape and find the best match to the measured profile. Pearson correlation coefficient (PCC) [25] was calculated to evaluate the correlations between the measured profiles and Gaussian models.

3.1.3 Results and Discussion

3.1.3.1 SAC calibration experiment with laser

Figure 3-9a shows the energy distribution of the laser beam in a two-dimensional plane generated by the FM. By integrating the energy along Y-axis at each position on X-axis, an energy distribution along the X-axis is given (as shown in Figure 3-9d). Equation 3-5 is the formula of this transformation:

$$Q(x) = \int q(x, y) dy \quad (3-5)$$

In this equation, $Q(x)$ is the one-dimensional energy distribution along X-axis, and $q(x, y)$ is the two-dimensional energy distribution on the plane.

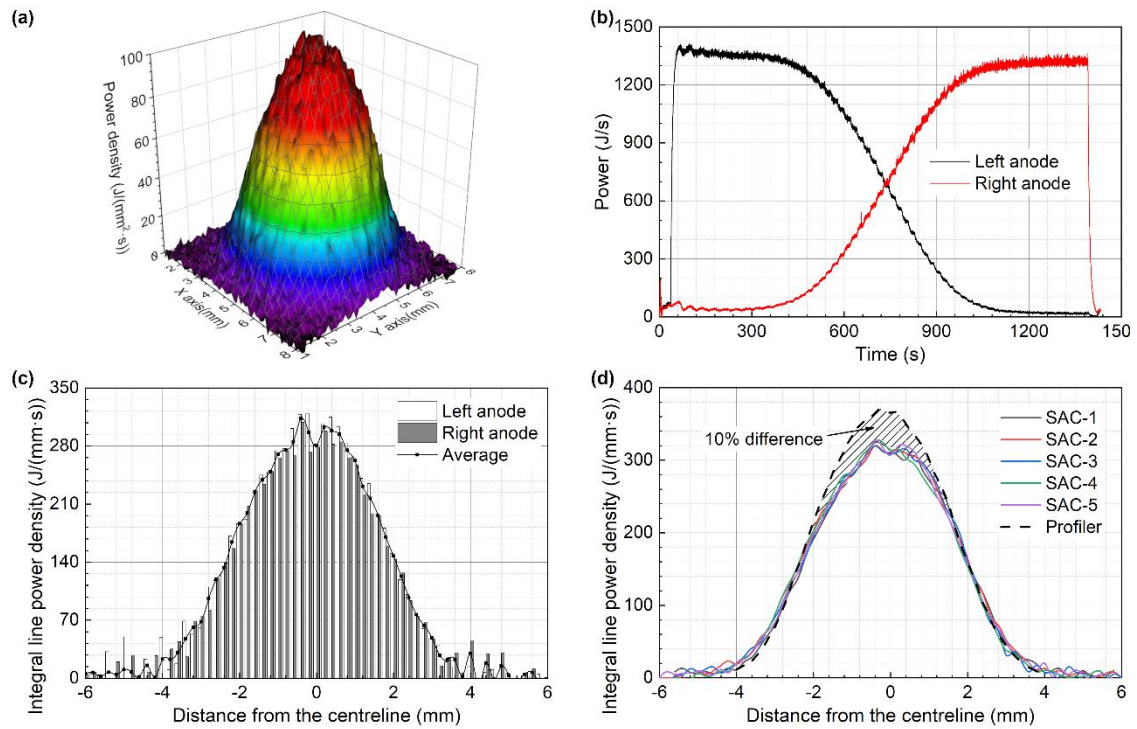


Figure 3-9 Laser measurement results: (a) laser beam energy distribution on a two-dimensional plane, (b) energy that goes through two anodes calculated by temperature data, (c) laser beam energy profile generated from the SAC, and (d) comparison of the profiles generated from the SAC and the FM.

Following the laser reference measurement, the same laser beam was measured using the SAC calibration. Temperature data was collected by the SAC in the laser calibration experiment. After processing the temperature data using Equation 3-1, histories of the energy that two anodes received were generated, as shown in Figure 3-9b. The black coloured curve represents the received energy of the left anode, on which the plasma arc was started, whereas the red curve was the received energy of the right anode. Both curves present a stair-like shape because of the 30 seconds delay time of each increment. By calculating the averaged energy level difference between every two adjacent increments, as explained in Equation 3-3, a laser energy distribution profile was constructed (Figure 3-9c). We can see that despite some slight fluctuations, the laser profile shows a bell-shaped energy distribution with a smooth curve. By comparing the multiple results from the repeated SAC measurement with the profile generated by the FM profiler in Figure 3-9d, we can see that the shape of the SAC result matches the FM result very well with a similar root width of about 8 mm. A minor

asymmetry caused by the slight divergence from the vertical position to the laser processing head is shown on the SAC profile. The overall energy density of the SAC profile is approximately 10% lower than that of the FM profile. This difference could be caused by two reasons. The first reason is that despite using heat-insulating material for the SAC device, a small amount of energy could be lost during the experiment. The second reason could be the reflection and radiation loss on the graphite coated surface. Nevertheless, the results of repeated SAC measurements show good consistency. Slight noise can be observed in these results. But it did not affect the overall shape of the energy distribution.

Two conclusions can be drawn from this laser calibration experiment. First, it demonstrated that the SAC has the capability of generating a clear and detailed profile of a stable laser and, therefore, can be doing the same for the profiling of a PTA if provided stably. The second is that the noise caused by the instrument is low and would not affect the measurement of an electric arc energy source.

3.1.3.2 Arc shape stability study

For PTA energy profiling, a PTA with a current of 130A was used, and the initial SAC setup was first tested. Both current and temperature data were collected during the process (Figure 3-10a and Figure 3-10b). Two energy distribution profiles of the arc were generated from these two dataset outputs. (Figure 3-10c and Figure 3-10d). Both the current profile and the temperature profile show bell-like shape distributions. However, they are not very symmetrical, whereas an axial symmetric distribution would be expected, indicating that the arc shape was distorted during the measurement. The arc distortion was also confirmed by arc images. Figures 3-11a and b are the images of the PTA before and after crossing the interface of the anode. It can be observed that the arc foot was stretched towards the interface. The stretching direction gradually switched to the opposite direction when the arc crossed the interface. Repeated tests were conducted by reversing the moving direction of the arc, and the arc foot was always stretched to the interface. There are three possible explanations for this effect. The first is that the plasma arc might be attracted to the edges of the copper anodes at the interface. It has been shown that arc root might lean to the edge of a substrate

when approaching it due to a higher electron concentration at the sharp edge [26]. The second explanation is that electrical conductivity is zero at the interface, and the presence of this electrical barrier might influence the stability of the arc shape.

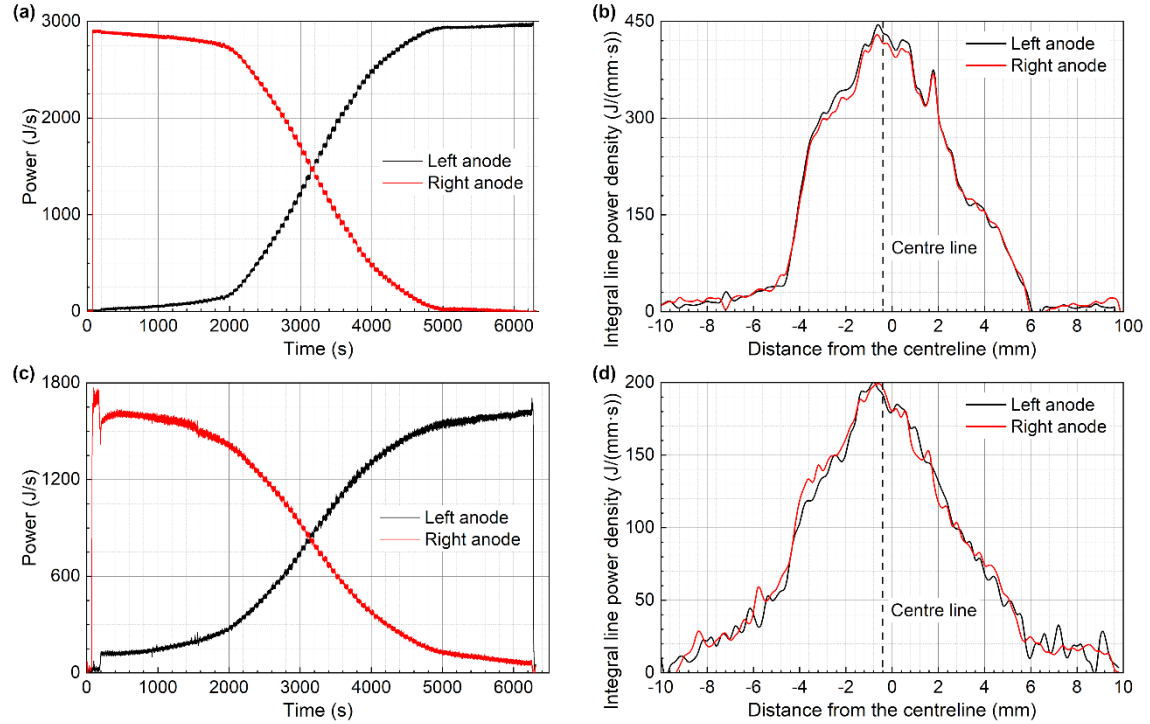


Figure 3-10 Results of the initial SAC arc measurement: (a) energy that goes through two anodes calculated by current data, (b) arc energy profile generated from the current data, (c) energy that goes through two anodes calculated by temperature data, and (d) arc energy profile generated from the temperature data.

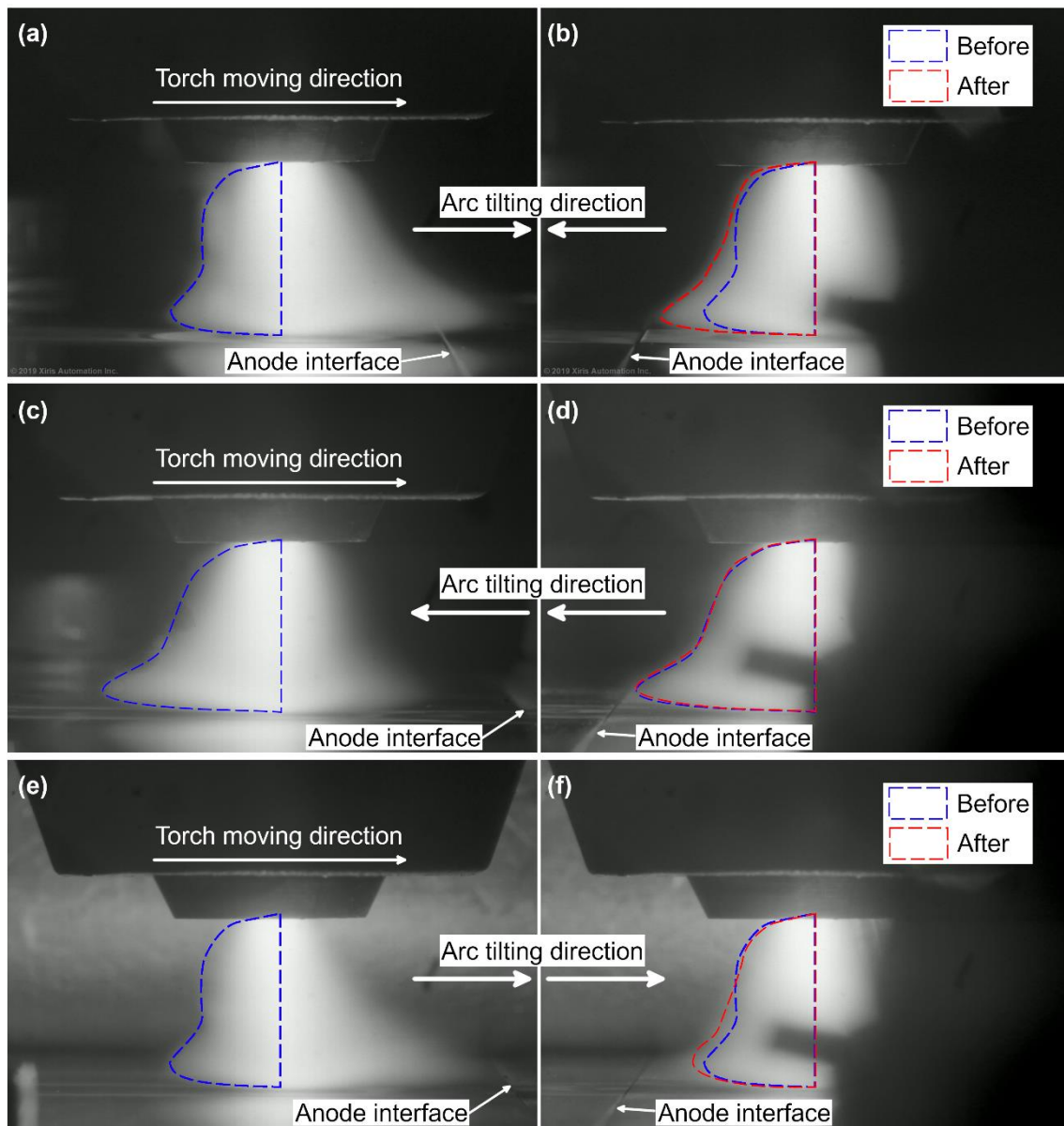


Figure 3-11 Images of the arc before and after crossing the interface with different grounding conditions: (a) and (b) grounded at both sides with an insulated interface, (c) and (d) grounded at the right side with a connected interface, and (e) and (f) grounded at the left side with a connected interface.

This kind of distortion seriously affects the quality of the measured profile. Different grounding conditions were tested to find out the cause of the arc stretching distortion. Figures 3-11c and d and Figures 3-11e and f show the arc images with a physically contacted interface and a single grounding, either on the left or the right anode. We can see that the arc shape was still slightly distorted. However, without the electrical barrier at the interface, the distorted shape stayed

stationary during the traversing. In Figures 3-11c and d, the arc foot stretched to the left when the grounding was on the right anode. In Figures 3-11e and f, the arc foot was stretched towards the right when the grounding was on the left anode. Instead of being 'attracted' by the interface, the arc foot consistently pointed to the opposite side of which the grounding was located. It should be noted that removing the insulation between the anodes only slightly changed the gap distance of the interface. The fact that the dynamic shape changing disappeared completely when connecting the anodes proves that the shape of the interface has little to do with the arc distortion. Previous manuscripts mentioned that arc root would be blown to the opposite side by the electromagnetic field associated with the current flow when getting close to an asymmetric earth return connection [1, 27]. Based on the correlation between the ground position and the arc stretching direction, it can be concluded that the arc stretching distortion was caused by off-centre grounding.

In the experiment using the modified SAC setup, the hypothesis that grounding position affects arc shape was further verified. Video Images of arc were captured during the calorimetry (Figures 3-12a and b). It can be observed that slight distortion of the arc shape is still present when using the modified SAC. However, by comparing them to the arc images from the initial SAC (Figures 3-12c and d, same as Figures 3-11a and b), we can see that the overall arc shape distortion was significantly reduced. And the dynamic distortion of the arc shape upon crossing the interface was also mitigated.

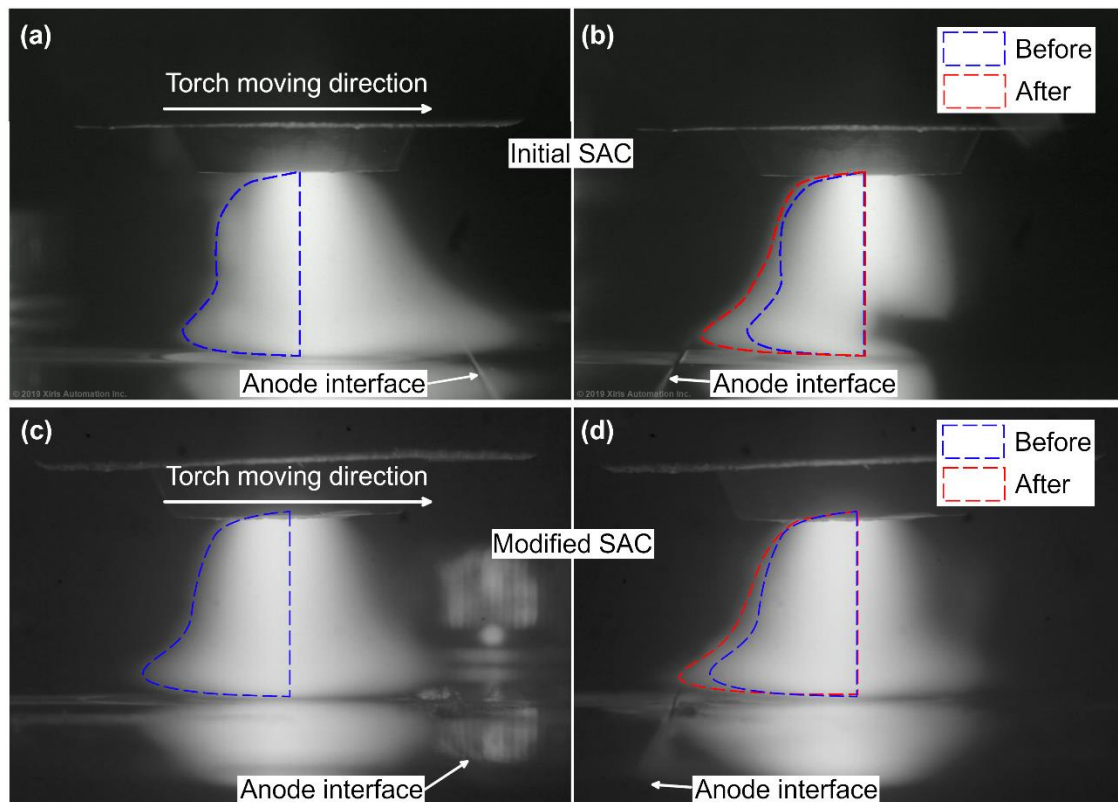


Figure 3-12 Images of the arc before and after crossing the interface: (a) and (b) with the initial SAC, and (c) and (d) with the modified SAC.

Figure 3-13 compares the current and the temperature profiles generated by the modified SAC and the initial SAC. The improvement in the arc stability was reflected in the energy profiles. Both the current and the temperature profiles show more symmetric bell-like shape distributions compared to the previous profiles. The top of the modified SAC profile is rounder and even, while the previous profiles were irregular at the top. The arc foot is also more symmetric. The width of the modified SAC current profile is a bit more concentrated than the previous profiles without the distorted arc foot, indicating that the stretching distortion was reduced. The overall traversing was rather even and smooth with less lagging, and more accurate arc profiles were captured.

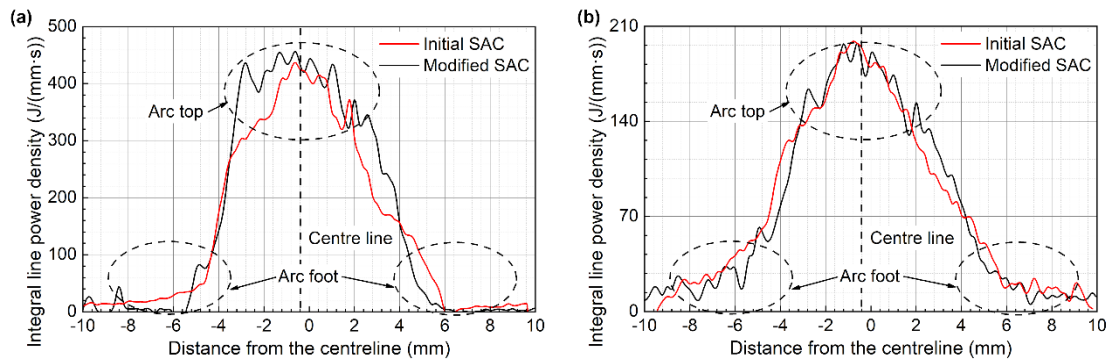


Figure 3-13 Comparison of the profiles generated by initial and modified SAC: (a) current data generated profiles, and (b) temperature data generated profiles.

3.1.3.3 Repeated measurement of PTA

Repeated measurements of PTA with a current of 130A were carried out with the improved system. In Figure 3-14, the results of nine measurements are shown. Data from each measurement are indicated as thin coloured lines, and the averaged results are shown as bold black curves. The outcome is still varying for each individual measurement. A few fluctuations appeared in some of the results. Some fluctuations appeared at the same positions on both the current profile and the temperature profile. Considering that the laser calibration experiment has demonstrated a good signal to noise rate of the SAC setup, it is reasonable to conclude that these fluctuations are caused by the arc behaviour. The torch was directly driven by the linear actuator with a repeating accuracy of 63 μm to ensure that it was moved in even increments. A possible explanation for the fluctuation is that the arc root might not strictly follow the torch due to the limited stiffness of the plasma body. It is difficult to ensure that the arc root is moved in exact equal increments. A slight random defect seems to be unavoidable for each individual measurement. Nevertheless, the averaged profile shows a rather smooth and symmetric outline, indicating that the signal can be improved by averaging several measurements to overcome the random fluctuations. The averaged current density profile and the temperature distribution profile are compared in Figure 3-14c. The temperature profile peak energy level is about 47% of the current profile peak energy level. The overall width of the temperature profile is wider than the current profile, whereas the current profile has a more

concentrated column. The column of the temperature profile presents a more conical shape with a sharper top. The descending at two sides is slower with a wider out-reaching foot. Previous researchers have also found similar phenomena showing that the energy transferring area is generally more extensive than the current-conducting area [14, 17]. This can be explained by the fact that although the current density is the dominating factor in the temperature distribution within an anode, other energy transfer mechanisms such as radiation and convection of hot gases also have a noticeable effect on heat transfer. Evans et al. measured a 100 A PTA and demonstrated that 11% of the arc power was transmitted by the shielding gas, 16% was transferred by the plasma gas, 4.2 % by electron thermal energy and 20% by anode effects, which added up to total energy efficiency of 51.2% [28]. These mechanisms will reduce the temperature gradient between different zones and smoothen the temperature distribution. The total energy amount of the profile is calculated by integrating the area of the energy profile. By dividing the total energy amount of the temperature profile by that of the current profile, an arc efficiency of 56% was obtained. This arc efficiency matches with the results in some previous literature [13, 28-30]. Some literature also reported higher PTA arc efficiency [31, 32]. The inconsistent value of arc efficiency being reported might be due to different experimental parameters, such as current intensity, plasma gas flow rate, shielding gas flow rate, nozzle orifice size, etc. Another factor worth noting is that the energy profiles generated from the current data assumed that the voltages of the two anodes were the same. Nevertheless, previously in the laser calibrating experiment, we have shown that the temperature profile reflects the actual laser energy density accurately. Based on this, we can infer that the temperature profile directly reflects the energy delivered to the anode surface.

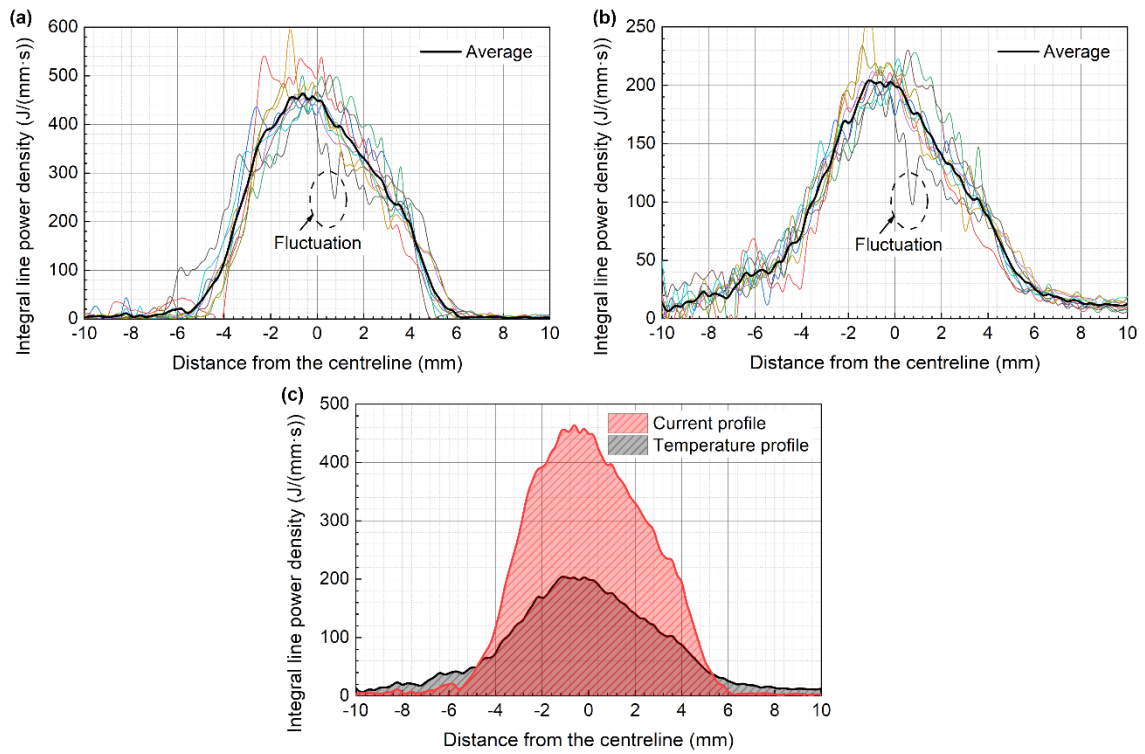


Figure 3-14 (a) Repeated current measurements results: (b) repeated temperature measurements results, and (c) comparison between the current and temperature data generated profiles.

3.1.3.4 Comparison of the measured profile with Gaussian model

In Figure 3-15a, Gaussian distributions with r of 5.5, 6.0, 6.5 and 7.0 and placed together with the current profile. Among these different Gaussian profiles, we can see that the Gaussian profiles can eclectically match the measured current profile with a similar range and shape when $r = 6.5$ with a higher PCC. However, the Gaussian distribution has a sharper and higher peak, while the SAC profile has a broader and rounder top and drops more steeply at both sides.

