

CRANFIELD UNIVERSITY

WAI JUN LAI

MITIGATION OF START/STOP DEFECTS IN CIRCUMFERENTIAL
LASER AND HYBRID LASER WELDING OF TUBULAR
OFFSHORE STRUCTURES

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
PhD in Renewable Energy Marine Structures (REMS)

DOCTOR OF PHILOSOPHY
Academic Year: 2020 - 2021

Supervisor: Dr Supriyo Ganguly
Associate Supervisor: Dr Wojciech Suder
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This thesis is submitted in fulfilment of the requirements for the
degree of Doctor of Philosophy

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ABSTRACT

In recent years, the offshore wind industry's growth and increased demand for larger and stronger offshore wind turbines have led to significant research into the joining and manufacture of thick section tubular structural steels. Advances in joining processes, such as high productivity laser and hybrid laser welding, will reduce lead times and manufacturing costs of offshore wind turbine support structures compared to conventional arc welding processes. However, defect formation associated with laser keyhole initiation and termination at the weld intersection of circumferential welds and methods of mitigation is not fully understood nor documented. Therefore, to enable high productivity laser and hybrid laser welding for circumferential welding applications, further research into the mitigation of defects at the weld intersection of circumferential welds due to laser and hybrid laser weld start and stops are necessary.

In this thesis, investigations into factors affecting the formation of laser keyhole initiation and termination related defects at the weld overlap start/stop region and methods of mitigation were carried out, by controlled experimentation, for both laser and hybrid laser-arc welding processes. Defect formation at the weld overlap start/stop region were monitored using weld cameras and characterised using optical microscopy.

The underlying cause of defects at the weld overlap start/stop region in laser keyhole, and hybrid laser-arc welding is associated with keyhole collapse and instability during laser termination. These defects can be successfully mitigated using various weld termination regimes, such as laser power ramp-down and laser defocusing in autogenous laser keyhole welding, and a combination of laser power ramp-down and arc current sloping in hybrid laser-arc welding. Results show that the amount of deoxidising elements in the steel influences the weld penetration depth and defect formation in the steady-state welding condition and during the application of a laser termination regime in autogenous laser keyhole welding.

Keywords:

Laser keyhole welding, Laser weld termination, Weld start/stop defects, Laser power ramp-down, Laser defocusing.

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LIST OF ABBREVIATIONS

OWT	Offshore Wind Turbine
SAW	Submerged Arc Welding
GMAW	Gas Metal Arc Welding
SMAW	Shielded Metal Arc Welding
FCAW	Flux-Cored Arc Welding
LW	Laser Welding
HLW	Hybrid Laser Welding
HAZ	Heat-affected Zone
HL-AW	Hybrid Laser – Arc Welding
HL-GMAW	Hybrid Laser – Gas Metal Arc Welding
TMCP	Thermo-Mechanically Controlled Processes
HL-SAW	Hybrid laser – Submerged arc welding
GTAW	Gas Tungsten Arc Welding
PAW	Plasma Arc Welding
VPPAW	Variable Polarity Plasma Arc Welding
FZ	Fusion Zone
BM	Base Material
BOP	Bead on Plate
DIC	Digital Image Correlation
GBF	Grain Boundary Ferrite
PF	Polygonal Ferrite
AF	Acicular Ferrite
WF	Widmanstätten Ferrite
SEM	Scanning Electron Microscope
CMT	Cold Metal Transfer
P-MIG	Pulsed – Metal Inert Gas
CTWD	Contact Tip to Workpiece Distance
WFS	Wire Feed Speed

Chapter 1

Introduction

1.1 Background and motivation

1.1.1 Offshore wind structures

Over the past decade, there has been a substantial increase in offshore wind turbine (OWT) installations to reduce the need for fossil fuel-based electricity generation. In 2019, 502 OWT with an average rated capacity of 7.8 MW were connected to the grid, an increase of 93 OWT from the previous year, giving a cumulative capacity of 22 GW across 12 countries within Europe [1]. To achieve renewable energy targets of 450 GW by 2050, as shown in Figure 1-1, further production and installation of OWT are necessary.

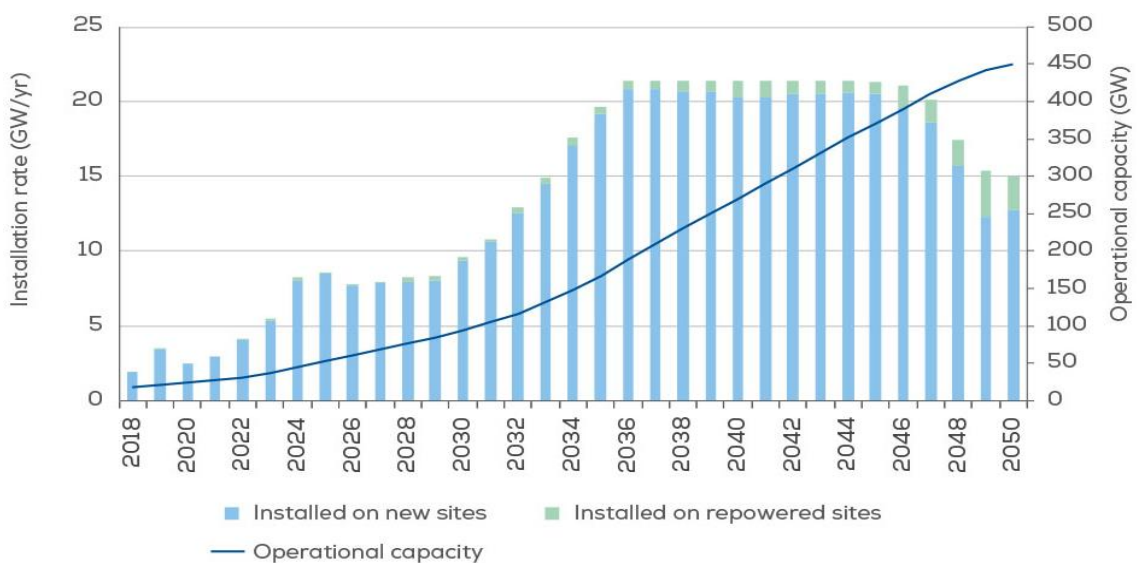


Figure 1-1: Required installation rate to achieve 450 GW by 2050 [2]

1.1.2 Manufacture of thick section large tubular steel structures

An OWT comprises of three main structural components, the tower, transition piece, and foundation structure. The most common foundation structure design used is the monopile, which is a large tubular structure, that is driven into the seabed. All these structural components are typically manufactured from S355 grade structural steel plates of varying grades and dimensions [3,4]. S355 structural steel is primarily used for offshore applications due to its suitable mechanical properties, such as strength and toughness, which is essential especially at sub-zero temperatures. Although there are much higher strength structural steels available, the weldability of these steels can be more challenging.

The fabrication of these structures involves several steps, as shown in Figure 1-2. Firstly, the plates are rolled into tubular sections using 3 or 4 roller bending machines. The rolled sections are then longitudinally butt-welded together to form cans ranging from 3 – 4 m in length. Secondly, several of these cans are then circumferentially butt-welded together until the desired length of the structure is reached [5]. The size and dimensions of these structures, such as the length, diameter, and wall thickness, vary for each design case and wind farm location. Factors, such as the turbine size and load, dynamic wind-wave loading conditions during operation, and soil conditions, affect the designs significantly.

The diameter and wall thickness of a monopile typically range from 3 - 7 m, and 40 - 90 mm, respectively. However, as demand increases and technology advances, larger turbine sizes with higher output capacity are being developed, which require larger and stronger monopiles. To support these larger turbines, manufacturers, such as the EEW group, are producing large monopiles, known as XL monopiles [6]. These XL monopiles have diameters up to 10 m and wall thicknesses up to 120 mm.

Currently, the preferred welding process used for the manufacture of these large tubular structures is Submerged Arc Welding (SAW) of various configurations due to its high deposition rate and productivity for joining large thickness plates [7]. Multiple welding passes and typically wide weld grooves are required due to the high plate thickness and to allow for weld torch accessibility. However, SAW is only suitable for flat or horizontal – fillet welding positions due to the nature of the welding process. The manufacture of XL monopiles would require additional materials and weld passes, leading to increases in material costs, person-hours, and lead times.

Other welding processes, such as Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW) or Flux-Cored Arc Welding (FCAW), are also used but have lower productivity compared to SAW. These welding processes are mostly used to manually weld small thicknesses and secondary ancillary steel components, e.g. ladders, platforms, and railings, to the transition piece [8].

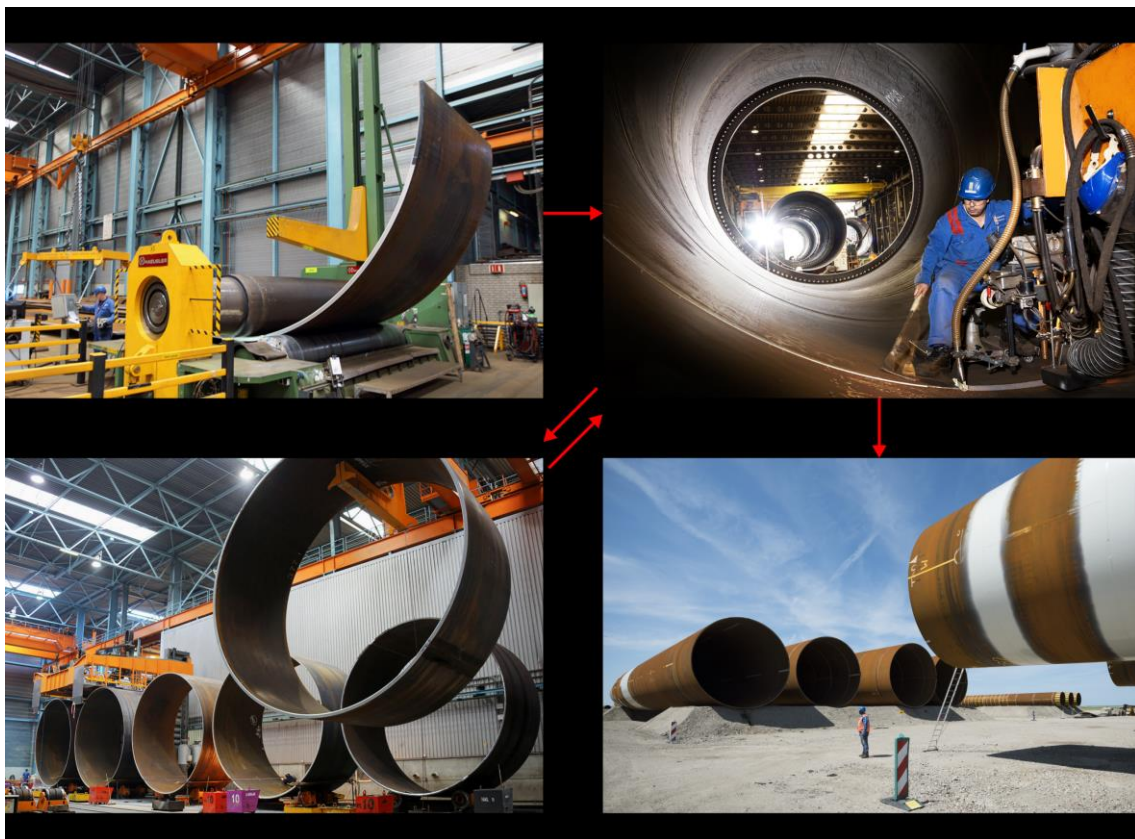


Figure 1-2: Example of monopile structure manufacturing process: (a) plate rolling, (b) SAW, (c) tubular sections, (d) monopile [9,10]

1.1.3 Alternative manufacturing processes: High productivity welding processes

Laser Welding (LW) or Hybrid Laser Welding (HLW) can potentially lead to substantial reductions in material costs and lead times across the manufacturing process. LW or HLW can offer several advantages over conventional arc welding processes due to the high focus-ability and flexibility of the heat source. The high energy density process enables low heat input, high aspect ratio welds when operating in keyhole mode without the need for wide weld grooves.

Some advantages, when compared with arc welding processes are [11]:

- Increase in productivity and cost savings due to increased penetration depths at faster travel speeds (up to 10 m/min), reducing the number of welds for a given plate thickness.
- Material cost savings due to reduced filler material and weld groove size
- Reduced weld zone sizes and lower heat input welds, giving narrower heat-affected zones (HAZ), reduced residual stresses.
- Potential for welding higher strength structural steels because of the lower heat input and distortions induced into the material.
- Improved welding flexibility allowing for complex geometries and welding positions due to the optical delivery system and non-contact process.

However, focusing solely on the welding characteristics, some disadvantages of LW in keyhole mode that require consideration are [11]:

- High cooling rates associated with high travel speeds and lower energy input can lead phases formed via shear transformations, e.g., martensite, resulting in high hardness and low ductility welds.
- Joint fit-up tolerance, gap between plates, and beam alignment to the workpiece can be an issue, however, these issues can be overcome with the application of filler material or when combining the laser with a secondary heat source like GMAW in HLW.
- Defects related to keyhole collapse and keyhole closure during welding and laser termination, such as porosity and keyhole voids can severely affect the fatigue life and structural integrity of the welds.

In most welding processes, defect occurrence is higher at the weld initiation and termination points due to poor control of weld parameters or incorrect procedure at the weld start and stop areas. In arc welding, weld initiation points can lead to excess weld reinforcement and overlap, and incomplete fusion from cold starts, whereas weld terminations typically lead to weld craters, cracks, undercut and porosity. In LW processes, defects at the weld initiation and termination points can be more severe when operating in keyhole mode due to the higher aspect ratio welds. At LW initiation points, undercuts, underfill, over penetration or excess weld reinforcement may occur. For LW termination points, solidification cracking, keyhole collapse leading to porosity or voids, and underfill are likely to occur. During laser termination, defects are certain to occur if the laser is terminated abruptly and without a suitable termination procedure.

In longitudinal welds, start/stop defects can be removed using weld run-on and run-off plates at either end of the workpiece. However, in circumferential welds, the application of these plates is not possible. Weld starts and stops remain within the workpiece at the weld start/stop intersection, and methods of mitigation are required. Currently, there are few applications of laser keyhole mode welding for circumferential welding of tubular sections because of these issues. However, the study and development of successful mitigation techniques would result in significant improvement in weld quality and weld productivity, especially for circumferential welding applications. The adaptation of laser keyhole mode welding for circumferential welding applications will bring down manufacturing costs by increasing the manufacturing productivity of thick section large tubular steel structures.

Defect formation associated with laser keyhole initiation and termination and how systematically it can be mitigated through control of the laser welding parameters are not fully understood nor documented. The effects of welding parameters, material composition, thermal cycle, solidification behaviour, keyhole dynamics, and weld geometry on laser keyhole start/stop defects need to be studied further.

1.2 Research aim and objectives

The aim of this research project is to investigate the defect formation associated with laser keyhole weld start/stop defects in circumferential welds and propose process-based mitigation methods to eliminate such defects.

The objectives are:

- Investigate and assess the potential of defect formation and mitigation in different weld termination procedures in laser keyhole welding.
- Understand and identify the factors affecting the formation of laser keyhole weld start/stop related defects in circumferential weld overlap intersection.
- Investigate the impact of different laser termination procedures and the effect of material composition on defect formation at the weld overlap start/stop region.
- Identify the fundamental process parameters which allow for control of penetration depth in hybrid laser-arc welding.
- Evaluate the mitigation methods for weld start/stop defects in hybrid laser arc welding.

An illustration of the research methodology applied to meet the research aim and objectives is shown in Figure 1-3.

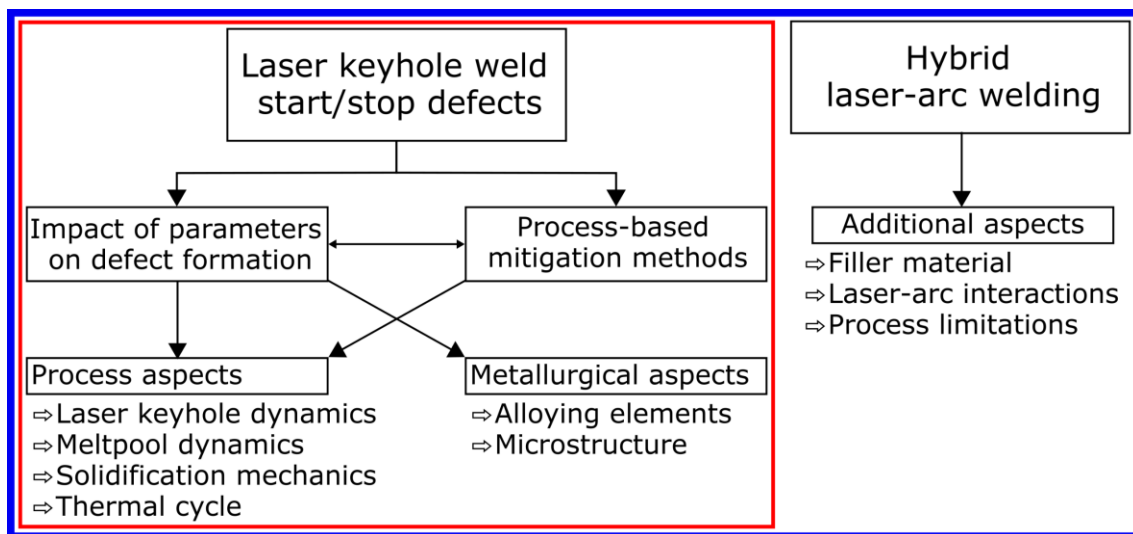


Figure 1-3: Research methodology

1.3 Thesis structure

This thesis contains nine main Chapters, references, and appendices. Chapter 2 consists of a literature review focused on three main topics: laser keyhole welding phenomena, material alloying elements, and weld initiation and termination defect formation and mitigation. A brief overview of submerged arc, laser, and hybrid laser-arc welding are presented, which highlights the current advancements and application of these welding processes in more detail.

Chapter 3 is the methodology. The experimental set-up and approach, materials, process parameters, sample preparation, material characterisation and mechanical testing procedures used throughout this thesis are described.

Chapters 4 to 7, cover all aspects of the research methodology, shown previously in Figure 1-3. Each core chapter contains the following sections: an introduction, methodology, results, discussion, and conclusion.

Chapter 4 focused on the most applicable process-based mitigation methods for laser keyhole weld start/stop defect formation.

Chapter 5 investigated the effect of inter-pass temperature and thermal cycle on the weld overlap start/stop region and how they affect the formation of defects and weld microstructure. Parts of this chapter has been written into a paper that is published in the *International Journal of Advanced Manufacturing Technology*.

Chapter 6 studied the effect of different laser keyhole weld termination regimes and material composition on weld overlap start/stop defects. Parts of this chapter has been written into a paper that is published in the *Journal of Manufacturing Processes*.

Chapter 7 investigated hybrid laser-arc welding process parameters and how they impact the weld profile and weld start/stop defect formation.

Chapter 8 gives an overall discussion and summarises the findings and conclusions from the four core Chapters (4-7).

Finally, Chapter 9 presents the main conclusions and recommendations for future work.

Chapter 2

Literature review

2.1 Overview of welding processes for manufacturing thick section large tubular steel structures

2.1.1 Conventional fabrication process: Submerged arc welding

SAW is an arc welding process that requires a continuously fed, consumable electrode, such as filler wire, to form an electric arc that melts the filler wire and workpieces, joining them together upon solidification. The main difference compared with other typical arc welding processes is the method used to protect the electric arc and weld zone from contamination. In SAW, a bed of granulated flux covers the electric arc and weld zone, providing a gas shield and slag layer, as shown in Figure 2-1. The flux removes the need for shielding gas and prevents weld metal spatter, sparks, fumes, and arc radiation, improving the weld quality, and the working environment and conditions significantly [12].

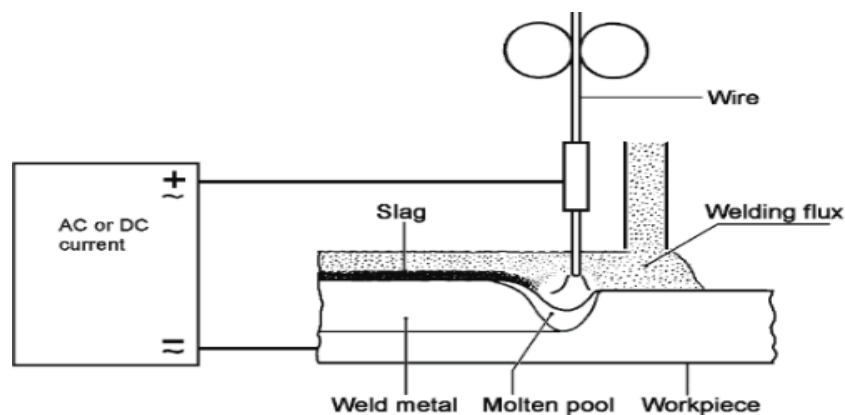


Figure 2-1: Schematic diagram of SAW [12]

Joining of thick plates using arc welding processes typically requires multiple weld passes, wide weld grooves, and welding from both sides. There are three different types of welding passes in multi-pass welding, root, fill, and cap or cover passes. The root pass is the first weld pass that joins the base material together and provides a base for subsequent weld passes. Typically, root passes are carried out using Gas Metal Arc Welding (GMAW). Subsequent weld passes are named filler passes and are conducted using SAW. Finally, the last weld pass is the cap or cover pass. Double V or U – joint grooves are commonly used with weld groove angles ranging from 30 - 90° depending on the thickness to be welded [13]. The weld groove allows for good arc striking and weld fusion between the filler material and parent material. It also allows for weld torch access and positioning, and the cleaning and de-slagging of weld beads before the next weld pass takes place, which is necessary for SAW due to the flux and slag formation. The welding of significantly thick plates used for the fabrication of monopiles require several welding passes and filler material to fill the weld grooves. An example of a 90 mm thick monopile weldment with 21 weld passes is shown in Figure 2-2 [14]. Depending on the welding procedure used by manufacturers, the number of weld passes can be significantly more, resulting in higher lead times and filler material usage.

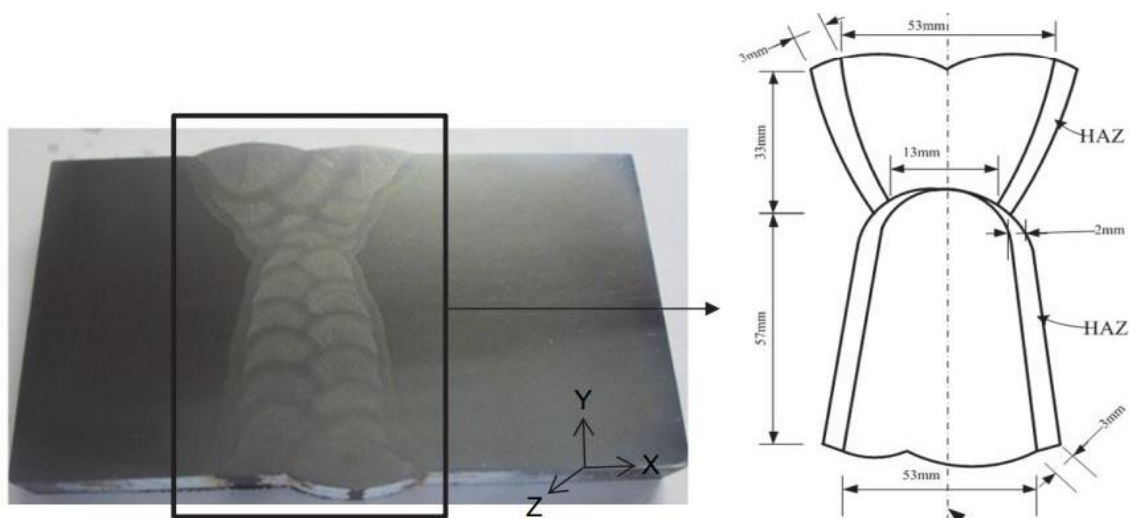


Figure 2-2: 90 mm monopile weldment and schematic of dimensions [14]

Process limitations and advancements

The SAW process has certain limitations, however, significant improvements to the process has maintained its popularity for thick section welding.

Limitations

The use of flux and the resultant large melt pool in SAW is a disadvantage of the welding process. The flux reacts with contaminants to form slag, which is a waste material that must be removed before conducting another weld pass. The removal and disposal of slag can be costly regarding the removal process and amount of material wasted [15]. The high heat input and large melt pool can also be detrimental to the weld properties due to the formation of coarser grains, which lead to a reduction in weld impact toughness [16].

Another limitation, and probably the most important, is that welding is limited to the flat or horizontal – fillet welding position (1G welding position). The molten metal and slag will flow out of the weld joint due to gravity unless the welding torch is orientated above the workpiece. For the fabrication of large tubular structures, such as monopiles, it means that circumferential welds will have to take place with the tubular sections on several large pipe rotators with the welding torch fixed above the weld groove. This limitation reduces the flexibility of the welding process.

Alternatively, welding in the 5G welding position where the welding torch travels around the circumference of the stationary tubular structure would improve the flexibility of the manufacturing process. Welding in 5G would negate the need for large pipe rotators and the rotation of the large tubular sections. However, adjustments to the welding parameters may be necessary to overcome the effect of gravity at various welding positions around the circumference of the weld.

Advancements

There are several process variants of SAW and methods which can improve weld productivity by increasing the weld deposition rate or minimising the size of the weld groove required. Certain process variants and methods can increase weld deposition rate by 20 – 100 %, as shown in Figure 2-3 [12].

Some examples are:

- multiple weld torches (tandem welding)
- multiple wire electrodes (twin-arc welding, cold and hot wire addition)
- long stick-out welding,
- addition of powders or cut wires into the weld.