An efficiency factor η of 56% was implemented to the Gaussian profiles to meet the energy amount of the temperature data. Gaussian distributions with r of 6.5, 7.0, 7.5, and 8.0 are compared with the measured temperature profile in Figure 3-15b. The Gaussian profiles fitted the measured profile quite well. Particularly, PCC was higher when given an r of 7.0 mm but with a slightly higher peak value, while a larger r of 8.0 allows it to better match the peak value of the measured profile. The shape of the temperature profile is more like the Gaussian profiles with similar top geometry and descending trend. However, with these results, we

can confirm that the Gaussian model is usable with a plasma gas flow rate of 0.8 L/min and orifice size 3.9 mm, which were used in this study as they were set for wire + arc additive manufacturing which a low arc pressure is needed to avoid keyhole defects. It should be noted, however, that the shape of the arc energy distribution may not always be as similar to a Gaussian model. In welding and cutting applications, the plasma gas flow rate is usually higher and with a smaller orifice size to achieve higher penetration. Especially for thick plate welding, for example, plasma gas flow rate is about 2 to 10 L/min with an orifice size of about 3 mm [33]. So, the arc dimension demonstrated in the measured profile in this study is relatively wide and more like the dimension of a tungsten inert gas arc [6, 13, 14].

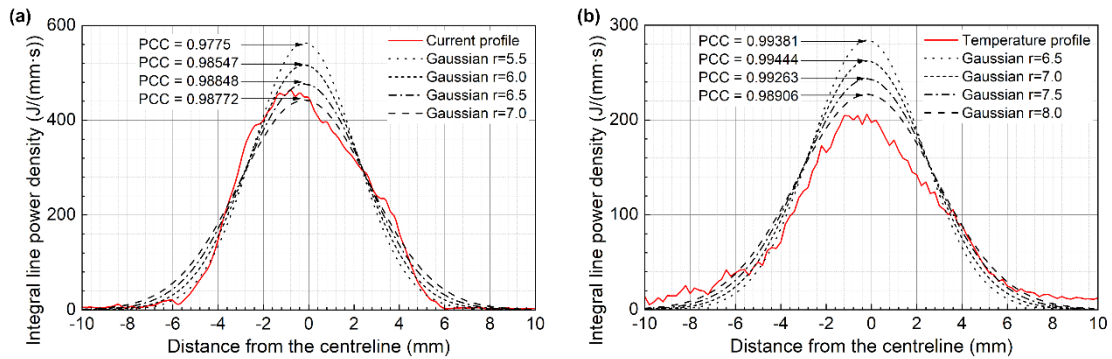


Figure 3-15 Measured profiles fitted with Gaussian profiles: (a) current data generated profile and (b) temperature data generated profile.

3.1.4 Conclusions

From the investigations conducted and the results discussed above in this study, some conclusions can be summarised:

1. A laser beam measured by the hollow needle diagnosis system can be used to calibrate the SAC method. It showed that the SAC has the capability of generating a clear and detailed energy profile of a laser and, therefore, of a stable electric arc.
2. Ground wire position has a significant influence on arc behaviour in the SAC. Centralised and even distances to the arc spatial section and the

ground wire location reduce the arc distortion during the interface traverse, and a more symmetrical profile can be generated.

3. Slight fluctuations of the measured profile were not due to instrument noise but caused by erratic movement of the arc root. This kind of erratic movement is likely caused by incomplete rigidity of the plasma body and is therefore unavoidable. Still, defects of the individual profiles can be mitigated by averaging the repeated measurement results.
4. The plasma column of the current profile is more concentrated and narrower than the temperature profile. And the temperature profile that was calibrated by the laser experiment is shown to reflect the energy absorption distribution of the arc directly. The absorption rate of the arc energy in this study is about 56%. A Gaussian model fits the measured profile well with a radius of about 7 mm.

3.1.5 Acknowledgement

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3.1.6 References

- [1] Weman, K. (2011). Welding processes handbook. Elsevier.

- [2] Haddad, G. N., & Farmer, A. J. D. (1984). Temperature determinations in a free-burning arc. I. Experimental techniques and results in argon. *Journal of Physics D: Applied Physics*, 17(6), 1189.
- [3] Murphy, A. B., & Farmer, A. J. D. (1992). Temperature measurement in thermal plasmas by Rayleigh scattering. *Journal of Physics D: Applied Physics*, 25(4), 634.
- [4] Farmer, A. J. D., & Haddad, G. N. (1988). Rayleigh scattering measurements in a free-burning argon arc. *Journal of Physics D: Applied Physics*, 21(3), 426.
- [5] Thornton, M. F. (1993). Spectroscopic determination of temperature distributions for a TIG arc. *Journal of Physics D: Applied Physics*, 26(9), 1432.
- [6] Richardson, I. M. (1991). Properties of the constricted gas tungsten (plasma) welding arc at elevated pressures (Doctoral dissertation, Cranfield Institute of Technology).
- [7] Gomes, A. M. (1983). Criteria for partial LTE in an argon thermal discharge at atmospheric pressure; validity of the spectroscopically measured electronic temperature. *Journal of Physics D: Applied Physics*, 16(3), 357.
- [8] Cram, L. E., Poladian, L., & Roumeliotis, G. (1988). Departures from equilibrium in a free-burning argon arc. *Journal of Physics D: Applied Physics*, 21(3), 418.
- [9] Olsen, H. N. (1963). The electric arc as a light source for quantitative spectroscopy. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 3(4), 305-333.

- [10]Bober, L., & Tankin, R. S. (1970). Investigation of equilibrium in an argon plasma. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 10(9), 991-1000.
- [11]Fanara, C., & Richardson, I. M. (2001). A Langmuir multi-probe system for the characterization of atmospheric pressure arc plasmas. *Journal of Physics D: Applied Physics*, 34(18), 2715.
- [12]Mott-Smith, H. M., & Langmuir, I. (1926). The theory of collectors in gaseous discharges. *Physical review*, 28(4), 727.
- [13]Nestor, O. H. (1962). Heat intensity and current density distributions at the anode of high current, inert gas arcs. *Journal of applied physics*, 33(5), 1638-1648.
- [14]Schoeck, P. A. (1963). An investigation of the anode energy balance of high intensity arcs in argon. *Modern developments in heat transfer*, 353-400.
- [15]Egerland, S., Colegrove, P., & Williams. (2017). Investigation of low current gas tungsten arc welding using split anode calorimetry. *Science and Technology of Welding and Joining*, 22(1), 71-78.
- [16]Vilarinho, L. O., & Fanara, C. . (2003). A modified split-anode detector for the study of the anode region of atmospheric pressure arc plasmas. *Measurement Science & Technology*, 15(15), 67.
- [17]Tsai, N. (1983). Heat distribution and weld bead geometry in arc welding (Doctoral dissertation, Massachusetts Institute of Technology).
- [18]Suder, W. J. (2011). Study of fundamental parameters in hybrid laser welding (Doctoral dissertation, Cranfield University).

- [19]Beyer, E., Herziger, G., & Loosen, P. (1986). A Diagnostic System For Measurement Of The Focused Beam Diameter Of High Power CO₂-Laser. High power lasers and their industrial applications, 650, 170-177.
- [20]Schwede, H., Märten, O., Kramer, R., Wolf, S., Brandl, V., & Hänsel, K. (2009). Characterizing high-power laser beams to detect the thermal load of optics and to identify limitations within the design of the optical system. Solid State Lasers XVIII: Technology and Devices, 7193, 71930E.
- [21]Schwede, H. (2010). Observe the Beam at the Center of Interest. Laser Technik Journal, 1(7), 44-47.
- [22]Kramer, R., Schwede, H., Brandl, V., Wolf, S., & Märten, O. (2005). Laser beam diagnostics according to ISO and their impact on practical application. Optical Design and Engineering II, 5962, 765-773.
- [23]ISO 11146 Test methods for laser beam width, divergence angles and beam propagation ratios, Beuth Verlag, Berlin, 2005
- [24]<https://www.primes.de/en/products/beam-distribution/focus-measurement/focusmonitor-fmplus.html>
- [25]Pearson, K. (1896). Mathematical Contributions to the Theory of Evolution. III. Regression, Heredity, and Panmixia. Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character, 187, 253–318.
- [26]Lancaster, J. F. (Ed.). (2013). The Physics of Welding: International Institute of Welding. Elsevier.
- [27]Smythe, W.B. (1988). Static and dynamic electricity. Hemisphere Publishing.

- [28] Evans, D. M., Huang, D., McClure, J. C., & Nunes, A. C. (1998). Arc efficiency of plasma arc welding. *Welding journal*, 77(2), 53-58.
- [29] DuPont, J. N., & Marder, A. R. (1995). Thermal efficiency of arc welding processes. *Welding Journal-Including Welding Research Supplement*, 74(12), 406s.
- [30] Fuerschbach, P. W., & Knorovsky, G. A. (1991). A study of melting efficiency in plasma arc and gas tungsten arc welding: a method for selecting optimal weld schedules to minimise net heat input is derived from calorimetric measurements. *Welding Journal*, 70(11), 287-297.
- [31] Haelsig, A., Kusch, M., & Mayer, P. (2012). New findings on the efficiency of gas shielded arc welding. *Welding in the World*, 56(11), 98-104.
- [32] DIN EN 1011-1: Welding – Recommendations for welding of metallic materials – Part 1: General guidance for arc welding; German version EN 1011-1:2009.
- [33] Norrish, J. (2006). *Advanced welding processes*. Elsevier .

3.2 Measurement of PTA with varying parameters

3.2.1 Experimental

Following the 130A PTA SAC measurement in Section 3.1, the influence of different parameters on the energy distribution of a PTA was studied. The modified SAC configuration, as demonstrated in Section 3.1, is used for this part of the study. PTAs with different current intensities, plasma gas composition (PGC) and plasma gas flow rate (PGFR) were measured. Three current intensity levels, 110A, 130 A and 150A, were tested. Three types of shielding gas were used to provide different PGCs: Pureshield argon gas was used as pure argon, Alushield Light and Alushield Universal welding gas were used as argon/helium composited gas with helium compositions of respectively 30% and 50%. Two PGFRs, 0.2L/min and 0.8 L/min, were tested. Table 3-3 and Table 3-4 list the parameters of the measurements. The size of the PTA can be calculated by the D86 definition. According to the D86 definition, the energy spot size is determined by the area containing 86% of the total energy, as shown in Figure 3-16 [1].

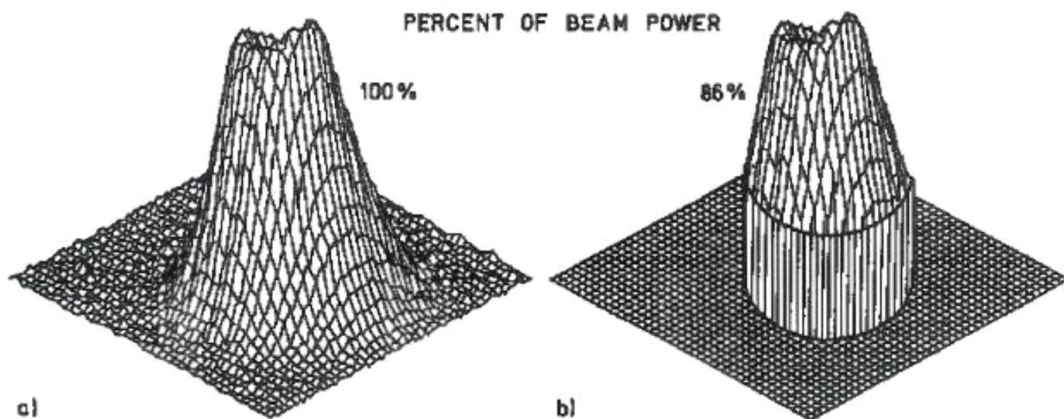


Figure 3-16 Profile diameter according to D86 definition [1].

Table 3-3 Fixed parameters for the PTA measurement.

Shielding gas / L/min	15
Distance between the torch and the anodes / mm	8
Orifice size / mm	3.9

Electrode diameter / mm	4
Electrode Tip Angle / degree	40
Electrode Tip Set-back / mm	2.4

Table 3-4 Altered parameters for the PTA measurement.

Current / A	Plasma gas / L/min	PGC
110	0.8	Pure Ar
130		
150		
130	0.2	70% Ar + 30% He
	0.8	
		50% Ar +50% He

3.2.2 Results and discussion

3.2.2.1 Current intensity

Figure 3-17 shows averaged energy distribution results with three different current intensities generated from the current and the temperature data. It can be seen from both types of energy distribution that the peak energy intensity increased with a higher current intensity. Table 3-5 shows the corresponding voltage levels measured with these three current intensities. Arc efficiency was calculated by dividing the received energy calculated from the temperature data by the total energy calculated from the current data and is shown in Table 3-5. It shows that arc efficiency did not change significantly with current intensity.

The shape of the energy profile became more symmetric with a higher current intensity. With the current intensity of 110 A, both the temperature and the current energy profile show an irregular top shape. The energy peak deviates from the centre of the arc and presents in a ramp shape. As the current intensity increases, the energy peak gradually moves to the arc centre, and the top shape turns from a ramp shape to a symmetric cone shape. It might be because the stiffness of the plasma column was enhanced with a higher current intensity and voltage, and the arc distortion was eased. The area of the energy profile expended, and the dimension of the arc slightly increased. Figure 3-18 shows the diagram of the

correlation between the current and the PTA D86 spot size. The diameter of both the current and temperature profiles increase with increasing current intensity, and the increase of the temperature profile diameter is less significant.

The energy efficiencies with varying current intensity were calculated and compared in Table 3-5. The energy efficiency shows no significant correlation with current intensity, and the slight deviation might be due to the inconsistency of the arc conditions.

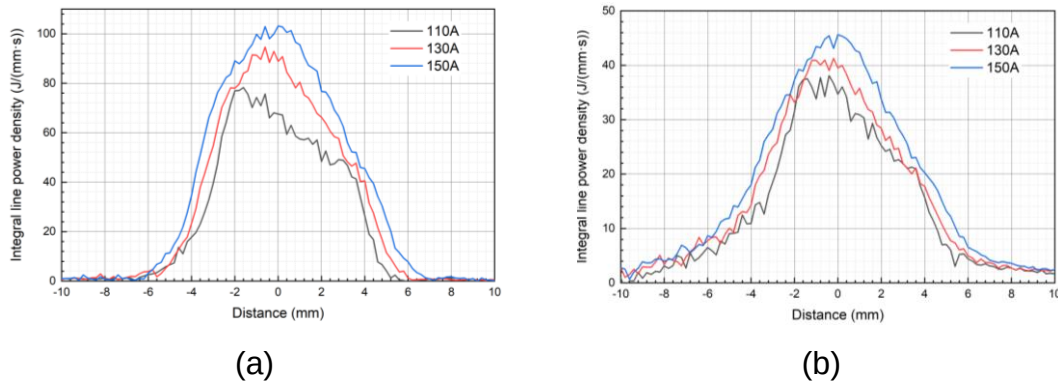


Figure 3-17 Results of the PTA measurement with varying current intensity: (a) current profiles, and (b) temperature profiles.

Table 3-5 The voltage level and energy efficiency with varying current intensity.

Current / A	Voltage / V	Energy efficiency
110	21.5	53%
130	23.5	56%
150	25.0	53%

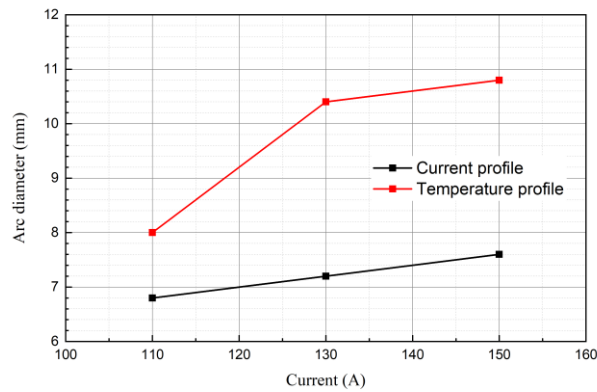
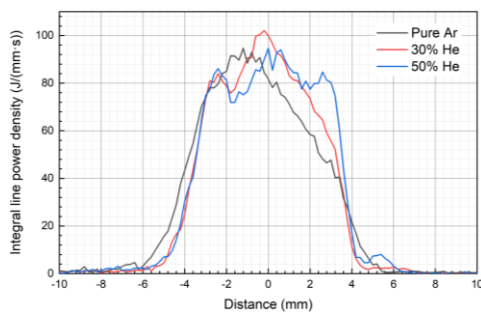


Figure 3-18 Correlation between current and arc diameter.

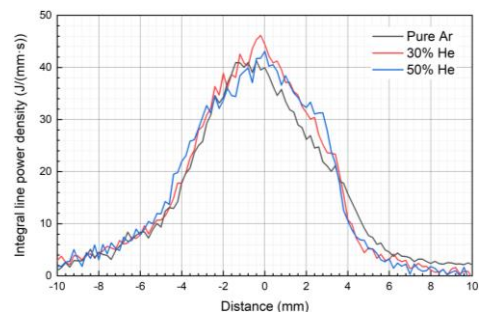
3.2.2.2 PGC

Figure 3-19 shows averaged energy distribution results with three different types of PGC generated from respectively the current and the temperature data. The shape of the current energy profile changes from a cone shape to a top-hat shape, whereas the diameter of the arc is barely changed. Contrary to the current profiles, the temperature profiles do not show essential differences when using different PGCs. The D86 arc diameter slightly reduced with an increasing He percentage, indicating that He can contribute to a more concentrated plasma body. In this study, the mechanism of the He percentage on the energy distribution of the PTA was not further studied, and future investigation can be carried out.

Table 3-6 lists the corresponding voltage level and energy efficiency with different PGCs. The voltage and the energy efficiency did not significantly change when the percentage of the helium increased.



(a)



(b)

Figure 3-19 Results of the PTA measurement with different PGC: (a) current profiles, and (b) temperature profiles.

Table 3-6 The voltage level and energy efficiency with varying PGC.

PGC	Voltage / V	Energy efficiency
Pure Ar	23.5	56%
30% He	23.2	57%
50% He	23.8	56%

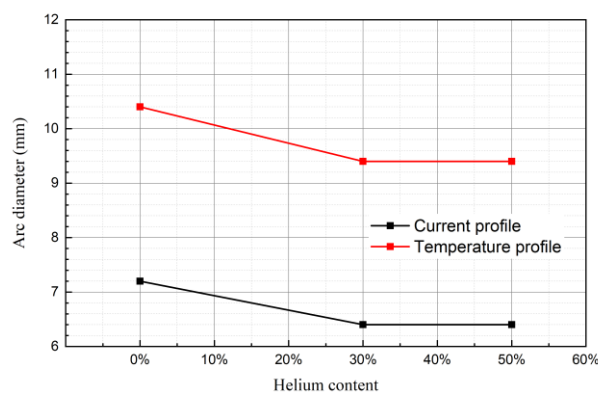


Figure 3-20 Correlation between PGC and arc diameter.

3.2.2.3 PGFR

Figure 3-21 shows the averaged energy distribution results with two different PGFRs generated from respectively the current and temperature data. In the w-DED process, a lower PGFR was usually selected to avoid keyhole. In this part of the measurement, two lower PGFRs are compared to see how they affected the energy distribution of the PTA. Table 3-7 lists the corresponding voltage level with different PGFRs. When increasing the PGFR from 0.2 L/min to 0.8 L/min, the voltage increased from 22.5 V to 23.5 V. The energy efficiency did not change with the PGFR. From both the current and the temperature energy profiles, the increase of the total energy was reflected on the top of the profile. The top of both the energy profiles is raised up, indicating that only the energy at the centre region is increased, and the outer region is not affected. The D86 diameter of the arc reduces with an increasing PGFR because more energy is concentrated at the

centre. The D86 diameters of both the current and temperature profiles increase with a higher PGFR because less energy is concentrated in the centre region.

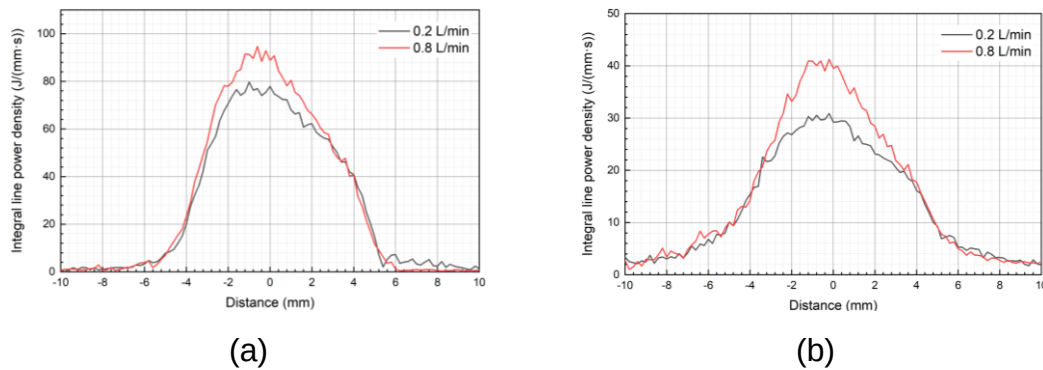


Figure 3-21 Results of the PTA measurement with different PGFR: (a) current profiles, and (b) temperature profiles.

Table 3-7 The voltage level and energy efficiency with varying PGFR.

PGFR	Voltage / V	Energy efficiency
0.2 L/min	22.5	55%
0.8 L/min	23.5	56%

3.2.3 Conclusion

1. Within the range of 110 A to 150 A, a higher current intensity would lead to a larger D86 arc diameter and a higher total energy amount.
2. The shape of the PTA current profile changed from a cone shape to a top-hat shape when the He content of the PGC increased from 0% to 50%, while the total energy remained unchanged.
3. The energy amount at the centre of the arc increased when the PGFR increased from 0.2 L/min to 0.8 L/min.
4. In this study, the energy efficiency of the PTAs did not significantly change with the varying parameters.

3.2.4 Reference

- [1] Suder, W. J. (2011). Study of fundamental parameters in hybrid laser welding (Doctoral dissertation, Cranfield University).

4 Theoretical and Experimental Dynamic Thermal Characterisation of a Scanning Laser

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ABSTRACT

The thermal dynamics characterisation of a scanning laser (SL) was studied using both experimental and numerical approaches. SL experiments were conducted with different oscillation frequencies and laser beam sizes. An innovative solution dependent convection boundary (SDCB) method was introduced to reduce the element amount of the finite element (FE) model by simulating the thermal conduction of the adjacent material around the bead region. An equivalent bar-shaped heat source was introduced as a simplified substitution of the quasi-steady-state SL transient heat source. Results showed that the oscillation frequency could significantly affect the SL interaction mode, especially with a smaller beam size. Both keyhole mode and transition mode generate unstable melt pools. SL process with a conduction mode could benefit good energy efficiency and a stable melt pool. Conduction mode interaction was easier to be achieved with a larger beam size. Both the experimental and numerical results show that the melt pool shape reached a quasi-steady state when the oscillation frequency reached 13.6 Hz and higher, and the equivalent heat source model can be used to replace the SL transient energy source model. 86% of the computing time was reduced by applying the SDCB method.

Keywords: Scanning laser; Solution dependent Convection boundary; FE; Laser welding

4.1 Introduction

Additive manufacturing (AM) has developed rapidly in the last few decades and shows excellent advantages over traditional manufacturing methods. Bead shape control and geometry accuracy are essential for the metal AM process. The feasibility of applying hybrid processes to the metal AM process has also been studied in recent decades to overcome the limitation of conventional single energy source AM and improve the bead shape control and geometry accuracy. Qian et al. [1] developed a PTA-laser hybrid technology to improve the accuracy and metallurgical performance of the deposition. Liang et al. [2] proposed a GTA-CMT hybrid welding process. Bead shape was achieved with decreased contact angle and better dilution. Zhang et al. [3] used a low-power pulsed laser-assisted MIG arc welding (L-M) for metal AM and studied how laser affected layer width and height. They reported that the L-M AM method showed the potential to fabricate thin-wall components with better surface quality, higher stability, and higher deposition efficiency. Li et al. [4] investigated the single bead and intersections deposited by a laser-CMT hybrid AM method. The validation experiment showed that the optimised parameters significantly improved the geometry quality of the bead. Previous research using hybrid processes was mostly focused on improving the process stability and bead geometry. However, the bead shape control capability is restricted by the lack of manipulability of the energy distribution of the hybrid energy source. Wang et al. [5] developed a wire-based PTA-laser hybrid AM method for large-scale components. In this system, two laser beams were added at two sides of a PTA. Compared to the conventional hybrid AM process, the energy distribution of the PTA-laser hybrid process can be manipulated by changing the laser positions and power arrangement. The bead shape control using the PTA-laser hybrid was also investigated. The results showed that the bead width could be controlled by the laser power and travel speed. This method increased the deposition rate with a higher process tolerance. It also achieved independent control of the bead shape and the deposition rate. However, current hybrid AM processes were conducted by combining multiple conventional energy sources. The bead shape control

capability was restricted by the fixed energy distribution of each individual energy source. An innovative energy source whose energy profile can be precisely designed and dynamically changed is needed to achieve full control of bead shape for the hybrid AM process.

Scanning laser (SL) has been utilised in many processes such as welding, marking, cladding, and cutting [6-11]. In welding applications, many advantages of using a scanning laser have been identified. For example, by oscillating the laser beam at a high frequency with a given amplitude, the welding zone can be significantly enlarged, providing greater tolerance for edge preparation. Rubben et al. [6] first developed a scanning laser (SL) welding method to improve the gap tolerance and welding quality. In his work, a laser beam with a beam size of about 0.1 mm was used, oscillating across the weld while advancing with a maximum frequency of 200 Hz. Since then, SL has been widely used in welding applications. For example, Choi et al. [7] applied a low-frequency scanning laser for welding 6K21 Al alloy and found that the solidification crack sensitivity was minimised at an oscillation frequency of 5 Hz. Schedewy et al. [8] studied the quasi-steady-state of the 200µm and 250µm beam size SL processes for the welding of slot-tab joints and found that the overlapping of adjacent beam paths should be closely controlled. Other studies have also been conducted on using a SL with a larger beam size, which can be used for applications that require a thinner and broader melt pool, e.g., cladding and coating. Cheng et al. [9] used a SL with 1000-1300 W of power and 2 mm beam size to melt NiTi wire and coated on AISI 316 stainless steel to obtain a clad track. The scanning speed was between 8 to 25 mm/s. Cui et al. [10] studied the deposition of Co-based power feeding cladding on tool steel using a SL with a beam diameter of 4 mm, power of 1.7 kW and scanning speed of 5 mm/s. Jiao et al. [11] deposited a layer of T15M high-speed steel alloy powder on the Q235 substrate surface using a SL with a beam diameter of 3 mm and power of 600 W. These studies showed that a broad and thin melt pool of a larger beam size SL can benefit in the coating and cladding applications. Hypothetically, a broad and thin melt pool could also contribute to the AM process. More importantly, the shape and energy profile of the SL can be designed and changed once the melt pool reaches a quasi-steady state.

Therefore, SL has the potential to be applied in the hybrid AM process as a bead shape control energy source. However, limited research has focused on the dynamic thermal characteristics and the quasi-steady state of a SL, which is essential to verify the possibility of using a quasi-steady-state SL as an equivalent stationary energy source.

Finite element modelling (FEM) has been widely used for studying the thermal behaviour of the welding processes [12-14]. However, transient FEM simulation of the welding process has proved to be rather time-consuming [14]. The mesh density of the welding region, which is the domain of interest, needs to be high enough to depict the heat source with rapid thermal change and high thermal gradients. The graded meshing strategy, which uses larger elements in areas farther from the welding area, is commonly used to reduce the number of elements [15]. It is difficult to mesh complicated structures with graded brick elements. Pyramid or wedge elements are usually used. However, they have a negative effect on computational efficiency and convergence [16]. The self-adaptive mesh refinement technique was developed in the 1970s [17] and has been used in FEM simulations [18]. This method allows the mesh grid to be recalculated during the solving process to adapt to changes in the results, thereby reducing the number of elements. Mesh grid generation technique has also been investigated to boost the computing speed by optimising the mesh quality [19], [20]. However, the adaptive mesh refinement technique involves recalculating the mesh grid after each step, which increases the running time of the simulation. Therefore, despite the significant improvement in the element amount, the mesh refinement itself can be time-consuming. Ding et al. [14] introduced a steady-state method to overcome the problem of the long processing time during wire plus arc additive manufacturing (WAAM). Unlike the conventional transient method that uses a time increment scheme to model the moving welding torch, the steady-state method attaches an Eulerian reference frame to the welding torch with the material “flowing” through the mesh. The whole process can be solved using only one single time step. The limitation is that this method can only be utilised for quasi-steady-state processes, such as the single direction WAAM process on a large plate.

This study studied the dynamic thermal characterisation of a SL using both experimental and numerical approaches. SL experiments were conducted to investigate the melt pool dynamics with different oscillation frequencies and laser beam sizes. Thermal images and highspped images were captured to analyse the thermal dynamics of the SL melt pool. A solution dependent convection boundary (SDCB) method was introduced to improve the computing efficiency of the SL simulation. The SDCB method used convection interfaces to replace the thermal conduction of the substrate and reduced the element amount of the transient SL model. A full-scale model was calibrated using the experimental thermal histories. The results of the SDCB partial model were compared to the full-scale model. The interaction mode with varying oscillation frequency and laser beam size was analysed, and the quasi-steady state of the SL melt pool was studied.

4.2 Methodology

4.2.1 SL experiment setup

Figure 4-1a shows the experimental setup of the SL process. A JK 3000FL 3 kW continuous-wave fibre laser (wavelength 1.08 μm) was redirected by a Raylase SUPERSCAN-III galvanometer-based scanner (GS) head and projected vertically onto the substrate. The focus distance of the GS was 620 mm, and the minimum focused laser beam size was 0.3 mm. During the SL experiment, the laser beam was defocused by moving the substrate closer to the GS. Three distances between the substrate and the GS and the corresponding beam sizes were used, as listed in Table 4-1. The laser power was measured by a LASERPOINT W-12K-D55-SHC-U laser calorimeter.

Table 4-1 Defocused laser beam sizes

Distance between the GS and the substrate / (mm)	Laser beam size / (mm)
595	1
565	2

510	4
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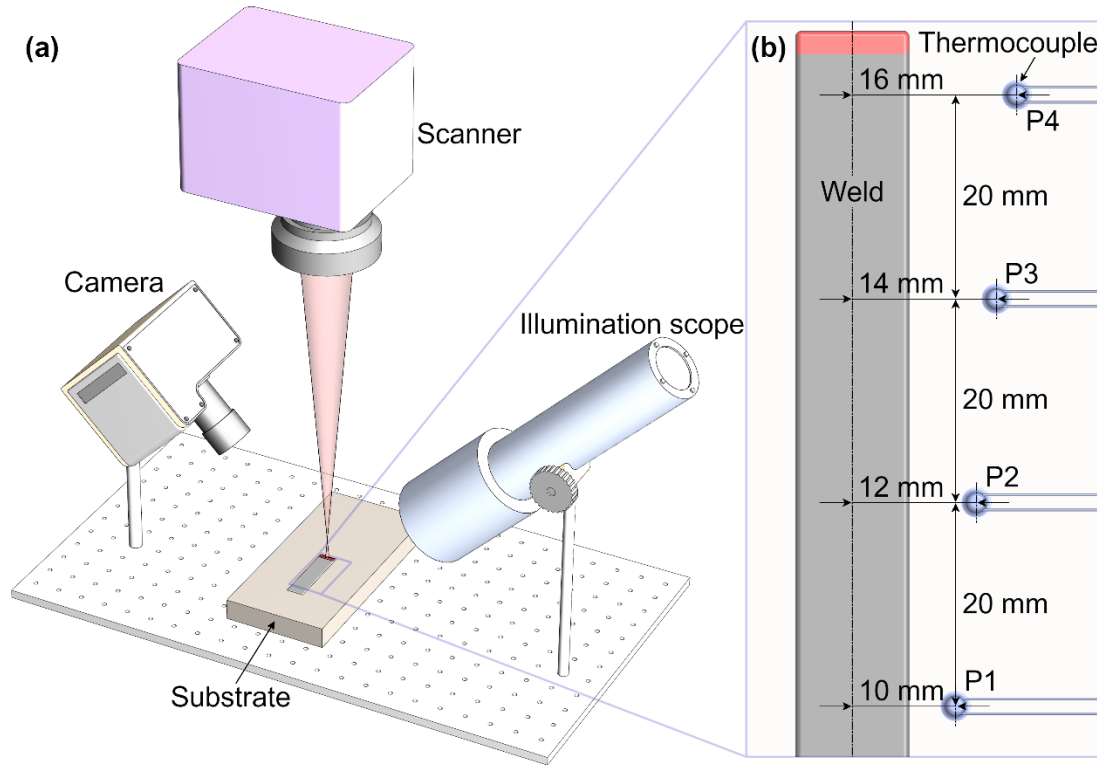


Figure 4-1 (a) Configuration of the SL experiment, and (b) positions of the thermocouples.

A Phantom MIRO 4M highspeed camera was set on the side of the substrate to capture highspeed images of the melt pool dynamics with a recording frame rate of 8100 frames per second. The substrate was illuminated by a green light-emitting diode (LED) illumination system to enhance the image quality and reduce glare caused by the laser beam. The reflected laser was filtered by a filter mounted in the front of the highspeed camera lens, allowing only the green light to pass through. A FLIR A325 thermal camera was used with a FOL18 IR lens to capture the thermal image of the substrate and melt pool during the process. The surface of the substrate was cleaned with acetone and coated with graphite spray, which improves the absorption efficiency of the laser energy and makes it more

uniform. Also, graphite coating can reduce the reflection of the substrate surface and benefits the capturing of the thermal images with better thermal accuracy and higher image quality [21].

The scanning pattern of the GS was edited and controlled by the SCAPS SAMLight scanner application software installed on a controlling personal computer. A saw-wave oscillation pattern was applied, as illustrated in Figure 4-2a. The scanning width (w_s) was defined by the crosswise moving distance of the laser beam centre and was set to 10mm. d_s is the increment of the scanning pattern.

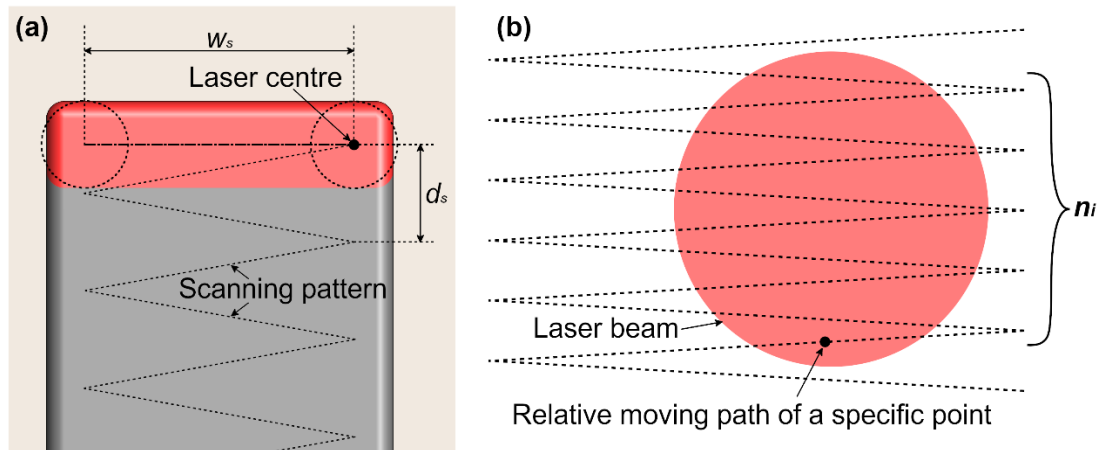


Figure 4-2 (a) Laser scanning pattern, and (b) number of interactions during scanning.

The scanning frequency F_s was determined by the scanning speed v_s and the scanning width of the SL w_s , as shown in Equation 4-1. The increment of the scanning pattern d_s is determined by the scanning frequency F_s and the advancing speed v_a , as shown in Equation 4-2.

$$F_s = \frac{v_s}{2w_s} \quad (4-1)$$

$$d_s = \frac{v_a}{F_s} \quad (4-2)$$

The oscillation frequency F_s ranged from 1.7 to 54.4 Hz, and correspondingly d_s ranged from 2 mm to 0.0625 mm. The advancing speed of the SL was 3.4 mm/s. In a laser process, the period that a certain point is irradiated can be defined as the interaction time. The energy delivered to this particular point denoted as the specific point energy E_{sp} , is proportional to the product of power density q_p , interaction time t_i and the area of the specific point A_{sp} , which also corresponds to the product of the absorbed laser power P_L and interaction time of each interaction t_i . For an SL process, a particular point might interact with the laser beam more than once. Figure 4-2b illustrates the relative movement of a specific point on the substrate that passes across the laser beam section during scanning. The number of interactions n_i is defined as how many times the laser beam passes the specific point. The number of interactions n_i is determined by the laser beam size D_L and the increment of the scanning pattern d_s , as shown in Equation 4-3, and the total specific point energy can be calculated by Equation 4-4:

$$n_i = \frac{D_L}{d_s} \quad (4-3)$$

$$E_{sp} = \sum_{1}^{n_i} q_p A_{sp} t_i = \sum_{1}^{n_i} P_L t_i \quad (4-4)$$

A calibration experiment was designed to provide temperature histories as reference data to calibrate the full-scale FE model. S275 mild steel plates with dimensions of 200 mm × 200 mm × 25 mm were used as substrates. Four K-Type thermocouples were attached to measure the thermal histories at four positions with different distances to the centre of the bead, as indicated in Figure 4-1b. A 4 mm laser beam size was selected, and a lower laser power of 1.45 kW was used to avoid the damage of the thermocouples, and a lower oscillation frequency of 1.7 Hz was used to allow a longer response time for the thermocouples to capture the fluctuation of the temperature.

5 different oscillation frequencies and 3 laser beam sizes were further tested. The parameters are listed in Table 4-2. A higher laser power of 2.7 kW was applied to provide sufficient energy amount for different interaction modes. Cross-section images of the SL bead were obtained to analyse the bead geometries and the penetration. A volume indicator $V_{indicator}$ was introduced to evaluate the volume of the melt pool:

$$V_{indicator} = A_{surface}A_{cross-section} \quad (4-5)$$

where $A_{surface}$ is the top surface area of the melt pool, and $A_{cross-section}$ is the cross-section area of the melt pool.

Table 4-2 Parameters for the quasi-steady-state SL experiment

Power / (W)	Laser beam size / (mm)	Oscillation frequency / (Hz)
2700	4	1.7
		3.4
		6.8
		13.6

		27.2
		54.4
	2	1.7
		3.4
		6.8
		13.6
		27.2
		54.4
	1	1.7
		3.4
		6.8
		13.6
		27.2
		54.4

4.2.2 SL simulation

4.2.2.1 Solution dependent convection boundary (SDCB) method

Convection is the heat transfer due to the bulk motion of the medium fluids (air, water, etc.), while thermal conduction represents the heat transfer within solid material [22]. The convection and the thermal conduction in the FEM are computed using the following equations:

$$Q_{cv} = hA(T_b - T_f)C\rho \quad (4-6)$$

$$Q_{cd} = \frac{\lambda}{L}A(T_1 - T_2)C\rho \quad (4-7)$$

In Equation 4-6, Q_{cv} represents the energy that transfers at the convection boundary, h is the convection efficiency that determines by the type and condition of the fluid flow, A is the area of the boundary, T_b is the node temperature at the

boundary as part of the node result, T_f is the bulk temperature of the fluid flow, C is the specific heat capacity of the material, and ρ is the density. In Equation 4-7, Q_{cd} represents the energy that transfers during the thermal conduction, λ is the thermal conductivity of the substrate material, L is the length of the computed element along the conducting direction, T_1 and T_2 are the temperature of the computed node and the adjacent node. We can see that in the FEM analysis, thermal conduction and convection are similar. The concept of the solution dependent convection boundary is to replace the thermal conduction of the adjacent material with a convection interface. In this way, a significant amount of material can be removed, and the element number can be reduced.

However, thermal conduction and convection are not exactly the same. Figure 4-3 illustrates the difference between thermal conduction and convection in the FEM simulation. In the convection simulation, the fluid flow temperature T_f is set as a constant in the pre-processing. In the thermal conduction simulation, however, the temperature of the adjacent node T_2 is part of the result variables and keeps changing over time. When heated by the energy source, an increased T_2 would slow down the thermal conduction, while the convection would not be affected due to the constant T_f . When replacing the adjacent material with a convection interface, T_f needs to be adjusted during the calculation to simulate the changing of the T_2 . A flow chart that explains the SDCB subroutine during the calculation is shown in Figure 4-3c.

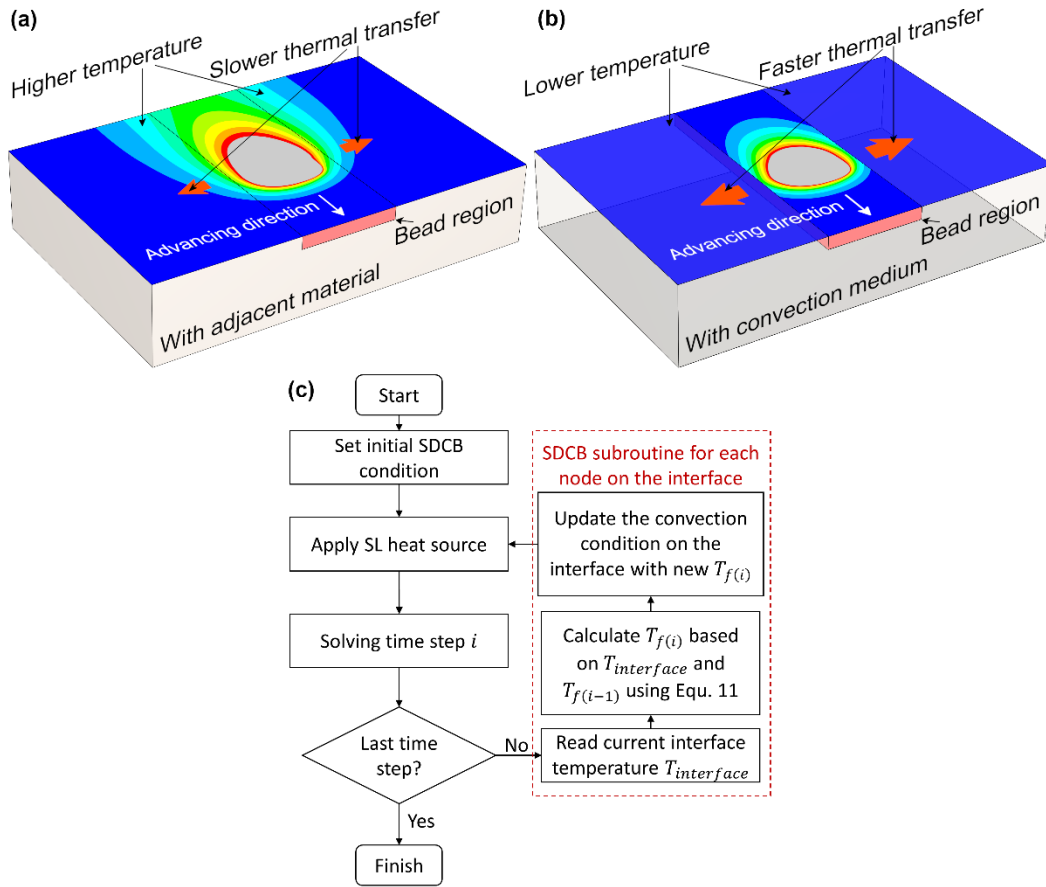


Figure 4-3 The difference between thermal conduction and convection: (a) thermal conduction, (b) convection, and (c) is the flow chart that illustrates the SDCB subroutine during the calculation.

In the SDCB method, the T_f was adjusted during the calculation to simulate the temperature change of the adjacent material when replacing the adjacent material with a convection interface. A solution dependent iterated function was introduced to recalculate T_f after each step. Equation 4-8 shows the principle of how the thermal energy of the adjacent material was simulated:

$$Q_{ad(i)} = Q_{input} + a_{preserve}^{dt} Q_{ad(i-1)} \quad (4-8)$$

In this equation, $Q_{ad(i)}$ and $Q_{ad(i-1)}$ represent the thermal energy that the adjacent material at the current step and the previous step, Q_{input} represents the

energy transferred from the bead region to the adjacent material, dt is the time increment of the timestep, and an energy preserving coefficient $a_{preserve}$ is set to determine how fast the thermal energy of the adjacent material decreases as an exponential function of time. Equations 4-9 and 4-10 further show the calculation of the $Q_{ad(i)}$ and Q_{input} :

$$Q_{ad(i)} = T_{f(i)} C \rho \quad (4-9)$$

$$Q_{input} = a_{input} dt (T_{interface} - T_{f(i-1)}) C \rho \quad (4-10)$$

here, $T_{f(i)}$ and $T_{f(i-1)}$ represent the temperature of the adjacent material at the current time step and the previous step, $T_{interface}$ is the temperature at the SDCB interface of the previous step, a_{input} is introduced as the energy input efficiency to determine how much additional thermal energy is transferred from the bead region to the adjacent material per unit time based on the thermal gradient. Compared to the change of the thermal difference at the interface, the specific heat capacity and the density did change much by the temperature. Assuming that the specific heat capacity and density are constant, a solution dependent iterated function for the T_f was obtained by combining Equations 4-8, 4-9 and 4-10:

$$T_{f(i)} = a_{input} dt (T_b - T_{f(i-1)}) + a_{preserve}^{dt} T_{f(i-1)} \quad (4-11)$$

It is noteworthy that this iterated function worked as an empirical model to simulate the change of the adjacent material temperature during the conduction. The input energy coefficient a_{input} and the energy loss coefficient $a_{preserve}$ need to be calibrated.

4.2.2.2 Full-scale model and SDCB partial model.

A sensitive study on the dimension of the full-scale model was conducted before the SL numerical study by changing the width and thickness of the model. The dimensions of the tested models are listed in Table 4-3. Six widths with a constant thickness of 25 mm and three thicknesses with a constant width of 132 mm were computed. The experimental parameters used for the sensitive study were the same as the calibration experiment.

Table 4-3 Dimensions of the models for the scale sensitive study

Varied width	Varied thickness
207 mm × 60 mm × 25mm	132 mm × 60 mm × 25 mm
182 mm × 60 mm × 25mm	132 mm × 60 mm × 20 mm
157 mm × 60 mm × 25mm	132 mm × 60 mm × 15 mm
132 mm × 60 mm × 25mm	
107 mm × 60 mm × 25mm	
82 mm × 60 mm × 25mm	

Based on the sensitive study results, a full-scale model with a dimension of 132 mm × 60 mm × 25 mm was built as the reference case for the simulation study, as shown in Figure 4-4. The bead region was set to 17 mm × 60 mm × 4 mm and was meshed with an element size of 0.5 mm, which is 1/8 of the laser beam radius, to provide a high resolution for the SL dynamic thermal field. The rest of the substrate was meshed with a grid size of 2 mm. Overall, 124448 elements were

generated.

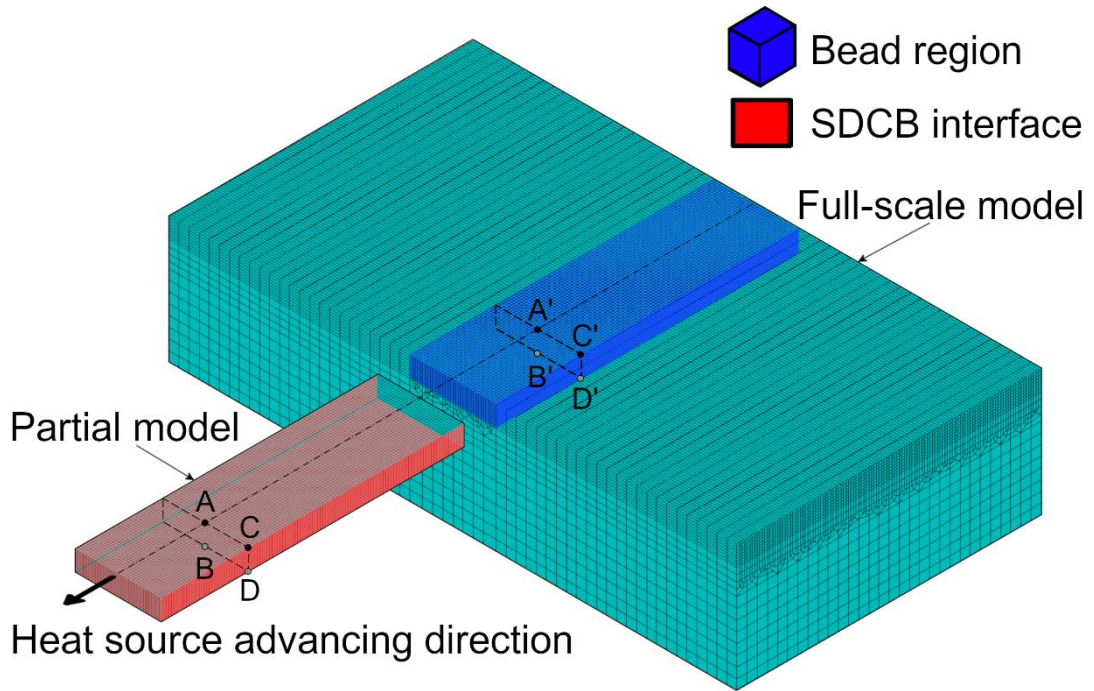


Figure 4-4. Meshed grid of the full-scale model and the partial model.

A partial model was built with only the bead region with a dimension of 17 mm × 60 mm × 4 mm (Figure 4-4). Element size was set to 0.5 mm, which is the same as the bead region in the full-scale model, and 32640 elements were generated. The top, front and rear surfaces were also applied with a constant convection efficiency of $5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for the ambient air cooling. The side surfaces and the bottom surface were applied with the SDCB interfaces. Another regular convection boundary (RCB) partial model was tested by replacing the SDCB interfaces with regular convection boundary conditions that have a constant bulk temperature T_f . The two partial models were calibrated by fitting the thermal histories with the full-scale model results at four positions, as indicated in Figure

4-4. An oscillation frequency of 1.7 Hz was used for the calibration of the RCB and the SDCB partial models.

A Gaussian energy source model was used as the laser beam energy source. The distribution of this Gaussian energy source model is shown below:

$$Q(x, y) = \frac{3\eta Q_{total}}{\pi r^2} \exp[-3(x^2 + y^2)/r^2] \quad (4-12)$$

where Q represents the energy density of the arc on a plane surface, Q_{total} represents the total laser power, x and y are the relative coordinates to the centre of the arc, r is a parameter that determines the radius of the energy source and was set to 2 mm, η is the laser energy absorption rate on the substrate. The absorption rate was calibrated by the experimental results.

When this Gaussian energy source is oscillation with an infinitely high frequency, we can consider that the energy of the heat source is evenly distributed on the amplitude direction and become a bar-shaped Gaussian distribution. Equation 4-13 shows the equivalent steady-state heat source of the SL. The energy at a specific position is integrated as the laser beam goes across the scanning amplitude. The energy distribution of the equivalent heat source model can be calculated as below:

$$Q_{equivalent}(x, y) = \int_{-W/2}^{W/2} \frac{3Q_{total}}{\pi r^2} \exp\left\{-\frac{3[(x - x')^2 + y^2]}{r^2}\right\} / W dx' \quad (4-13)$$

$$W = w_s + 2r \quad (4-14)$$

where $Q_{equivalent}$ is the bar-shaped equivalent heat source distribution, W is the overall width of the equivalent energy source, and w_s is the scanning width. The

converting of a scanning laser beam profile to an equivalent bar-shaped heat source profile by Equation 4-13 is illustrated in Figure 4-5.

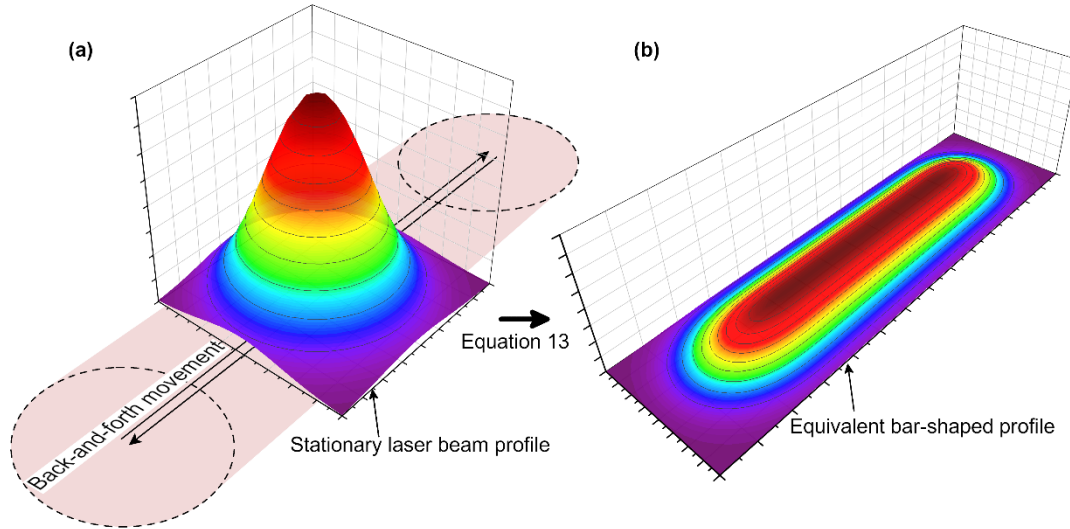


Figure 4-5. Illustrative diagram of converting a scanning laser beam profile to an equivalent bar-shaped heat source profile: (a) a stationary laser beam profile and its moving pattern, and (b) converted equivalent heat source profile.