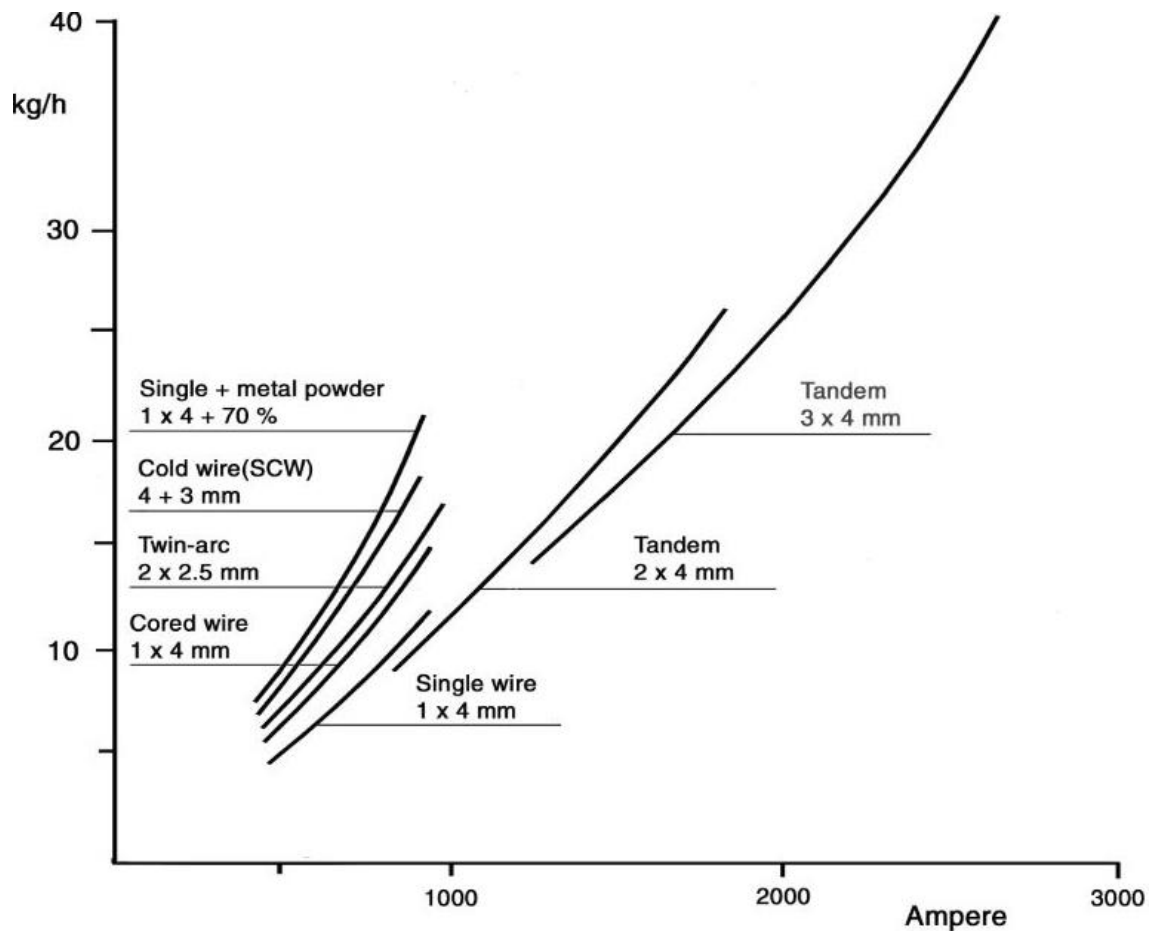


Figure 2-3: Methods to increase weld deposition rate in SAW [12]

Specific process variants with multiple electrodes allow for higher deposition rates at faster welding speeds. It is possible to achieve weld penetration ranging from 9 -16 mm using welding speeds of up to 1.5 m/min, double the conventional SAW welding speed [17].

Cold wire addition is a suitable method to offset the reduction in weld toughness due to the high heat input of the weld process. Other methods of improving weld toughness is through the addition of flux with alloying elements that promote the formation of certain inclusions and fine grain phases, such as acicular ferrite [18].

To reduce the amount of flux used and wasted, recycling and reusing of the slag formed during welding as recycled flux is a possibility. The recycled slag, with the addition of desired deoxidisers and binders, can be reused as flux through several processing steps of reclamation and milling. Researchers have shown that recycled slag is reliable and equivalent to virgin flux, potentially reducing the amount of waste material significantly [19].

Advancement in welding techniques, such as narrow-gap welding, can reduce the number of weld passes, weld groove size, angle and preparation, and filler material required to weld the same plate thickness. However, more precise joint fit-up is required due to the reduced weld groove size and positioning of the welding torch and wire, which can lead to additional costs [20]. A reduction in welding speed is also likely with the narrow-groove welding technique, which could impact weld productivity and efficiency despite the reduced number of weld passes.

2.1.2 Alternative high productivity welding processes: Laser keyhole welding and hybrid laser-arc welding

Laser welding utilises high energy density in the form of a focused beam to join materials together. Three distinct laser welding modes exist, conduction mode, transition or mixed-mode, and keyhole mode welding, as shown in Figure 2-4. The welding mode is dependent on process parameters, such as energy density, and the physical properties of the alloy being joined.

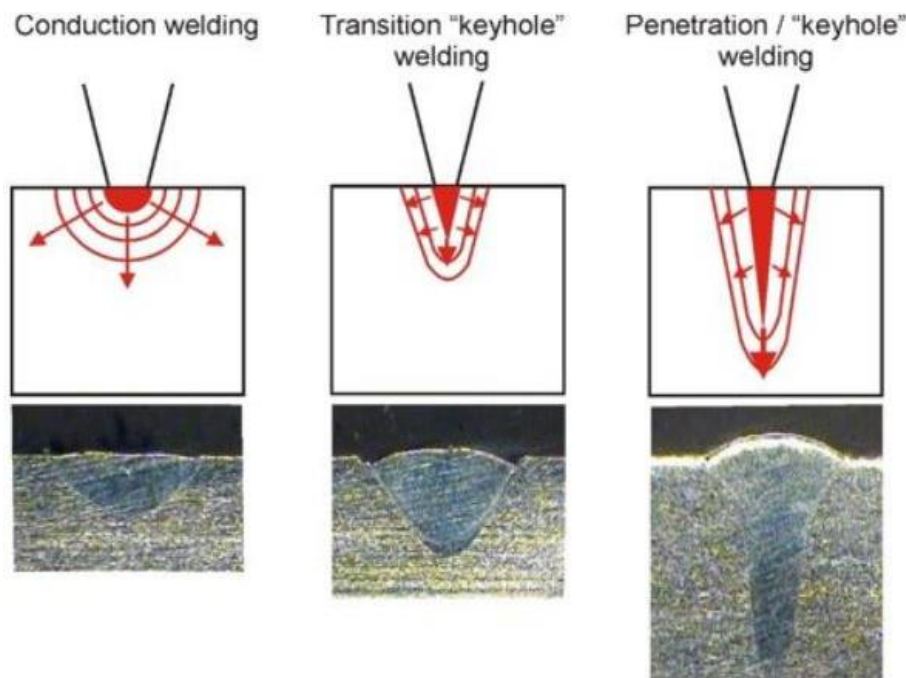


Figure 2-4: Graphical illustration of different laser welding modes [21]

In conduction mode welding, the melting of material and the transfer of thermal energy from the laser into the workpiece surface is via conduction. Conduction mode welding is achieved by using process parameters that give lower power densities, usually below a value of 0.5 MW/cm^2 . Parameters, such as large beam spot size areas, and low power and travel speeds are used depending on the material [21]. A stable weld process with shallow weld bead profiles, like those seen in typical arc welding processes, is achieved as a result.

On the other hand, as the laser power density and applied energy increases, the material vaporisation threshold is overcome, and the material begins to vaporise. The vaporisation releases gases, which expand and forms a recoil pressure that acts on the molten metal surface and causes a depression in the molten material.

At this stage, the transition mode begins and if there is sufficient energy applied, material vaporisation continues. The recoil pressure and molten metal depression will continue to increase, leading to the formation of a cavity known as a keyhole.

The formed keyhole gives the name for the welding mode, which requires much higher power densities in the order of $1 - 1.5 \text{ MW/cm}^2$. Penetration of the material continues until there is a balance between the laser energy, heat transfer and fluid flow, and between the vapour recoil pressure, hydrostatic forces and surface tension forces [22]. A constant balance between these forces is necessary for stable keyhole and fixed penetration depths. Any imbalance of these forces could lead to an unstable keyhole and cause the keyhole to collapse, resulting in defects. Keyhole collapse can cause a loss in penetration, weld surface waviness, underfill, spatter, and gas entrapment, resulting in porosity and keyhole voids. [23–30]. Porosity can cause crack initiation, severely impacting the structural integrity of the welds depending on the location of the defects [31,32]. High fatigue resistance is necessary for these structures that are subjected to both cyclic and dynamic loading.

The high aspect ratio of laser keyhole welds is beneficial for weld productivity; however, it also makes the welds more susceptible to defect formation. High aspect ratio welds results in rapid solidification, keyhole instability, and with the lack of molten metal can result in surface undercuts, shrinkage cavity defects and solidification cracking, as shown in Figure 2-5 [33].

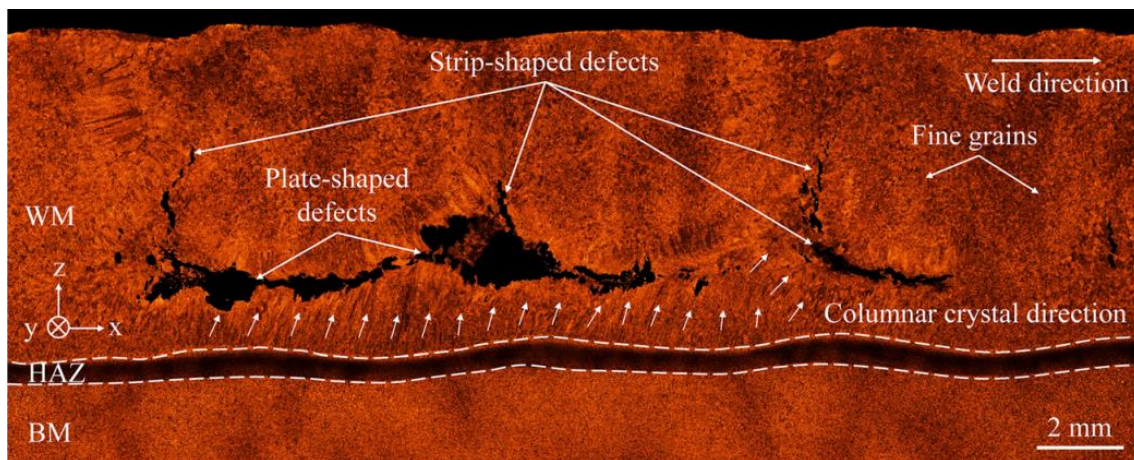


Figure 2-5: Longitudinal macrograph of periodic solidification defects in deep penetration laser welding [33]

However, when the balance of forces is maintained, high quality, defect-free welds at staggering weld speeds is possible, which makes this process highly attractive for mass production manufacturing.

Laser welding is typically operated in either conduction or keyhole mode welding as the weld is more stable and leads to better weld quality. Whereas transition or mixed-mode welding is avoided as the instability of the weld mode can lead to defect formation.

Process limitations and advancements

Limitations

Precise joint fit-up tolerance and beam positioning to the workpiece is required for laser keyhole welding as any misalignment can lead to defects, severely affecting the weld quality. Adequate clamping, beam alignment systems, or alternative laser configurations are necessary to achieve a good joint fit-up. Therefore, additional costs for these equipment need to be considered.

Another limitation of lasers is material absorptivity, reflectivity, and thermal conductivity. Materials, such as aluminium and copper alloys can be challenging to weld due to their high reflectivity and thermal conductivity. Back reflection of laser light can damage the fibre optics and laser system and is also a waste of energy. Therefore, preventative measures are required like optical isolators, which are often used to control back-reflected light. However, they come with certain disadvantages and are another additional cost [34]. In practice, a welding angle is typically applied to ensure reflected light is directed away from the laser weld head.

Advancements

Methods for improving joint fit-up tolerance and gap bridging include wire feeding, beam oscillation, dual beam, beam manipulation, and the addition of a secondary heat source, such as GMAW or another laser [35–39]. However, many of these options involve ancillary equipment, which increases cost and can reduce weld productivity due to process parameter limitations.

Development into shorter wavelength lasers compared with the typical 1070 nm of Nd: YAG lasers has addressed the challenges with welding highly reflective materials. Welding of copper alloys is achievable using lasers with wavelengths of 450 and 515 nm due to the increased absorptivity of the laser light [40,41].

Advantages of laser keyhole welding comes from its high energy density, which results in high aspect ratio, deep penetration welds that are achievable using high welding speeds and thereby, lower heat input. It is possible to achieve full penetration welds in 25 mm thick S355 steel using a 30 kW autogenous fibre laser and welding speeds up to 2.4 m/min, as shown in Figure 2-6 [42].

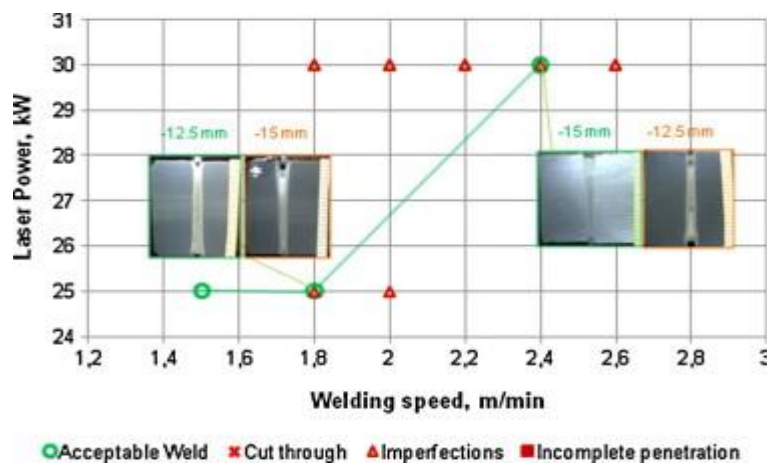


Figure 2-6: Weld quality window for S355, 25mm thickness [42]

The potential of welding at high weld speeds reduced the heat input, which minimises distortion and reduces the size of the HAZ and the effect of HAZ softening and weakening. For the welding of thicker plates, this is a significant advantage as it leads to reduced weld passes, material usage and weld groove sizes. These factors increase weld productivity and reduce production costs significantly. However, the use of high welding speeds can lead to high cooling rates and solidification stresses. Therefore, the likelihood of solidification cracking will increase, which is detrimental to the weld integrity. High cooling rates also lead to the formation of hard and brittle microstructural phases, such as martensite. An excessive hardness of an average of 493.5 HV was obtained in the S355 welds carried out by Sokolov et al. [42], which are much higher than the acceptable level of 350 HV for these grade of structural steels [7].

As with SAW, there are several configurations and methods which can lead to further improvements in both weld productivity and weld quality of laser welding. For the welding of thick section steels, reduced pressure laser welding or laser welding in vacuum can provide substantial improvements in penetration depth and weld quality under some circumstances [43–46]. Acceptable quality welds with penetration depths between 30 and 40 mm was achieved with a laser power of 16 kW and weld speed of 1 m/min at a reduced pressure of 0.1 kPa in SM400A low alloyed steel by Sokolov et al. [43]. Narrow-gap laser welding is also another possibility due to advancements in process and parameter control.

However, the most practical and common method is the combination of a laser with an electric arc, which is commonly known as Hybrid Laser – Arc Welding (HL-AW). The addition of the arc source allows for filler material to be added easily as it can be difficult to melt filler wire in autogenous laser welding. Autogenous laser welds often exhibit undercuts due to the lack of material and the addition of filler material solves this issue.

2.1.2.1 Hybrid laser-arc welding

HL-AW combines a laser and a secondary heat source, such as the electric arc, to simultaneously create one melt pool. The benefits of both processes are combined whilst avoiding the drawbacks of each process. Deeper penetration welds at increased welding speeds can be achieved without comprising the joint fit-up tolerance seen in autogenous laser welding. Although the heat input increases due to the combination of two heat sources, the increased penetration and welding speeds can result in a net reduction in the cumulative heat input when compared with arc welding. The lower heat input results in lower distortion welds, which is beneficial for welding of thick plates [47].

There are several combinations and configurations of HL-AW depending on the power sources used, such as a hybrid laser – gas metal arc welding (HL-GMAW), as shown in Figure 2-7. With the arc source there is the addition of filler material, which opens new possibilities and improved mechanical properties compared to autogenous laser welding. The addition of filler metal is vital for the welding of thick sections, not only for filling the weld groove but also for replacing elements

lost during the welding process due to vaporisation. The concentration of strengthening alloying elements can also be added or controlled using filler metal to improve the mechanical properties of the weld joint. Most high strength structural steels that have enhanced toughness, achieved by grain boundary strengthening without expensive alloying elements are manufactured from thermo-mechanically controlled processes (TMCP). Autogenous laser welding of certain TMCP steels, such as S700MC can result in welds with a high content of hardening phases during cooling. These hardening phases leads to precipitation hardening by fine dispersion deposits, which reduces weld ductility [48]. Therefore, HL-AW or laser with filler wire addition is recommended to control and reduce the content of specific alloying elements within the weld.

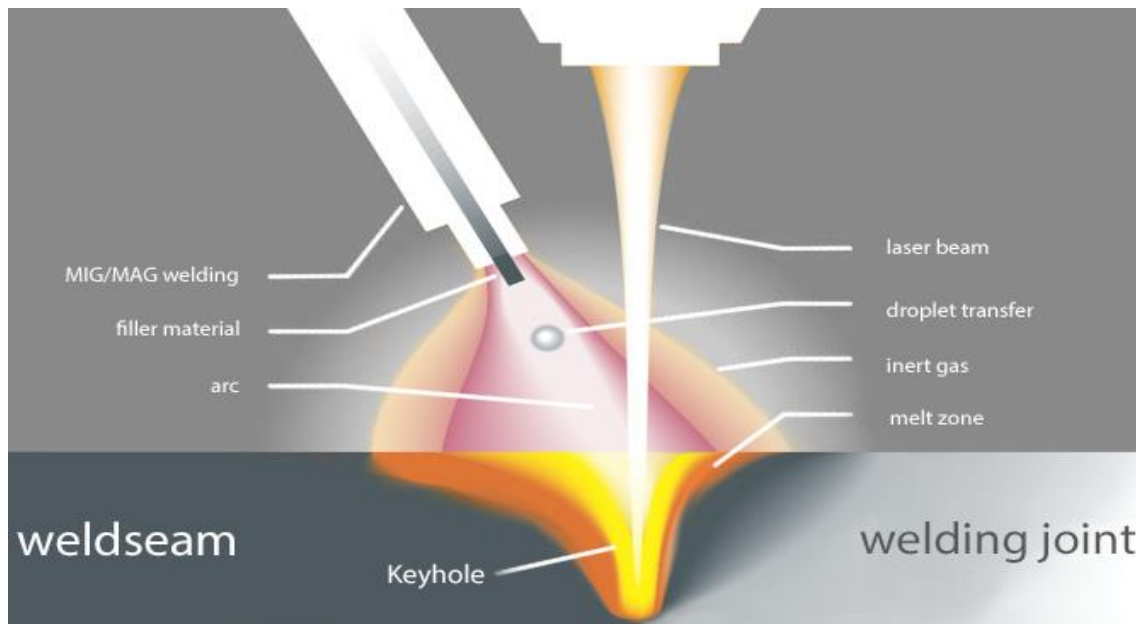


Figure 2-7: HL-GMAW schematic [49]

Like with laser welding, HL-GMAW is utilised in similar industries for structural applications within automotive and shipbuilding [50,51]. Recently the oil and gas industry has developed an interest in HL-GMAW due to the possibility of welding pipeline grade steels with higher productivity [52].

Several researchers have demonstrated the potential of HL-GMAW for improving welding productivity using various configurations and techniques. Gook et al. showed that acceptable welds that meet requirements for line pipes in API 5L or ISO 3183 specifications in X80 grade steel is possible using HL-GMAW with a

modified spray arc mode [53]. Plate thicknesses of 23.4 mm were welded using an HL-AW weld pass on one side of the plate, and a GMAW weld pass on the other side with a weld groove of 45°.

Other configurations of HL-AW has also been investigated, such as the combination of a laser source with a SAW source (Hybrid laser – Submerged arc welding, HL-SAW), which has been demonstrated by Reisgen et al. [54]. The author has shown the significant advantage of HL-AW through the reduction of weld passes and weld groove size required for a given plate thickness as compared with conventional arc welding processes, as shown in Figure 2-8. By using a double sided-V joint with a root of 25 mm, plates of 35 mm thick S235 and X65 grade steels can be welded in two passes. Typically, 26 weld passes are required using a combination of GMAW and SAW for this plate thickness. The research shows that the potential of this alternative welding process compared to conventional arc and laser welding processes is very attractive and beneficial. However, by introducing another power source, the complexity of the welding process increases significantly. A thorough understanding of the process dynamics of each power source, how they interact, and how they affect the melt pool during welding is necessary to achieve high-quality, defect free welds.

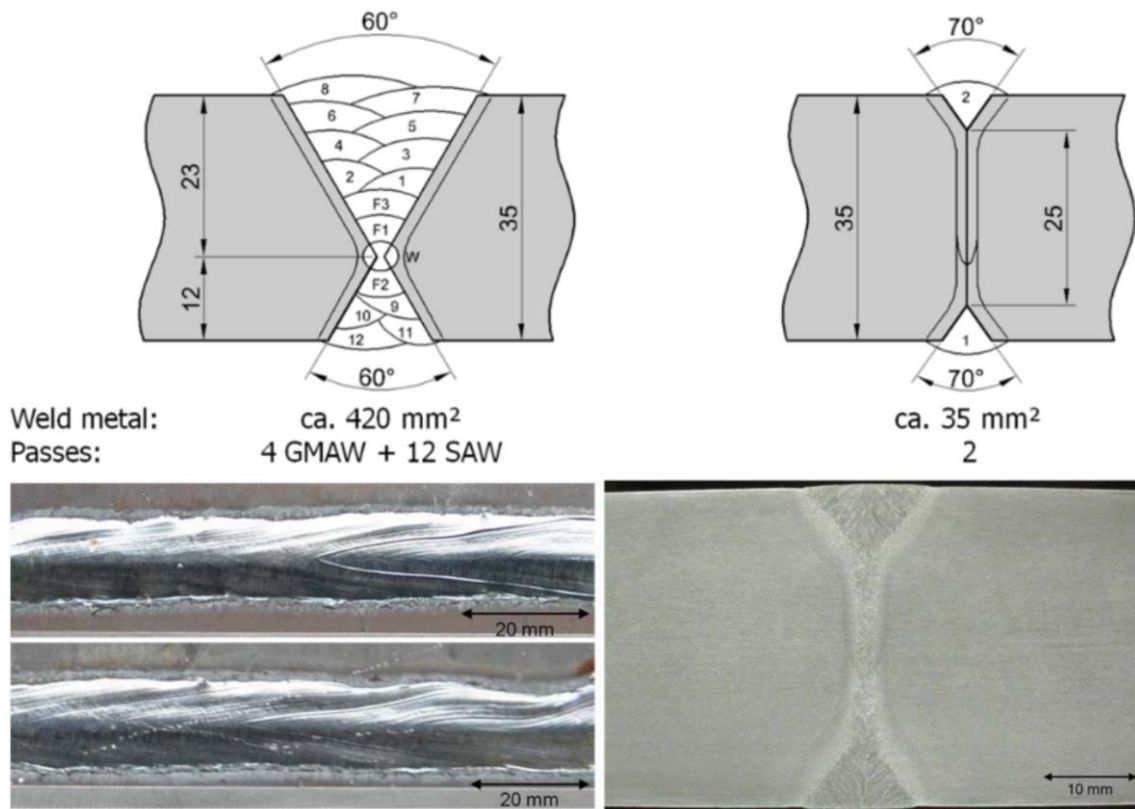


Figure 2-8: HL-SAW, top) weld groove comparison of SAW and HL-GMAW in plates of 35 mm, bottom) weld seam and cross-section of HL-SAW [54]

Further advancements and research include narrow-gap and multi-pass HLAW due to improved process and parameter control in recent years. Karhu and Kujanpää showed that the welding of 60 mm thick AISI316L-B stainless steel plates was possible in 15-20 weld passes using a combination of a defocused laser and HLAW with a narrow-gap, multi-pass welding technique [55]. The authors also indicated that using HLAW alone, only 10 weld passes was required to fill a 60 mm weld joint using the narrow-gap multi-pass weld approach. Bunaziv et al. utilised a cut wire addition approach with multi-pass welding without the need of a weld groove in 50 mm low carbon alloy steel using a combination of arc, laser, and HLAW in a total of 4 weld passes [56]. The flexibility of the laser and advancements in HLAW process control has enabled and broadened the maximum weldable thicknesses of plates, such that thicknesses of 50 – 60 mm and above are possible with laser and HLAW using a multi-pass welding approach.

High productivity welding processes, such as laser keyhole and HL-AW offer significant advantages, such as increased weld productivity and reduced material costs, over conventional arc welding processes like SAW. Conventional SAW requires large weld grooves, multiple weld passes, lots of filler material, and high heat input to penetrate and weld thick sections. On the other hand, laser keyhole welding and HL-AW can potentially penetrate the same thickness with less or no filler material and smaller weld grooves with a reduced number of passes. However, the complex phenomena associated with deep penetration laser keyhole welding makes it difficult to achieve high-quality, defect free welds if not fully understood. Laser keyhole welding phenomena have been researched and understood well in steady-state welding as discussed in section 2.3.

One of the main issues in deep penetration welding, is how to initiate and terminate the weld successfully and avoid initiation and termination related defects. Defects in deep penetration welds may not be easily corrected making the weld unacceptable. In steady-state welding, defect free welds can be obtained by maintaining a stable keyhole and solidification behaviour. However, during weld initiation and termination, the weld is unstable and prone to defect formation. Therefore, the following section focuses on weld initiation and termination defects and methods of mitigation for circumferential welding applications.

2.1.3 Circumferential welding – Weld start/stop intersection

Circumferential welding of tubular steels is usually associated with the manufacture of pipes or tubular structures within the pipeline and construction industries. Key areas of research involve the study of residual stresses at weld starts and stops at the weld overlap in single and multi-pass welding of steel pipes [57–59]. Higher residual stresses are typically observed at the weld start/stops, and these stresses are more significant if the weld is terminated abruptly [60]. The increase in residuals stresses at weld overlap start/stop region can lead to the generation of defects and in some cases, failure when under service and load.

The start/stop intersection of a circumferential weld is a location that is prone to weld defects and inconsistencies due to the initiation and termination of a weld bead. In longitudinal welds, run on and off plates are welded to each edge of the workpiece to contain any weld initiation and termination defects, and are then subsequently removed. However, for circumferential welding applications, this preventative method is not feasible due to the intersecting weld overlap of the weld start and stop position. Any defects due to the start and stop remain within the workpiece, as shown by the schematic in Figure 2-9.

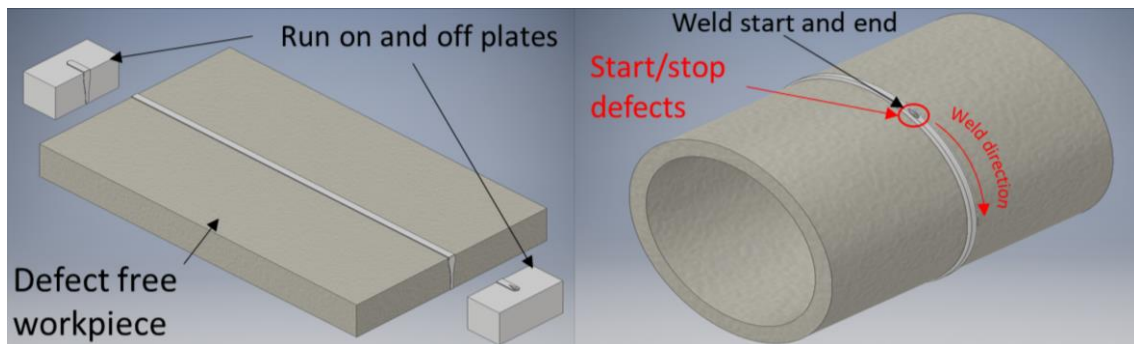


Figure 2-9: Schematic of longitudinal weld and use of run-on and run-off plates vs circumferential weld start/stop intersection

Therefore, suitable methods and techniques are required to prevent or mitigate defects during the initiation and termination of a weld bead in circumferential welds. There are several ways that defects can form and several methods of mitigation depending on the welding process used when run-on and run-off plates are not feasible.