A personal computer (PC), equipped with a quad-core Intel Core i7-6700HQ processor with a base frequency of 2.6 GHz and 64.0 GB random access memory (RAM) was used to run the calculations. The computational time of different models was summarised.

4.3 Results and discussions

4.3.1 SL melt pool dynamics study

Figure 4-6a shows the thermal images from the 4 mm SL experiment with different oscillation frequencies. When the steel was melted, the reflectance of the surface raised dramatically, and the emissivity dropped rapidly. As a result, the melting pool in the thermal images was detected as a dark area surrounded

by the highlighted contour [21]. The shapes of the melt pool are oval with a lower oscillation frequency of 1.7 Hz. As the oscillation frequency increases, the melt pool shape changes to a symmetric triangle with rounded corners. The dynamic changing of the melt pool shape is gradually eased and turns into a constant shape when the oscillation frequency increases to 13.6 Hz and higher.

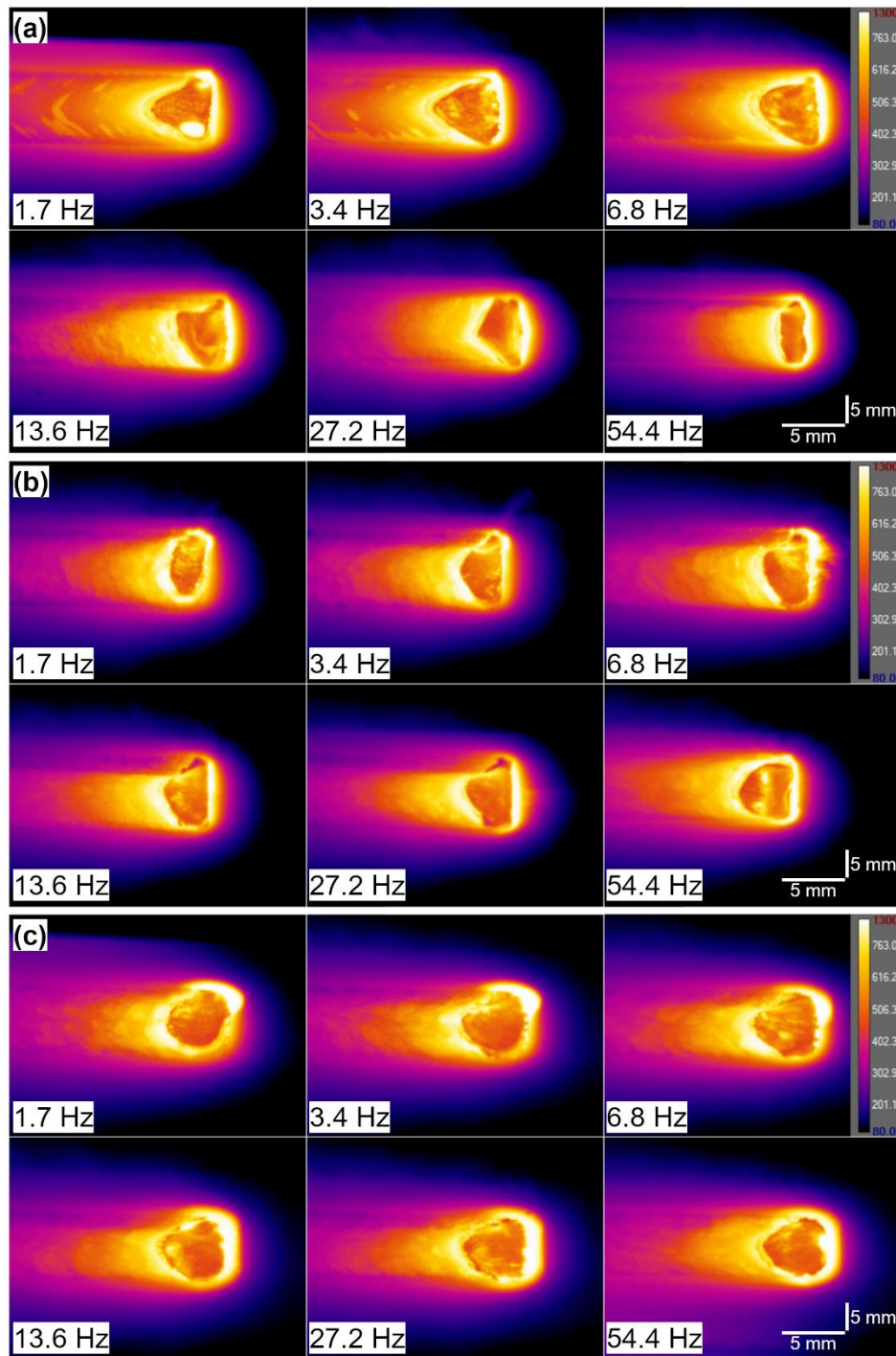


Figure 4-6. Thermal images of the SL melt pools with different oscillation frequencies: (a) 1 mm beam size SL, (b) 2 mm beam size SL, and (c) 4 mm beam size SL.

Figure 4-6b shows the thermal images of the melt pool with 2 mm beam size SL. Overall, the top surfaces of the 2 mm beam size SL melt pools are smaller than the 4 mm beam size SL melt pools, and slightly increase with an increased oscillation frequency and become stable with an oscillation frequency of 3.4 Hz and higher.

Figure 4-6c shows the thermal images of the SL melt pool with a laser beam size of 1 mm. The melt pool dynamic of the 1 mm beam size SL further deviates from the 4 mm and 2 mm SL. The top surface of the 1 mm beam size SL decreases dramatically with an increased oscillation frequency and changes from a sharp triangle shape to a bar shape, which is significantly different to the 4mm and 2 mm beam size SL.

In the research of Assuncao et al. [23], a transition mode of the laser welding process was demonstrated between the keyhole mode and the conduction mode. They reported that the switch between conduction mode and keyhole mode was not a sharp effect but with a transition mode between these two modes. This transition mode is caused by a region where the pressure generated by vaporisation is too low to overcome the surface tension and form a significant keyhole. When increasing the energy input during this mode, most of the extra energy is used in vaporising more material until a significant keyhole is formed and the overall absorption rises. The laser is also absorbed or redirected by the evaporation plume before it hits the substrate surface. Hence, the energy delivered to the substrate in the transition mode is reduced compared to the conduction mode. The reduction in energy efficiency was also reported in the study of Matthews et al. [24]. Figure 4-7 shows the results from Matthews's work.

Both the absorptivities of the tungsten and aluminium discs show a slight decrease during the transition mode and increase rapidly when the recoil pressure starts to form a keyhole, and multiple reflections occur in the keyhole depression.

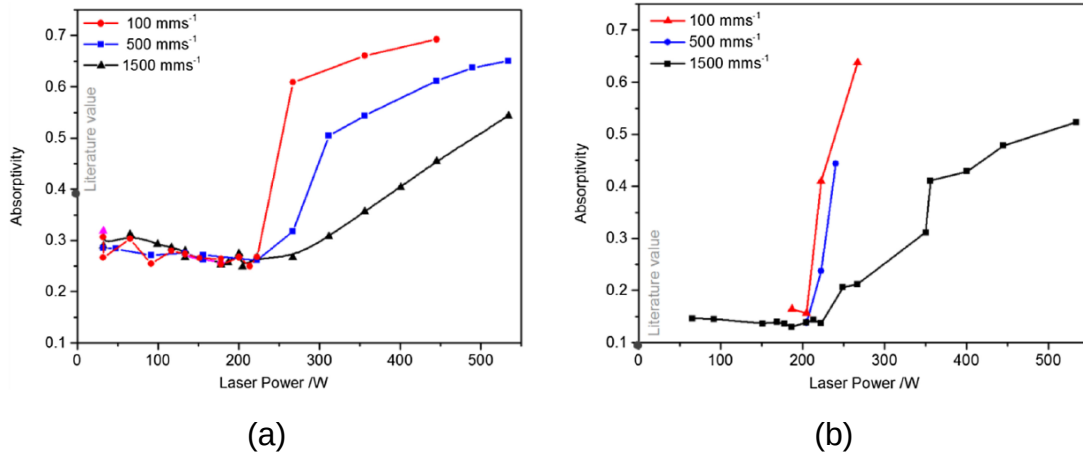


Figure 4-7. Effective absorptivity as a function of laser power for scan speeds 100, 500, and 1500 mm/s: (a) tungsten discs, and (b) aluminium discs. [24]

Figure 4-8a shows the cross-sections with a 1 mm beam size SL. Two sharp corners are observed at the bottom edges of the melt pool with a low oscillation frequency of 1.7 Hz. These sharp corners might be caused by the transverse moving of a keyhole, indicating that a keyhole was formed. As the oscillation frequency F_s increased, the interaction time t_i was reduced with an increased number of interactions n_i . The thermal history of the irradiated surface became evenner with lower peak temperatures. Therefore, the interaction mode switched from keyhole mode to transition mode, leading to a dropping in melting efficiency. The sharp edges of the melt pool cross-section become blunt and eventually disappear, and the penetration depth is significantly shallower. Figure 4-9a shows the highspeed image captured during the 1 mm laser scanning with a 54.4 Hz

oscillation frequency. Vaporised fume ejected from the laser spot with intense fluctuation of the liquid surface and splatter, indicating an unstable melt pool condition during the process.

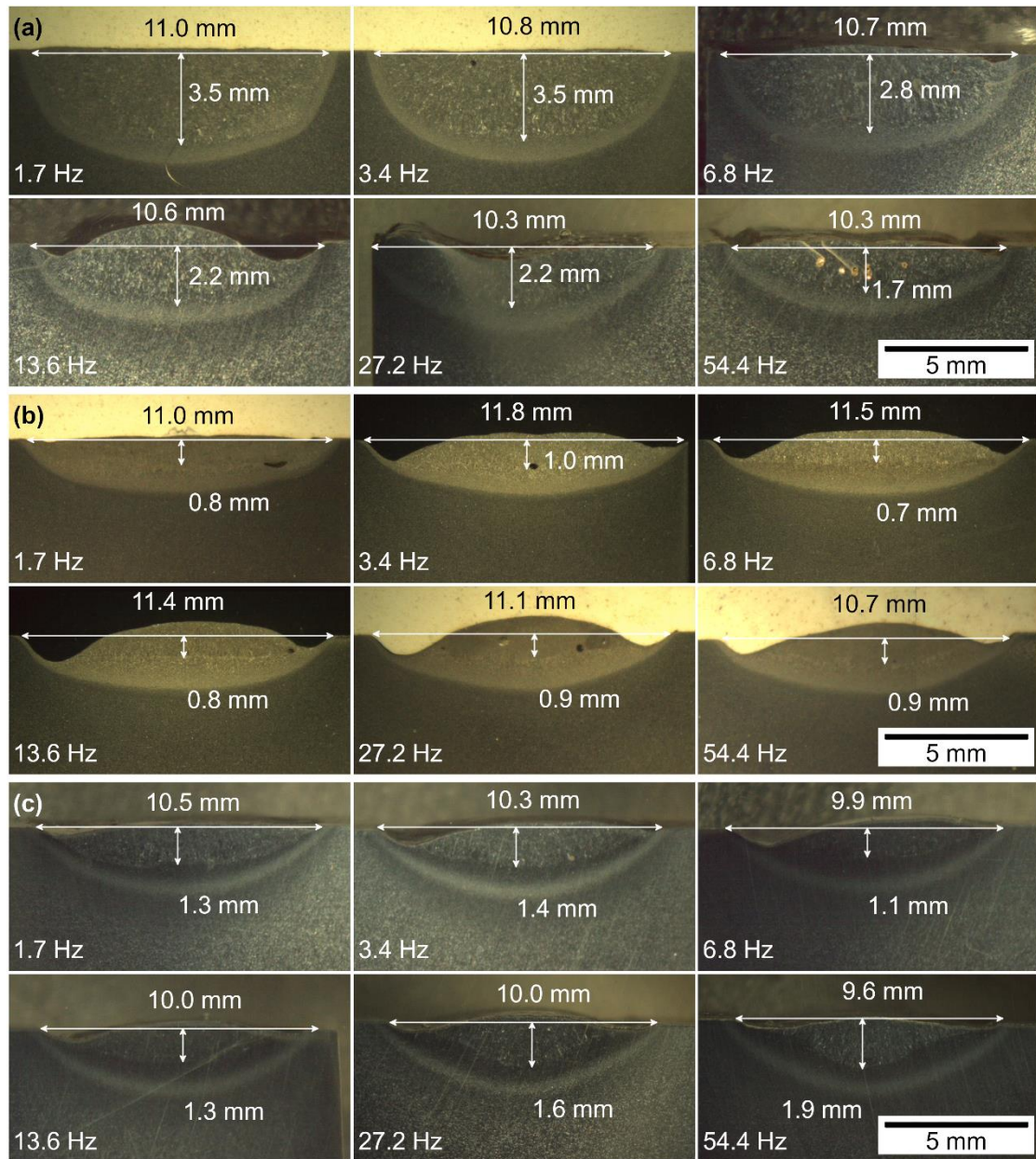


Figure 4-8. Cross-sections of the SL process with different oscillating frequencies and beam sizes: (a) 1 mm, (b) 2 mm, and (c) 4 mm.

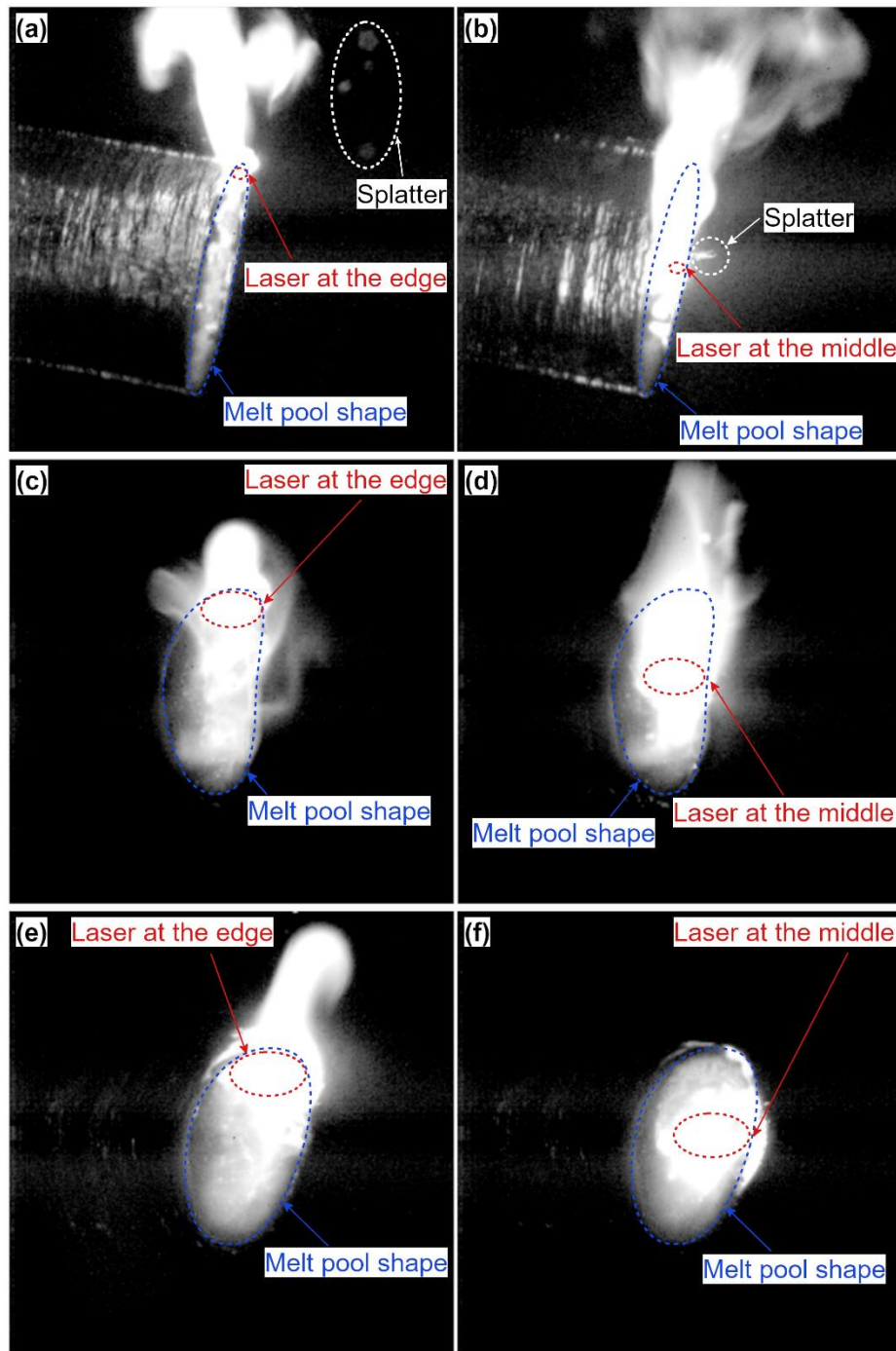


Figure 4-9. Highspeed images of the SL with 54.4 Hz oscillating frequency.

Different laser beam size SL melt pools were captured with laser beam positioned respectively at the edge and the middle: (a) and (b) 1 mm, (c) and (d) 2 mm, and (e) and (f) 4 mm.

Compared to the 1 mm beam size SL with keyhole mode, the penetration depth of the 2mm beam size SL is much shallower without sharp corners at the bottom edges of the melt pool when using a lower oscillation frequency of 1.7 Hz (Figure 4-8b). A possible explanation is that by using a larger beam size of 2 mm, the power density q_p was reduced, but the number of interactions n_i was increased. The thermal history of the irradiated surface was more even with lower peak temperatures. Vaporised fume would be generated once the peak temperature exceeded the boiling temperature of the steel. Therefore, the interaction mode switched to transition mode. With higher oscillation frequency, both processes switch to transition mode and show similar penetration. The interaction mode was transformed to transition mode when increasing the laser beam size. Severe undercuts can be observed at the edges of the bead with higher oscillation frequencies, further indicating the unstable melt pool condition during the transition mode. Figure 4-9b shows the highspeed images of the 2 mm beam size laser with an oscillation frequency of 54.4 Hz. The vaporised plume was still present but was less intense and with fewer spatter than the 1 mm beam size SL. This shows that compared to the 1 mm beam size SL, the transition mode of the 2 mm beam size SL was more stable and closer to the conduction mode.

The cross-sections of the 4 mm beam size SL melt pool show no severe undercut with low and high oscillation frequencies (Figure 4-8c) and suggest more stable melt pool conditions. Figure 4-9c shows the highspeed images of the 4 mm beam size SL with an oscillation frequency of 54.4 Hz. Slight vaporised fume ejected when the laser beam reached the edge of the melt pool, with no vaporised fume generated when the laser beam came to the centre of the melt pool. This might

be because the interval time between two interactions is shorter when the laser beam reaches the edges within each turning and then followed by a longer gap before the laser beam comes back to the edges. The peak temperature at the edges is higher compared to the centre of the melt pool, with even interval time between interactions. Therefore, the interaction at the edges was in transition mode, while in the centre was conduction mode. This may explain why the penetration at the edges is lower than the centre, as shown in the cross-section with an oscillation frequency of 54.4 Hz (Figure 4-8c). Nevertheless, the melt pool condition is stabler with an interaction mode closer to a conduction mode.

Figure 4-10a shows the melt pool surface area measured from the thermal images corresponds to the oscillation frequency. The surface area of the 1 mm beam size SL significantly reduces with an increased oscillation frequency due to the rapid drop down of the absorptivity and energy losses through vaporisation. The melt pool surface area of the 4 mm beam size SL is constant, indicating that the melt pool surface is independent of the oscillation frequency with a conduction mode domain interaction. The melt pool area of the 2 mm beam size SL fluctuated with the oscillation frequency, possibly because of the unstable melt pool condition during the transition mode. The melt pool area of the 4 mm beam size SL is generally broader due to a larger beam size and conduction mode interaction. Figure 4-10b shows the melt pool volume indicator corresponds to the oscillation frequency. The melt pool volume of the low oscillation frequency 1 mm beam size SL keyhole mode is essentially larger than the processes with transition mode and conduction mode interaction. This matches the conclusion in Matthews's work that the absorptivity with keyhole mode is dramatically higher

than transition and conduction mode. The volume to the 2m beam size SL melt pool is smaller than that of the 4 mm beam size SL, which further confirms that absorptivity reduces when switching from conduction mode to transition mode. Overall, it can be concluded that a larger beam size of 4 mm can benefit a stable melt pool condition and a better absorptivity to obtain a broad and thin melt pool for the quasi-steady SL.

Based on the conclusion of the SL experiment, the following simulation was designed with the assumption of a conduction mode SL. 4 mm beam size laser was applied for the quasi-steady-state SL simulation to ensure a conduction mode interaction and generate a broad and thin melt pool with stabler melt pool.

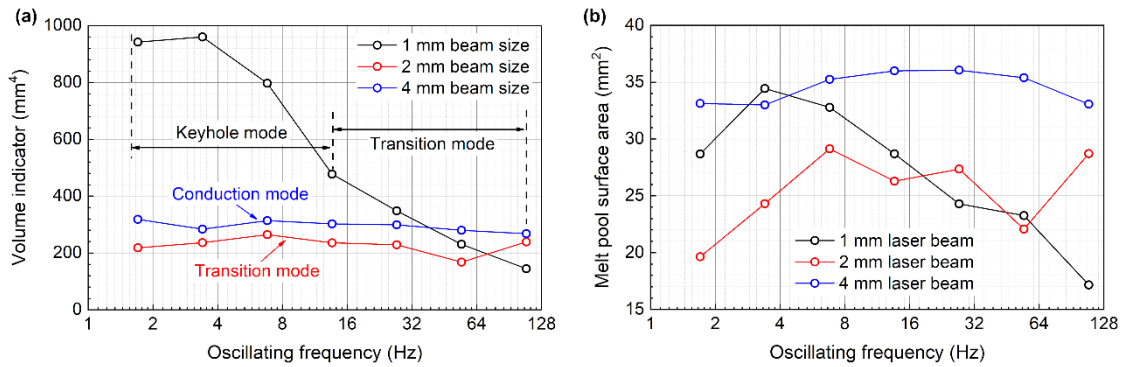


Figure 4-10. (a) Correlation of melt pool surface area vs. oscillation frequencies, and (b) correlation of volume indicator vs. oscillation frequencies. The X-axis is labelled in a logarithmic format.

4.3.2 Finite element study of SL

Figure 10 shows the thermal histories at Position C' indicated in Figure 4 of the full-scale models with different widths and thicknesses. In Figure 10a, it can be observed that thermal history barely changed when the width was wider than 132

mm. When using a width narrower than 132 mm, the cooling of the substrate started to slow down. Figure 10b further shows that changing of the thermal histories as a function of the thickness with a width of 132 mm. Thermal history is more sensitive to thickness compared to width. The scale of the full-scale model mainly determines two factors that affect the cooling trend, which are the area of the ambient convection and the volume of the adjacent material. Cooling trending would be slowed down without sufficient area of the ambient convection and volume of the adjacent material. Based on the result, a dimension of 132 mm × 60 mm × 25mm was selected for the full-scale model.

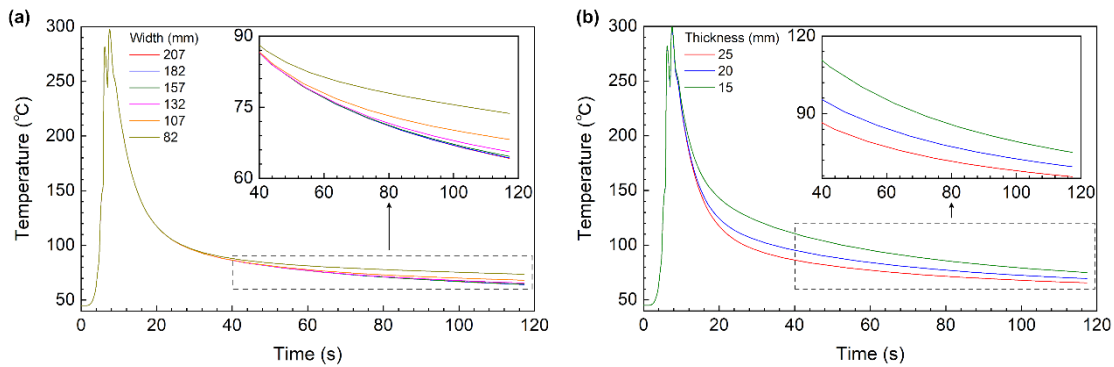


Figure 4-11. Results of the sensitive study on the size of the full-scale model.

Thermal histories at Position C' are compared: (a) with different widths and a thickness of 25 mm, and (b) with different thicknesses and a width of 132 mm.

Thermal history results of the full-scale model and calibrating experiment were compared, as shown in Figure 4-12. The absorption rate of the SL and the ambient cooling convection efficiency of the substrate surface were calibrated. After the calibration, the overall trending of the modelling thermal histories matches the thermocouples results well with only slight deviations. A constant

convection efficiency of $5 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ was used on the outer surfaces of the model to represent the ambient air cooling, and the SL absorption rate was set to 55%.

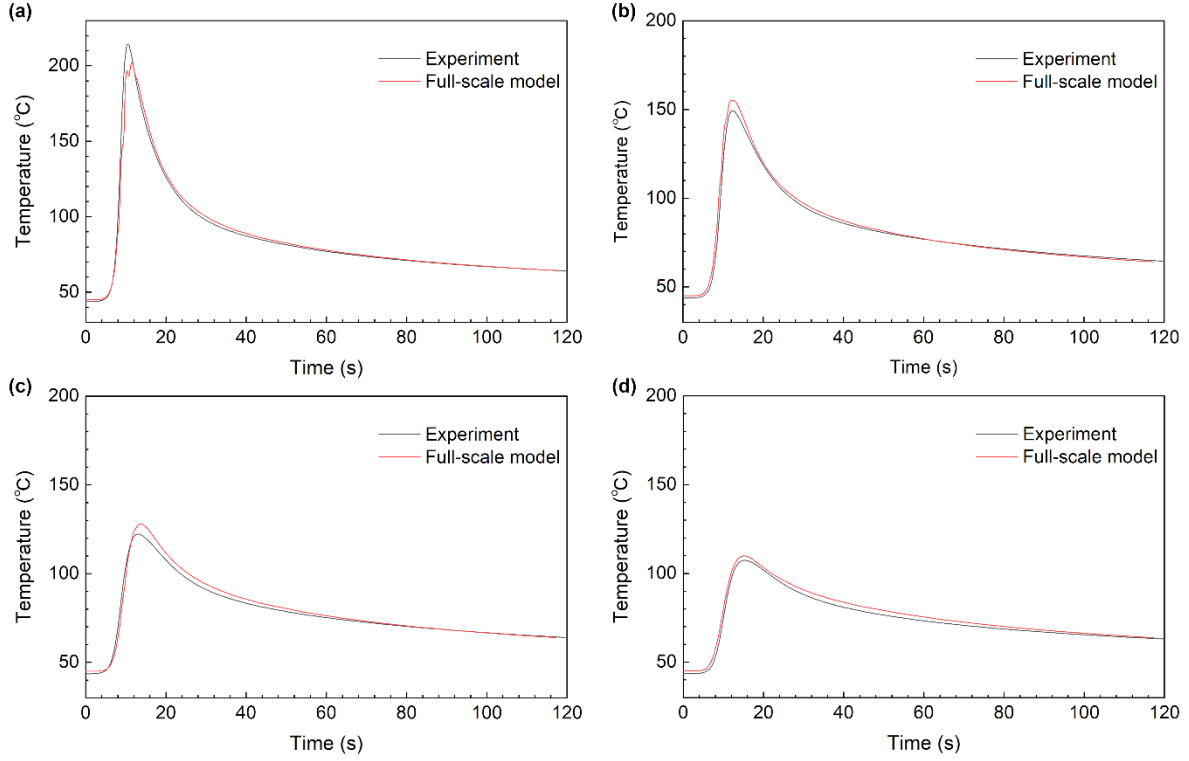


Figure 4-12. Comparing the full-scale model results and the thermocouples results at four positions: (a) P1, (b) P2, (c) P3, and (d) P4.

The SDCB model parameters, including energy input efficiency a_{input} , energy preserving efficiency $a_{preserve}$ and SDBC convection coefficient h , were calibrated based on the full-scale model results. Figure 4-13 shows the changing of the thermal history when adjusting a_{input} , $a_{preserve}$ and h . Figure 4-13a shows the thermal histories with varying $a_{preserve}$. It can be observed that $a_{preserve}$ only affects the cooling stage. A higher $a_{preserve}$ represents that more energy is preserved after each timestep, therefore a slower cooling speed. Figure 4-13b and Figure 4-13c show that both a_{input} and h affect the peak temperature of the interacting stage. The difference is that a_{input} is correlated to both the peak temperature and the cooling speed, whereas h has more influence on the peak temperature than the cooling rate. The SDCB were calibrated by adjusting these three parameters to fit the peak temperature and cooling speed of the full-scale

model thermal history results. After the calibration, the convection coefficient (h) of the SDCB was set to $15000 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, the energy input efficiency a_{input} was set to 23% per second, the energy preserving efficiency $a_{preserve}$ was set to 99.6% per second, and the convection coefficient for the RCB was set to $12000 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ with a constant bulk temperature T_f of 45°C .

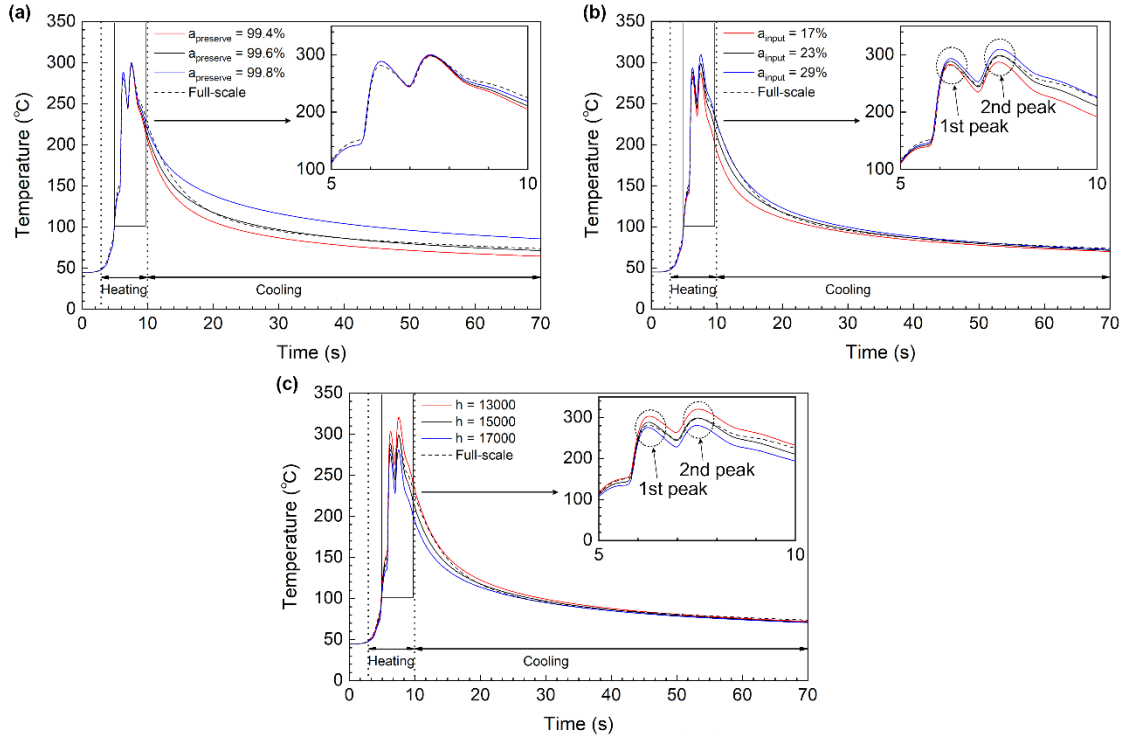


Figure 4-13. Thermal histories with varied SDCB parameters: (a) energy preserving efficiency ($a_{preserve}$), (b) energy input efficiency (a_{input}), and (c) convection coefficient (h).

During the calculations, 600 timesteps were computed for both the full-scale model and the SDCB model. Figure 4-14 compares the computing time of these two models. With a much less element amount, over 86% of the computing time was reduced by using SDCB, showing that the SDCB method has significantly improved computing efficiency.

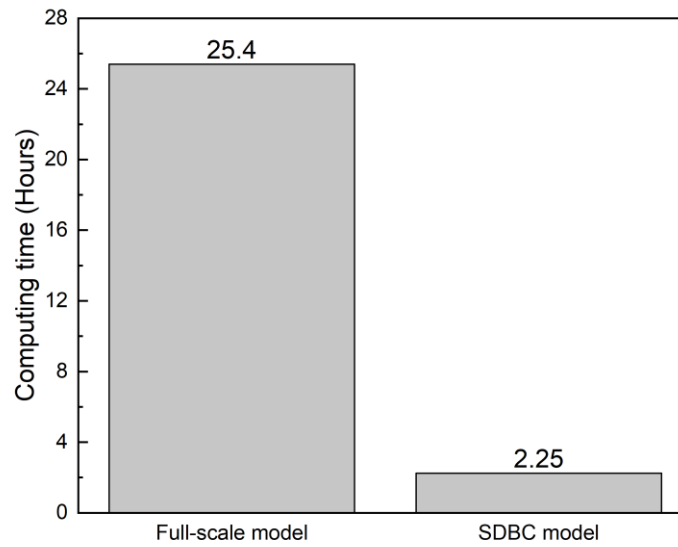


Figure 4-14. Comparison of the computing time using the full-scale model and the SDCB partial model.

Figure 4-15 includes the thermal contour results of three different models in top views. The thermal contour of the RCB model is shorter than the full-scale and SDCB partial model, while the thermal contours of the SDCB model and the full-scale model are similarly distributed.

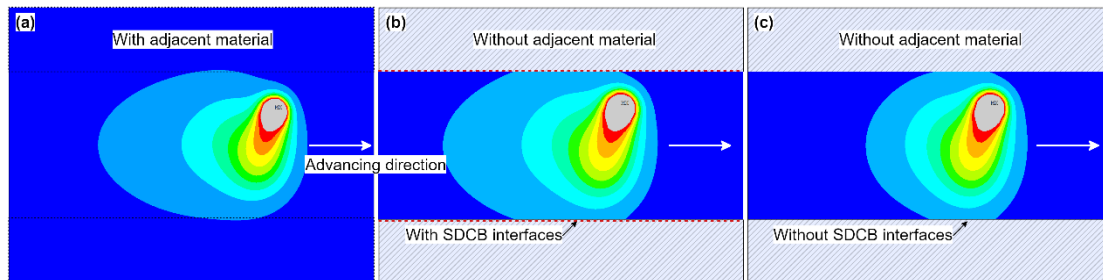


Figure 4-15. The thermal contour of the three models: (a) full-scale model, (b) SDCB model, and (c) RCB model.

Figure 4-16 shows the thermal histories of the full-scale model and the RCB and SDCB partial models. A significant difference is that the cooling trend of the RCB model drops faster than the other two models, while the thermal histories of the full-scale model and the SDCB model are well matched at all four positions. Besides the overall cooling trend, the thermal conduction also affected the thermal behaviour during the interaction. Position A and C are located on the top

surface of the substrate and are directly affected by the heat source. Consequently, the effect of the thermal conduction with the adjacent region is relatively less significant when the heat source goes across. Position B and D are located at the bottom surface of the model. These two positions are closer to the interface than to the heat source and are affected more by the thermal conduction of the adjacent material. Figures 4-16c and d show the thermal histories of Positions B and D when the heat source was above these positions. The temperature of these three models reaches the same level at the first peak and deviates at the second peak. At the second peak, the SDCB model and full-scale model match each other and are higher than the first peak, whereas the temperature of the RCB model at the second peak is lower than the first peak. This is evidence that the SDCB not only simulated the cooling trending but also successfully simulated the thermal behaviour of thermal conduction.

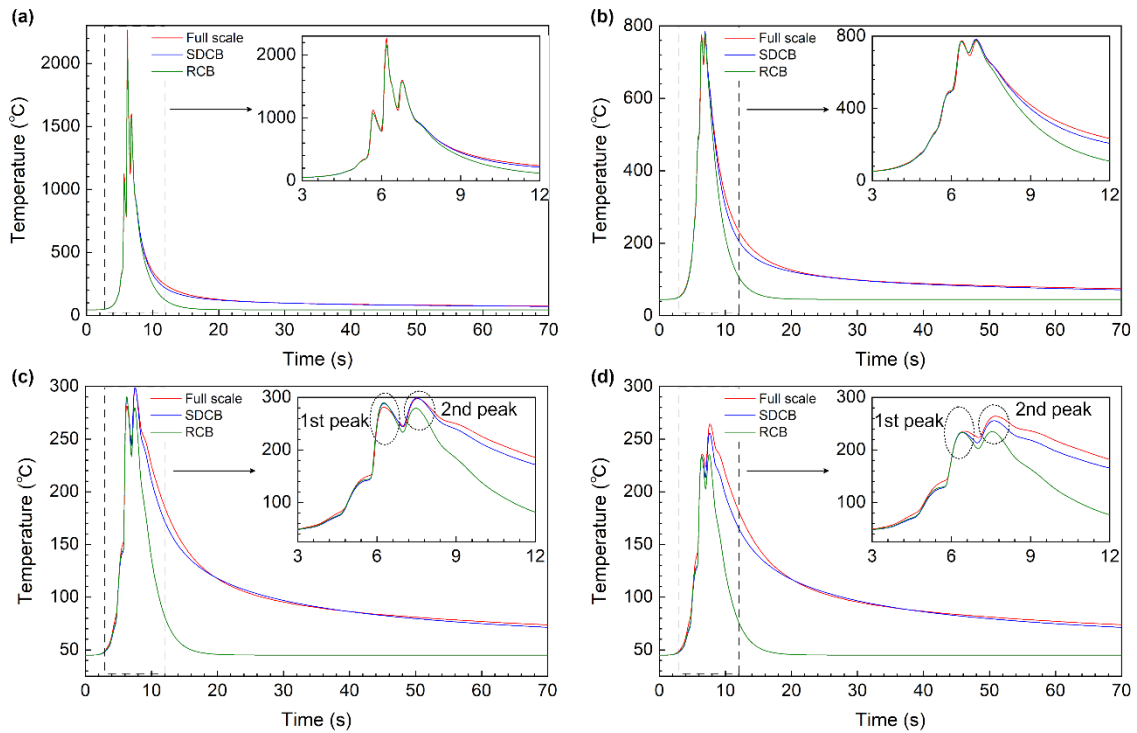


Figure 4-16. Comparison of the sampling position results among three models:
(a) Position A, (b) Position B, (c) Position C, and (d) Position D.

Figure 4-17 shows the simulation results of the SL process with a 4 mm beam size. In the simulation results, the grey area outlines the area with a temperature

exceeding 1500 °C, which is approximately the melting point of the steel and represents the melt pool shape. The melt pool shape in the simulation result is similar to the melt pool shape presented in the thermal images (Figure 4-6a) and reached the same constant shape with an oscillation frequency of 13.6 Hz. The simulated melt pool shape of the equivalent bar-shaped energy source is presented in Figure 4-17. The melt pool shape of the equivalent heat source is highly similar to the melt pool with higher oscillation frequencies, indicating that quasi-steady state melt pools were formed.

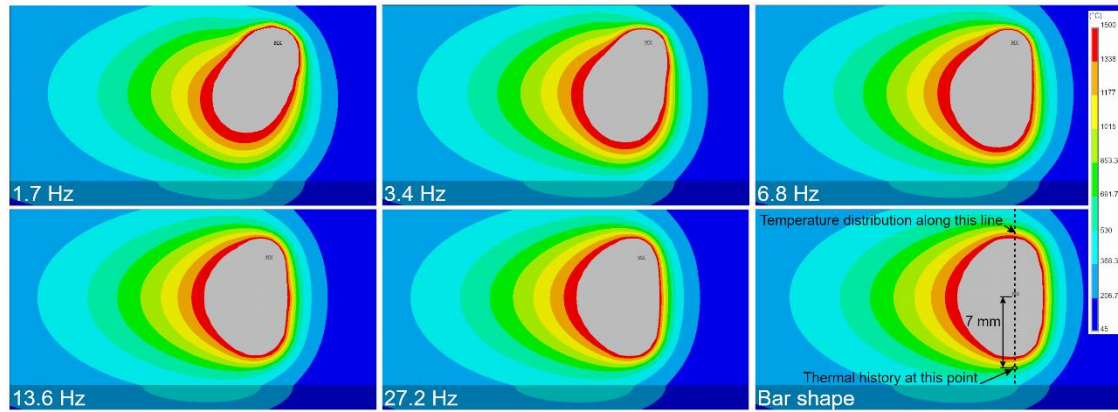


Figure 4-17. Simulation results of the 4 mm beam size SL melt pool with different oscillation frequencies.

The temperature distribution of the melt pool along the scanning width (Figure 4-17) when the laser beam reached the edge was plotted in Figure 4-18 further to analyse the thermal dynamics of the melt pool. The black line represents the temperature distribution of the bar-shaped equivalent heat source, and the coloured lines represent the temperature distribution of the SL with different oscillation frequencies. The dashed line represents the melting point of steel. As the oscillation frequency increases, the temperature field changes from an

asymmetric shape to a symmetric shape. The width above the dashed line shifts to the centre and becomes similar to the bar shape heat source. The temperature distribution of the 13.6 Hz and the 27.2 Hz SL resemble the temperature distribution of bar shape with an oscillation frequency of 27.4 Hz, further indicating that the thermal distribution of the melt pool was stabilised. Based on this, the capability of using a bar-shaped equivalent energy source to simulate a quasi-steady-state SL energy source is verified. This equivalent energy source model can be applied in the steady-state modelling method. Steady-state modelling is much more efficient than the transient model and could be used for the study and assist the design of the MES source.

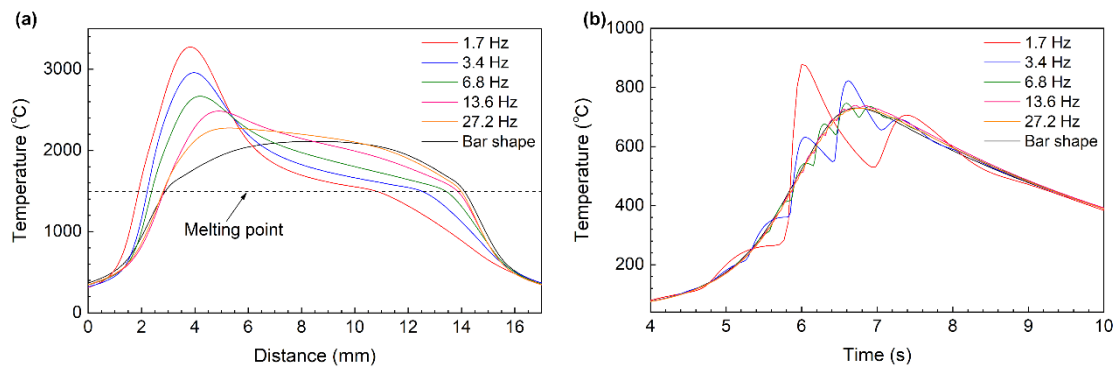


Figure 4-18. (a) Temperature distribution of the melt pool across the scanning width, and (b) thermal histories at the edge of the SL 7 mm to the centre line.

4.4 Conclusions

1. The oscillation frequency has a significant effect on the SL interaction mode, especially with a smaller beam size. A keyhole mode interaction has a high absorptivity, whilst transition and conduction modes have a lower absorptivity. Both keyhole mode and transition mode generate unstable melt pools. So, conduction mode is optimum for the SL process with good energy efficiency

and a stable melt pool. Compared to smaller beam sizes (1 mm and 2 mm), conduction mode interaction was easier to be achieved with a larger beam size (4 mm).

2. The SDCB model has been developed, and the results of the SDCB partial model showed that SDCB successfully simulated the thermal conduction of the adjacent material around the bead region. The element amount of the model was significantly reduced by 74%. 86% of the computing time was reduced.
3. An equivalent bar-shaped heat source model was introduced to replace the SL transient heat source model. Both the experimental and numerical results show that the melt pool shape reached a quasi-steady state when the oscillation frequency reached 13.6 Hz and higher, and the equivalent bar-shaped heat source model can be used to replace the SL transient heat source model.

4.5 Acknowledgement

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4.6 Reference

- [1] Qian, Y. P., Huang, J. H., Zhang, H. O., & Wang, G. L. (2008). Direct rapid high-temperature alloy prototyping by hybrid plasma-laser technology. *Journal of materials processing technology*, 208(1-3), 99-104.

- [2] Liang, Y., Hu, S., Shen, J., Zhang, H., & Wang, P. (2017). Geometrical and microstructural characteristics of the TIG-CMT hybrid welding in 6061 aluminum alloy cladding. *Journal of materials processing technology*, 239, 18-30.
- [3] Zhang, Z., Sun, C., Xu, X., & Liu, L. (2018). Surface quality and forming characteristics of thin-wall aluminium alloy parts manufactured by laser assisted MIG arc additive manufacturing. *International Journal of Lightweight Materials and Manufacture*, 1(2), 89-95.
- [4] Li, R., Wang, G., Ding, Y., Tang, S., Chen, X., Dai, F., ... & Zhang, H. (2020). Optimisation of the geometry for the end lateral extension path strategy to fabricate intersections using laser and cold metal transfer hybrid additive manufacturing. *Additive Manufacturing*, 36, 101546.
- [5] Wang, C., Suder, W., Ding, J., & Williams, S. (2021). Wire based plasma arc and laser hybrid additive manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 293, 117080.
- [6] Rubben, K., Mohrbacher, H., & Leirman, E. (1997). Advantages of using an oscillating laser beam for the production of tailored blanks. *Lasers in Material Processing*, 3097, 228-241.
- [7] Choi, K. D., Ahn, Y. N., & Kim, C. (2010). Weld strength improvement for Al alloy by using laser weaving method. *Journal of Laser Applications*, 22(3), 116-119.
- [8] Schedewy, R., Dittrich, D., Standfuß, J., & Brenner, B.. (2008). LBW of high stiffness light weight structures generated by scanned fiber laser beams.

ICALEO 2008: 27th International Congress on Laser Materials Processing, Laser Microprocessing and Nanomanufacturing.

- [9] Cheng, F. T., Lo, K. H., & Man, H. C. (2004). A preliminary study of laser cladding of AISI 316 stainless steel using preplaced NiTi wire. *Materials Science and Engineering: A*, 380(1-2), 20-29.
- [10] Cui, C., Guo, Z., Liu, Y., Xie, Q., Wang, Z., Hu, J., & Yao, Y. (2007). Characteristics of cobalt-based alloy coating on tool steel prepared by powder feeding laser cladding. *Optics & Laser Technology*, 39(8), 1544-1550.
- [11] Jiao, X., Wang, J., Wang, C., Gong, Z., Pang, X., & Xiong, S. M. (2018). Effect of laser scanning speed on microstructure and wear properties of T15M cladding coating fabricated by laser cladding technology. *Optics and Lasers in Engineering*, 110, 163-171.
- [12] Gao, X. S., Wu, C. S., Goecke, S. F., & Kügler, H. (2017). Numerical simulation of temperature field, fluid flow and weld bead formation in oscillationsingle mode laser-GMA hybrid welding. *Journal of Materials Processing Technology*, 242, 147-159.
- [13] Matsumoto, M., Shiomi, M., Osakada, K., & Abe, F. (2002). Finite element analysis of single layer forming on metallic powder bed in rapid prototyping by selective laser processing. *International Journal of Machine Tools and Manufacture*, 42(1), 61-67.
- [14] Ding, J., Colegrove, P., Mehnen, J., Ganguly, S., Almeida, P. M. S. , & Wang, F. , et al. (2011). Thermo-mechanical analysis of wire and arc additive layer manufacturing process on large multi-layer parts. *Computational Materials Science*, 50(12), 3315-3322.

- [15]Huang, H. C., & Usmani, A. S. (2012). Finite element analysis for heat transfer: theory and software. Springer Science & Business Media.
- [16]Ruppert, Jim. "A Delaunay refinement algorithm for quality 2-dimensional mesh generation." *Journal of algorithms* 18.3 (1995): 548-585.
- [17]Gago, J. P. D. S. R., Kelly, D. W., Zienkiewicz, O. C. , & Babuska, I.. (1983). A posteriori error analysis and adaptive processes in the finite element method: part ii—adaptive mesh refinement. *International Journal for Numerical Methods in Engineering*, 19(11), 1621-1656.
- [18]Joshi, A., Bangerth, W., & Sevik-Muraca, E. M. (2004). Adaptive finite element based tomography for fluorescence optical imaging in tissue. *Optics Express*, 12(22), 5402-5417.
- [19]Knupp, P., & Steinberg, S. (2020). Fundamentals of grid generation. CRC press.
- [20]Liseikin, V. D. (1999). Grid generation methods (Vol. 1). Berlin: Springer.
- [21]Kim, K., & Feng, S. S. (2016). Thermal Mapping Using Infrared Thermography. In *Application of Thermo-Fluidic Measurement Techniques* (pp. 215-250). Butterworth-Heinemann.
- [22]Bergman, T. L., Incropera, F. P., DeWitt, D. P., & Lavine, A. S. (2011). Fundamentals of heat and mass transfer. John Wiley & Sons.
- [23]Assuncao, E., Williams, S., & Yapp, D. (2012). Interaction time and beam diameter effects on the conduction mode limit. *Optics and Lasers in Engineering*, 50(6), 823-828.
- [24]Matthews, M., Trapp, J., Guss, G., & Rubenchik, A. (2018). Direct measurements of laser absorptivity during metal melt pool formation

associated with powder bed fusion additive manufacturing processes.
Journal of Laser Applications, 30(3), 032302.

5 Multi-energy source (MES) configuration for bead shape control in wire-based directed energy deposition (w-DED)

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ABSTRACT

A multi-energy source (MES) method featuring a high-power scanning laser (SL) was used to achieve independent control of layer width and height in a wire-based directed energy deposition (w-DED) process. In the MES system, a plasma transferred arc (PTA) was employed to create an initial melt pool and melt the wire, and a SL was used to reshape the melt pool and precisely control the bead width. The whole setup was enclosed in a glove box filled with pure argon atmosphere to avoid any oxidation effects. The distance between the SL and the PTA and different laser scanning strategies were investigated. Images of the melt pool with varying scanning widths were captured. A bead shape control strategy was demonstrated by using the wire feeding rate to control layer height and the laser scanning width to control the layer width independent of each other. The advancing speed was adjusted in proportion to the scanning width to keep the same specific process energy of the SL. The experiment results demonstrated that the MES approach provides independent control of layer width and height. Walls were built using the MES to show that it can be used for w-DED additive manufacturing.

Keywords: Wire additive manufacture; Wire-based directed energy deposition; Multi-energy source; Scanning laser

5.1 Introduction

Wire-based directed energy deposition (w-DED) additive manufacture (AM) has developed rapidly due to advantages such as short lead times compared to

forgings, low material waste compared to machining, and high design flexibility [1-3]. w-DED AM processes have much higher deposition rates and lower material waste than powder-based methods, leading to the potential to produce large-scale and near-net-shape metallic components in many industry sectors, including aerospace, aviation, and power generation [4–7]. Conventional single energy source w-DED AM that uses the same energy source such as metal inert gas (MIG), tungsten inert gas (TIG), and plasma transferred arc (PTA) to melt the wire and substrate at the same time has been widely used. Bead shape control of the single energy source w-DED AM has been investigated by many researchers. Dinovitzer et al. [8] used the Taguchi method to study the effect of different process parameters, including wire feed speed, travel speed, and current on the bead geometry in a TIG deposition process with a current range between 50 to 59 A. They concluded that the layer width decreased whilst the layer height increased with an increase in wire feed speed. Travel speed had a significant effect on layer width but a minor effect on layer height. Layer width increased with increasing current. Martina et al. [9] investigated the PTA deposition of titanium for a much wider range of parameters (e.g., current ranged from 120 to 300 A). They found that effective wall width increased with the increase of the current and the decrease of the travel speed, and layer height increased with the increase of the wire feed speed and the decrease of the current. In a w-DED AM process, material per unit length, which determines the cross-sectional area of the bead, is controlled by the wire feed speed to travel speed ratio, while deposition rate is controlled by the wire feed speed for a given constant wire diameter. However, while maintaining a constant wire feed speed to travel speed ratio, the effective wall width decreases with an increasing wire feed speed, resulting in a narrower and taller wall [10]. Consequently, the deposition rate is restricted by the bead cross-section. Another limitation is that the thermal conditions during the deposition process vary with the bead shape. A higher wire feed speed to travel speed ratio can achieve a larger cross-sectional area, but it will increase the heat input of the process for MIG based processes [11]. Microstructure and mechanical properties are therefore affected. For conventional electric arc single energy source processes, the energy distribution

and dimension of an electric arc are not controllable. Layer width and height will be affected simultaneously when the parameters are changed. Bead shape can only be optimised by adjusting parameters such as current, arc length, wire feed speed, etc.