2.2 Weld initiation and termination: defect formation and methods of mitigation

Weld initiation defects, such as lack of fusion, excessive weld reinforcement or burn-through, spatter, and cracking is due to poor control of the weld parameters leading to insufficient or excessive, heat or filler being applied. Similarly, weld termination defects, such as root sagging, porosity, cracking, craters, and cavities, are also due to poor control of welding parameters and molten metal solidification and usually occur when the weld is terminated abruptly. In arc welding where the welds are relatively shallow, weld craters and cracks that form are often removed by manual grinding and then re-welded. However, in deep penetrative welds seen in laser keyhole welding, remedial action is not always possible. Therefore, a process-based solution is necessary, which requires a deeper understanding of how the defects form. Literature on weld initiation and termination defect phenomena, formation, and mitigation are rather limited for laser keyhole welding processes but are starting to emerge.

2.2.1 Gas metal arc welding and gas tungsten arc welding

In gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW), the use of filler material and relatively shallow welds lead to less severe initiation and termination related defects. However, the initiation and termination of the weld can still be challenging and susceptible to defects if incorrect or insufficient weld parameters are used. For thick section welding, multiple weld passes are required, which increases the likelihood of start/stop defects forming unless suitable mitigation methods are applied.

2.2.1.1 Weld initiation defects and methods of mitigation

GMAW initiation defects are a result of inadequate starting parameters, such as too high or low current or voltage, depending on the thickness and material of the workpiece welded. During GMAW initiation, short-circuiting or lack of fusion defects (cold start) may occur. Typically, a higher starting current is used to help initiate the arc and avoid these defects [61]. However, this may lead to burn-through when welding thin plates or spatter and, excessive weld reinforcement as the welding current is linked to the feeding speed of the electrode wire.

2.2.1.2 Weld termination defects and methods of mitigation

Weld craters and crater cracking, as shown in Figure 2-10, are common when parameters are not appropriately controlled during GMAW termination. Guo et al. [62] found that weld craters form due to the arc pressure and droplet impingement, causing a depression in the weld pool and solidifying. Well known techniques to prevent weld craters and crater cracks in GMAW is to reduce the size of the weld pool before terminating the arc, known as “tail-out”. The “tail-out” technique is where a gradual reduction of the welding current or acceleration in weld travel speed or both is applied [63]. Another technique involves the rapid breaking and restriking of the arc at the termination point to fill the weld crater with filler material, a common practice in manual welding processes [63]. To prevent crater formation, Guo et al. applied a variation of the “tail-out” technique, a “back-up” crater filling technique, where the current is gradually reduced, and the welding direction reversed. The back-up crater filling technique allowed the weld crater to fill and solidify slowly without cracking [62].

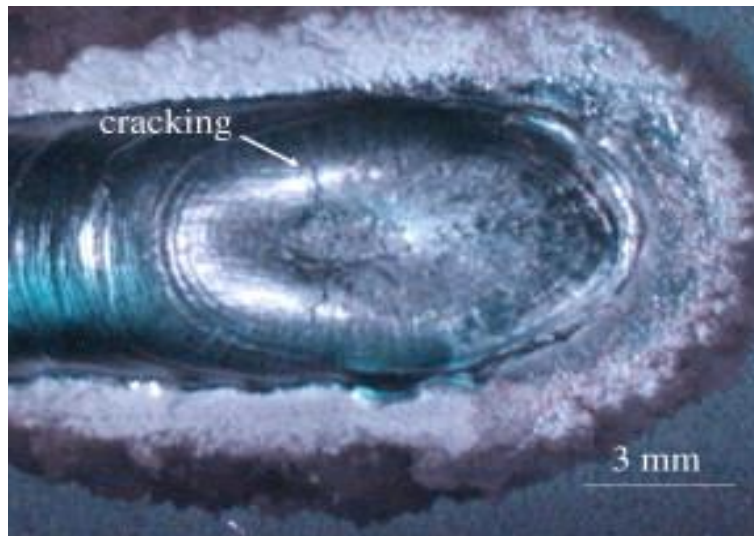


Figure 2-10: GMAW end crater with cracking [62]

The effect of material and shielding gas composition also has an impact on crater crack susceptibility as was observed by Nage and Raja in GTAW [64]. Weld crater cracks was also observed in GTAW of an aluminium-copper alloy [65]. In both cases, the crater cracks formed due to how the molten metal solidified. Further explanation on solidification behaviour and cracking is shown in 2.3.4.

2.2.2 Plasma arc keyhole welding

In plasma arc welding (PAW) deep penetrative welds can be achieved by operating in keyhole mode where a keyhole is formed due to the arc pressure.

2.2.2.1 Weld initiation defects and methods of mitigation

Keyhole generation during the start of a weld can be challenging in PAW due to the complexity of the process parameters and keyhole dynamics, which may lead to keyhole instability and collapse. Keyhole collapse can lead to keyhole defects in the form of a cavity or voids within the weld, resulting in porosity, as shown by Narita et al. [66]. To ensure that a stable keyhole is formed during weld initiation, Zheng et al. showed that a gradual increase in plasma gas flowrate and current generates a smooth keyhole formation and transition to steady-state welding [67].

2.2.2.2 Weld termination defects and methods of mitigation

Keyhole defects, such as keyhole cavities and porosity, are also more likely to occur during weld termination if an arc is terminated abruptly. Wang et al. [68] attempted two approaches to close the keyhole cavity generated at the termination point in variable polarity plasma arc welding (VPPAW) of an aluminium alloy. The two approaches applied were the decrease of current whilst increasing the welding speed and secondly, the decrease of plasma gas flowrate and welding speed whilst maintaining an appropriate welding current. Experiments were carried out in single-pass butt welds, and successful closure of the keyhole was achieved using the second approach. It was found that the weld geometry at the termination point is dependent on the energy input and dynamics of the keyhole and weld pool during solidification. The author carried out further experiments using these findings by firstly replicating a circumferential weld onto a flat plate using two overlapping single-pass welds, and finally conducting a circumferential weld on a pipe. Keyhole closure without defects at the weld start/stop region was achieved in both experiments showing that control of the energy input and keyhole dynamics is essential to achieve successful keyhole closure and termination.

2.2.3 Laser keyhole and hybrid laser-arc welding

The formation of laser initiation and termination defects are like those seen in GMAW and PAW depending on the welding mode the laser is operated in.

2.2.3.1 Weld initiation defects and methods of mitigation

Laser keyhole initiation related defects, such as excessive weld reinforcement and spatter occur because of thermal expansion and movement of molten metal behind the formed keyhole during laser traverse and solidifying. Simulations of laser keyhole formation by Cho et al. showed how complex dynamics occur between the vapour recoil pressure and surface tension forces resulting in upward and downward oscillations in the melt pool centre [69]. These oscillations may well result in an irregular weld surface or concavity at the laser initiation point upon solidification.

Solidification cracking is another issue in laser keyhole welding due to the higher solidification rate, shrinkage stresses and differences in solidification pattern when compared with arc welding [70]. Solidification cracking is also likely to occur at laser initiation and termination points due to the differences in microstructure, weld geometry, and solidification behaviour between the base and weld metal.

During laser initiation on thin sheets, burn-through can easily occur due to the high-power density of the laser. A similar burn-through defect was observed by Forsman et al. during laser initiation at the edge of an aluminium workpiece but was not observed during laser termination [71]. Forsman et al. described this phenomenon as “overheating”, which is a result of the reduced heat-sink at the starting edge and high conductivity of aluminium. The beginning of the weld was intermittent and showed signs of burn-through, melt pool widening, and voids. To prevent overheating, Forsman et al. applied a gradual ramp-up of laser power during laser initiation, reducing the amount of thermal energy absorbed by the workpiece when compared with initiating the weld at full laser power [71]. This shows that control of the starting parameters and applied energy is also necessary depending on the material and workpiece thickness.

2.2.3.2 Weld termination defects and methods of mitigation

In laser keyhole mode welding, the formation of termination defects, such as weld craters, crater cracking, keyhole cavities and porosity, can occur like those seen in arc welding processes. These defects typically form due to keyhole instability and collapse during laser termination, especially when the laser is terminated abruptly.

As the laser terminates, there are several phenomena that occur within a certain time frame. The extinction of plasma from the formed keyhole, the decay of vaporisation recoil pressure and the collapse of the keyhole driven by surface tension forces, all occur prior to the keyhole collapsing [72]. Therefore, it is necessary to ensure that the keyhole is closed without collapsing to avoid defects, such as keyhole cavity or porosity during laser keyhole termination. Laser keyhole termination defects are often more severe than laser keyhole initiation defects due to the rapid solidification of deep keyhole cavities. Examples of laser keyhole cavities due to abrupt laser keyhole termination are shown in Figure 2-11.

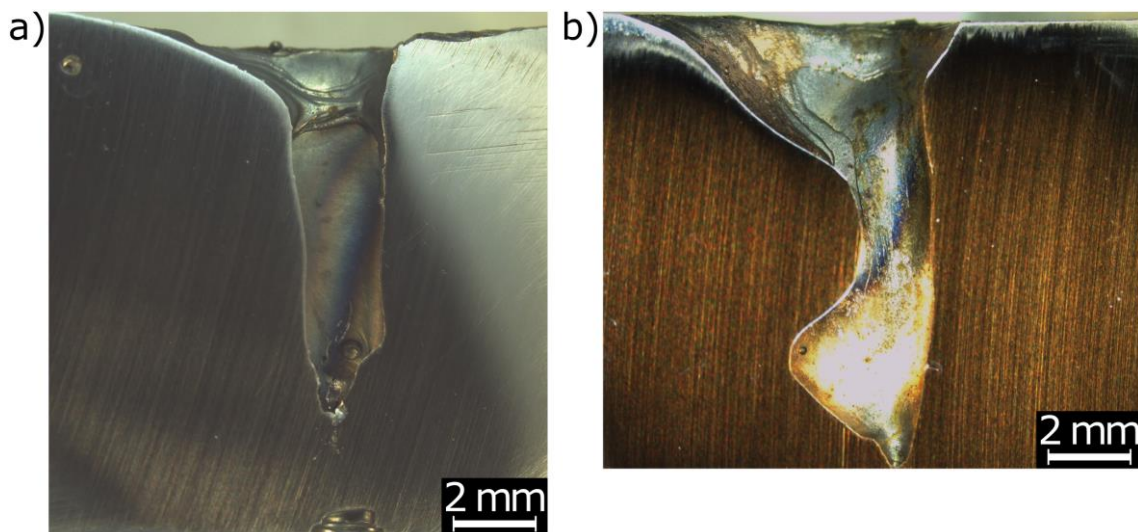


Figure 2-11: Laser keyhole weld cavities, a) abrupt laser termination at weld overlap start-stop region, b) abrupt laser termination in longitudinal weld

Solidification cracks at the laser weld termination point can occur across the whole plate thickness and propagate along the length of the weld [73], as shown in Figure 2-12.

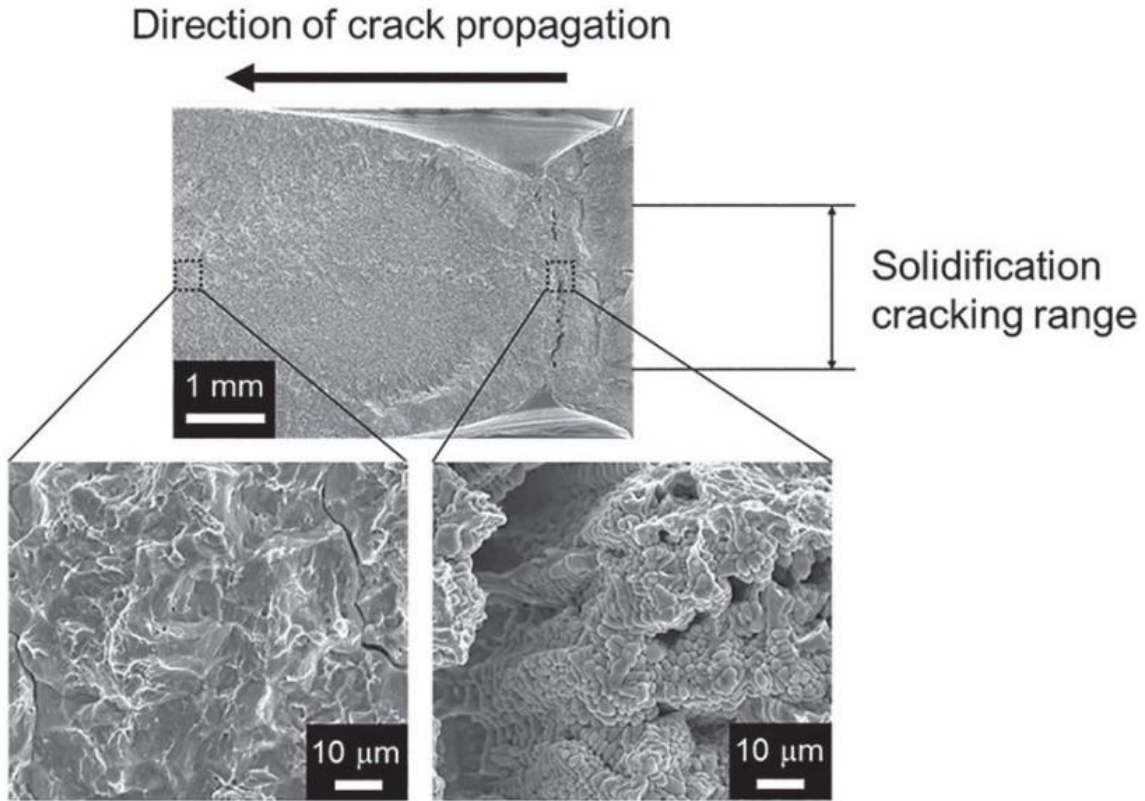


Figure 2-12: Laser termination point solidification crack and SEM images of fracture surface [73]

There are a variety of methods for closing the keyhole, suppressing, and preventing the formation of laser termination defects, known as laser weld termination regimes. Majority of these laser weld termination regimes involve the manipulation of different laser parameters to try and control the laser keyhole dynamics and solidification behaviour of the melt pool during laser termination. However, to ensure that successful keyhole closure is achieved, and laser keyhole termination defects are prevented, a deeper understanding of the effect of different laser welding parameters, fundamental laser keyhole welding phenomena, and material composition is necessary. Interactions between the laser, arc source, filler material and parameters also need to be considered.

2.2.4 Electron beam welding

Electron beam welding is like that of laser beam welding, where a beam is used to join materials together. However, instead of photons directed to the workpiece via optical lenses, electron beam welds are formed by a high stream of electrons accelerated with electrical and magnetic fields [74]. A vacuum or reduced pressure environment is necessary for the operation of the electron beam to avoid electron scatter by gas molecules. Therefore, much higher penetration depths of 300 mm can be achieved with electron beam welding due to the reduced pressure and high focus-ability of the electron beam [75,76]. Electron beam welding parameters are like those of arc welding, where the power is controlled by the beam voltage and current.

2.2.4.1 Weld initiation defects and methods of mitigation

Initiation defects obtained in electron beam welds are like that of laser welding. Excess weld reinforcement at the weld start due to the accumulation of fused metal can be mitigated by slowly increasing the beam current at the start of the weld (ramp-up), like the other welding processes [74].

2.2.4.2 Weld termination defects and methods of mitigation

Defects at the termination of an electron beam weld is like those observed in abrupt laser keyhole terminations, where a deep keyhole cavity or crater, porosity, undercuts, and cracking may occur. Other defects that are known to occur in electron beam welding due to the high solidification of the molten metal are “cold shuts” or “spiking” defects, where incomplete fusion of weld metal occur, typically at the weld root in partial penetration welds. Again, similar ramp-down mitigation methods to those of arc and laser welding are used. In electron beam welding, a gradual decrease of the beam current is applied when terminating the weld [77]. However, the occurrence of cold shut defects can still occur in the weld start/stop overlap section despite the application of a beam current ramp-down at the end of a weld. Therefore, further process control of the beam current to maintain the stability of the molten metal at the weld root is necessary. This phenomenon would apply to deep penetration laser keyhole welding.

2.3 Laser keyhole welding phenomena

As was previously described in section 2.1.2, laser welding comprises of three different welding modes. For the welding of thick sections that require deep penetration, laser keyhole welding is the most suitable.

Various phenomena occur during laser keyhole welding that affect weld productivity and quality during laser keyhole initiation, steady-state welding, and laser keyhole termination. The laser keyhole is a vapour cavity surrounded by molten metal, and there are several dynamics present within this multi-physical system, such as the laser-matter interaction, liquid-vapour interaction, melt pool dynamics, heat transfer, and solidification behaviour during welding [78]. A simple schematic of the laser keyhole and different physical states is shown in Figure 2-13. Different phenomena occur in each various physical state and boundary. These various phenomena are directly affected by independent factors, such as the laser source, weld process parameters, workpiece material and the welding environment. The complexity is increased further when the laser is combined with an arc source in HL-AW.

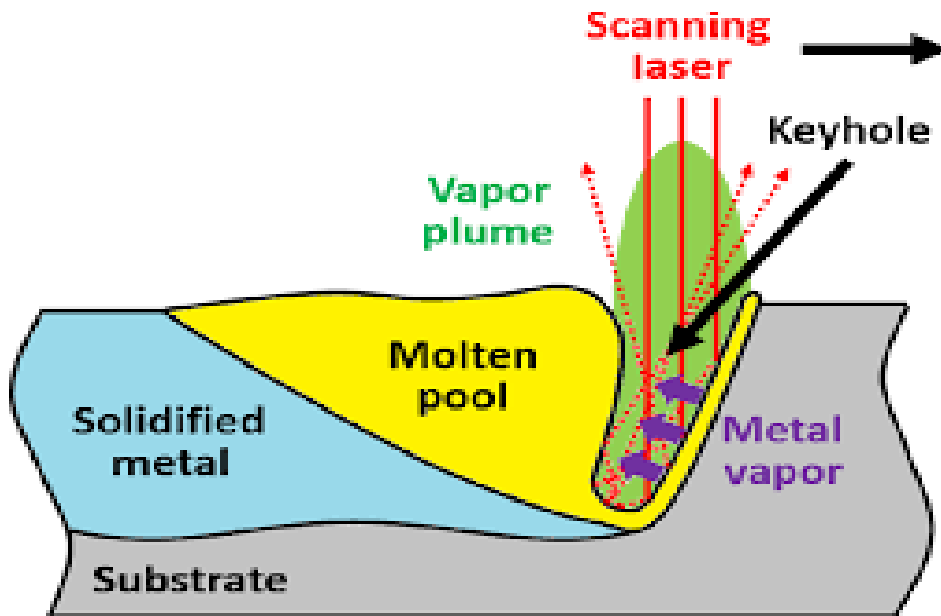


Figure 2-13: Laser keyhole schematic example [78]

2.3.1 Laser-matter interaction

The absorption of laser light by the workpiece and laser keyhole is mainly governed by two mechanisms, Fresnel absorption and inverse Bremsstrahlung absorption. Both mechanisms are affected by the wavelength of the laser and material of the workpiece due to the refractive index of the material and interaction with the generated vapour plume [79,80]. The more dominant mechanism of the two in laser welding with Nd: YAG laser sources is Fresnel absorption as there is little effect of inverse Bremsstrahlung absorption by the keyhole plume due to the shorter wavelength and lower ionisation temperature [81]. However, particulates within the weld plume can scatter and affect the amount of laser absorption the keyhole receives [82,83]. Fresnel absorption is also dependent on other factors, such as the incidence angle and direction of polarisation, hence the amount of laser absorption is also dependent on the keyhole geometry [78,80,84].

Once the laser keyhole has formed by the vapour recoil pressure, the laser light is then directly absorbed and reflected, multiple times, inside the keyhole, as was shown previously in Figure 2-13 by the red arrows. A large proportion of the laser energy is absorbed initially by the inclined keyhole front wall and then reflected multiple times to root of the keyhole and rear keyhole wall [85]. Therefore, multiple reflections are highly dependent on the keyhole geometry and front keyhole wall inclination angle [86,87]. The multiple reflection phenomenon can improve heat transfer to the melt pool, resulting in increased penetration depth. However, the multiple reflections may also lead to an uneven distribution of thermal energy, resulting in localised heating or a lack of heating in certain areas within the keyhole [88].

The laser beam focal position and focal length are also key factors that affect the distribution of the laser energy and absorption by the workpiece. A change in focal position or focal length affects the transfer of thermal energy within the keyhole, resulting in changes to the keyhole geometry, melt pool dynamics, and defect formation [27,89,90]. Typically, an increase in penetration depth is obtained when the focal position is below the work surface, due to increased vaporisation from the inward beam divergence within the keyhole [91].

To achieve successful laser termination without defects, the laser keyhole cavity needs to be gradually closed without collapsing. The keyhole is required to transition from a full penetration open keyhole to a partial penetration closed keyhole, whilst avoiding instability and subsequent collapse. During this transition, the keyhole geometry is also changing, which will affect the laser absorption, multiple reflections, and heat transfer within the keyhole.

2.3.2 Liquid–vapour interaction

There are two locations where liquid-vapour interaction takes place: the vapour cavity and surrounding molten metal, and the melt pool surface with the atmosphere. The interaction between the two mediums can affect keyhole and melt pool dynamics, and therefore, affecting the keyhole geometry and weld quality.

2.3.2.1 Vapour cavity and surrounding molten metal

Within the keyhole cavity, the vaporisation of the front keyhole wall by the incident laser beam generates a strong vapour recoil pressure and perpendicular vapour flow, towards and colliding with, the rear keyhole wall and molten metal [86,92]. The vapour recoil pressure is one of the dominant driving forces for keyhole formation and fluid flow in the depth direction. The vapour flow causes friction forces that act on the rear keyhole wall and molten metal, causing a drag force upwards as the vapour tries to escape from the keyhole [93]. In certain instances where the vapour friction force is strong enough to overcome surface tension forces, the molten metal at the top surface of the keyhole exit can be ejected as spatter [25,94].

The magnitude and direction of the vapour and melt pool flow affect the keyhole and weld pool geometry, as shown by several researchers using numerical modelling, in-situ x-ray radiography and high-speed cameras [28,78,93,95]. The welding parameters such as laser power and welding speed have a strong influence on the angle of the keyhole front wall, and therefore, the keyhole geometry and weld pool, as shown by the simulated model in Figure 2-14 by Tan et al. [28]. The material used in the simulation by Tan et al. was 304 stainless

steel and the physical properties of the material can be found in the corresponding reference in Table 1 [28].

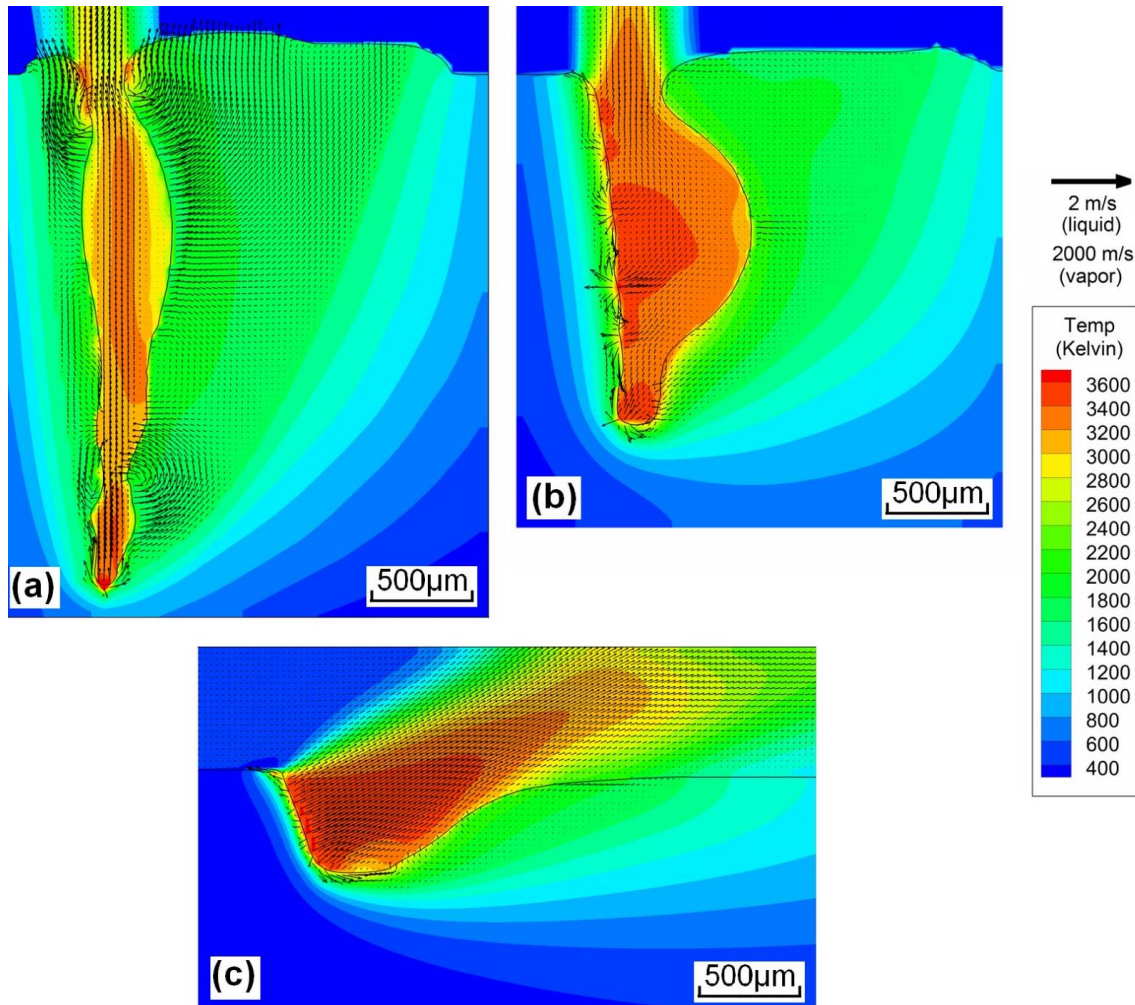


Figure 2-14: Simulation results showing different keyhole geometries in partial penetration welds in 304 stainless steel at constant laser power, $P = 1$ kW, and increasing weld speeds: (a) $v = 0.5$ m/min, (b) $v = 2$ m/min, (c) $v = 10$ m/min [28]

At high power or low weld speeds, the keyhole is deep and narrow with the keyhole front wall relatively vertical, so most of the laser absorption and vaporisation takes place at the bottom of the keyhole. The generated vapour flows upwards and out of the keyhole instead of towards the rear keyhole wall. Any keyhole fluctuations due to an imbalance of vapour pressure and surface tension can easily lead to keyhole collapse and porosity formation at the keyhole root due to the narrow keyhole cavity [28,29,96].

At medium laser power and weld speeds, the inclination of the keyhole front wall increases, and this affects the laser absorption and vapour flow direction accordingly. The direction of the vapour flow is now towards the rear keyhole wall and causes a pressure to push and expand the keyhole and molten metal [28].

At significantly high weld speeds, the angle of the keyhole front wall is large, and the direction of the vapour flow is now towards the top of the rear keyhole front wall. The direction of the vapour flow causes the keyhole exit to expand, resulting in an open triangular shape depression in the melt [28].

2.3.2.2 Melt pool surface with atmosphere

The atmosphere or shielding gas can lead to changes in the melt pool surface, temperature gradient and fluidity. Surface-active elements in the atmosphere or shielding gas, such as oxygen, can change the temperature gradient and surface tension depending on the amount present and acting on the melt pool. Above a certain percentage, oxygen can lead to a positive temperature gradient, and increases melt pool fluidity. In contrast, the opposite is true for low amounts of oxygen, where instead a negative temperature gradient is present. Therefore, there can be a significant effect on the melt pool dynamics, such as Marangoni flow, which will be discussed in more detail in section 2.3.3.

Other interactions of the atmosphere with the molten pool are oxidation, and more precisely, the formation of an oxide layer or slag. These formations are due to alloying elements in the material and can protect the melt pool from further interactions with the atmosphere, improving weld quality. However, it can also negatively impact the welding process due to the formation of slag inclusions, and changes to melt pool viscosity and surface tension. These coupled effects can lead to instability, variable weld penetration, and defects [97–99].

The effect of different alloying elements is described further in section 2.6

2.3.3 Melt pool dynamics and heat transfer

Melt pool dynamics are significant when there is a large volume of molten metal and, therefore, high hydrostatic pressure, such as at low weld speeds. At high weld speeds, where only a small volume or layer of liquid is present, the main driving force in the weld is the vapour recoil pressure and resulting frictional forces as discussed in section 2.3.2.1.

One of the main mechanisms within the melt pool is Marangoni flow, which is dependent on the surface tension and temperature gradient, and buoyancy forces. Marangoni flow defines the direction of material flow and melt pool geometry [100]. The direction of material flow depends on the temperature gradient and surface tension effect. As previously mentioned in section 2.3.2.2, the surface tension and temperature gradient can be affected by surface-active elements, such as sulphur and oxygen. Oxygen changes the surface tension and temperature gradient resulting in different material flow directions. When the amount of dissolved oxygen in the melt pool is low, a negative temperature gradient is present, which leads to an outward flow direction, as shown in Figure 2-15 [101–103]. However, when the amount of dissolved oxygen increases beyond a certain threshold, the temperature gradient becomes positive, and the flow direction changes to an inward flow direction. These changes in flow direction is known to affect weld penetration and the formation of defects [97,101,104].

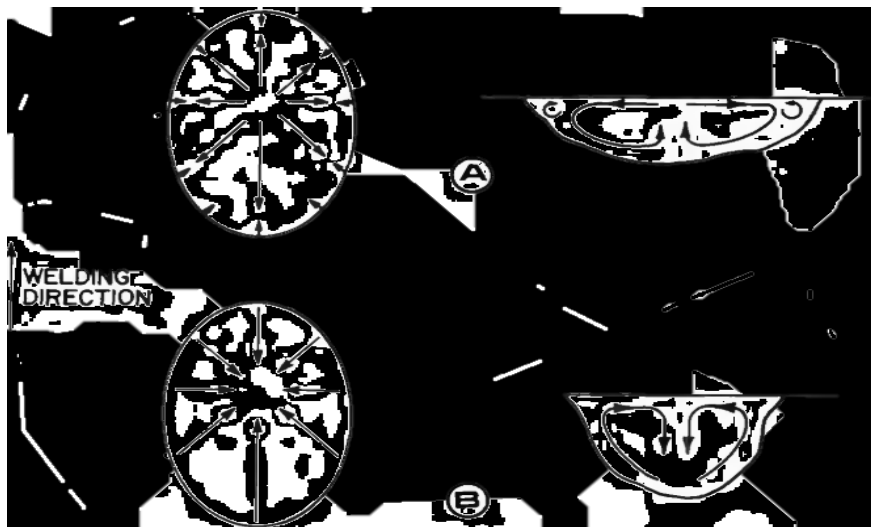


Figure 2-15: Change of Marangoni flow direction due to surface tension gradient, A) negative temperature gradient, B) positive temperature gradient [101]

2.3.4 Solidification behaviour and defect formation

A typical weldment can be broken down into three specific zones, the fusion zone (FZ), heat affected zone (HAZ), and the unaffected base material (BM). The FZ is the volume of the material that is melted during the welding process. The HAZ is the area of the material that experiences significant heating below the melting threshold of the material and subsequent cooling. The change in temperature alters the microstructure and mechanical properties of the material and is particularly important for alloys, such as steel, which exists at different crystallographic phases at different temperatures. The geometry of the FZ and HAZ widely depends on the material, welding parameters, melt pool dynamics, and cooling rate. The size of the HAZ depends on the thermal diffusivity of the material, which is affected by the thermal conductivity and heat input. Materials with high thermal diffusivity, such as aluminium, can transfer the heat away faster resulting in a high cooling rate and small HAZ. Welds with small HAZ are also seen in laser welding due to the high energy density and faster welding speeds resulting in a low heat input when compared with arc welding.

The weld integrity and mechanical properties are largely dependent and controlled by the solidification behaviour of the FZ and HAZ. Microstructural characteristics, such as microstructural phases, grain size and shape, and inclusions are all affected by how the melt pool solidifies. Therefore, the microstructure depends primarily on the material composition, temperature gradient, and cooling rate. The variation in microstructure correlates with the temperature gradient of the FZ and heat flow, affecting both the weld mechanical properties and formation of defects.

Laser welding parameters that influence the heat input and cooling rate, such as laser power and welding speed, have a significant effect on the weld microstructure. The cooling rates in laser keyhole welding can be above 10^3 K/s, which is significantly higher than those seen in conventional arc welding processes [105,106]. The low heat input, high cooling rate welds usually result in

microstructure with fine grain structures and high hardness phases. The effect of cooling rate and welding speed on grain growth, shape, and size is clearly shown in Figure 2-16. The melt pool at the lower weld speed has less curvature due to the slower flow and solidification, resulting in broader columnar grains to form.

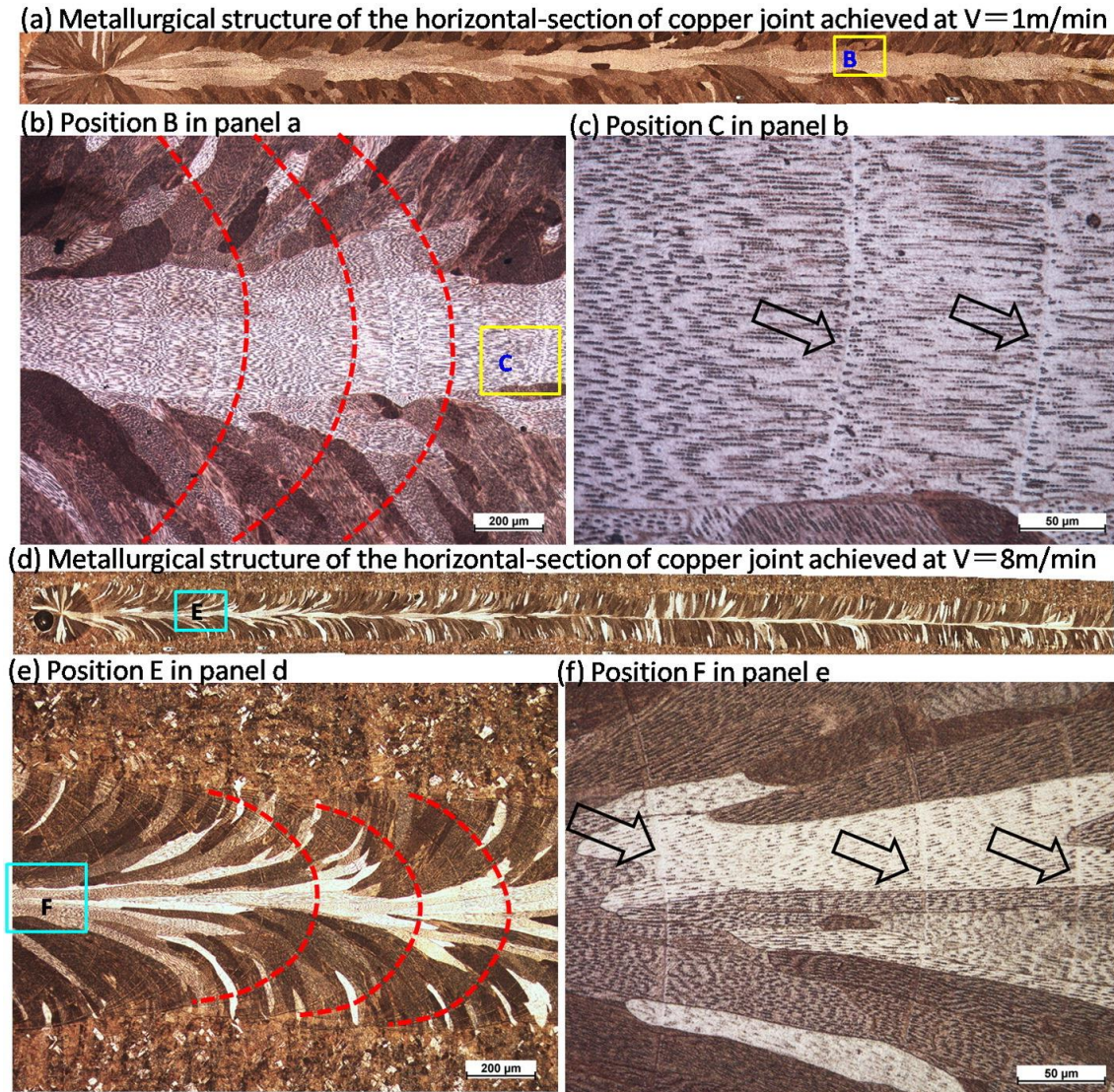


Figure 2-16: Effect of welding speed on metallurgical structure of copper joints achieved with a laser power of 4 kW [107]

2.3.4.1 Solidification defects

Solidification cracking

Solidification cracking can easily form depending on the material, process parameters and workpiece thickness [108]. Materials like aluminium, are prone to cracking due to their high thermal expansion and diffusivity. Cracks typically form in the semi-solid state between grains where there is either insufficient liquid metal to fill cavities or due to significant solidification stresses from material expansion and contraction [109,110]. The material composition and weld geometry also have a significant effect on the formation of cracking [33]. In steels, the percentage of impurities, such as phosphorous and sulphur, can increase crack susceptibility. These impurities segregate when molten and during solidification can form a liquid film between dendrites in the mushy zone of the inter-dendritic region due to their low freezing temperatures [111,112]. Difference in liquidus-solidus temperatures in an alloy, such as aluminium-copper, can also result in an accumulation of a liquid film in the mushy zone of the inter-dendritic region [65]. Nagira et al. observed weld crater cracking because of the accumulation of copper in the liquid film and high localised strain during solidification [65].

Solidification cracking can be prevented by reducing the solidification rate of the melt pool, thereby reducing the solidification and shrinkage stresses. This can be achieved by increasing the heat input or slowing down the cooling rate, either by changing the weld parameters or by applying preheating. Materials that are more susceptible to cracking due to their chemical composition may require the use of suitable filler materials to prevent solidification cracking. Appropriate shielding gas composition was also found to aid in reducing crack susceptibility of stainless steels [64]. Nitrogen can reduce the secondary dendrite arm spacing during solidification, which decreases the accumulation of sulphides in the inter-dendritic regions. However, depending on the chemical composition of the stainless steel, too much nitrogen can give preference for different alloying element segregation, increasing the solidification cracking tendency [64].

Laser welding can offer high productivity, but metallurgical aspects must also be considered otherwise the maximum achievable productivity is limited.

Porosity and cavities

Defects, such as porosity and cavities can form because of rapid solidification of the melt pool. Entrapped gasses in the melt pool may not have sufficient time to escape before the melt pool solidifies, resulting in porosity formation. In laser keyhole welding, keyhole instabilities that lead to keyhole collapse can cause cavities and voids to form that may remain in the weld during solidification [23,29,113]. An example of keyhole collapse and porosity formation at different interaction times in laser spot welding is shown in Figure 2-17. Abrupt laser termination is like laser spot welding due to the rapid solidification of the melt pool. However, differences in melt pool dynamics and material flow due to the laser beam traverse needs to be accounted for.

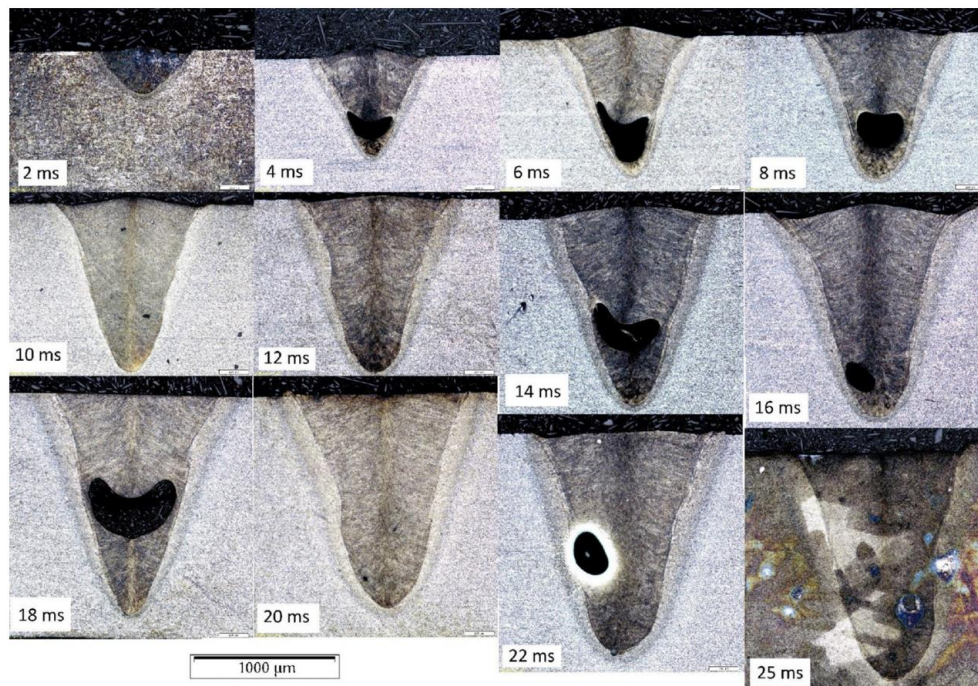


Figure 2-17: Macrographs of porosity in laser welds due to keyhole collapse at different laser interaction times [23]

These defects are likely to form in laser keyhole welding due to their low heat input and high aspect-ratio welds if incorrect process parameters are used. They are also likely to form when the weld is unstable, such as during laser keyhole initiation and termination [114]. Therefore, the solidification rate of the keyhole and melt pool will have a major influence on the formation of defects, especially during laser keyhole termination when the heat input is likely to be reduced.

2.4 Influence of arc in hybrid laser-arc welding

In HL-AW, the combination of a laser with an arc source allows filler material to be added and increases the number of welding parameters, as highlighted in section 2.1.2.1. The arc introduces other phenomena in the form of droplet impingement, arc pressure, and electromagnetic forces. These phenomena combined with the previously discussed laser keyhole welding phenomena has a significant effect and makes the welding process more complex.

2.4.1 Laser-arc interactions

Interactions between the laser and arc source can affect laser absorption and the arc behaviour depending on the distance between the two heat sources and the configuration (laser leading or arc leading) [115,116]. Under certain conditions, the stability of the arc can increase due to the influence of laser radiation. Several researchers have reported that the arc plasma ionisation is enhanced, and the arc constricted, due to the laser radiation and change in plasma composition due to material vaporisation [117,118]. Droplet impingement and in rare circumstances, wire chopping; when the filler wire detaches without melting completely, can disturb the laser absorption or laser keyhole causing it to collapse [119,120]. The stability of the keyhole and balance of forces within can easily be disturbed if the welding parameters change. Therefore, maintaining a stable keyhole and avoiding keyhole collapse during laser termination in both autogenous laser and HL-AW can be challenging. Other factors, such as the arc source, arc transfer mode, and arc welding parameters affect the synergistic interactions between the two sources and can lead to different weld productivity and weld quality [121–124]. The type of shielding gas and filler material used also has a significant effect on the welding process and microstructure [125–127].

Currently literature on the interaction between the laser and arc source during weld termination and during the application of a termination regime is insufficient. How exactly the laser absorption or arc stability changes when the welding parameters are altered during weld termination requires further research.

2.5 Laser and hybrid laser-arc weld termination regimes

2.5.1 Autogenous laser weld termination regimes

There are several methods or termination regimes for closing the keyhole and reducing the crater at the end of a laser weld, such as: laser defocusing, reduction of weld speed, lateral movement of the beam, and reducing the laser power, or any combination thereof [128]. The preferred or most utilised method of reducing and eliminating these issues as described by Dawes is by the ramping down of laser power and/or accelerating the welding speed due to ease of process control and implementation [129]. However, the gradual reduction in penetration when ramping down the laser power can lead to porosity due to keyhole fluctuation and closure. Dawes has suggested that it is difficult to fully eliminate root porosity and cracking in thick sections with weld thicknesses above 5 - 6 mm. In HL-AW, the addition of the arc source and filler material may aid in the filling of the weld crater or cavity and slow down the solidification rate at the termination point.

In recent studies, Gook et al. applied different termination regimes in autogenous laser keyhole welding of 8 mm thick S355J2 sections to understand the defect formation during laser keyhole termination [130]. The authors found that both laser power ramp-down and laser defocusing termination regimes are prone to root sagging defects at the transition from full penetration to partial penetration welding. The severity of the root sagging defects increased with increasing weld ramp-down and defocus distances [130]. An example of root sagging and weld surface dropout due to laser power ramp-down termination is shown in Figure 2-18. However, the appearance of the welds prior to laser power ramp-down in Figure 2-18 do not look optimised and these welding parameters used would affect the transition from full penetration to partial penetration.

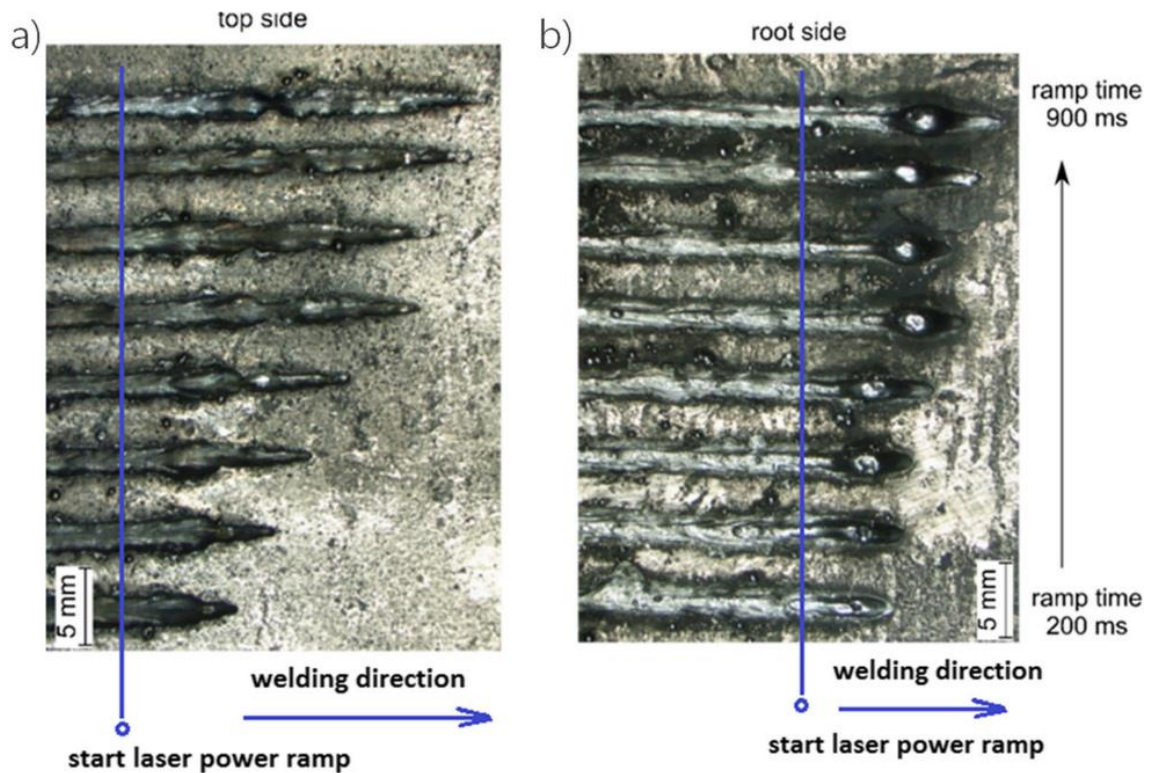


Figure 2-18: Weld root at different ramp-down times of the laser power in 8 mm thick S355J2, a) top side of weld surface, b) root side of top surface [130]

Other defects like end crater cracks were found to increase with weld termination distance and varied with the amount of laser defocusing applied. Unfortunately, the formation of end crater cracks could not be avoided with the laser defocusing termination regime used by the authors and a remedial weld pass using a defocused laser beam was necessary. The additional process step required to correct and mitigate the end crater defects decreases productivity.

2.5.2 Hybrid laser-arc weld termination regimes

In HL-AW, successful circumferential welds without termination defects on 8 mm thick A304 stainless steel tubes was achieved using a laser power-ramp down termination regime, as shown in Figure 2-19 [131]. The authors only achieved successful keyhole closure without significant defects at the weld termination point using one case of laser power ramp-down parameters. These methods have produced satisfactory effects but require careful trial and error and is only optimised for a specific weld case as previously stated.

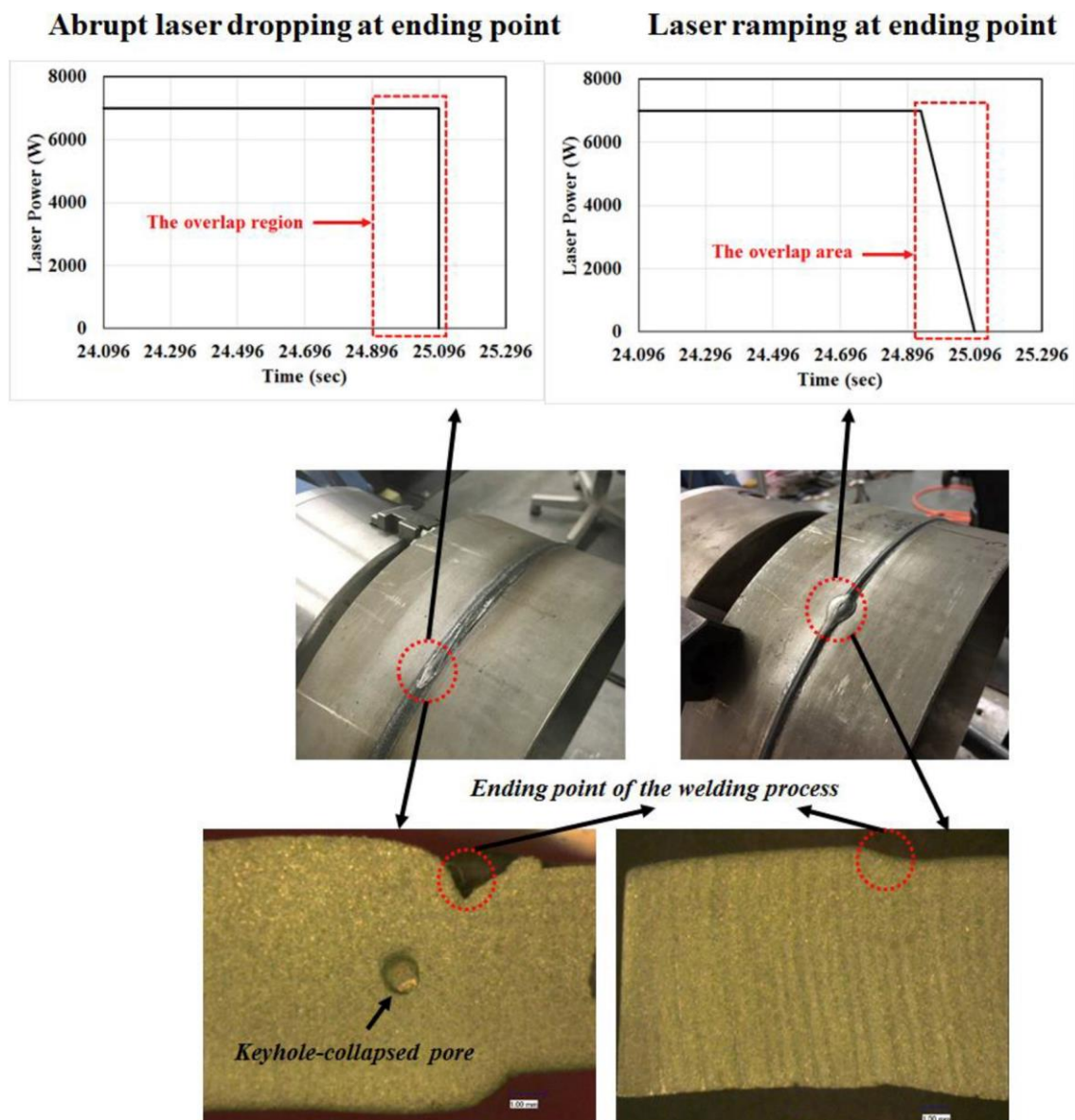


Figure 2-19: Formation of pore due to keyhole collapse and mitigation using laser ramping at the termination point [131]

2.6 Effect of alloying elements on weld pool behaviour in structural steels

Previous sections indicated how the material type and composition can behave differently during laser processing, and how they can affect the formation of defects. The following section focuses on S355 grade structural steel composition and how the different alloying elements can affect the melt pool dynamics and flow direction, solidification, and formation of defects.

The chemical composition for S355 grade structural steel is shown in Table 2-1. Small amounts of other alloying elements, such as Nickel, Chromium, Molybdenum, Aluminium, Vanadium, Niobium, and Titanium, are typically added for grain refinement and deoxidation purposes, and to increase corrosion resistance properties. These alloying elements should not impact weld performance significantly. However, certain elements can potentially influence the flow direction in the presence of a high temperature gradient often seen in deep penetration laser welding.

Variations of S355 steel grades, such as S355J2, has higher impact energy tolerance at lower temperatures and are more commonly used for offshore structures. The composition and percentage of alloying elements also varies depending on the manufacturer and batch.