A laser beam is also used in single energy source deposition. Schulz et al. [12] achieved process maps using a semi-analytical approach to study the bead width as a function of wire feed rate, laser power, and laser intensity distribution in a laser wire deposition process. Abioye et al. [13] developed a process map to predict process characteristics and bead geometry in the laser wire deposition process and studied the relationship between the input parameters (wire feed speed, travel speed, and laser power) and the resulting bead characteristics (contact angle, width-height aspect ratio, and dilution ratio). Mok et al. [14] studied the bead shape of the deposition using a bar-shaped stationary laser beam. Independent control of the layer height and layer width was achieved in specific ranges by adjusting wire feeding rate and laser power correspondingly. However, due to the limitation of the laser beam shape, the bead shape range was restricted. Because the power density profile of the laser beam can be independently controlled without changing the dimension, layer height can be controlled with greater independence compared to the arc-based process. But the layer width control was limited by the laser beam dimension. Also, compared to electric arc processes, laser processes are expensive and with lower energy efficiency.

Multi-energy source (MES) is a concept that combines more than one energy source to overcome the limitation of the conventional single energy source process. Several studies have focused on bead shape control using MES. Näsström et al. [15, 16] investigated a cold metal transfer (CMT) arc-laser hybrid AM process of steel. They found that the CMT arc with trailing laser configuration improved the process stability, surface finish and geometric feature capability. Pardal et al. [17] studied the benefits of introducing a concentric laser as a secondary power source in a CMT-based WAAM of titanium. Compared to the CMT process alone, the hybrid process stabilised the arc and improved the bead

shape with a higher deposition rate. Zhang et al. [18] investigated a MIG-laser hybrid AM of aluminium and obtained similar results. The surface quality of the components was improved significantly by adding a laser, and the efficiency of material utilisation was increased by 15%. The above studies [15-18] focused mainly on improving the surface finish of the MIG-based WAAM process by adding a laser. Miao et al. [19] compared the microstructure and mechanical properties of aluminium parts deposited by a TIG-laser hybrid AM process and a TIG-based WAAM process. They found that the addition of the laser led to more uniform element distribution and finer grains caused by the strengthened fluid flow and high cooling rate in the laser-affected zone. Wu et al. [20] studied the microstructure and mechanical properties of the Al-Au alloy deposited by a TIG-laser hybrid AM process. They stated that the grain size is smaller, and the Cu element was distributed more homogeneously in the laser-arc-affected zone than in the arc-affected zone in each layer. The main focus of research on TIG-laser hybrid AM presented to date [19, 20] has been on the improvement of microstructure and mechanical properties by introducing additional low power laser sources. Wang [21] et al. introduced a laser-PTA hybrid additive manufacturing for the deposition of Ti-6V-4V. An MES that consisted of a PTA and two stationary laser beams was introduced. Two laser beams were placed at the sides of the melt pool to provide more energy on the edges. This method increased the deposition rate with a higher process tolerance. It also achieved independent control of the bead shape and the deposition rate. However, this work did not further study the independent control of the layer height and the layer width.

In previous studies, scanning lasers (SL) were mainly used in welding applications to improve gap tolerance and weld quality [22-24]. For example, Hao et al. [24] studied the effects of oscillating beam parameters on weld morphologies. The results showed that the weld cross-section becomes more homogeneous with an increase of oscillating frequency because of the forming of a quasi-steady melt pool. Some research has focused on the SL-arc hybrid process. Cai et al. [25] used an SL-metal active gas (MAG) hybrid welding method for the bead on plate welding of high-strength steel. Weld porosity defects

were suppressed due to the stirring effect of the SL to the molten pool. To the best knowledge of the authors, no systematic study about bead shape control using the SL-arc hybrid process has been reported.

In this study, an SL-PTA MES system was introduced that combines the advantages of an SL and a PTA. The SL can be used as a quasi-steady-state energy source to reshape the melt pool and precisely control layer width. Unlike other conventional energy sources, the shape of a SL can be changed by adjusting the scanning pattern, and the energy distribution of the SL can be designed by using different scanning speeds in different regions if the SL reaches a quasi-steady state. A PTA can be employed in front of an SL as an efficient energy source to create an initial melt pool and melt the wire. The absorption efficiency of a PTA is higher than that of a laser and is, therefore, a better option to initial the melt pool. The scanning device that was used in this study was a galvanometer-based scanner (GS) [26]. The GS is one of the most used scanning devices nowadays for both one-dimensional and two-dimension scanning and is suitable for an extensive range of applications [27].

In the PTA-SL MES system, a variety of parameters can be adjusted to obtain a particular combination of a layer height and a layer width. Therefore, a bead shape control strategy was designed to control the bead shape systematically. In this strategy, layer width is controlled by SL scanning width, and layer height is controlled by wire feed speed. Correspondingly, advancing speed is adjusted according to scanning width to keep the same specific process energy. Walls were built to demonstrate that the SL-PTA MES system can be utilised in the w-DED AM process.

5.2 Experimental procedure

5.2.1 Setup

The configuration of the PTA-SL MES setup is shown in Figure 5-1. A PWP Viper MC plasma torch was placed in front of a SL with an angle (α_2) of 25 degrees to the vertical. The PTA was generated by an EWM Tetrix 552 power supply. A Migatronik KT4 wire feeder was employed in the front of the PTA with an angle

(α_1) of 4 deg. to the horizontal to feed the wire from the front. A JK 3000FL continuous wave fibre laser (wavelength 1.08 μm) was applied to generate the laser energy. The laser beam was directed by a Raylase SUPERSCAN-III GS scanning head and projected onto the substrate vertically, and was defocused to give a 4 mm beam diameter. A 4 mm laser beam size ensured that the laser was in conduction mode during the process even at higher laser powers. The distance between the SL and the PTA (d_1) was measured from the intersection of the PTA torch centre line and the substrate surface to the centre of the laser. The distance between the PTA torch to the substrate (d_3) was measured from the centre of the copper nozzle to the substrate in the vertical direction. The scanning width (w_s) was measured by the crosswise moving distance of the laser beam centre. Parameters of the configuration are listed in Table 5-1. The experimental setup is illustrated in Figure 5-2. Two Aerotech CNC actuators were used to move the substrate in the vertical (Y-axis) direction and the horizontal (X-axis) direction while the MES heat source remained stationary. The movement of the actuators, the triggers of the PTA power supply, and laser machine were controlled by a A3200 machine controller installed on a personal computer (PC). A Phantom MIRO-4M high-speed camera was set up behind the MES to capture the dynamics of the melt pool with a recording frame rate of 6000 frames per second. The whole setup was enclosed in a glove box filled with pure argon. The oxygen level was measured by a GS SENSOREINHEIT oxygen monitor and was kept below 500 ppm. S275 mild steel plates with a dimension of 200 mm $\times$ 45 mm $\times$ 12.5 mm were used as substrates, and 1.2 mm diameter LNM 20 steel wire was used as feedstock. The composition of the feedstock is listed in Table 5-2. The ceramic nozzle was removed from the PTA torch as shielding was provided by the inert argon atmosphere. The fixed parameters for the SL and the PTA are listed in Table 5-3 and Table 5-4.

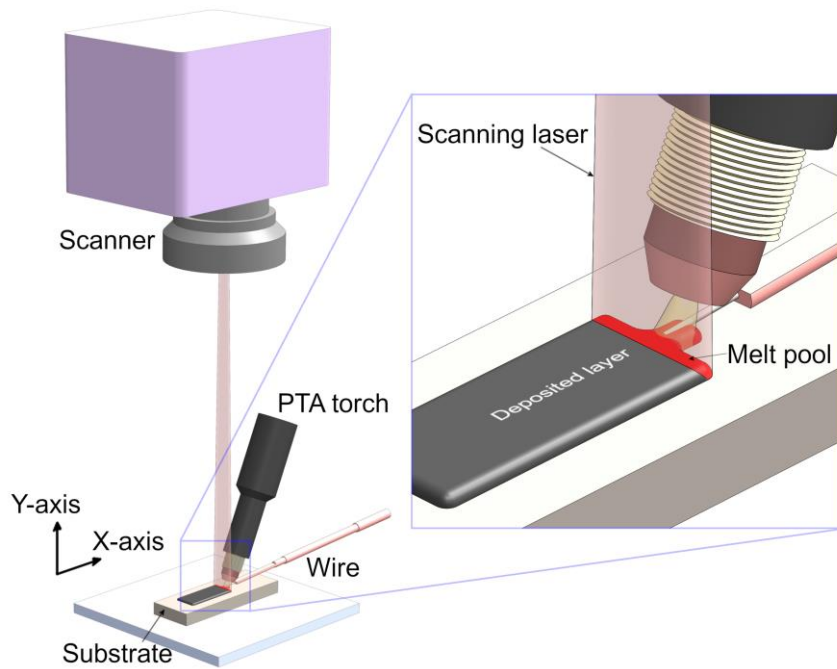


Figure 5-1 Configuration of the SL-PTA MES.

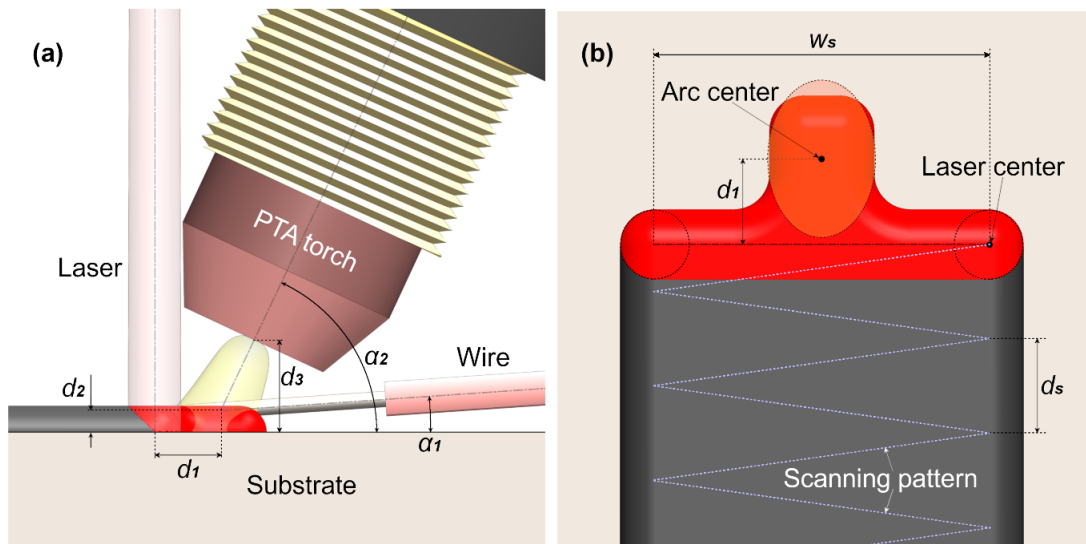


Figure 5-2 Position of the torch, laser and wire: (a) side view, and (b) top view.

Table 5-1 Parameters for the MES configuration.

SL-PTA distance (d_1) / (mm)	6.5
Wire-substrate distance (d_2) / (mm)	1

Torch-substrate distance (d_3) / (mm)	7
Feeding wire angle (α_1) / (degree)	4
Torch angle (α_2) / (degree)	25

Table 5-2 Chemical compositions (wt. %) of the feedstock.

C	Mn	Si	Cr	Mo	Fe
0.08	0.9	0.6	2.5	1.0	Balance

Table 5-3 Parameters for the SL

Power / (W)	2700
Wavelength / (μm)	1.08
Focal length / (mm)	250
Distance between the laser head and the measuring plane / (mm)	305

Table 5-4 Parameters for the PTA.

Current / (A)	140
Voltage / (V)	21.5
Orifice size / (mm)	3.9
Electrode diameter / (mm)	4
Electrode Tip Angle / (degree)	40
Electrode Tip Set-back / (mm)	2.4

5.2.2 Preliminary experiment

5.2.2.1 SL energy distribution

The scanning pattern was edited and controlled by the SCAPS SAMLight scanner application software installed on the control PC. In this study, the GS oscillated the laser beam in a back-and-forth pattern transverse to the advancing direction, and the substrate was moved in the advancing direction. By combining these two movements, a saw wave scanning pattern was achieved on the substrate, as shown in Figure 5-3. The scanning frequency F_s was determined by the scanning speed v_s and the scanning width w_s of the SL, as shown in Equation 5-1. The

increment of the scanning pattern d_s is determined by the scanning frequency F_s and the advancing speed v_a , as shown in Equation 5-2. In this study, the scanning speed v_s was above 2000 mm/s. As a result, the scanning frequency F_s was above 100 Hz and the d_s was less than 0.008 mm, which is much smaller than the laser beam size. Therefore, a slight change in the scanning frequency when changing the scanning width would not affect the forming of a quasi-steady-state melt pool.

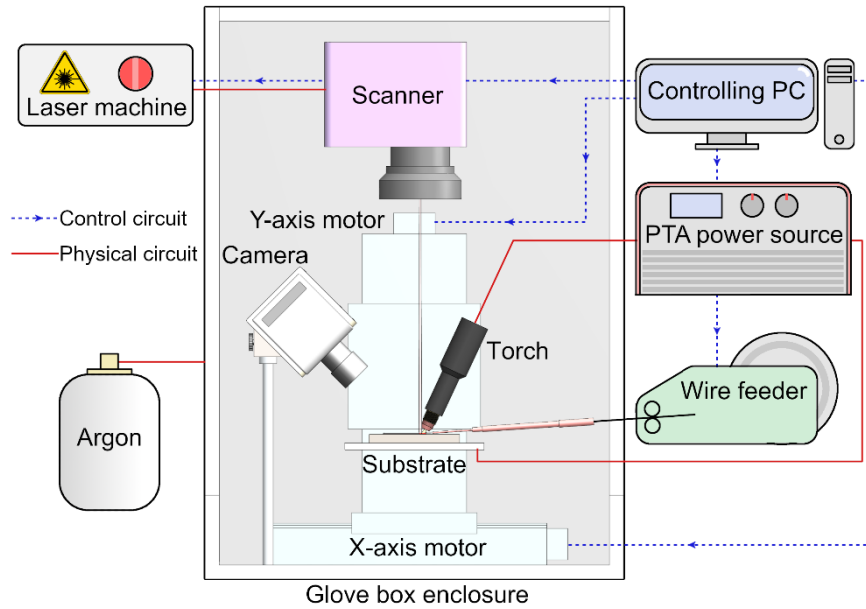


Figure 5-3 Diagram of the MES system setup.

$$F_s = \frac{v_s}{2w_s} \quad (5-1)$$

$$d_s = \frac{v_a}{F_s} \quad (5-2)$$

In a laser process, the period that a certain point is irradiated can be defined as the interaction time. The energy delivered to this particular point denoted as the specific point energy E_{sp} , is proportional to the product of power density q_p , interaction time t_i and the area of the specific point A_{sp} , which also corresponds

to the product of the absorbed laser power P_L and interaction time t_i . For an SL process, a particular point might interact with the laser beam more than once. Figure 5-4 illustrates the relative movement of a specific point on the substrate that passes across the laser beam section during scanning. The number of interactions n_i is defined as how many times the laser beam passes the specific point. The number of interactions n_i is determined by the laser beam size D_L and the increment of the scanning pattern d_s , as shown in Equation 5-3, and the total specific point energy can be calculated by Equation 5-4:

$$n_i = \frac{D_L}{d_s} \quad (5-3)$$

$$E_{sp} = \sum_{1}^{n_i} q_p A_{sp} t_i = \sum_{1}^{n_i} P_L t_i \quad (5-4)$$

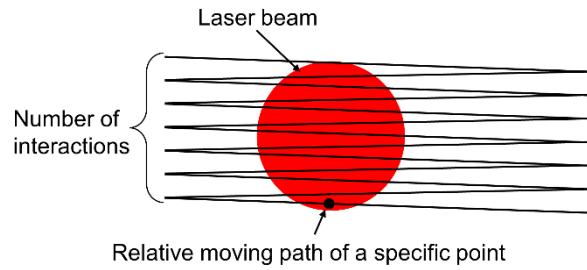


Figure 5-4 The number of interactions during scanning.

In the SL process, with the same interaction number, a slower scanning speed gives a longer interaction time and, therefore, higher specific point energy. With the assumption of the SL thermal field reaching the quasi-steady state, different SL energy distributions could be achieved by changing the scanning speed during scanning, that is, changing the interaction time. Two energy distribution profiles were compared, as shown in Figure 5-5, and the melt pool wettability was studied. The energy of the PTA was mainly concentrated at the centre of the MES. Correspondingly, the energy of the SL at the centre can be lowered. The GS can provide a maximum linear speed of 16500 mm/s. This maximum speed was used at the centre region of the SL to deliver the lowest energy. A reference scanning speed of 4125mm/s was applied for two side areas. In the scanning pattern of

Profile 1, the SL scanning laser speed was kept constant at 4125mm/s on the side regions. Whereas in Profile 2, the scanning speed decelerated to 25% (1030mm/s) at the edge. Figure 5-5a diagrams the scanning speed along the scanning path of these two profiles. The energy distribution density profiles can be calculated as shown in Figure 5-5b.

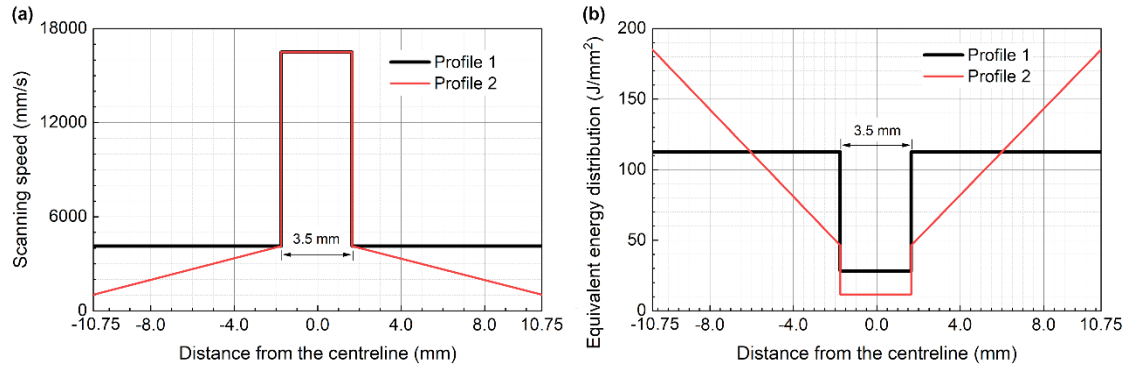


Figure 5-5 Energy profiles for melt pool study: (a) scanning speed along the scanning path, and (b) equivalent energy distribution along the scanning path.

5.2.2.2 SL-PTA distance

The effect of the PTA-SL distance d_1 on the melt pool stability was investigated. Three different PTA-SL distances, 10.5 mm, 6.5 mm, and 2.5 mm, were set. Figure 5-6 illustrates the relative position of the SL and PTA melt pools with different SL-PTA distances.

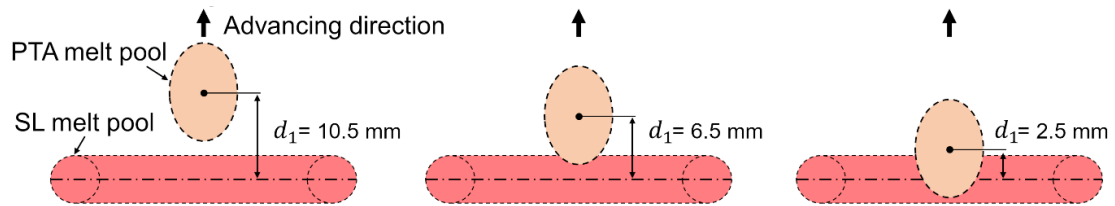


Figure 5-6 Diagrams of three different SL-PTA distances.

5.2.3 Shape control strategy

In the MES system, parameters that can be adjusted include SL power, PTA power, wire feeding rate, SL scanning width, advancing speed, etc. More than

one combination of the process parameters can be set to achieve a particular set of layer width and layer height. Therefore, a bead shape control strategy was needed to control the width and the height of the layer systematically. The deposition rate R of a process can be expressed by how much wire is fed per unit time:

$$R = \frac{\pi d^2}{4} v_w \rho \quad (5-5)$$

where d is the wire diameter, v_w is the wire feeding rate, ρ is the density of the wire. Another approach of calculating the deposition rate is that if the cross-section of the bead is approximated as a rectangle, its area can be calculated from the layer width and the layer height. Correspondingly, the deposition rate can also be calculated by Equation 5-6:

$$R = whv_a \rho \quad (5-6)$$

where w is the layer width, h is the layer height and v_a is the advancing speed of the MES. Equation 5-7 was obtained by combining Equations 5-5 and 5-6:

$$\rho \frac{\pi d^2}{4} v_w = whv_a \rho \quad (5-7)$$

Equation 5-7 can further be transformed into Equation 5-8:

$$\frac{v_w}{h} = \frac{4}{\pi d^2} wv_a \quad (5-8)$$

In this study, the layer width was determined primarily by the scanning width. The laser beam power P_L , the wire feed speed v_w and the scanning speed v_s are kept constant. If the advancing speed v_a stays the same, a larger scanning width w_s would lead to a lower scanning frequency F_s and a fewer number of interactions n_i , and consequently a lower specific point energy E_{sp} according to Equations 5-2, 5-3 and 5-4. To keep the same specific point energy for a larger scanning width, the advancing speed needs to be lowered to maintain the same number of interactions. Therefore, in Equation 5-8, wv_a is kept constant to maintain the same specific point energy. Correspondingly, $\frac{v_w}{h}$ is kept constant. Therefore, in

this strategy, the layer width was determined by the scanning width, the advancing speed was determined by the scanning width, and the layer height was determined by the wire feeding rate.

A bead shape control experiment was determined to evaluate the bead shape control strategy. Twenty cases with five different layer heights and four different layer widths were tested to prove the independence of the width and the height controls of the bead shape. Table 5-5 lists the scanning widths and the corresponding advancing speeds for different layer widths, and Table 5-6 lists the wire feeding speeds for different layer heights. A set of PTA-only experiments were also tested with all four advancing speeds using a constant wire feed speed of 6 mm/s without the SL reshaping to compare with the MES before the MES experiments.

Table 5-5 Varied scanning widths and the corresponding advancing speeds.

Scanning width w_s / (mm)	Advancing speed v_a / (mm/s)
16.5	0.8
20.0	0.67
23.0	0.57
26.5	0.5

Table 5-6 Varied wire feed speeds.

Wire feeding speed v_w / (mm/s)
6
12
18
24
30

5.2.4 MES wall building

5.2.4.1 MES wall building with different layer heights.

After the bead shape control study, three wall building cases were carried out using three different layer heights. The parameters are listed in Table 5-7. When

initialising the MES melt pool, the SL started with a smaller scanning width of 10 mm and increased to the targeted scanning width by steps.

Table 5-7 Parameters for wall building with different layer height.

	Wall1	Wall 2	Wall 3
Scanning width w_s / (mm)	20	20	20
Advancing speed v_a / (mm/s)	0.67	0.67	0.67
Wire feeding speed v_w / (mm/s)	6	12	24
Number of layers	26	13	9

5.2.4.2 MES wall building with different SL energy distributions.

Two different SL energy distributions were used to construct two walls to study the influence of SL energy distribution on the narrowing of the width during MES multilayer deposition. The larger scan width is 26.5 mm to observe the width changes better. The parameter sets that were used are listed in Table 5-8. The scanning speed arrangements and SL energy distribution profiles are diagrammed in Figure 5-7. The scanning speed decelerated at the edges to respectively 25% (1030 mm/s) in Profile 3 and 10% (413 mm/s) in Profile 4.

Table 5-8 Parameters for wall building with different SL energy profiles.

	Wall4	Wall 5
Scanning width w_s / (mm)	26.5	26.5
Advancing speed v_a / (mm/s)	0.5	0.5
Wire feeding speed v_w / (mm/s)	12	12
Number of layers	13	13

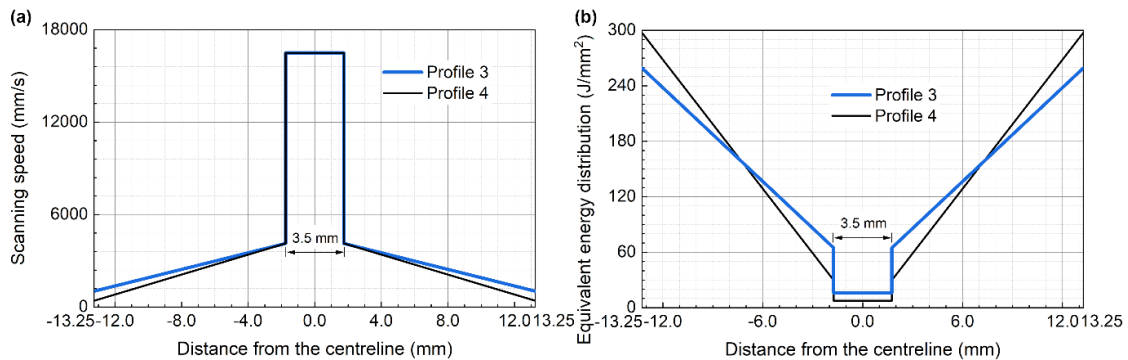


Figure 5-7 Energy profiles for wall width study: (a) scanning speed along the scanning path, and (b) equivalent energy distribution along the scanning path.

5.2.4.3 Microstructure and microhardness.

Microstructure and microhardness were analysed on the Wall 1 cross-section to analyse the microstructure isotropic of the MES process. Images at six positions, as indicated in Figure 5-8, were captured using an optical microscope (OM). The Vickers hardness testing was done at room temperature along two lines on the cross-section, which are the vertical centre line and the horizontal line at the half height, as shown in Figure 5-8. A 200g load was applied for 15 seconds at a spacing of 1 mm.