Table 2-1: Typical chemical composition of S355 low carbon steel [132]

Material	Wt. % max						
	C	Mn	Si	S	P	N	Cu
S355	0.2	1.60	0.55	0.025	0.025	0.012	0.55

2.6.1 Phosphorous and sulphur

As previously mentioned in 2.3.4.1, impurities, such as phosphorus and sulphur, can result in defects depending on the amount present but are usually low enough so that they are not detrimental [132]. Higher amounts of sulphur can be added to improve the machineability of certain steels but are offset by increasing the amount of manganese to prevent embrittlement and cracking [132,133].

Sulphur is also a surface-active element and has a similar effect as oxygen on the surface tension and temperature gradient, and change in flow direction [101,104]. The effect of sulphur on material flow was experienced in electron beam welding [134]. The presence of sulphur leads to a positive surface tension resulting in an inward surface flow. The inward flow direction gave rise to an upward flow resulting in surface ripple formation during solidification.

2.6.2 Manganese and silicon

Manganese and silicon are core elements and deoxidisers and increases the hardenability and tensile properties of the carbon steel [135]. Manganese is also necessary to counter the embrittlement and loss of ductility due to sulphur [133], where a typical manganese to silicon ratio above 10:1 is recommended. Both manganese and silicon promote slag formation in the form of Manganese Oxide and Silicon Dioxide in the presence of oxygen.

In welding, these elements react with oxygen to protect the melt pool and prevent oxygen ingress [136]. The difference in dissolved oxygen and the formation of slag on the melt pool surface can affect the surface tension and temperature gradient, and material viscosity [99,137]. Therefore, the combined effect of these elements, amount of dissolved oxygen, and slag formation can lead to keyhole and melt pool instability and changes in melt pool dynamics, as previously discussed in 2.3.3. These factors can result in variable penetration depth as was observed in the welding of stainless steels [97,99]. Changes in surface tension and melt pool flow was observed by Ahsan et al. when using filler materials with varying amounts of manganese, silicon, and dissolved oxygen [138]. Low amounts of manganese and silicon in the filler material had higher amounts of dissolved oxygen, promoting a positive surface tension and inward flow direction.

The inward flow direction caused the slag formation to congregate along the middle of the weld bead, as shown by the schematic and high-speed video image in Figure 2-20.

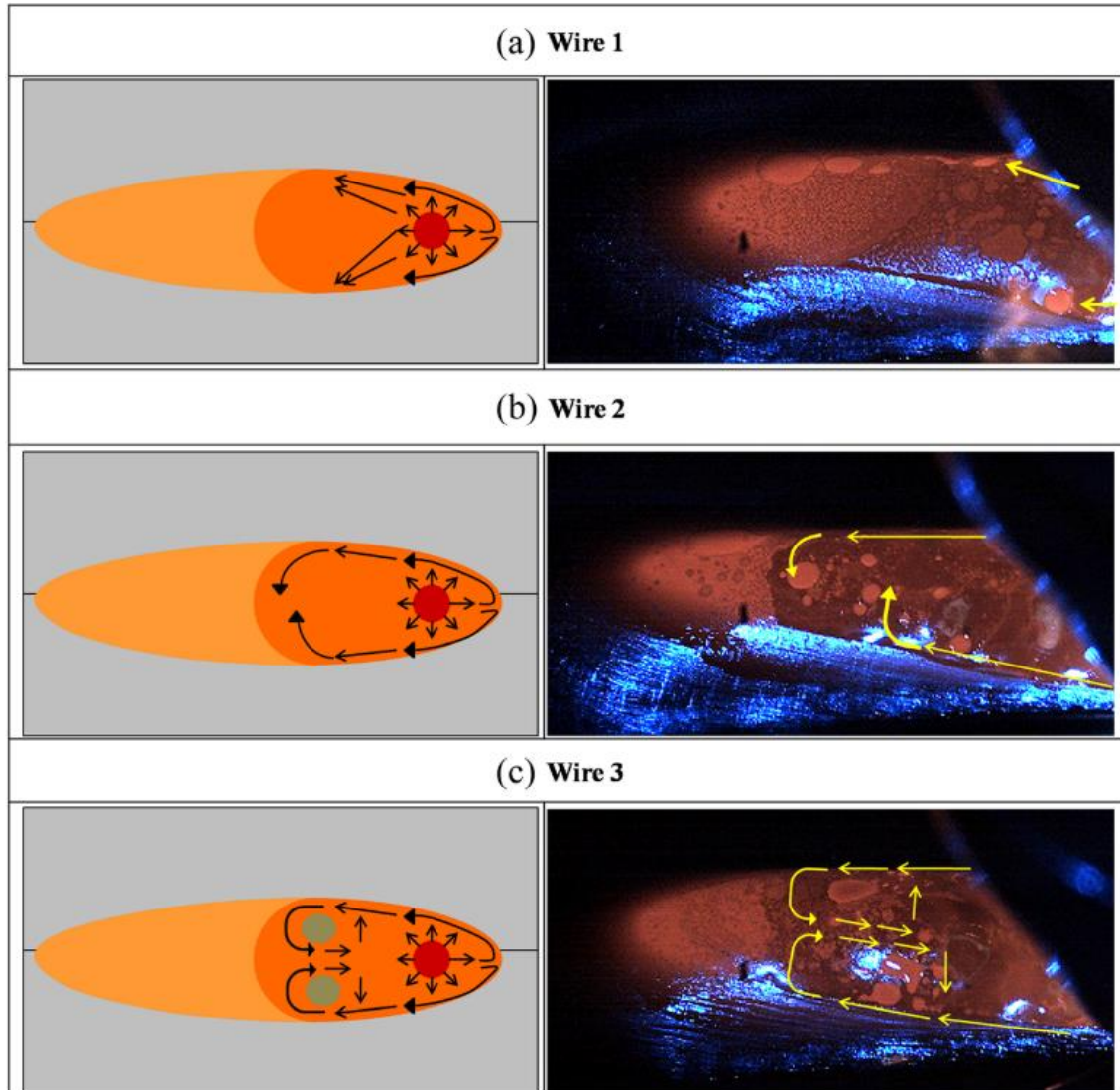


Figure 2-20: Schematic and image of weld pool flow pattern and slag formation location, a) low Si & Mn, b) medium Si & Mn, c) high Si & Mn [138]

2.7 Summary

There is still little research on laser keyhole initiation and termination defect formation and mitigation under different processing conditions. Further research on the effects of different laser termination regimes on keyhole and melt pool dynamics and defect formation is required to enable laser keyhole welding for circumferential welding applications.

It is unknown what the most optimum keyhole termination rate is in deep penetration laser keyhole welding to avoid keyhole collapse. The keyhole termination rate determines the length of the weld overlap start/stop region in circumferential welds. If the weld overlap region is too long, it increases welding time, affecting weld productivity. If it is too short, the weld may not intersect. The influence of inter-pass temperature during laser keyhole termination on defects at the weld overlap start/stop region is also unknown.

Various laser termination regimes, such as laser power ramp-down and laser defocusing affect the laser keyhole termination, keyhole and melt pool dynamics, and heat transfer differently. In deep penetration welding, the reduction in heat input during laser power ramp-down at the termination point may be detrimental to the solidification behaviour and requires further study.

It is known that different compositions of steels can affect melt pool dynamics and flow behaviour. However, there is no research on how and if different compositions of steel affect laser weld terminations when applying different laser termination regimes.

The complex phenomena in HL-AW and how the laser and arc parameters affect the welding process during the application of a termination regime also requires further study as there is little research.

Chapter 3

Methodology

3.1 Experimental equipment and set-up

3.1.1 Materials and plate preparation

S355J2+N grade high strength, low carbon structural steel plates of varying thicknesses supplied by West Yorkshire Steels were used for all experiments. The typical chemical composition for this grade of steel is shown in Table 3-1 and the specific chemical composition of S355J2+N steel plates used in each experiment is available in each subsequent chapter due to their variation.

Table 3-1: Typical chemical composition of S355J2+N low carbon steel [132]

Material	Wt. % max					
	C	Mn	Si	S	P	Cu
S355J2+N	0.2	1.60	0.55	0.025	0.025	0.55

The plates with were cut to specific dimensions depending on the experiment and cleaned with acetone to remove dust or grease. For some autogenous laser welding experiments, the plates were machined to specific thicknesses to remove mill scale and cleaned with acetone prior to welding.

External optical emission spectroscopy was carried out on S355J2+N plate batches in Chapter 6.

3.1.2 Weld clamping and motion system

A 6-axis Fanuc M700i B45 robot integrated with a single-axis translation stage was used for all experiments. All autogenous laser welding experiments were carried out in the 2G welding position using either a clamping fixture or a fabricated 2G welding jig to secure the plates in place. The 2G welding jig was intentionally designed to be open on both sides allowing for the top and bottom of the plates to be viewed. For the hybrid laser-arc welding experiments, welds were carried out in the 1G welding position and standard faceplate clamps were used to secure the plates to the single-axis translation stage.

3.1.3 Autogenous laser welding

An IPG continuous wave fibre laser (IPG YLR-8000) with a maximum power output of 8kW was used as the laser source for all experiments conducted for this thesis. The laser is fully integrated with the Fanuc robot allowing it to be controlled through executed commands on the robot teach pendant. The laser welding head is mounted to the 6-axis Fanuc robot and positioned horizontally for 2G welding, as shown in the experimental setup in Figure 3-1. The laser is transmitted through a fibre with a core diameter of 0.3 mm and, a collimation lens and focusing lens of 125 mm and 250 mm focal length, respectively. The combination of these optics gives a laser beam with a focal spot beam diameter of 0.6 mm. The focal spot was positioned on the top surface of the workpiece for all autogenous laser experiments. The laser was tilted by an angle, $\theta = 10^\circ$, opposite to the welding direction, i.e., laser pushing, to avoid any damage to the laser by back reflection. All the welds were carried out without any shielding gas to minimise any interaction with the gas plume unless stated otherwise in subsequent chapters.



Figure 3-1: Experimental set-up for autogenous laser welding

3.1.3.1 Laser welding fundamental parameters

The main parameters used in laser welding and within this thesis can be calculated using the following equations:

$$\text{Laser power density, } P_d, [kW/mm^2] = \frac{\text{Laser power (kW)}}{\text{Laser spot size area (mm}^2\text{)}} = \frac{4 \times P}{\pi \times \phi^2} \quad 3-1$$

$$\text{Interaction time, } t_i, [ms] = \frac{\text{Laser spot size diameter (mm)}}{\text{Welding speed (m/min)}} = \frac{\phi \times 60}{v} \quad 3-2$$

$$\text{Laser Heat input, } Q_{Laser}, [kJ/mm] = \frac{\text{Laser power (kW)}}{\text{Welding speed (m/min)}} = \frac{P \times 60}{v} \quad 3-3$$

3.1.4 Weld monitoring

Various monitoring devices and equipment were used at different stages of research. A Yokogawa DL 750 oscilloscope was used for signal monitoring of temperature and laser power.

For the monitoring of arc current, voltage and WFS in Chapter 7, an AMV Weldmon 4000 from Triton electronics was used.

Image monitoring was performed using Xiris XVC-1000 weld cameras.

3.2 Experimental approach

The following sections illustrate the experimental approach and procedures carried out in this thesis.

3.2.1 Circumferential weld replicated on to a flat plate

To simplify the process of circumferential welding on pipes, the circumferential weld was replicated onto a flat plate via two overlapping weld seams with an elongated weld overlap, as shown in Figure 3-2. The elongated weld overlap allows for the start and termination points of the laser and varying weld overlap distances to be investigated independently of each other. Each point denoted as, A, B, C and D represents the two initiation points (A and B) and two termination points (C and D) as illustrated. Firstly, a full penetration, autogenous bead-on-plate (BOP) weld was conducted where the laser initiates at B and terminates at D. Then after a calculated delay time, simulating different pipe dimensions, the laser is reinitiated at point A, welding again at full penetration, and then terminating at point C. The intersection of the two weld seams ($\overline{BC}$) represent the start/stop region of a circumferential weld.

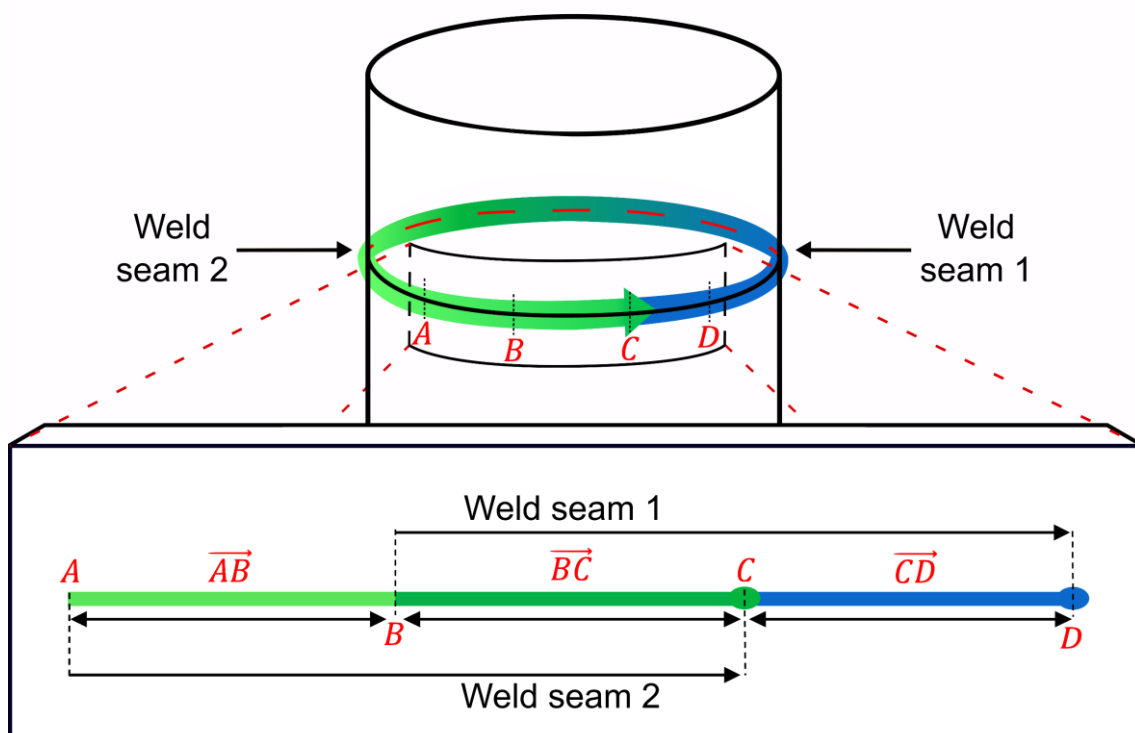


Figure 3-2: Illustration of circumferential weld replicated onto a flat plate

All welds carried out within this thesis were bead-on-plate (BOP). No butt welds were conducted within this thesis. Therefore, the thermal stresses generated during welding would be different to those experienced with the BOP welds and can lead to differences in certain defect formations, such as crack formation.

3.2.2 Replicating the welding of different pipe diameters

To replicate the welding of different pipe dimensions, without increasing the length of the workpiece, a delay time in-between the two weld passes can be introduced. The delay time is simply the period between the laser terminating at point D and reinitiating at point A and can be calculated using equation 3-4. It is calculated by subtracting the actual welding time and laser head traverse time from the theoretical time it would take to weld around a circumferential length of diameter, D , at a set welding speed, v . The actual welding time is the time taken to weld from point B to point D and from point A to point B, thus completing a circumferential weld.

$$\text{Delay time, } t_{\text{delay}}, [s] = t_{\text{circ}} - t_{\overline{BD}} - t_{\overline{AB}} - t_{\overline{DA}}^* \quad 3-4$$

Note $t_{\overline{DA}}^*$ is the time taken for the laser head to travel from point D to point A while it is not on at the maximum robot motion speed permitted.

3.2.3 Laser defocusing termination regime

Laser defocusing is achieved by gradually increasing the distance between the laser head from the workpiece (focal length) resulting in an increase in the laser spot diameter, as shown in Figure 3-3. The increase in focal length, z_{Focal} , and laser spot diameter is calculated by linear extrapolation of the beam profile.

$$\text{Focal length, } z_{\text{Focal}}, [mm] = \frac{\phi_{\text{Spot}} + a}{b} - \frac{\phi_{0.6} + a}{b} \quad 3-5$$

Where a and b are constants.

The laser power output is kept constant throughout the laser defocusing.

Unfortunately, this method of laser defocusing, which involves the movement of the laser head to achieve a larger spot diameter, has some implications that need to be considered. The robot that controls the motion of the laser head is programmed to move at a set input travel speed, v , in the direction of travel.

Therefore, the actual travel speed of the laser beam in the welding direction is different to the input travel speed of the laser head travel during laser defocusing.

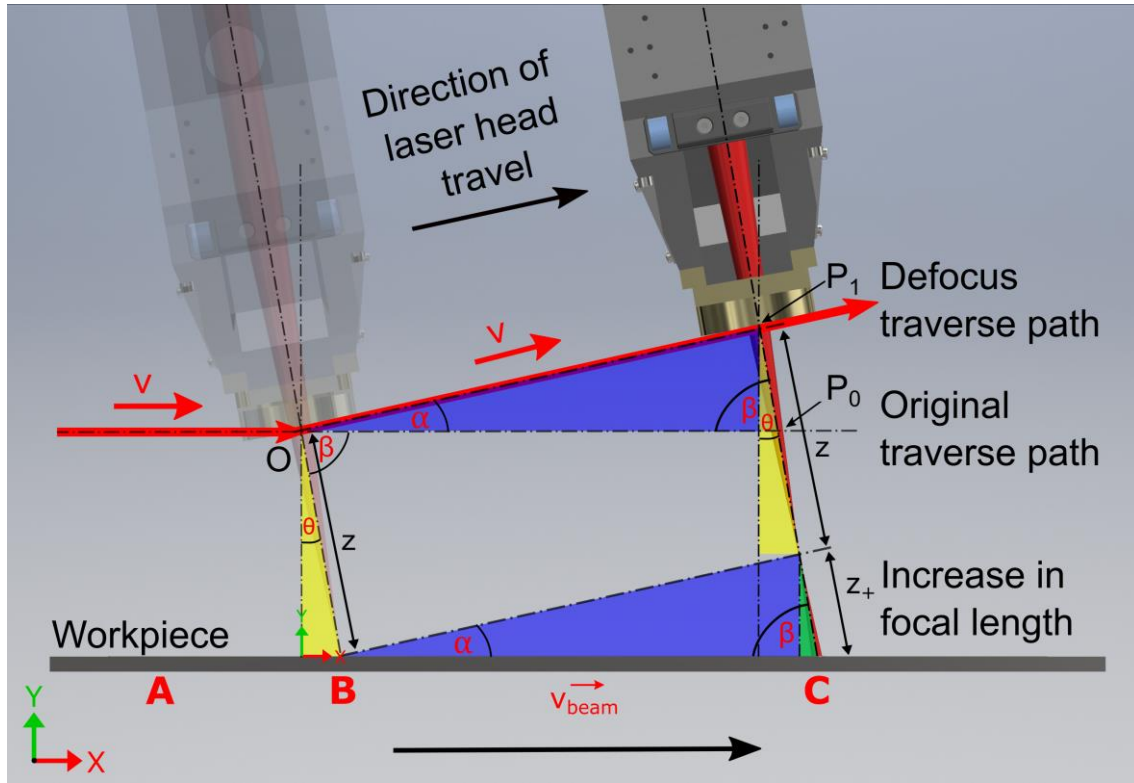


Figure 3-3: Laser defocusing schematic

The speed of the laser beam in the welding direction can be calculated using:

$$\text{Speed of beam in welding direction, } v_{beam}, [m/s] = \frac{\overline{BC} \times v}{\overline{OP_1}} \quad 3-6$$

where $\overline{BC}$ is a set weld overlap length, and $\overline{OP_1}$ is the laser traverse distance.

The change in X and Y direction due to the focal length (shown by the yellow and green triangles) and the distance $\overline{OP_1}$ can be calculated using the Pythagorean theorem. Distance $\overline{OP_1}$ is dependent on the focal length and weld overlap length.

For comparison, when the set input travel speed is programmed at 0.5 m/min and the laser is defocused to an end laser spot size of 4.2 mm. The speed of the laser beam in the welding direction is 0.39 m/min and 0.48 m/min for a weld overlap length of 40 mm and 80 mm, respectively.

Example calculations for the comparisons are given in Appendix A.

3.2.4 Verification and control of laser power ramp-down termination regime

Welding parameters, such as the laser power and travel speeds are controlled by triggering specific analogue and digital inputs and outputs via the Fanuc teach pendant. The laser power output is set via a registry value on the teach pendant, which corresponds with a specific value used for the analogue output from the robot to the laser power source. The laser power output set by the registry value has been previously calibrated with a power meter so that the programmed value into the teach pendant corresponds with the actual laser power output. To achieve a gradual reduction of laser power output, a simple loop which gradually reduces the registry value and therefore the analogue output value at a specified rate was programmed into the teach pendant. The laser power ramp-down program functions as a sub-program that can be called and runs only when a certain digital output is turned on. The program can be found in Appendix B.

The program was verified using a photodiode (placed inside the fibre cabinet between the feeding and process fibres) to measure the intensity of the light being delivered to the laser head, as shown in Figure 3-4. The photodiode gives an output signal range from 1 to 10 V and the output was recorded using a Yokogawa DL 750 oscilloscope using a sample rate of 100 Hz. A conversion from voltage to laser power output was calculated by measuring the photodiode readings at incremental laser powers from 0 kW to 8 kW.

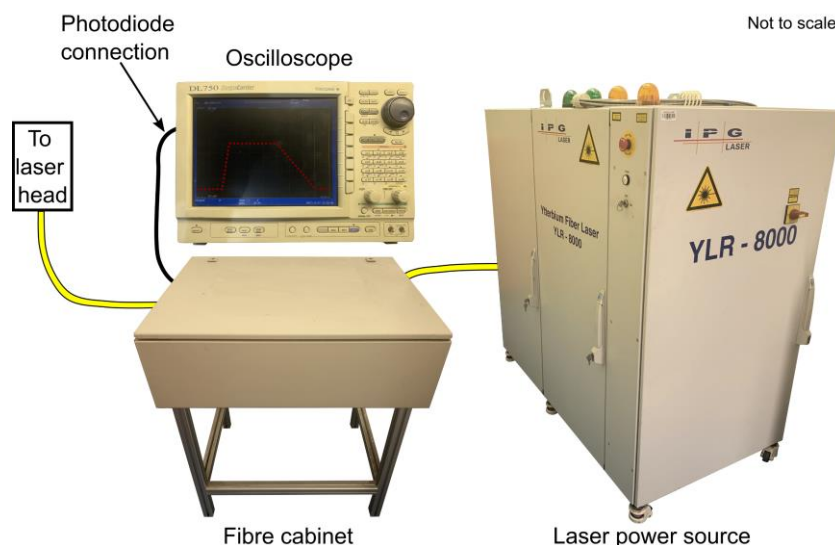


Figure 3-4: Illustration of laser power ramp-down verification set up

The laser power ramp-down program was tested at set laser powers from 2 kW to 8 kW. The laser was initiated at full power for 5 s, ramped down to 0 kW over 10 s, held for 1 s at 0kW, and then switched off. Figure 3-5 shows the recorded measurements from the photodiode and corresponding laser power.

A linear reduction of the measured voltage was observed, which correlates with the laser power ramp-down program for each case. Note that, despite setting the analogue value in the teach pendant at an equivalent of 0 kW, a negligible amount of laser power of 30-40 W was still emitted unless the laser was switched off.

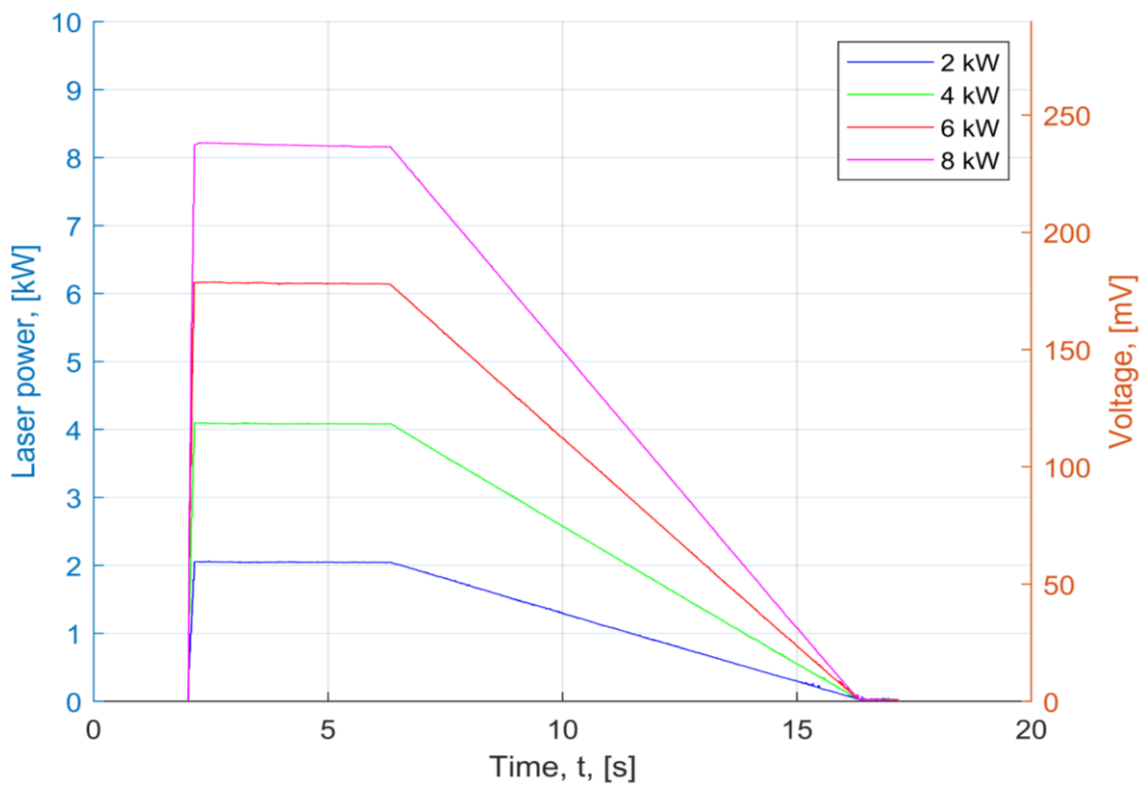


Figure 3-5: Voltage measurements of laser power ramp-down program

3.3 Metallography and sample analysis

3.3.1 Weld sample preparation

All weld samples were cleaned using acetone to remove any dirt and then photographed using a Canon EOS 400D Digital SLR Camera prior to cutting. For metallographic analysis, transverse and/or longitudinal samples were cut from weld samples, as shown in Figure 3-6 depending on the experiments. Transverse samples of lengths between 20 – 30 mm were cut from the middle of the weld seam sections $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$. Longitudinal samples were cut along the length of $\overline{BC}$ or at specific start/stop points from $A - D$.