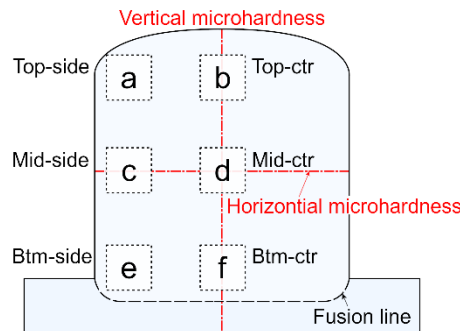


Figure 5-8 Microhardness along two directions and positions of the OM images: (a) top-side, (b) top-centre, (c) middle-side, (d) middle-centre, (e) bottom-side, and (f) bottom-centre.

5.3 Results and discussion

5.3.1 Shape control strategy

5.3.1.1 SL-PTA distance experiment

Figure 5-9 shows the MES process results using different SL-PTA distances (d_1). From the front ends of the beads, the melt pools can be seen slightly changed with the SL-PTA distance. With a faraway SL-PTA distance of 10.5 mm, the PTA and the SL melt pools did not merge (Figure 5-9a). A gap of approximately 2 mm is shown between the two melt pools. When moving the PTA closer to the SL,

the end of the PTA melt pool overlaid with the SL melt pool, and a hybrid melt pool was formed with the shape gradually transformed to a slightly wedged shape (Figure 5-9b). By narrowing the SL-PTA distance to 2.5 mm, most of the PTA melt pool overlaid with the SL melt pool, and a triangle shape hybrid melt pool was formed (Figure 5-9c). Figure 5-10 shows the cross-section images of these three beads. Incomplete fusion can be found in these cross-section images with SL-PTA distances of 10.5 mm and 2.5 mm (Figure 5-10a and Figure 5-10c), whereas no defect is found with an SL-PTA distance of 6.5 mm (Figure 5-10b). That is to say that even though the processes were continuous and stable, a too close or too far away distance between the scanning laser and the PTA will cause defects. When the PTA melt pool and the SL melt pools were separated, the cause of the incomplete fusion could be that the substrate at the middle of the SL was already solidified and could not be remelted by the SL. When having a too close SL-PTA distance, the possible reason for the defect could be that the SL scanned above the PTA and was affected by the PTA plasma body, which led to an unstable melt pool. Based on the results, an optimised distance of 6.5 mm was selected for the MES experiments.

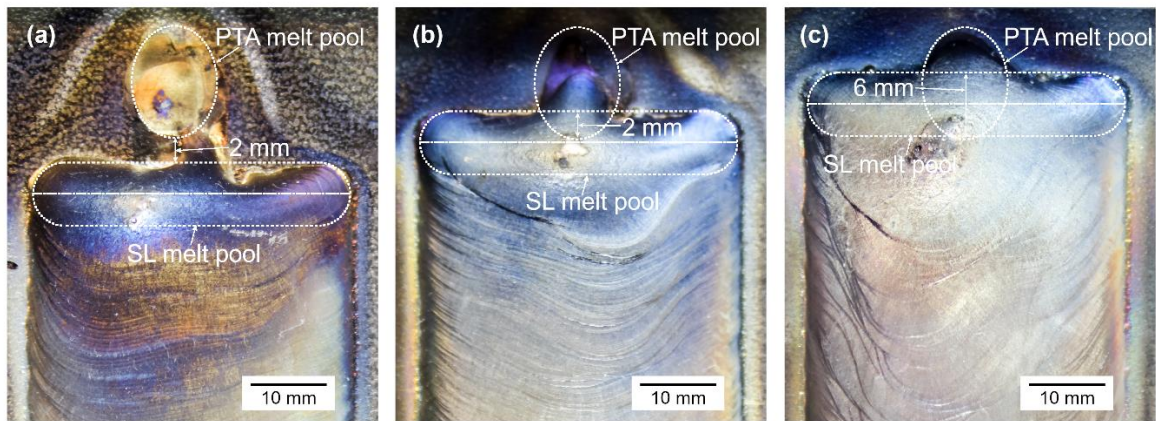


Figure 5-9 SL-PTA distance experiment results – melt pool images: (a) $d_1 = 8.5$ mm, (b) $d_1 = 6.5$ mm, and (c) $d_1 = 4.5$ mm.

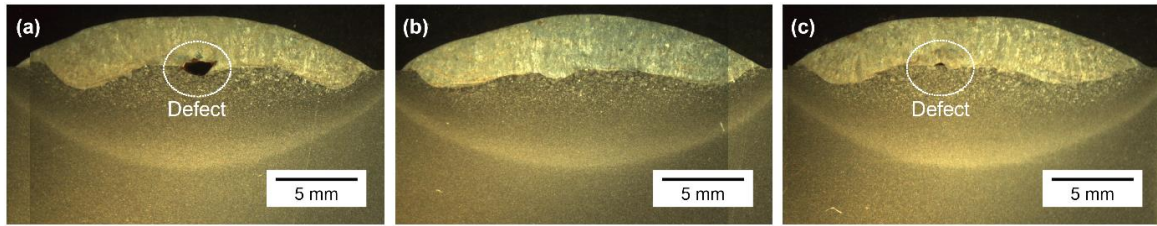


Figure 5-10 SL-PTA distance experiment results - cross-sections: (a) $d_1 = 8.5$. (b) $d_1 = 6.5$, and (c) $d_1 = 4.5$.

5.3.1.2 SL energy distribution experiment

Figure 5-11 shows the melt pool images with different SL energy distributions shown in Figure 5-5. Although the same scanning width was used for both profiles, the bead width of one using Profile 1 is significantly narrower than the one using profile 2. When using Profile 1 with evenly distributed energy at side regions (Figure 5-11a), the melted metal failed to be spread to the two ends of the scanning width of 21.5 mm, and a layer width of 17.6 mm was formed. When using Profile 2, more energy was provided at the edges, and the melt pool was spread across the whole scanning width with a layer width of 22 mm (Figure 5-11b). In the bead cross-section images, the penetration with the profile 1 SL (Figure 5-12a) at the middle is deeper than the Profile 2 SL (Figure 5-12b). That indicated that with Profile 1, more energy was concentrated at the centre, while the edges were not melted sufficiently due to the lack of energy. Wettability at the edges was therefore restricted. The total energy of these two profiles is the same, and only the energy distribution was adjusted. The temperature field of the PTA is higher at the centre and gradually decreases on two sides. As a result, the SL energy that was needed to heat the material and generate the melt pool was lower at the centre and higher at the sides. This experiment shows that a profiled SL can improve the broadening of the melt pool and spread across the whole scanning width.

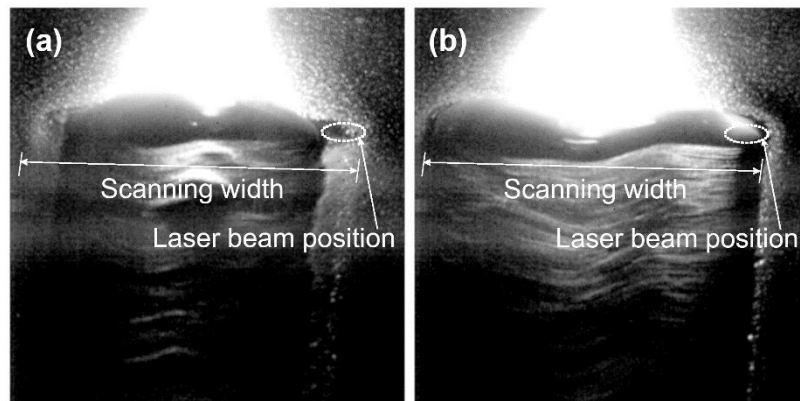


Figure 5-11 SL energy distribution experiment results –melt pool images: (a) with Profile 1 SL, and (b) with Profile 2 SL.

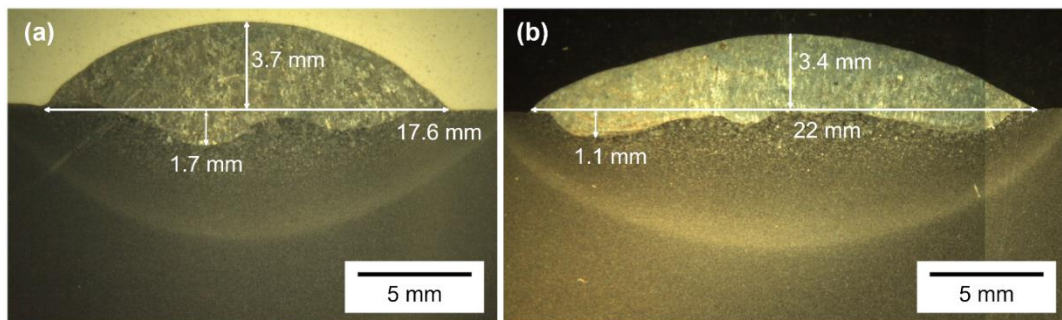


Figure 5-12 SL energy distribution experiment results –cross-section: (a) with Profile 1 SL, and (b) with Profile 2 SL.

5.3.2 Bead shape control experiment.

Figure 5-13a shows the bead geometry of the PTA-only process. The even and continuous ‘stack of dimes’ bead surface indicates that the process was stable, and the droplet transfer was smooth and even. Figure 5-13b shows the SL reshaped bead surfaces with different scanning widths. The surface roughness is fine with a smooth texture. The edges of the bead are straighter compared to the PTA-only process. The cross-section of the PTA-only bead in Figure 5-14a shows that the fusion between the added material and the substrate was sufficient, indicating that the substrate can be sufficiently melted by the PTA. Figure 5-14b further shows the cross-section shape of the corresponding SL

reshaped bead. The fusion between the added material and the substrate was sufficient without defect. Compared to the PTA-only process, the layer height was significantly lowered, and the layer width was increased, forming a rather flat cross-section shape. The penetration depth, however, was not dramatically affected. The SL only reshaped the melt pool but did not increase the penetration of the PTA initial melt pool. Figure 5-15 shows the images of the SL reshaped melt pool with changing scanning width. It can be observed that the ellipse-shaped PTA melt pool was spread and reshaped to a continuous wide-brimmed hat shape, with an ellipse-shaped front and bar-shaped back. Figure 5-16 shows the correlation between the layer width and height and the advancing speed. The layer height of the PTA-only bead decreased from 3.2 mm to 2.4 mm, and the layer width decreased from 7.6 mm to 6.7 mm when the advancing speed was increased from 0.5 mm/s to 0.8 mm/s. After reshaping by the SL, the layer height was kept to a more constant level between 0.7 mm and 1.0 mm, and the layer width decreased from 27 mm to 18 mm when increasing the advancing speed.



Figure 5-13 Comparison of the bead surface geometries: (a) PTA-only ($v_a = 0.5$ mm/s), and (b) SL-reshaped ($v_a = 0.5$ mm/s, $w_s = 26.5$ mm).

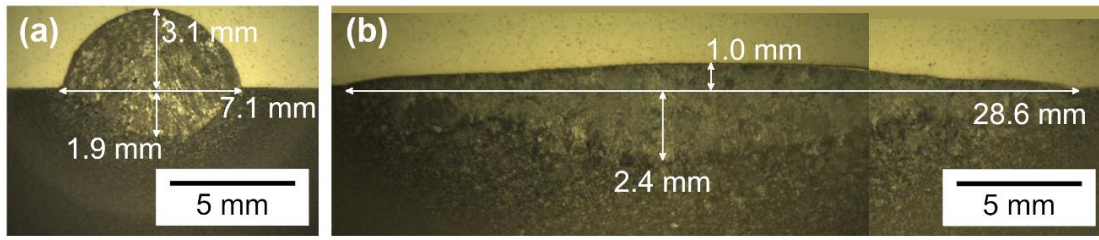


Figure 5-14 Comparison of the bead cross-sections: (a) PTA-only ($v_a = 0.5$ mm/s), and (b) SL-reshaped ($v_a = 0.5$ mm/s, $w_s = 26.5$ mm).

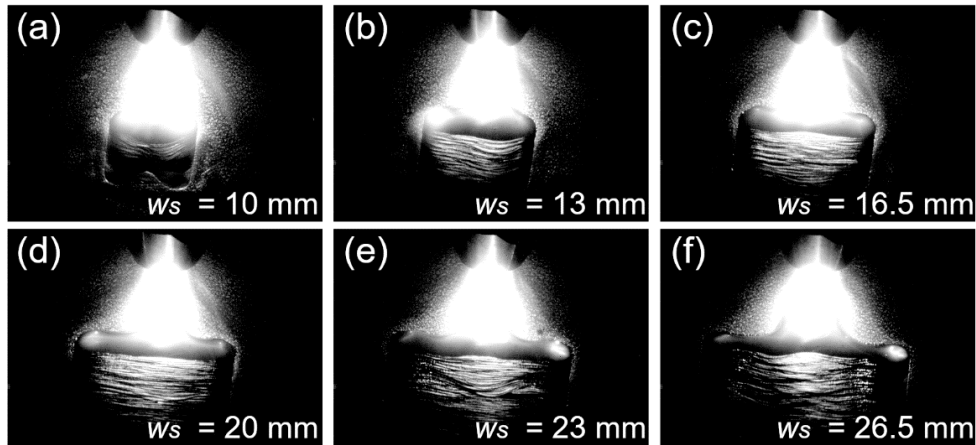


Figure 5-15 Images of the SL reshaped melt pool with different scanning widths: (a) $w_s = 10$ mm, (b), $w_s = 13$ mm, (c) $w_s = 16.5$ mm, (d) $w_s = 20$ mm, (e) $w_s = 23$ mm, and (f) $w_s = 26.5$ mm.

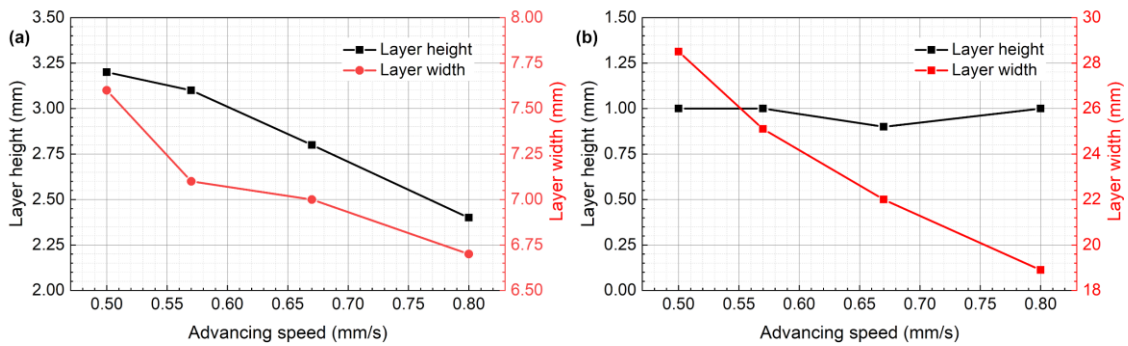


Figure 5-16 Correlation of layer height and width vs advancing speed: (a) PTA-only, and (b) SL-reshaped.

Ideally, a flat layer shape with round edges and small contact angles is required for w-DED AM. In this study, the SL-reshaped section shape is flatter, and the contact angle is relatively smaller, which is closer to the ideal layer shape.

Figure 5-17a is a scatter chart that shows the layer widths and layer heights of all 20 beads. We can see that those points are evenly distributed within a rectangular area in the diagram. All the bead sections in Figure 5-17b show good fusion between the fed material and the substrate. That means independence of the layer width and the layer height, with any combination within the rectangular chart possible.

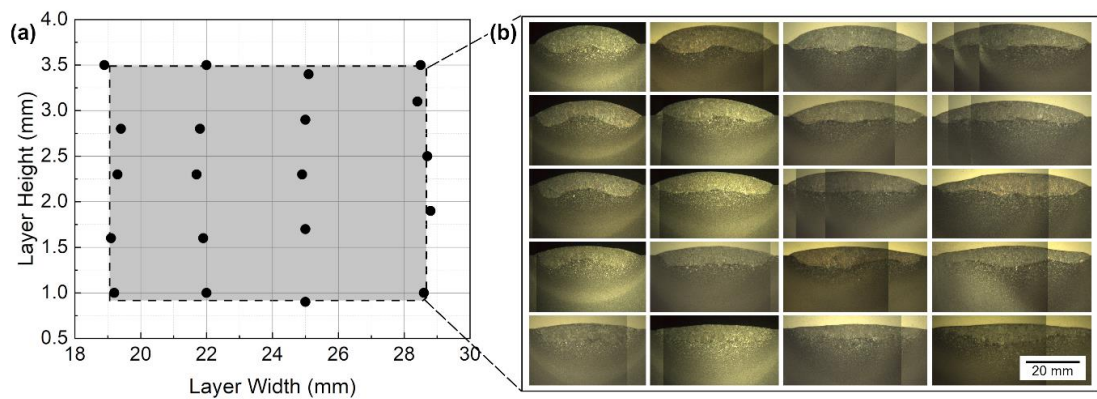


Figure 5-17 (a) Scatter chart of layer height vs layer width correlation, and (b) cross-section images.

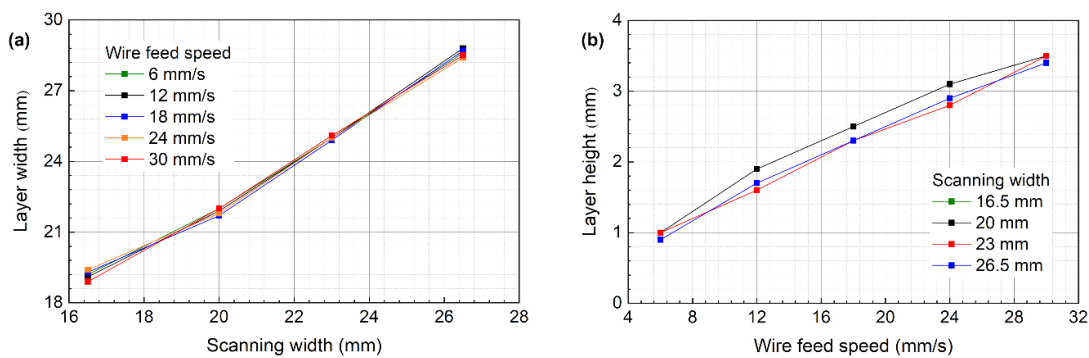


Figure 5-18 (a) Diagram of layer width with various scanning width at different wire feed speeds, and (b) diagram of layer height with various wire feed speed at different scanning widths.

Figure 5-18a shows the correlation between the scanning width and the layer width. Despite using different wire feeding speeds, the layer width is shown as a highly linear function of the scanning width. This further shows that the layer width was only determined by the scanning width. The layer widths are slightly wider than the scanning width because the laser beam dimension needed to be taken into account when the melt pool was formed.

Figure 5-18b shows the correlation between the wire feeding rate and the layer height. Similar to the layer width and the scanning width, the layer height is shown as a highly linear function of the wire feeding rate. That shows that the bead shape strategy of using the wire feeding rate to control the layer height is applicable. However, as the assumption of a rectangular bead shape was made, which the actual bead shape is not strictly followed, the correlation between the layer height and the wire feeding speed slightly deviates. Table 5-9 lists the width-height aspect ratios calculated by dividing width by height. The aspect ratios range from 5.4 to 28.6

Table 5-9 Width-height aspect ratios of all 20 cases.

$w_s / (\text{mm})$ $v_w / (\text{mm/s})$	16.5	20	23	26.5
6	19.2	22.0	27.8	28.6
12	11.9	13.7	14.7	15.2
18	8.4	9.4	10.8	11.5
24	6.9	7.8	8.6	9.2
30	5.4	6.3	7.4	8.1

5.3.3 MES wall building.

Figure 5-19 shows the geometry of the MES deposited wall from both the top and the side. A smooth surface finish quality is presented. Figure 5-20 shows the cross-sections with different layer heights but constant width determined by the scanning width. Wall 1 with thinner layers has a straight outline of the side surface (Figure 5-20a). Walls 2 and 3 were built with increased layer heights of 1.3 mm and 2.3 mm. The bead shape became less stable because more material was

added to the melt pool, and the side surface quality slight dropped (Figure 5-20b and Figure 5-20c). Slight collapse can be observed at the side of Wall 3 (Figure 5-20c).

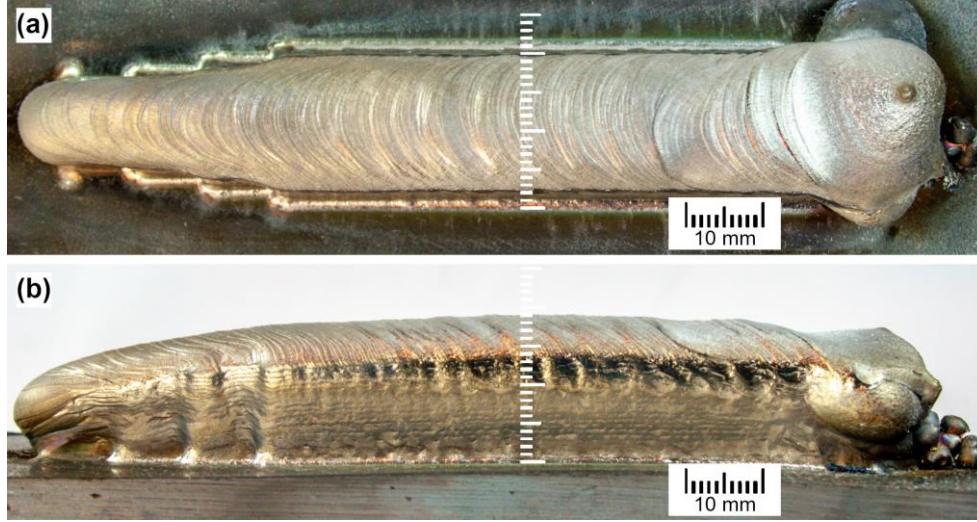


Figure 5-19 SL-PTA MES built walls ($w_s = 20$ mm, $v_w = 6$ mm/s): (a) top view, and (b) side view.

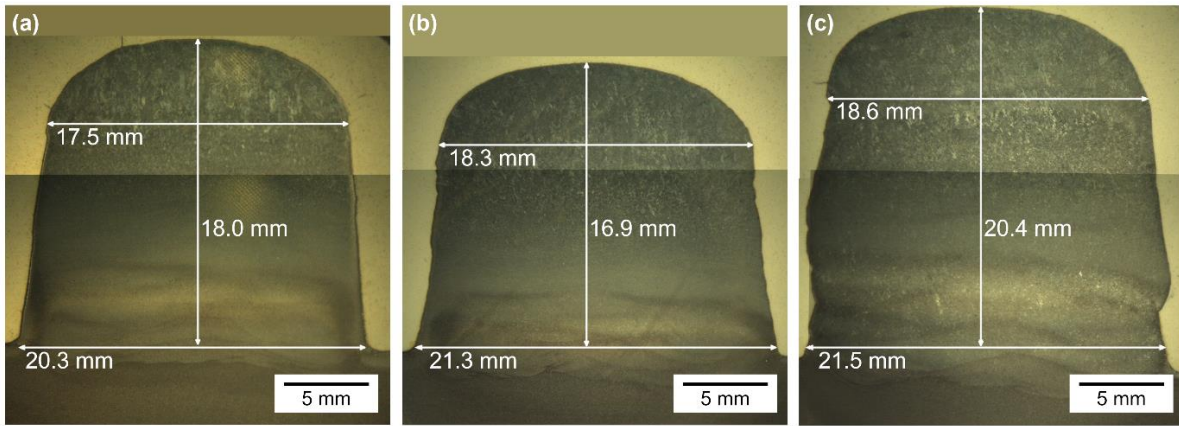


Figure 5-20 SL-PTA MES built walls cross-sections: (a) layer height = 0.7 mm, $v_w = 6$ mm/s, (b) layer height = 1.3 mm, $v_w = 12$ mm/s, and (c) layer height = 2.3 mm, $v_w = 18$ mm/s.

The width of all three walls narrowed from the bottom to the top. Another two walls were built with SL energy Profile 3 and 4 and a larger scanning width to analyse the possible reason for this phenomenon and a larger scanning width for a better observation of the width change. Figure 5-21 shows the cross-sections of the two walls. With more energy arranged at the edges, the width difference

between the bottom and the top was reduced from 5.8 mm to 3.6 mm, with a thinner layer height and wider wall width at both the bottom and the top. This indicates that SL energy distribution with more energy at the edges can contribute to reducing the width narrowing.

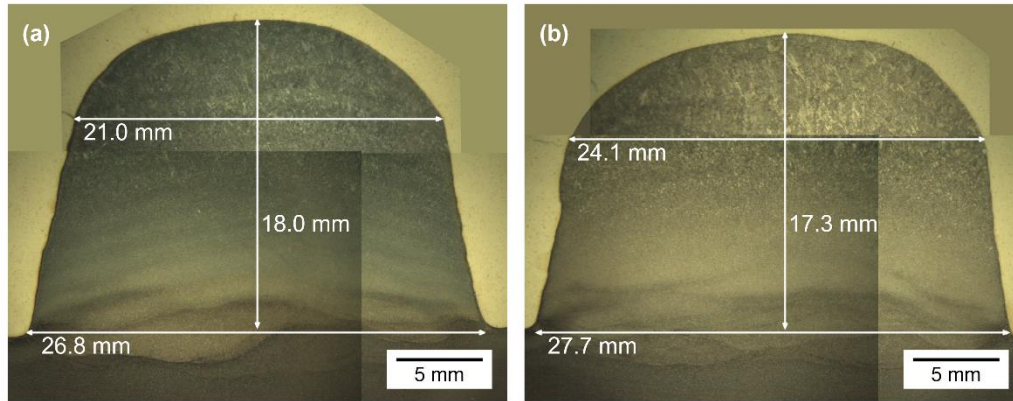


Figure 5-21 SL-PTA MES built walls cross-sections ($w_s = 26.5$ mm): (a) 25% scanning speed at the edges, and (b) 10% scanning speed at the edges.

A possible explanation for this issue can be that the top surface of each layer was not flat but transformed into a camber-shaped top surface. As illustrated in Figure 5-22, when the laser beam reached the edge of the cambered top surface, the laser beam was not vertical to the surface but with an angle. The interaction area of the laser beam was broadened due to the area sloping at the edges. The energy density was reduced because of the larger interaction area, and energy efficiency might be changed. Wettability was weakened at the edges, leading to the narrowing of the melt pool after each layer.

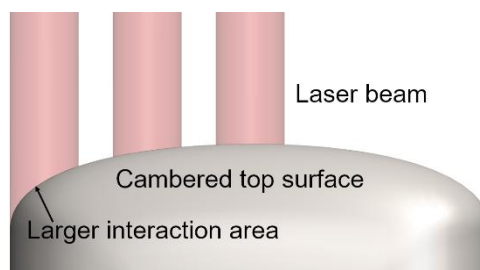


Figure 5-22 The interaction area changed when the laser beam approached the edge of the cambered top surface.