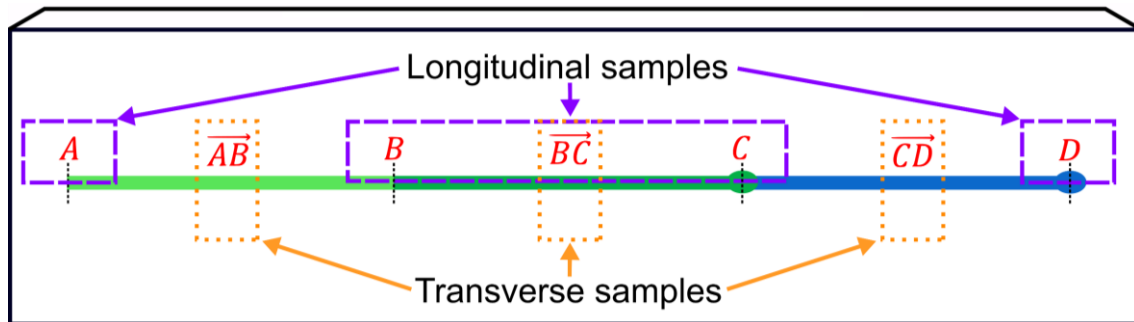


Figure 3-6: Schematic depiction of positions for metallographic sample extraction

All transverse weld samples and small longitudinal weld samples were either cold mounted using epoxy resin and hardener, or hot mounted using a thermosetting compound (Bakelite) into specifically shaped cylindrical moulds. The mounted samples fit into automated grinding and polishing machines. Large longitudinal samples were manually ground and polished due to the dimensions of the samples.

The weld samples were subjected to various grinding and polishing steps following preparation methods by Struers for medium carbon steels [139]. For the grinding step, varying grits of grinding paper: 120, 240, 1200, 2400 were used to flatten the samples and remove deep scratches. The polishing step involved using 3 μm diamond suspension on a MD-Plano or MD-DAC surface then OP-S colloidal silica suspension with water on a MD-Chem or multi-cloth surface.

All polished samples were etched using a 2% Nital etchant solution to reveal the microstructure for microscopic analysis.

3.3.2 Optical microscopy

To observe the weld profile and microstructure, Nikon Optiphot microscopes were used to take both macrographs and micrographs of all weld samples. For some of the large longitudinal samples found in Chapter 7, a Hirox RH-2000 3D digital microscope was used.

3.3.3 Weld profile measurements

Weld profile dimensions were measured by image analysis using AxioVision 4.9.1, a digital imaging measurement software. An example measurement of the weld top surface and longitudinal macrograph with 1 mm increments used in Chapter 4 is shown in Figure 3-7.

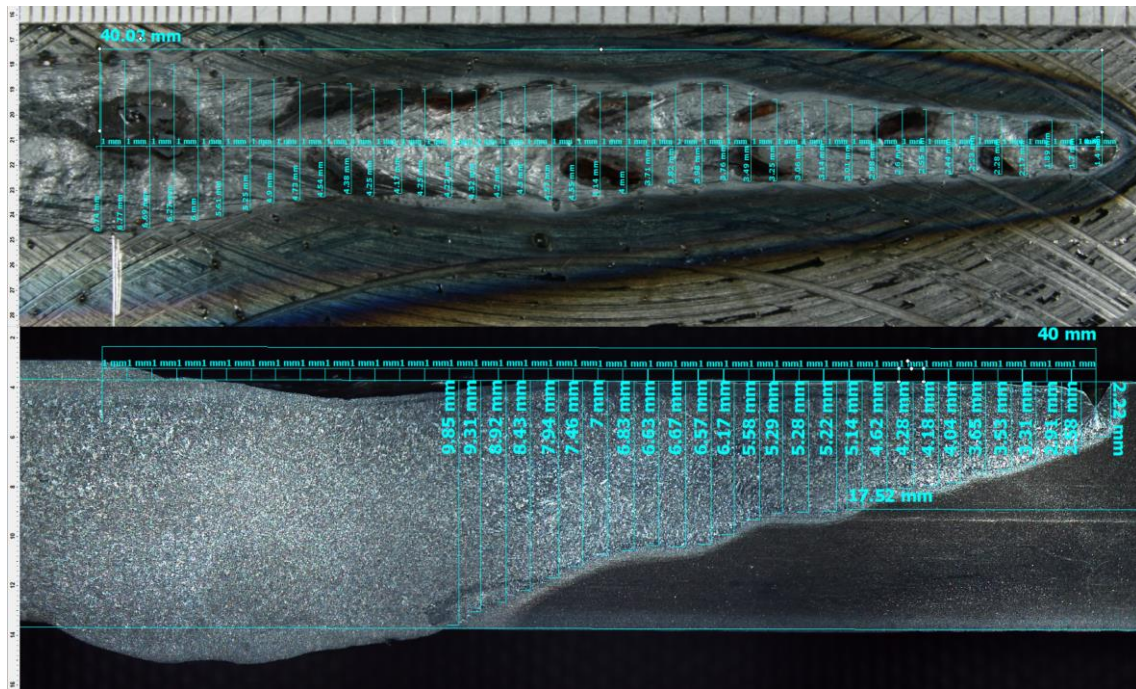


Figure 3-7: Example weld profile measurements using AxioVision

3.4 Mechanical testing

3.4.1 Micro-hardness testing

A Zwick/Roell ZHV μ Micro Vickers hardness machine with a diamond indenter was used to carry out all micro-hardness tests of weld samples. A load of 500 g and duration of 15 s was used. Micro-hardness profiles across the weld centreline in the mid-thickness of the transverse weld samples were taken with a 0.5 mm spacing between indents. For certain samples, micro-hardness profiles 2 mm from the top and root of the transverse weld samples were also measured.

3.4.2 Tensile test with digital image correlation (DIC)

In Chapter 6, tensile test results were described which were conducted using an electro-mechanical Instron 5500R machine with digital image correlation to measure the localised strain distribution pattern across the weld samples. Tensile testing was performed after sample preparation and DIC equipment set-up and calibration by a trained technician. The tensile test and post-treatment of the DIC video data were carried out by the author with initial guidance from the technician.

A load cell of 100 kN and a displacement rate of 1 mm/min was used. The set-up of tensile test machine and DIC system is shown in Figure 3-8.

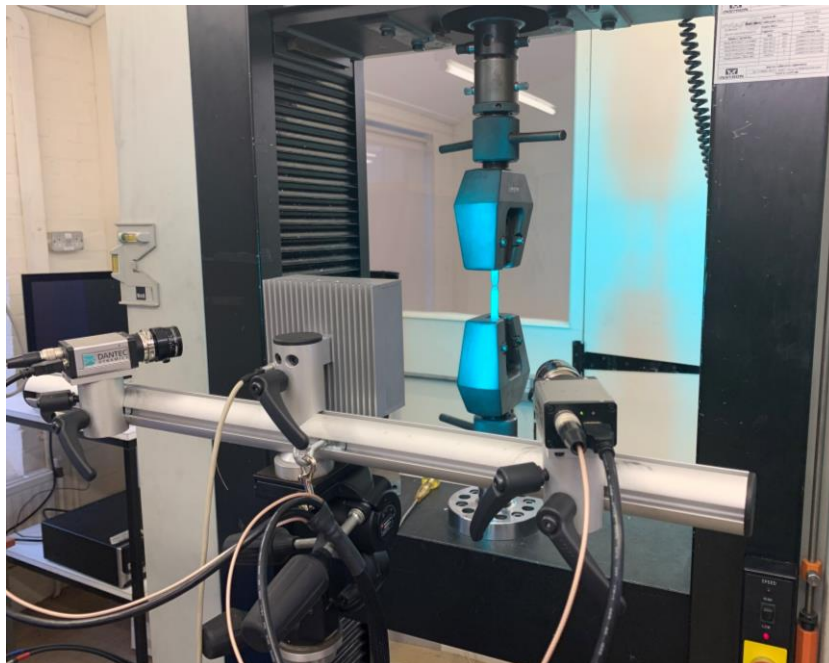


Figure 3-8: Tensile test setup with digital image correlation

3.4.2.1 Specimen design and preparation

Tensile specimens from specific locations of the weld samples were cut using wire electrical discharge machining to ensure superior surface finish and minimise the induction of additional machining stresses. A schematic of a weld sample showing the locations where the specimens were machined is shown in Figure 3-9. The tensile specimen design is shown in Appendix C.

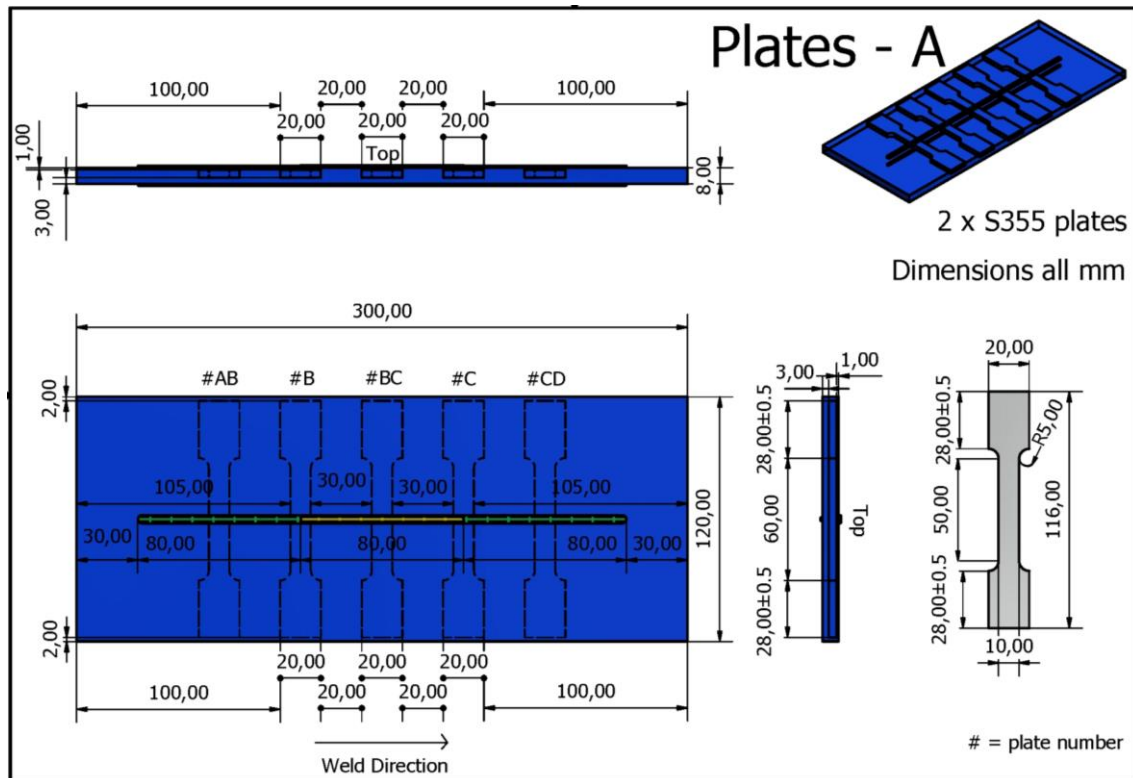


Figure 3-9: Drawing of weld sample and location of tensile specimens

All specimens were cleaned using acetone prior to spray painting with a speckled pattern consisting of white background with black dots on the surface, as shown in Figure 3-10.



Figure 3-10: Painted tensile specimen after DIC testing

3.4.2.2 DIC post-treatment

Post-treatment was carried out using Istra4D, a software by Dantec Dynamics, to process and analyse the video frames captured during the tensile tests. The software provides analysis of the localised straining pattern across the test specimen, which can be displayed as a strain contour map, as shown in Figure 3-11. Unfortunately, the paint lost adhesion and flaked away during testing when the sample began yielding due to the smooth surface of the specimen. The region where the paint was lost is evident during the post-treatment of the DIC data by the missing areas of data where the sample began necking, as shown on the right of Figure 3-11. ASCII files of each frame step were generated and extracted from the software for processing to calculate the local yield strength.

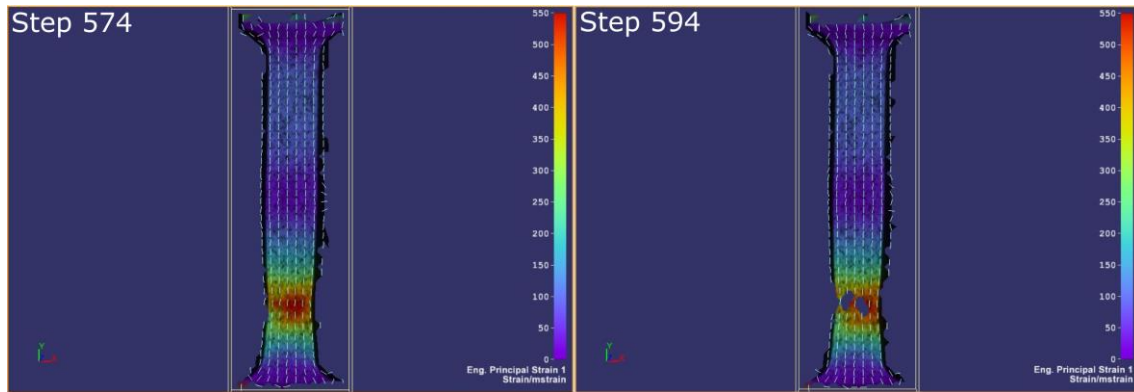


Figure 3-11: Strain map of the post-treated DIC using Istra4D software

3.4.2.3 Yield strength mapping

To calculate the local yield strength, three in-house codes developed in MATLAB by a research fellow within the Welding Engineering and Laser Processing Centre was used to process the data files generated in ASCII format. The codes extract the coordinates and principal engineering strain values from the data files and generates the global or local stress-strain curves and calculates the corresponding yield strength.

The three in-house codes were modified by the author to analyse and output specific properties and figures as desired. The modified codes plot the global stress-strain, the local stress-strain, and contour maps of the local strain and yield strength variation pattern across the specimen. These codes can be found in Appendix D.

A Young's modulus of 210 GPA and 0.2 % proof stress was used in the calculations of the yield strength. Estimations of the Young's modulus from the data were not possible due to the noise in the measured data. The frame step where the maximum load was applied or when the paint started to flake away was used as final iteration step in the code. An example of the plotted contour maps generated from the modified code and the local stress-strain plots from specific areas on the contour map is shown in Figure 3-12. The black parallel lines show the gauge length of the specimens. The contour map of the tensile specimen has been re-aligned and centred, such that the weld direction travels from -10 to 10 in the X-axis at 0 in the Y-axis for ease of comparison.

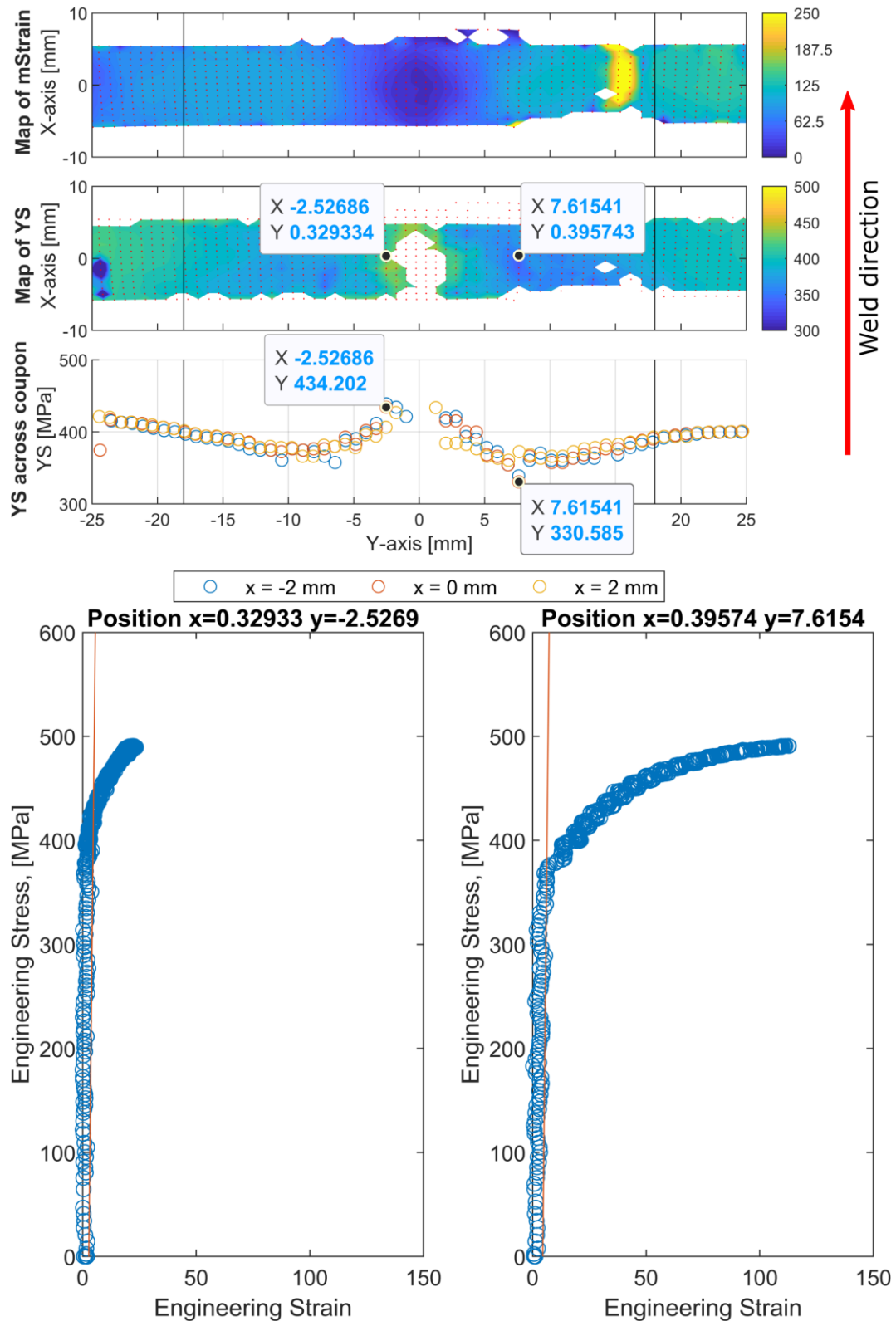


Figure 3-12: Example plot of localised strain and yield strength contour map, plot of the yield strength across the specimen, and local stress-strain plots from specific points

Chapter 4

Preliminary study of laser termination regimes: Laser defocusing and laser power ramp-down

4.1 Introduction

In full penetration laser keyhole welding, the abrupt termination of the laser at the end of a weld seam can lead to the formation of laser termination related defects, such as weld craters and cavities, cracks, and porosity. Therefore, an adequate termination regime must be applied to prevent the formation of these defects during laser keyhole termination.

The most common termination regime is laser power ramp-down, due to ease of process control and implementation. However, there can be several complexities involved due to the reduction in laser energy and penetration, which can lead to keyhole instabilities and subsequent collapse. Successful application of laser power ramp-down is usually achieved in a case-by-case basis with a set of welding parameters through a trial-and-error approach. There has been little research into the effects of laser power ramp-down or on how to achieve successful keyhole closure for different parameters. Another potential termination regime is the application of laser defocusing. Laser defocusing has become more common in recent years due to improvements in process control and development of motorised optics, such as motorised beam expanders. However, the application of laser defocusing as a laser termination regime has been rarely applied nor studied.

In this chapter, experiments were conducted to understand the effect of laser defocusing and laser power ramp-down termination regimes on the weld profile, keyhole closure, and laser termination defects, such as weld crater formations.

Different variables, such as the rate of laser defocusing, and end laser spot diameter, were studied in the laser defocusing experiment. For the laser power ramp-down experiment, the effect of ramp-down rate and ramp distance for a range of welding parameters were investigated. A combined application of laser power ramp-down with laser defocusing was also studied in the latter experiment to determine the merits of utilising a combination of both termination regimes. Different rates of laser keyhole termination were studied to investigate if there is an optimum keyhole closure rate using either termination regime.

4.2 Methodology

4.2.1 Experimental set-up

4.2.1.1 Laser defocusing termination regime

As-received plates of dimensions 300 x 85 x 7.8 mm were used within this experiment. The parameters used for this experiment are given in Table 4-1. The laser power and laser travel speed, were calculated using the *Power Factor Model* as proposed by Suder and Williams to achieve full penetration [140]. The different laser defocus angles were set by calculating the distance required for the laser beam to travel in the welding direction when the focal length was fixed, as shown in Figure 4-1.

Table 4-1: Parameters used in laser defocusing experiment

Parameters	Value
<i>Laser power, P, [kW]:</i>	6
<i>Initial travel speed, v_{AB}, [m/min]:</i>	1
<i>Laser head travel speed, $v_{laserhead}$, [m/min]¹:</i>	1 - 3
<i>End laser spot diameter, $\varnothing_{End}$, [mm]:</i>	3 6 9
<i>Laser defocus angle, α, [°]:</i>	30 45 50 70

¹ Programmed laser head travel speed from point B during laser defocusing

4.2.1.2 Laser power ramp-down and combined termination regime

Machined plates of dimensions 200 x 200 x 10 mm were used for this experiment. Three sets of welding parameters were selected from a series of trial welds that provided full penetration with uniform top and root surface quality. These parameters were used within this experiment and are given in Table 4-2.

Table 4-2: Parameters used in laser power ramp-down and combined termination regime experiment

Parameters	Value
Laser power, P , [kW]:	5.35 6.30 7.20
Initial travel speed, $v_{\overline{AB}}$, [m/min]:	0.30 0.45 0.60
Laser head travel speed, $v_{laserhead}$, [m/min] ¹ :	0.30 0.45 0.60
Ramp-down distance, $L_{\overline{BC}}$, [mm]:	40 60
End laser spot diameter, $\varnothing_{End}$, [mm]:	0.6 3.0

¹ Programmed laser head travel speed from point B during laser defocusing

Table 4-3 gives the weld sample names and parameter configurations.

Table 4-3: List of weld samples and parameter configurations

Sample ¹	P [kW]	$v_{laserhead}$ [m/min]	$L_{\overline{BC}}$ [mm]
Weld 2	5.35	0.30	40
Weld 3			60
Weld 6	6.30	0.45	40
Weld 7			60
Weld 10	7.20	0.60	40
Weld 11			60

¹ Prefix 'D' is added to the number for the combined termination regime samples

4.2.2 Experimental approach

4.2.2.1 Laser defocusing termination regime

Varying rates of laser defocus was achieved by defocusing to different laser end spot diameters at specific laser defocus angles, α , as shown in Figure 4-1. Different laser head travel speeds were also applied from point B to point C to broaden the rates of defocus. The laser defocus distance is dependent on the focal length and set laser defocus angle, α . The speed of the beam in the welding direction varies accordingly, as previously explained in section 3.2.3. The laser power is kept constant, and the laser beam speed reduced due to the method of laser defocusing. Therefore, the heat input increases during laser termination when compared with the steady-state weld region.

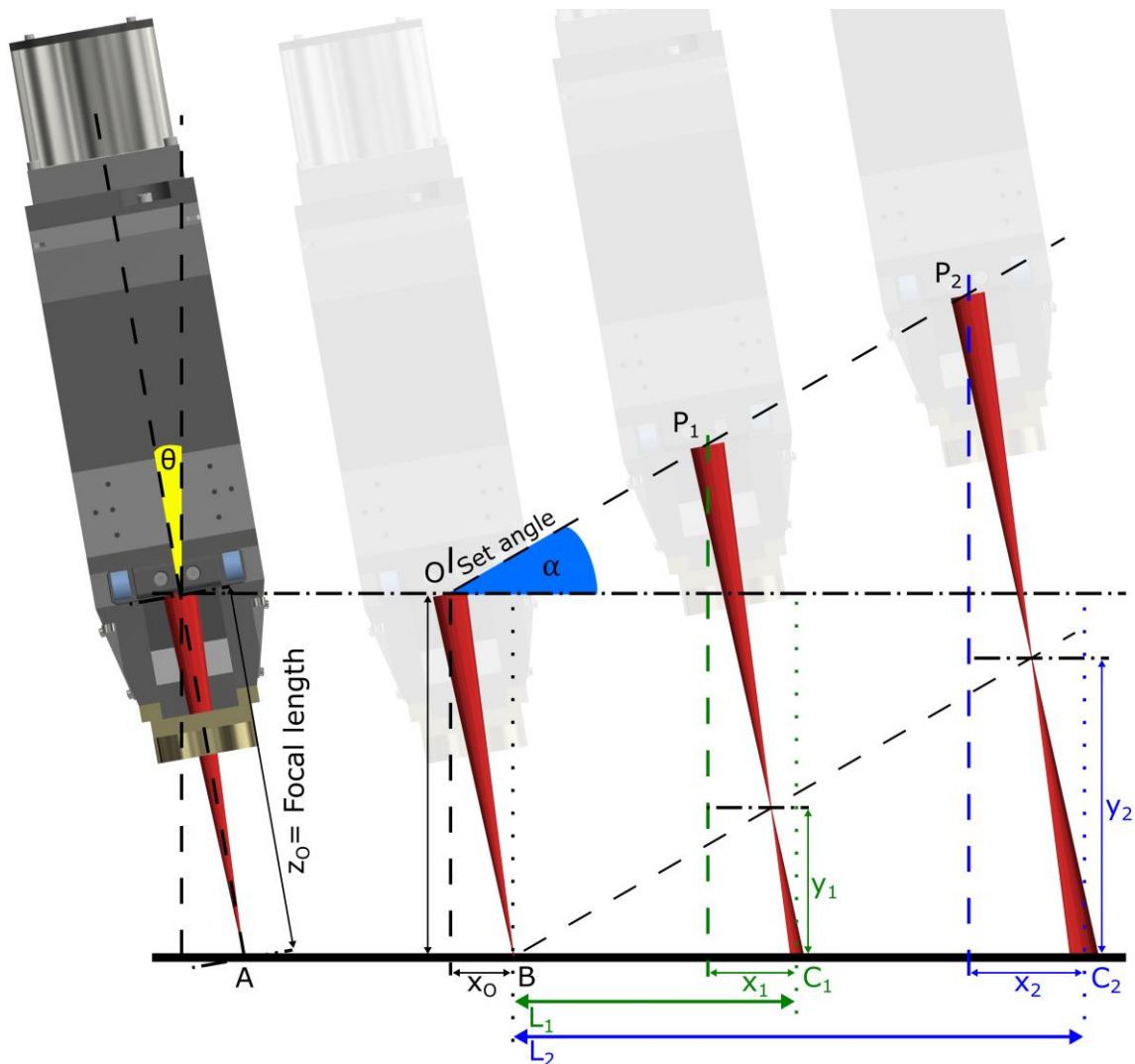


Figure 4-1: Schematic of laser defocusing termination regime

The change in laser power density and defocus distance for each parameter configuration is shown in Figure 4-2. The different laser head travel speeds and beam diameters result in varying interaction times for each parameter configuration as well.