Figure 5-23 shows the OM images taken from the six positions indicated in Figure 5-8. The microstructure can be generally classified into pearlite (P), polygonal ferrite (PF), acicular ferrite (AF) and bainite ferrite (BF). Lee et al. [28] reported the formation of these microstructures as a function of cooling rate. PF is usually formed with slow cooling rates and relatively low strength. AF is characterised by fine and irregular-shaped grains alignment in arbitrary directions and has a good combination of strength and toughness. BF is usually transformed at low temperatures and rapid cooling rates with lath-type morphology and high dislocation density. The microhardness of BF is relatively high but brittle. Figures 5-23a and b show the microstructures at the bottom of the Wall 3 cross-section. Air convection and less thermal cycling at the top position of the wall contributed to a fast cooling rate, which resulted in the formation of majorly BF and minorly PF microstructure. The half-height position of Wall 3, as presented in Figures 5-23c and d, presents majorly AF and minorly PF microstructure. The cooling rate at the half-height position was slower than at the top position due to longer thermal cycling, contributing to the formation of more AF and less BF. The prior austenite grain size shows no essential difference between the side and the centre of the wall at the half-height position. Figures 5-23e and f show the OM images at the bottom of the Wall 3 cross-section close to the fusion line, respectively at the centre and the side. Microstructure presents a majority of PF with minor P. Remelting and prolonged thermal cycling were the dominating factors at the bottom of the wall instead of convection and conduction to the base plate. Consequently, the cooling rate is the slowest at this position, which contributed to the forming of PF. Figure 5-24a is the microhardness transition along the central line from the bottom to the top of the wall. Microhardness at the bottom is lower due to a higher content of PF. With the increase of AF and BF, microhardness rises to an average level of about 330 Hv and stays constant at the half-height and top positions of the wall. Overall, no significant microstructure difference is shown between the centre and the side regions of the wall. This is further proved by the evenly distributed microhardness along the wall width (Figure 5-24b), which is evidence that the SL did not affect the microstructure isotropy of the wall.

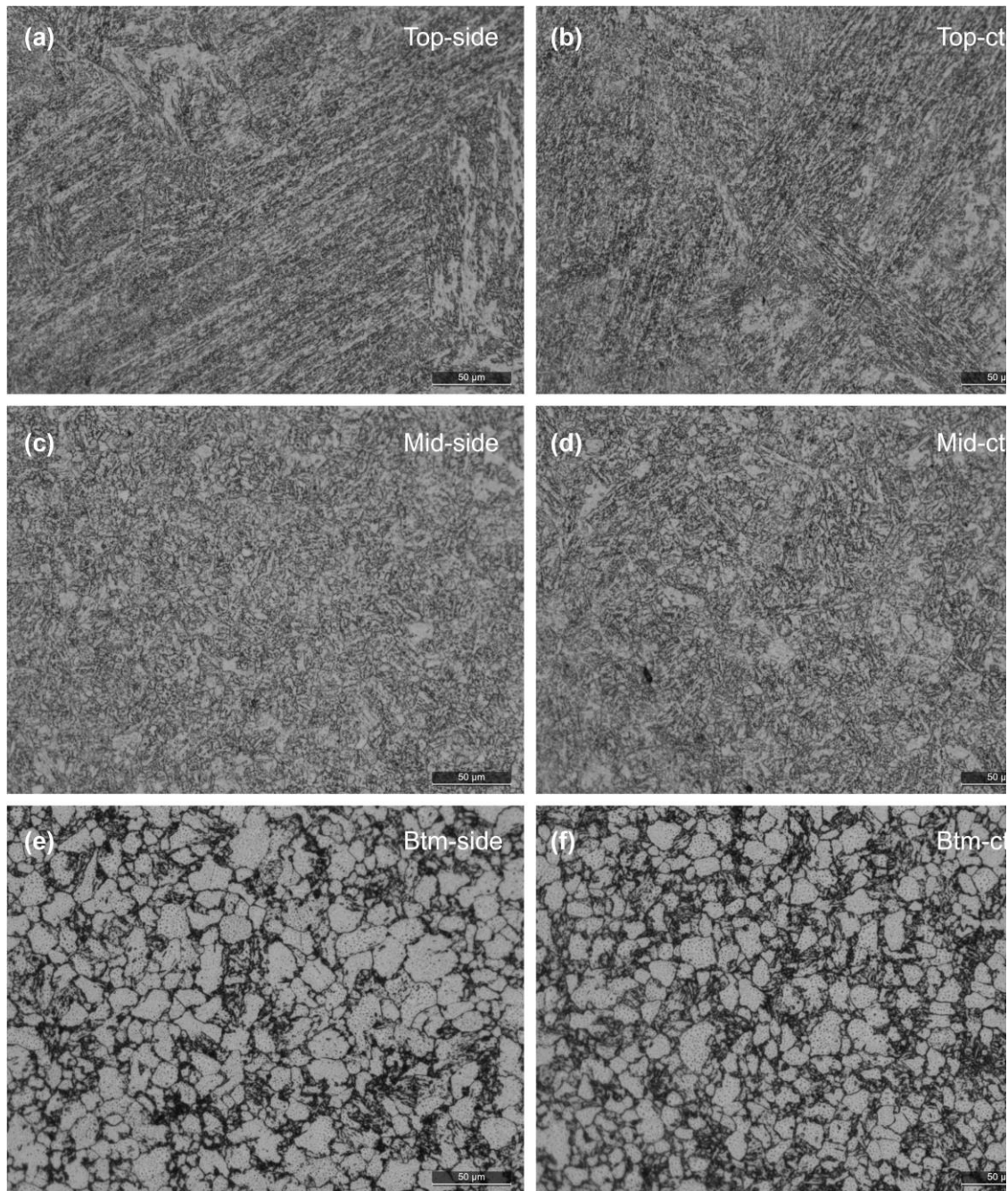


Figure 5-23 OM images of at different positions on the Wall 1 cross-section: (a) top-side, (b) top-centre, (c) middle-side, (d) middle-centre, (e) bottom-side, and (f) bottom-centre.

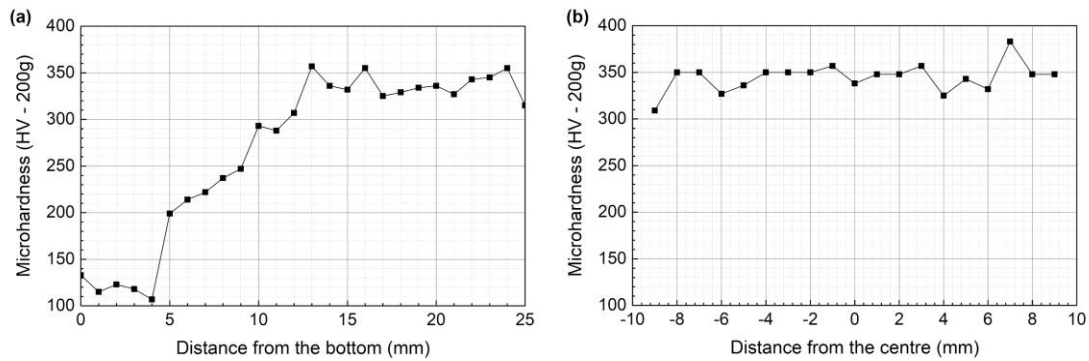


Figure 5-24 Microhardness along two directions: (a) vertical, and (b) horizontal.

5.3.4 Future work

The MES method has the capability to reshape the melt pool and achieve a broad range of bead shapes with high accuracy. It has the potential to dynamically change the layer width and the layer height during the deposition by programming the scanning width, advancing speed and the wire feeding speed. Layers with multi-section shapes can be easily deposited, and complex structures with near-net-shape can be built. Further studies are required to explore the capabilities of the MES w-DED AM utilising a dynamic scanning laser.

The mechanism of the width narrowing during the multi-layer deposition needs to be further studied and solved to achieve constant width for the part building. Therefore, understanding the mechanism behind this phenomenon is essential.

The MES can also contribute to the control of the thermal conditions independently of the bead geometry. In the conventional wire-based process, the energy input is difficult to adjust. Usually, in the conventional DED processes, a wider bead scale would lead to higher energy input and deeper penetration and affect the microstructure. The SL-PTA MES has the potential to control the energy input and improve the thermal gradient of the heat affect zone of the substrate and optimise the microstructure. The potential for independent thermal and geometry control should be studied as a mechanism to control the microstructure and properties of the deposited material.

5.4 Conclusions

1. By utilising a scanning laser in a multi-energy source system, a w-DED AM process has been developed that is capable of independent control of the layer height and width over a wide range.
2. A control strategy was developed where the layer width is controlled by the scanning width, and the layer height is independently controlled by the wire feed speed.
3. The plasma transferred arc scanning laser separation is a critical parameter to achieve a stable melt pool, thereby obtaining high-quality deposition without defects.
4. By adjusting the applied energy density across the scanning profile, much stable deposition can be achieved.
5. The layer width was reduced as n more layers were deposited during the multi-layer wall building showing that further process studies are required.

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5.6 Reference

- [1] DebRoy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., ... & Zhang, W. (2018). Additive manufacturing of metallic components—

process, structure and properties. *Progress in Materials Science*, 92, 112-224.

- [2] Guan, X., & Zhao, Y. F. (2020). Numerical modeling of coaxial powder stream in laser-powder-based Directed Energy Deposition process. *Additive Manufacturing*, 34, 101226.
- [3] Singh, A., Kapil, S., & Das, M. (2020). A comprehensive review of the methods and mechanisms for powder feedstock handling in directed energy deposition. *Additive Manufacturing*, 101388.
- [4] Baufeld, B., Brandl, E., & Van der Biest, O. (2011). Wire based additive layer manufacturing: Comparison of microstructure and mechanical properties of Ti-6Al-4V components fabricated by laser-beam deposition and shaped metal deposition. *Journal of Materials Processing Technology*, 211(6), 1146-1158.
- [5] Ding, D., Pan, Z., Cuiuri, D., & Li, H. (2015). Wire-feed additive manufacturing of metal components: technologies, developments and future interests. *The International Journal of Advanced Manufacturing Technology*, 81(1), 465-481.
- [6] Qi, Z., Cong, B., Qi, B., Sun, H., Zhao, G., & Ding, J. (2018). Microstructure and mechanical properties of double-wire+ arc additively manufactured Al-Cu-Mg alloys. *Journal of Materials Processing Technology*, 255, 347-353.
- [7] Cong, B., Qi, Z., Qi, B., Sun, H., Zhao, G., & Ding, J. (2017). A comparative study of additively manufactured thin wall and block structure with Al-6.3% Cu alloy using cold metal transfer process. *Applied Sciences*, 7(3), 275.
- [8] Dinovitzer, M., Chen, X., Laliberte, J., Huang, X., & Frei, H. (2019). Effect of wire and arc additive manufacturing (WAAM) process parameters on bead geometry and microstructure. *Additive Manufacturing*, 26, 138-146.
- [9] Martina, F., Mehnen, J., Williams, S. W., Colegrove, P., & Wang, F. (2012). Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 212(6), 1377-1386.
- [10] Almeida, P. M., & Williams, S. (2010). Innovative process model of Ti-6Al-4V additive layer manufacturing using cold metal transfer (CMT). In 2010

International Solid Freeform Fabrication Symposium. University of Texas at Austin.

- [11]Yehorov, Y., da Silva, L. J., & Scotti, A. (2019). Balancing WAAM production costs and wall surface quality through parameter selection: A case study of an Al-Mg5 alloy multilayer-non-oscillated single pass wall. *Journal of Manufacturing and Materials Processing*, 3(2), 32.
- [12]Schulz, M., Klocke, F., Riepe, J., Klingbeil, N., & Arntz, K. (2019). Process optimization of wire-based laser metal deposition of titanium. *Journal of Engineering for Gas Turbines and Power*, 141(5).
- [13]Abioye, T. E., Folkes, J., & Clare, A. T. (2013). A parametric study of Inconel 625 wire laser deposition. *Journal of Materials Processing Technology*, 213(12), 2145-2151..
- [14]Mok, S. H., Bi, G., Folkes, J., & Pashby, I. (2008). Deposition of Ti–6Al–4V using a high power diode laser and wire, Part I: Investigation on the process characteristics. *Surface and Coatings Technology*, 202(16), 3933-3939..
- [15]Näsström, J., Brueckner, F., & Kaplan, A. (2019). Measuring the effects of a laser beam on melt pool fluctuation in arc additive manufacturing. *Rapid prototyping journal*, 25(3), 488-495.
- [16]Näsström, J., Brueckner, F., & Kaplan, A. F. (2019). Laser enhancement of wire arc additive manufacturing. *Journal of Laser Applications*, 31(2), 022307.
- [17]Pardal, G., Martina, F., & Williams, S. (2019). Laser stabilization of GMAW additive manufacturing of Ti-6Al-4V components. *Journal of Materials Processing Technology*, 272, 1-8.
- [18]Zhang, Z., Sun, C., Xu, X., & Liu, L. (2018). Surface quality and forming characteristics of thin-wall aluminium alloy parts manufactured by laser assisted MIG arc additive manufacturing. *International Journal of Lightweight Materials and Manufacture*, 1(2), 89-95.
- [19]Miao, Q., Wu, D., Chai, D., Zhan, Y., Bi, G., Niu, F., & Ma, G. (2020). Comparative study of microstructure evaluation and mechanical properties of 4043 aluminum alloy fabricated by wire-based additive manufacturing. *Materials & Design*, 186, 108205.

- [20]Wu, D., Liu, D., Niu, F., Miao, Q., Zhao, K., Tang, B., ... & Ma, G. (2020). Al–Cu alloy fabricated by novel laser-tungsten inert gas hybrid additive manufacturing. *Additive Manufacturing*, 32, 100954..
- [21]Wang, C., Suder, W., Ding, J., & Williams, S. (2021). Wire based plasma arc and laser hybrid additive manufacture of Ti-6Al-4V. *Journal of Materials Processing Technology*, 293, 117080.
- [22]Rubben, K., Mohrbacher, H., & Leirman, E. (1997). Advantages of using an oscillating laser beam for the production of tailored blanks. *Lasers in Material Processing*, 3097, 228-241.
- [23]Yamazaki, Y., Abe, Y., Hioki, Y., Nakatani, M., Kitagawa, A., & Nakata, K. (2016). Fundamental study of narrow-gap welding with oscillation laser beam. *Welding international*, 30(9), 699-707.
- [24]Hao, K., Li, G., Gao, M., & Zeng, X. (2015). Weld formation mechanism of fiber laser oscillating welding of austenitic stainless steel. *Journal of Materials Processing Technology*, 225, 77-83.
- [25]Cai, C., Li, L., Tao, W., & Chen, X. (2017). Effects of weaving laser on scanning laser-MAG hybrid welding characteristics of high-strength steel. *Science and Technology of Welding and Joining*, 22(2), 104-109.
- [26]Montagu, J. (2015). Scanners: galvanometric and resonant. In *Encyclopedia of Optical and Photonic Engineering*, Second Edition (pp. 1-22). CRC Press.
- [27]Beiser, L. (1995). Fundamental architecture of optical scanning systems. *Applied optics*, 34(31), 7307-7317.
- [28]Lee, S. I., Lee, S. Y., Lee, S. G., Jung, H. G., & Hwang, B. (2018). Effect of strain aging on tensile behavior and properties of API X60, X70, and X80 pipeline steels. *Metals and Materials International*, 24(6), 1221-1231.

6 Summary, Conclusions, and Future work

6.1 Summary

The original hypothesis of this thesis is that an MES that combines the advantages of more than one energy source can achieve independent control of layer width and height for w-DED AM. When applying a high scanning frequency (typically above 100 Hz), it can be applied as an equivalent stationary energy source. The shape and energy distribution of this equivalent energy source can be designed and controlled during the DED process. By using the quasi-steady-state SL as a reshaping energy source, the shape of the DED melt pool can be precisely controlled. And due to higher energy efficiency, a PTA can be applied to generate an initial melt pool and melt the feedstock wire primary to the SL reshaping. In this way, the layer width can be therefore independently controlled by the SL.

Before the MES bead shape, the characteristics of each individual energy source need to be analysed to understand their limitations and advantages. Therefore, an energy source profiling study was carried out in Chapter 3 to investigate the energy distributions of different energy sources. In the previous research, the reliability of the SAC method was not fully verified. In this study, a laser beam that was measured by the rotating hollow needle method was used to calibrate the SAC method. The arc distortion issue is one of the challenges when measuring a PTA. An effective modified SAC method was introduced to reduce the arc distortion during the PTA measurement by placing the grounding under the copper anode plates. The energy distribution of PTA was then measured using the modified SAC. By using the modified SAC, the energy distribution of PTA with different parameters was obtained. The influence of those parameters on the PTA energy distribution was analysed, which provides the numerical basis for the study of the MES thermal analysis. The limitations and advantages of using a PTA as a single energy source were understood. The limitation can be concluded that the PTA energy distribution is restricted with limited manipulability. The spot size and energy profile can only be changed within a limited range.

The limitation of the PTA bead shape control ability has been demonstrated in Chapter 4, and the necessity of finding a precise reshaping energy source was revealed. Based on that, the feasibility of using the SL as a reshaping energy source in the MES was further studied in Chapter 4. The dynamic thermal characterisation of a SL process was studied using both experimental and numerical approaches. SL experiments were conducted with different oscillating frequencies and laser beam sizes. Thermal images and highspeed images were captured to analyse the thermal dynamics of the SL melt pool. Results showed that the oscillating frequency could have a significant effect on the SL interaction mode, especially with a smaller beam size. A keyhole mode interaction can ensure a high absorptivity, while a transition mode interaction has a low absorptivity. Both keyhole mode and transition mode generate unstable melt pools. SL process with a conduction mode could benefit a good absorption rate and stable melt pool. Compared to smaller beam sizes, conduction mode interaction was easier to be achieved with a larger beam size. In the SL simulation, an innovative solution dependent convection boundary (SDCB) method was introduced to reduce the element amount of the finite element (FE) model. In this method, the surrounding material of the bead region was replaced by SDCB interfaces that simulated the thermal conduction. A full-scale model was calibrated by the experimental thermal histories. The results of the SDCB partial model were compared to the full-scale model. It showed that SDCB successfully simulated the thermal conduction of the adjacent material around the bead region. Over 86% of the computing time was reduced. Both the experimental and numerical results show that the melt pool shape reached a quasi-steady state when the oscillating frequency reached 13.6 Hz and more, and the equivalent energy source model can be used to replace the SL transient energy source model. The availability of using SL as a designable reshaping energy source was verified.

Finally, in Chapter 5, an SL-PTA MES system was developed to test the hypothesis of using an MES to achieve high flexibility bead shape control with independent control of layer width and height. In the MES system, a PTA was employed in the front to create an initial melt pool and melt the wire, and an SL

was positioned behind the PTA to reshape the melt pool. The process was stable and consistent without splatter. The bead surface quality is good and with high accuracy. Some primary experiments, which included the SL-PTA distance study and the SL energy distribution study, were tested before the MES bead shape control study to achieve a stable process. The results showed that either a too close or too far away SL-PTA distance would lead to defects. The SL energy distribution can be manipulated by changing the scanning speed at different positions of the scanning pattern. An SL energy distribution with more energy arranged at the sides can benefit the broadening of the melt pool. Images of the melt pool with different scanning widths were captured during the process and showed that the SL successfully spread out the melt pool initialised by the PTA. In the MES system, more parameters can be adjusted to change the outcome of the process. A bead shape control strategy was demonstrated by using the wire feeding rate to control layer height and the laser scanning width to control the layer width independent of each other. The advancing speed was adjusted in proportion to the scanning width to keep the same specific process energy of the SL. Single layers with varying layer width and height were deposited. The results showed that layer width and height could be independently controlled with high accuracy. Several walls were built by the MES method. This shows that MES is capable of the multi-layer w-DED process. However, the layer width reduced when more layers were deposited and sloped side surfaces were formed. Two walls deposited with different SL energy distributions were compared to investigate the cause of the width reducing issue. The results showed that the width reducing problem could be mitigated by arranging more energy at the sides.

Overall, this thesis has shown that the MES can achieve precise bead shape control with independent control of the layer width and height for the w-DED process and has the potential to be applied in the future MES w-DED AM.

6.2 Conclusion

1. A laser beam measured by the hollow needle diagnosis system can be used to calibrate the SAC method. It showed that the SAC could generate a clear and detailed energy profile of a stable electric arc. Ground wire position has

a significant influence on arc behaviour in the SAC. Centralised and even distance between the arc spatial section and the ground wire location can remarkably reduce the arc distortion during the interface traverse. A more symmetrical profile can be generated. Slight fluctuations of the measured profile were not brought by instrument noise but caused by erratic movement of the arc root. This kind of erratic movement was led by the incomplete rigidity of the plasma body and is therefore unavoidable. Still, defects of the individual profiles can be mitigated by averaging the repeated measurement results.

2. The plasma column of the current profile is more concentrated and narrower than the temperature profile. And the temperature profile that was calibrated by the laser experiment reflects the energy absorption distribution of the arc directly. The absorption rate of the arc energy in this study is about 56%. A Gaussian model fits the measured profile well with a radius of about 7 mm.
3. By using a 4 mm laser beam with 2.7 kw power and 3.4 mm/s advancing speed, the melt pool shape became a quasi-steady state with a low oscillating frequency of 13.6 Hz. In the SL simulation, the quasi-steady-state SL can be replaced by an equivalent bar-shaped energy source. The SDCB method can be applied to replace the thermal conduction of the adjacent material. 86% of the computing time was saved. A conduction mode was easier to maintain when using a larger beam size of 4 mm. The interaction mode might turn to transition mode and keyhole mode with a smaller beam size (2 mm and 1 mm), which led to an unstable melt pool.
4. The quasi-steady-state SL has the capability to reshape and control the melt pool in the MES system. The layer width and the layer height can be controlled independently. By applying the bead shape control strategy, the layer width can be controlled by the scanning width, and the layer height can be controlled by the wire feed speed. The SL-PTA distance is essential to achieve a stable melt pool. Either a too close or too far away distance would lead to defects. Profiled energy distribution of the SL can contribute to broadening the melt pool. The layer width was narrower when more layers were deposited during the multi-layer wall building.

6.3 Future work

Several areas of this research can be continued by the author or others, which are listed below:

6.3.1 PTA SAC measurement

In this thesis, one of the causes of the arc distortion was discussed and revealed, and centre grounded SAC was introduced to reduce the arc distortion. However, as mentioned in the discussion in Section 3.1, arc distortion was still presented during the measurement of the PTA. The mechanism of the arc distortion was not fully understood. Further investigation can focus on analysing the other causes of the arc distortion and provide effective ways to stabilise the plasma body further to obtain symmetric PTA energy profiles.

PTAs with an initial range of parameters were measured in this work. To fully understand the energy distribution of a PTA and how it reacts to the changes of different parameters, PTAs with a wider range of parameters need to be measured. The effects of current intensity, arc length, PGC and PGFR on the spot size, energy efficiency and energy profile need to be further analysed.

6.3.2 The SDCB method

In the SL study presented in Chapter 4, the SDCB method was introduced and successfully reduced the element amount of the model. The iterative function of the SDCB that determined the changing of the adjacent material temperature was an empirical model. However, this iterative function is related to many characterisations of the substrate, such as the substrate scale, the material properties, room temperature, convection coefficient of the ambient cooling, etc. Future studies can focus on the analysis of the relationships between these characterisations and the iterative function of the SDCB.

6.3.3 Interaction mode of the SL process

In the quasi-steady state SL study in Chapter 4, the interaction mode under the condition of different laser beam sizes was investigated. A general conclusion was made that a conduction mode was easier to be reached when using a larger

beam size laser. However, the interaction mode of the SL is determined by the combination of interaction times, the number of interactions, the time gap between two interactions, laser power density, laser beam size, etc., which further correlated to the oscillating frequency and the advancing speed of the SL. Future research can investigate the condition of achieving a conduction mode for the SL DED process.

6.3.4 MES bead shape control

In Chapter 5, the bead shape control study was carried out by using an SL-PTA MES setup. The results have shown the great potential of the MES system bead shape control. A width changing wall deposition test was also presented to show that the MES bead shape can be programmed and dynamically changed during the process. This means that the MES method has the potential to be applied in the future w-DED AM and become a breakthrough in the metal AM that requires higher precision and larger scale. More importantly, the melt pool reshaping of the MES is dynamically designable and potentially programmable, which means that it can be integrated into an intellectual AM system in the future and contribute to the next generation of flexible manufacturing. In the future study, SL with higher power can be applied, and the width narrowing issue during wall building needs to be fixed. Later, an application study with the MES for building complicated structures can be conducted.

6.3.5 Challenges and opportunities

As addressed in the literature review in Chapter 2, the main challenges for w-DED AM mainly include manufacturing accuracy, quality assurance and demand for an automation system. At the same time, there are also opportunities for the development of w-DED AM with the concept of Industry 4.0 being put forward. The concept of Industry 4.0 was proposed for the fourth industrial revolution, which addressed the integration of automation, cloud computing, Big Data and Internet of Thing (IoT) in the modern manufacturing industry. Additive manufacturing plays a vital role in Industry 4.0. With the development of Industry 4.0, additive manufacturing technology will be widely used to produce small batches of customized products that offer construction advantages, such as

complicated, lightweight designs. Efficient additive manufacturing systems will reduce transport distances and stock on hand. At the same time, the advanced information technologies in industry 4.0 could also promote the development of AM. The concept of IoT could help to realize the unmanned workshops for w-DED AM, and the manpower can be saved efficiently. The concept of Big Data will help to realize the data sharing and processing, which could improve the CAD design, process optimization, and quality control for w-DED AM. The MES contributes to higher accuracy, higher building rate and flexible shape control, which can boost industry 4.0 upgrading in w-DED AM.

The emergence of AI technology will also promote the development of w-DED AM. Some scholars have proposed to apply AI in WAAM. AI is an essential process which includes learning, reasoning and self-correction. AI programs and controls machines similar to human intelligence. It is also an essential part of Industry 4.0, which copies intelligent human behaviour. It involves the applications of the computerized program in specialized machine automation that efficiently perform non-repetitive and complex tasks with robots. Thus, there is very little intervention whereby save the labour cost. Industry 4.0 is a connected ecosystem that increases communication, monitoring and automation. By combining the numerical analysing technique with AI technique, process predicting can be realised and integrated into the computerized program to achieve specialized machine automation. The high flexibility of the MES also allows a realization ability of the system.