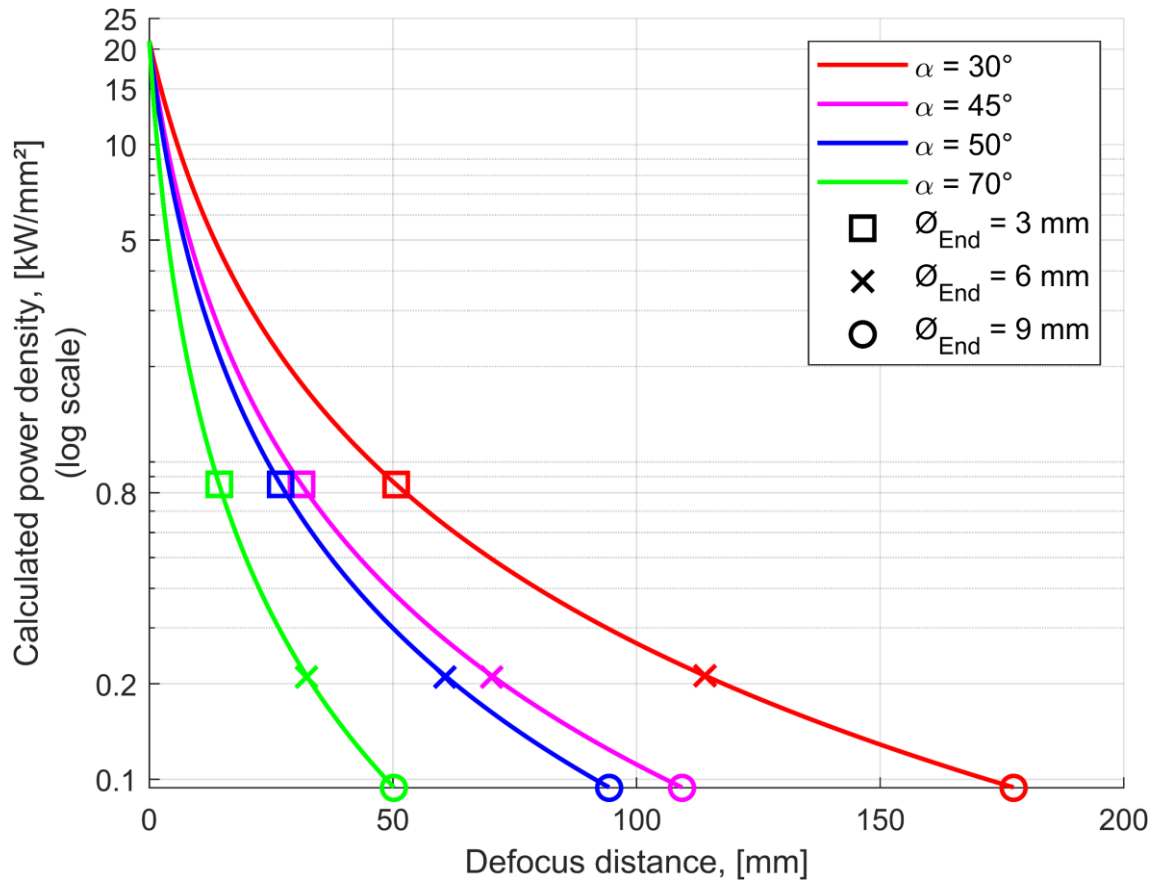


Figure 4-2: Calculated power density of laser defocusing at different laser defocus angles and end laser spot diameters using a laser power of 6 kW

4.2.2.2 Laser power ramp-down and combined termination regime

Abrupt laser termination without laser power ramp-down was conducted to obtain reference welds for comparison purposes. For the laser power ramp-down termination regime, a gradual reduction of laser power, from full power to 0 kW, was applied from point B to point C for each parameter configuration. Subsequent experiments applying a combined laser power ramp-down and laser defocusing to an end laser spot diameter of 3 mm was also studied. In the combined laser termination regime, a slight difference in the laser head travel distance and speed of the beam in the welding direction due to laser defocusing is observed (as described in section 3.2.3). Therefore, the rate of laser power ramp-down is slightly lower in the combined laser termination regime.

The change in laser power density and interaction time for each parameter configuration over a 40 mm distance is shown in Figure 4-3.

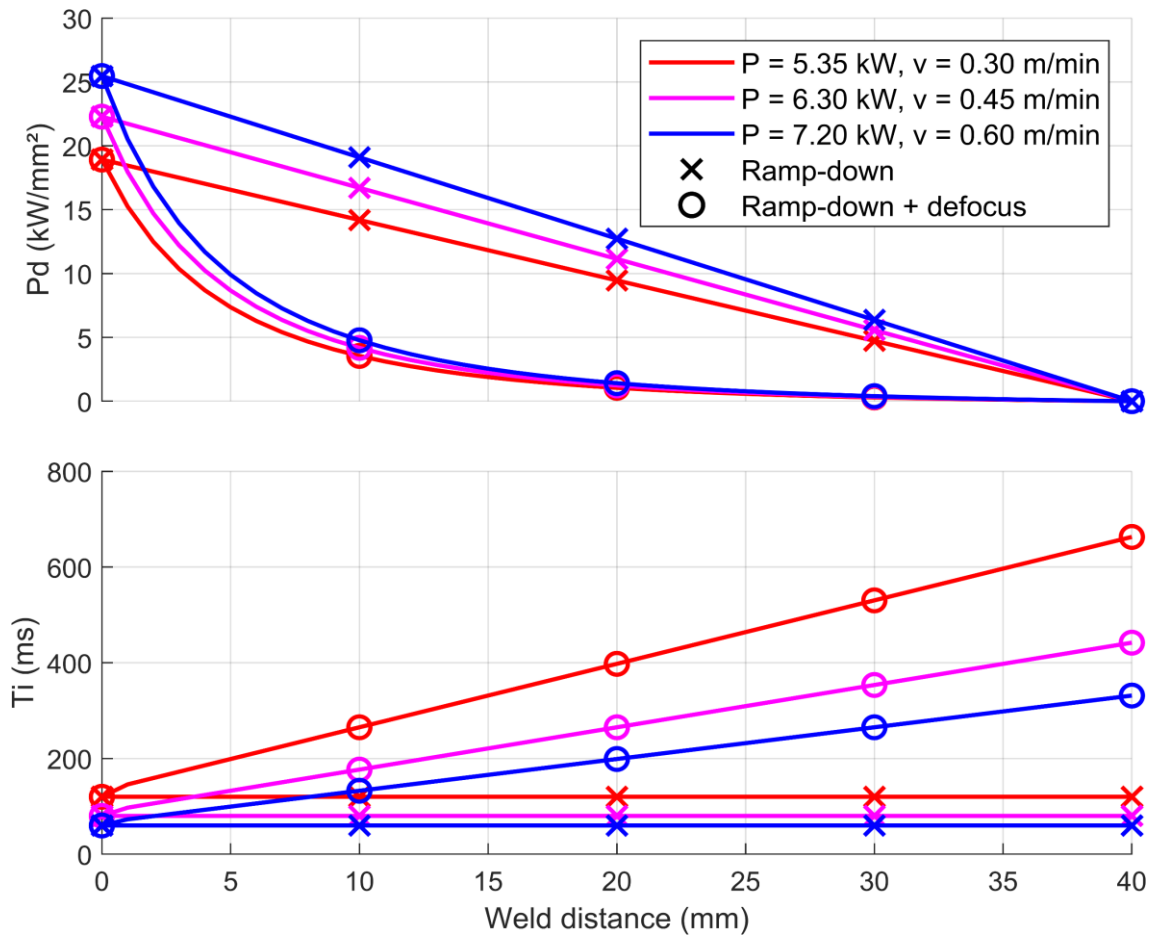


Figure 4-3: Calculated power density (top) and interaction time (bottom) of laser power ramp-down and combined laser power ramp-down + laser defocusing

4.3 Results

4.3.1 Laser defocusing termination regime

4.3.1.1 Laser termination and crater formation

Figure 4-4 shows the top and root surface of laser defocusing at a fixed laser defocus angle of 30° and different end laser spot diameters, highlighting examples of collapsed craters/cavity and surface depressions at the termination point. The root surface shows the point where full penetration ceases during laser defocusing. Collapsed weld craters at the termination point always occurred when laser defocusing to an $\varnothing_{End} = 3$ mm regardless of laser defocus angle. The collapsed weld craters also occurred when laser defocusing to an $\varnothing_{End} = 6$ mm, at a laser head travel speed of 1m/min, and at laser defocus angles of 30° and 45° . All other laser defocus parameter configurations tested that were not specified above, provided successful keyhole closure without keyhole collapse. However, surface depressions at the termination point were still present for all parameter configurations. All top and root surface images of each parameter configuration can be found in Appendix D.

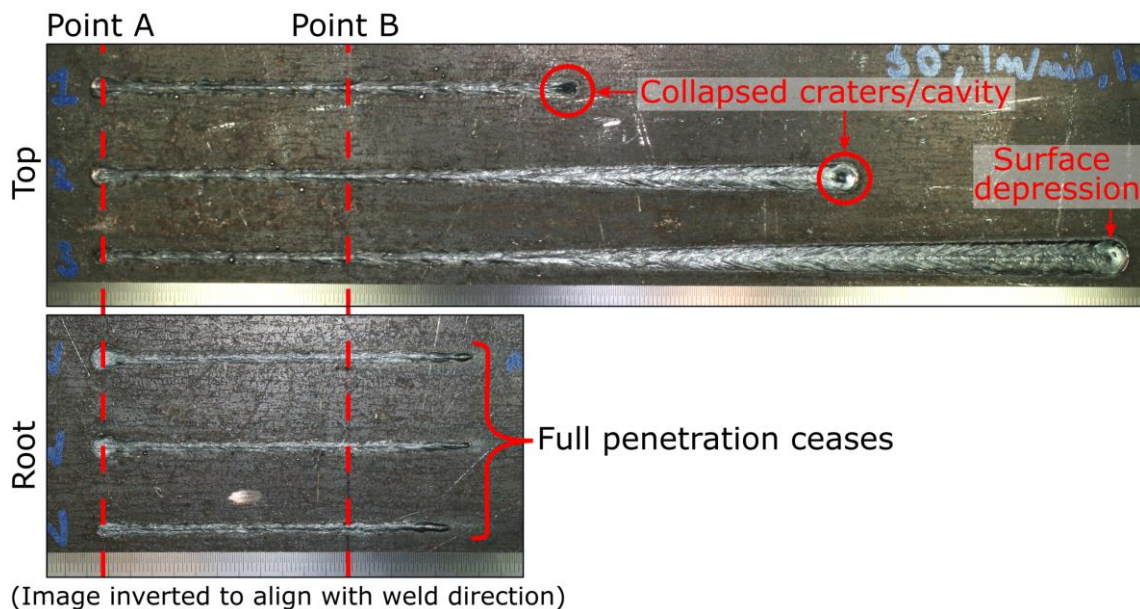


Figure 4-4: Top and root surface of weld samples achieved using laser defocusing at a laser defocus angle of 30°

The formation of the collapsed weld craters at the termination point depends primarily on the laser power density, as shown in Figure 4-5. Collapsed weld craters always occurred when the laser terminated at a laser power density of 0.85 kW/mm² (when terminating at an end laser spot diameter of 3 mm) in the case of these experiments. However, when the laser terminates at a power density of 0.2 kW/mm² (end laser spot diameter of 6 mm), the occurrence of collapsed weld craters reduces significantly. When the laser terminates at an end laser spot diameter of 9 mm (below 0.1 kW/mm²), no collapsed craters are visible. However, a surface depression or depressed crater remains.

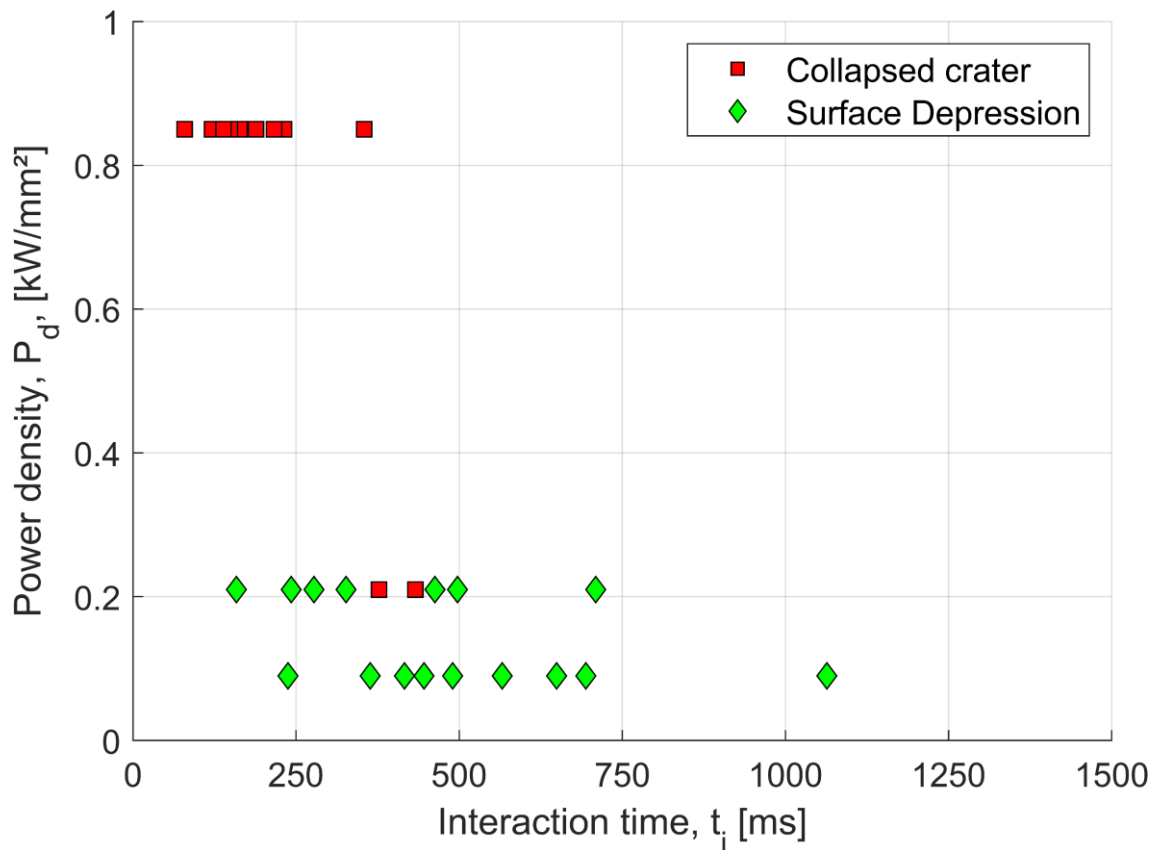


Figure 4-5: Calculated power density and interaction time of weld craters at termination point in the laser defocusing termination regime

4.3.1.2 Weld root and loss of full penetration

Figure 4-6 shows the weld root surface where full penetration ceases of several weld samples. A difference is observed in the length and shape of the weld root with different laser defocus angles (α) and beam defocusing speeds (v_{beam}). As the laser defocus angle increases (and the speed of the beam in the welding direction decreases), the weld root length (from the defocus point B) decreases, and the weld root widens.

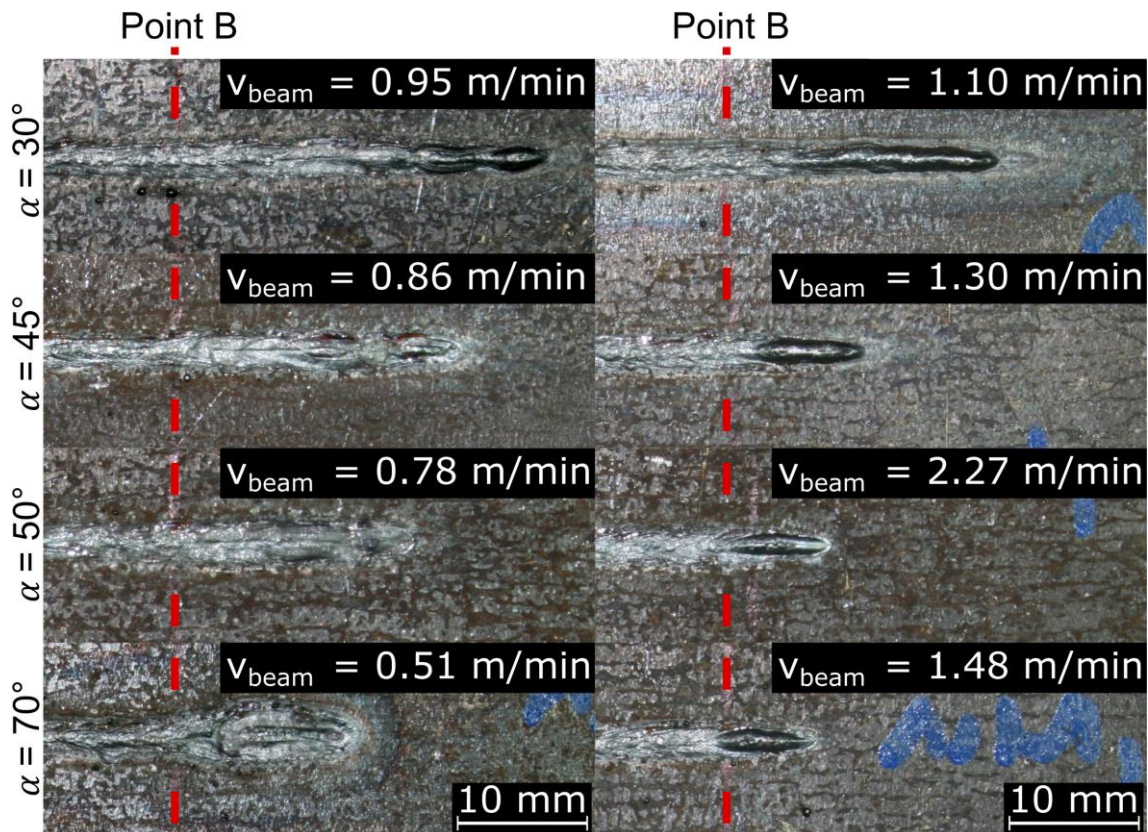


Figure 4-6: Root surface of weld samples at a laser head travel speed of 1 m/min and at different laser defocus angles

Figure 4-7 shows the calculated laser power density and interaction time where full penetration ceases for each weld sample. Where, α = set laser defocus angle, $v_{\text{laserhead}}$ = laser head travel speed, v_{beam} = resultant speed of the laser beam in the welding direction.

The graph shows a negative correlation between the laser power density and interaction time, which corresponds with the plate thickness of 7.8 mm. There is also a linear relationship between the distance where full penetration ceases and the interaction time for a given laser defocus angle, as shown in the bottom right graph in Figure 4-7.

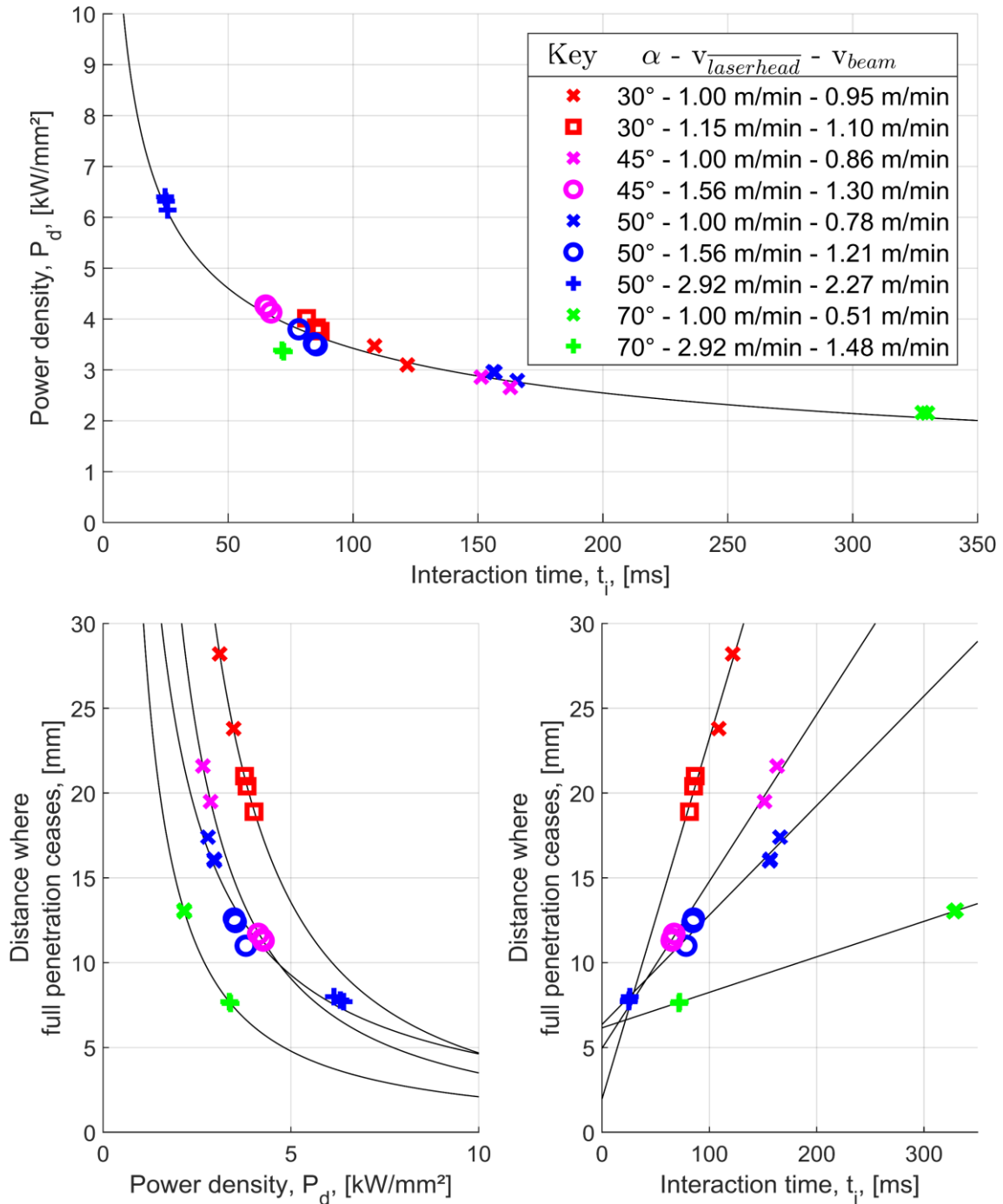


Figure 4-7: Calculated laser parameters at point where full penetration ceases during laser defocusing

4.3.1.3 Weld solidification cracking near crater

Transverse cross-sectional macrographs were taken 7 mm from the defocus point of each weld, where a laser defocus angle of 70° was applied. As shown in Figure 4-8, solidification cracking was observed near the top half of the weld before the collapsed crater when the laser defocused to a $\varnothing_{End} = 3$ mm. The crack is also located at the narrowest region within the weld. However, no cracks were present at the same location in the other two welds when the laser defocused and terminated at a larger end laser spot diameter.

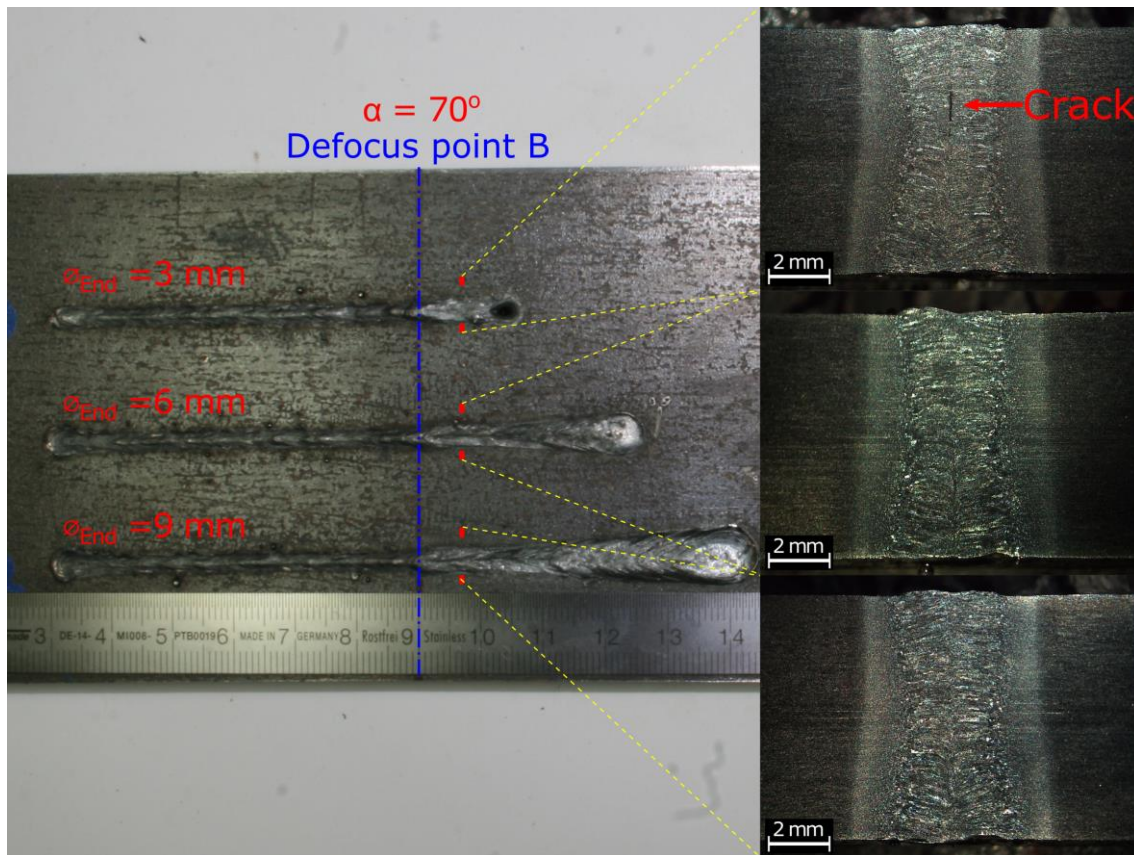


Figure 4-8: Solidification cracking near collapsed crater

4.3.1.4 Weld profile

Figure 4-9 shows the weld profile at specific laser power densities for each laser defocus angle, obtained at varying points throughout the defocusing termination distance. A decrease in penetration depth and transition from full penetration to partial penetration can be observed as the laser power density decreases. The weld profiles are similar at each specific laser power density despite the different laser defocus angles and laser defocusing rates used. However, the weld root width can be seen to widen slightly at 2.5 kW/mm² when laser defocusing at an angle of 70°. As the laser power density continues to decrease from 0.63 kW/mm² to 0.15 kW/mm², the penetration depth and weld width increase slightly with increasing laser defocus angle. The weld beads also exhibit a raised surface profile on the right-hand side due to gravity acting on the large melt pool as the welds took place in the 2G horizontal welding position.

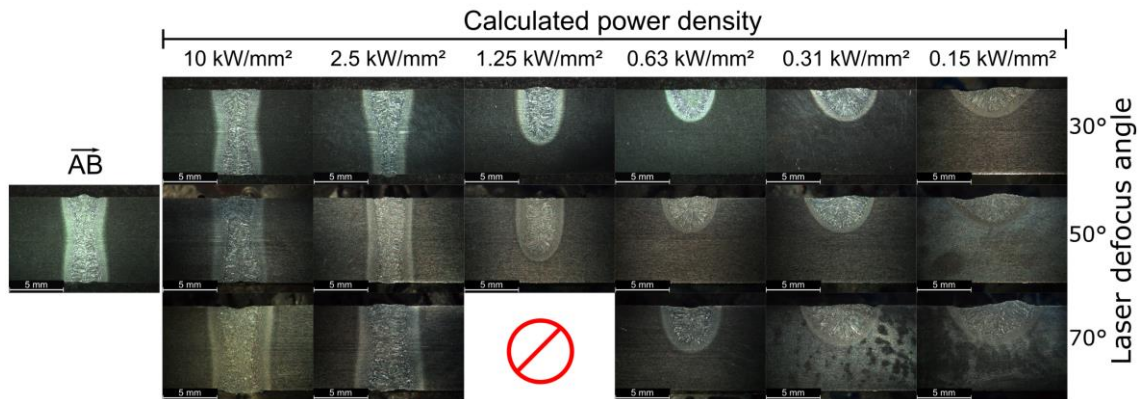


Figure 4-9: Transverse cross-sectional macrographs at specific calculated laser power densities for each laser defocus angle

Figure 4-10, Figure 4-11, and Figure 4-12 show the change in laser power density and weld profile for laser defocus angles of 30°, 50°, and 70°, respectively. The penetration depth for all laser defocus angles follows a parabolic trend corresponding with the change in laser power density. The weld width initially fluctuates before increasing linearly with the increasing laser spot diameter. A change in the depth-to-width ratio (D/W) is observed around a power density of 0.75 - 0.78 kW/mm² for all three laser defocus angles shown. The melt pool size increases marginally with the increase in laser defocus angle across the whole defocus distance.

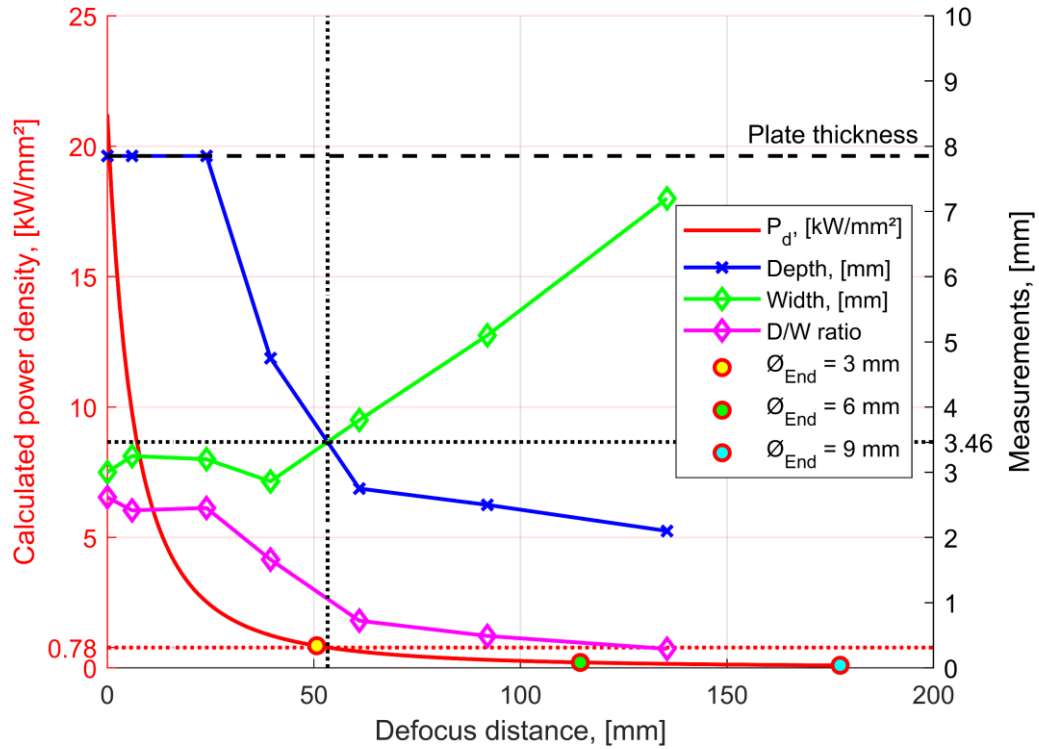


Figure 4-10: Change of penetration depth and weld width when laser defocusing at a defocus angle of 30°, $P = 6$ kW, $v_{\text{beam}} = 0.95$ m/min

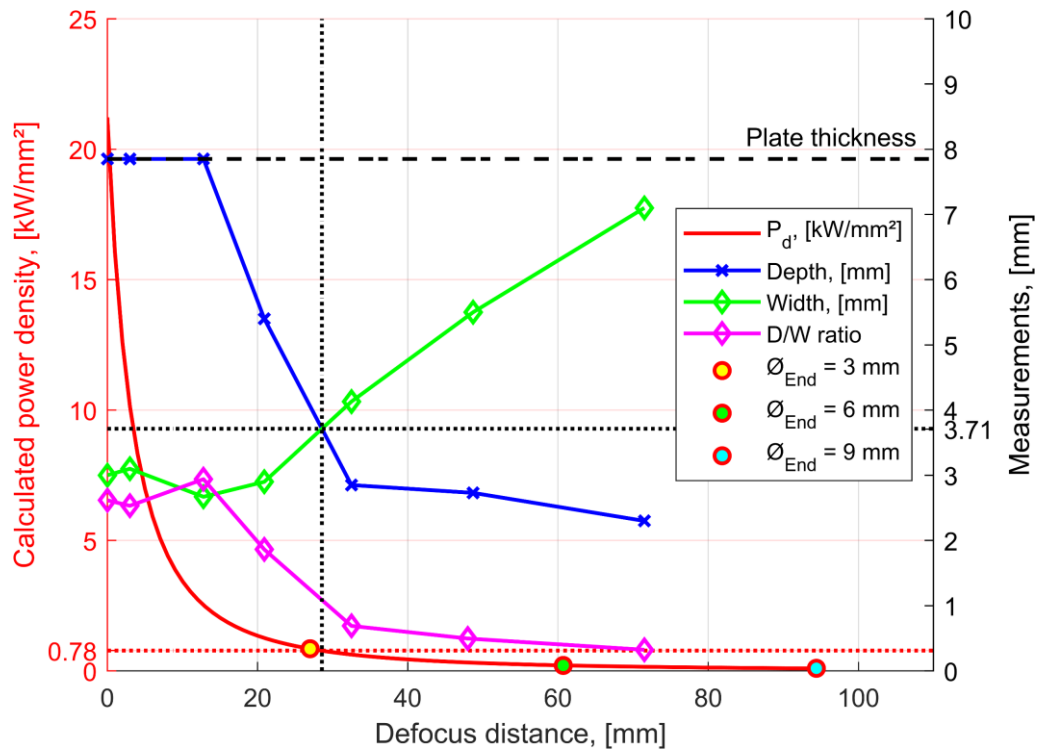


Figure 4-11: Change of penetration depth and weld width when laser defocusing at a defocus angle of 50°, $P = 6$ kW, $v_{\text{beam}} = 0.78$ m/min

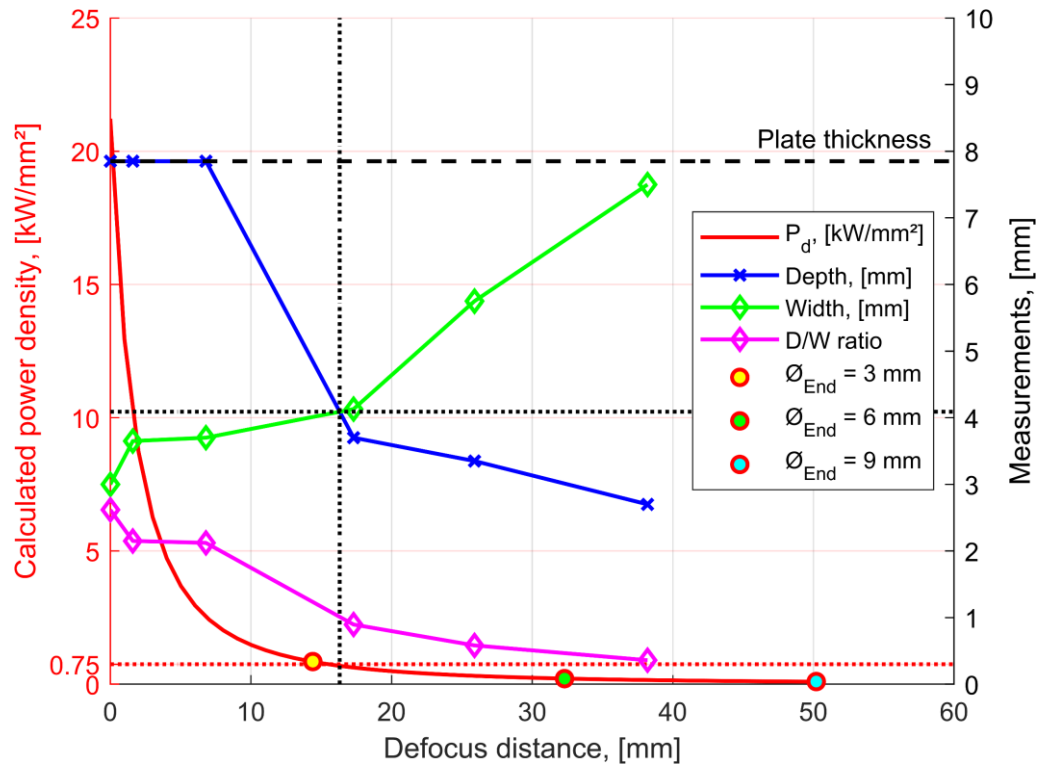


Figure 4-12: Change of penetration depth and weld width when laser defocusing at a defocus angle of 70° , $P = 6 \text{ kW}$, $v_{\text{beam}} = 0.51 \text{ m/min}$

4.3.2 Laser power ramp-down termination regime

4.3.2.1 Weld profile

Figure 4-13 and Figure 4-14 show the top surface and longitudinal macrographs of some weld samples from the laser power ramp-down termination and combined termination regime, respectively.

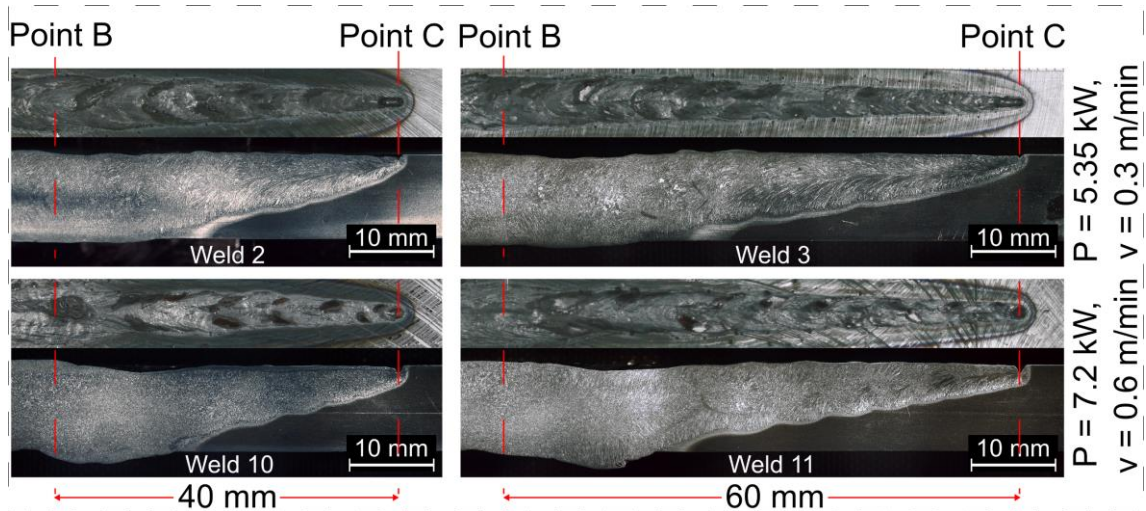


Figure 4-13: Weld surface and longitudinal macrographs of laser power ramp-down termination

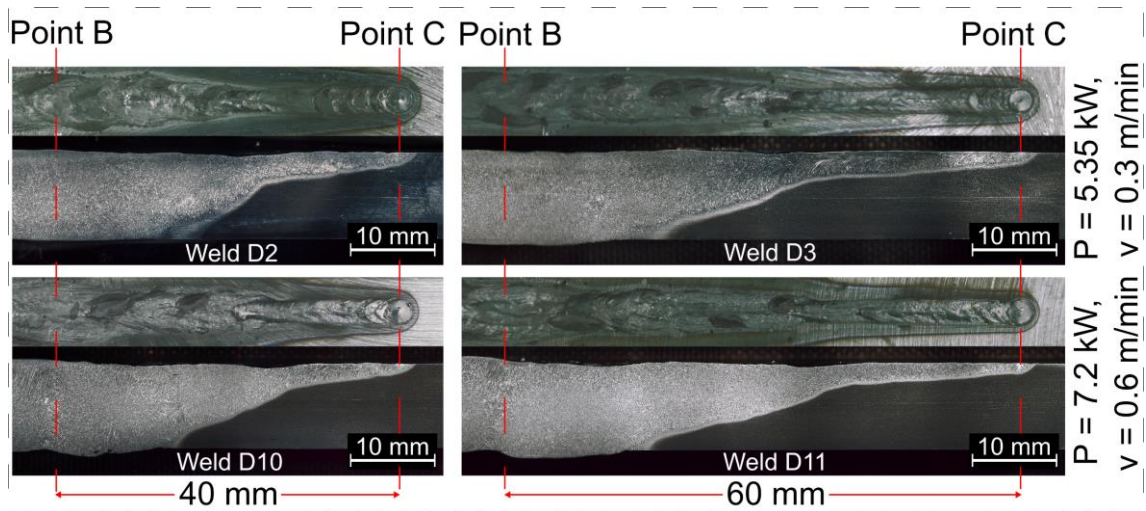


Figure 4-14: Weld surface and longitudinal macrographs of combined laser power ramp-down and laser defocusing termination

A clear difference between the weld profiles of the two termination regimes is noticeable. The reduction in penetration depth correlates with the change of power density for both termination regimes, as shown previously in Figure 4-3. Large melt pool and keyhole fluctuations can be observed from the varying penetration depth and weld width in the longitudinal macrographs and weld surface, respectively, during laser power ramp-down. However, this phenomenon is not seen when laser power ramp-down is combined with laser defocusing.

Figure 4-15 and Figure 4-16 show the measured penetration depth, weld width, and depth-to-width ratio from point B to point C for both 40 mm and 60 mm distances and for both laser termination regimes, respectively. Although different laser powers and weld speeds were used for each set of termination regimes and termination distances, the change in weld depth and width are identical in each case. The parameter configurations used for each weld sample is given in Table 4-3.

As the laser power begins to reduce in the laser power ramp-down termination regime, the weld width decreases instantaneously, whereas full penetration is maintained over a certain distance before ceasing. Both the penetration depth and weld width decrease linearly, as shown in Figure 4-15. The change in penetration depth correlates with the linear decrease of laser power and power density, as shown in Figure 4-3.

The depth-to-width ratio (D/W ratio) typically fluctuates between a value of 1.5 and 2 throughout the laser power ramp-down termination regime. However, peaks above a D/W ratio of 2 is observed for samples Weld 10 and Weld 11 at a distance between 7 mm and 17 mm, and 10 mm and 23 mm, respectively. These peaks above a D/W ratio of 2 correlates with the root sagging and surface dropout observed in Figure 4-13.

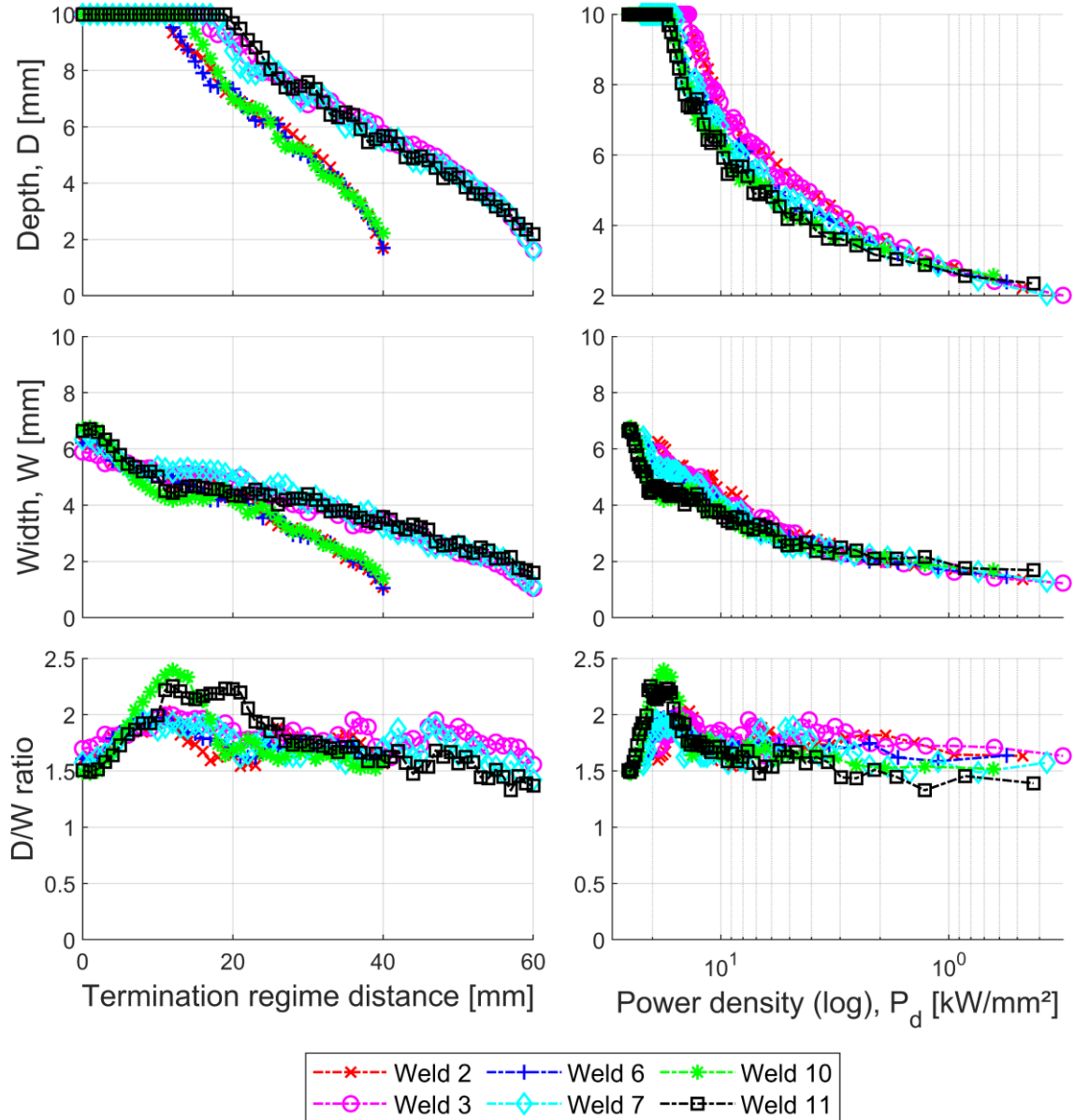


Figure 4-15: Change in weld profile with different termination distances and calculated laser power density during laser power ramp-down termination regime

In the combined termination regime, small variations in both the penetration depth and weld width are observed just before the weld width begins to stabilise for all parameter sets and both termination regime distances of 40 and 60 mm, as shown in Figure 4-16.

The D/W ratio initially fluctuates between a value of 1.5 and 2, like in the laser power ramp-down termination regime, but then decreases linearly. Smaller peaks above a D/W ratio of 2 is also observed at a certain distance into the termination. Again, these peaks correspond with root sagging and surface dropout, as shown

in Figure 4-14, but are less severe. Minor peaks during the linear decrease of the D/W ratio, e.g., between 20 – 25 mm for welds D2, D6 and D10, are observed and correlate with the small depression and narrowing of the weld surface before the penetration depth begins to stabilise, as shown in Figure 4-14. The penetration depth can be seen to gradually decrease as the weld width begins to stabilise around 3 mm, or when the D/W ratio decreases beyond a value of 1.

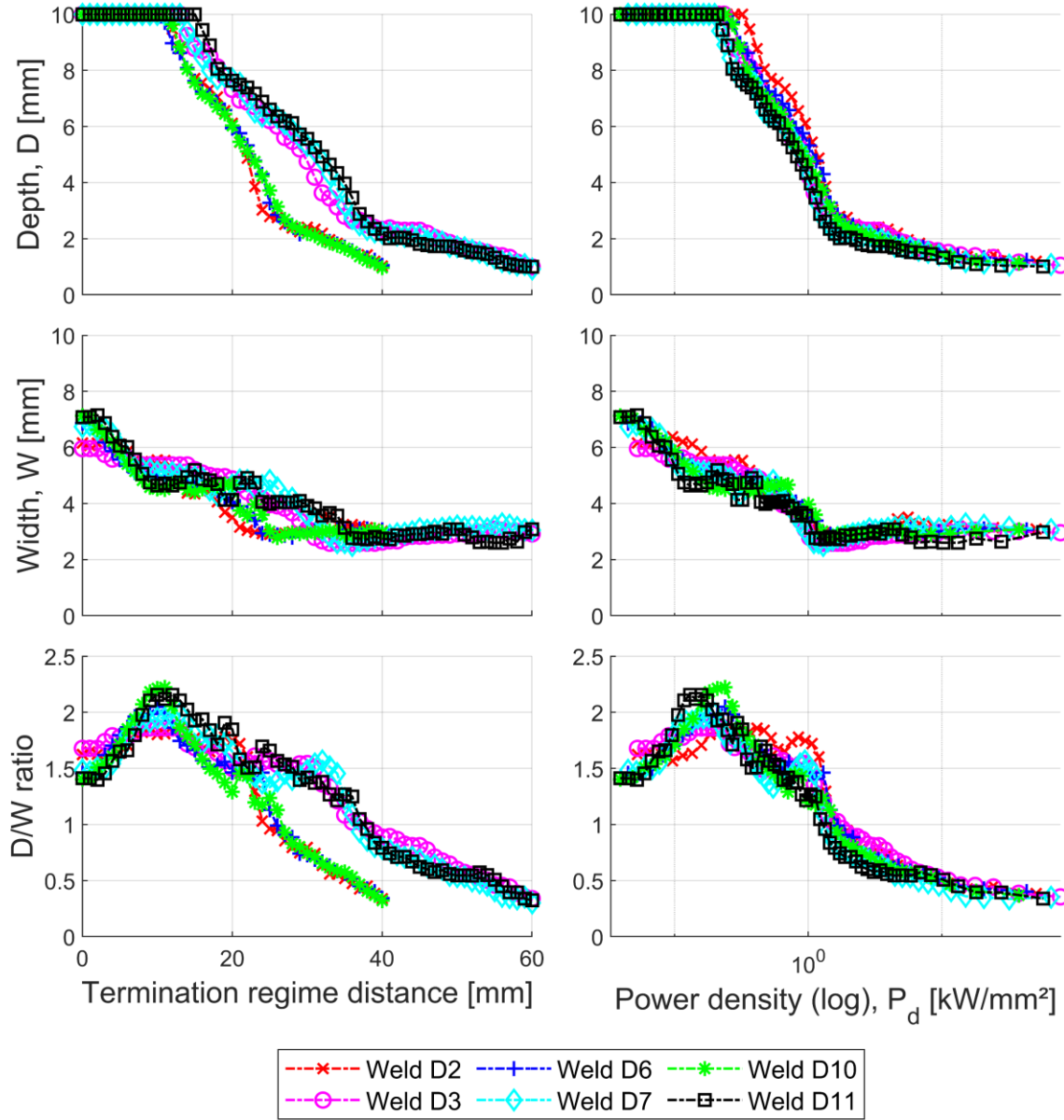


Figure 4-16: Change in weld profile with different termination distances and calculated laser power density during combined laser power ramp-down and laser defocusing termination regime

4.3.2.2 Weld crater formation

A close up of the weld craters from the samples shown in Figure 4-13 and Figure 4-14 are presented in Figure 4-17. When laser power ramp-down is applied as a termination regime, small weld craters remain at the termination point, and small depressions leading up to the termination point is present. However, when laser power ramp-down is combined with laser defocusing, there are no signs of weld craters or surface depressions at the laser termination point.

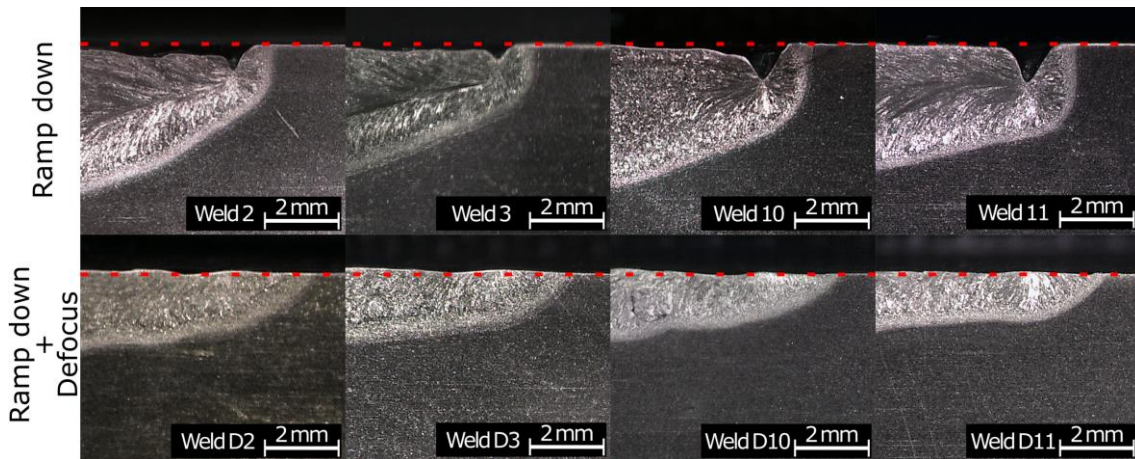


Figure 4-17: Longitudinal macrographs of weld termination points

Measurements of the weld termination point are shown in Figure 4-18 giving a clearer view of the weld profile at the termination point. Again, the parameter configurations used for each weld sample can be found in Table 4-3.

Despite the laser power reducing to 0 kW, there is still a substantial penetration of between 1.6 - 2.3 mm at the termination point in the laser power ramp-down termination regime. In the combined termination regime, a reduction in weld depth to 1 mm and an increase in weld width to 3 mm is observed instead. The increase in molten metal due to increased melting of the workpiece surface from the larger laser spot diameter in the combined termination regime allows for better control and solidification during laser termination. Therefore, there is less variability in the weld depth and width at the termination point when using a combined laser termination regime approach over just using laser power ramp-down alone.

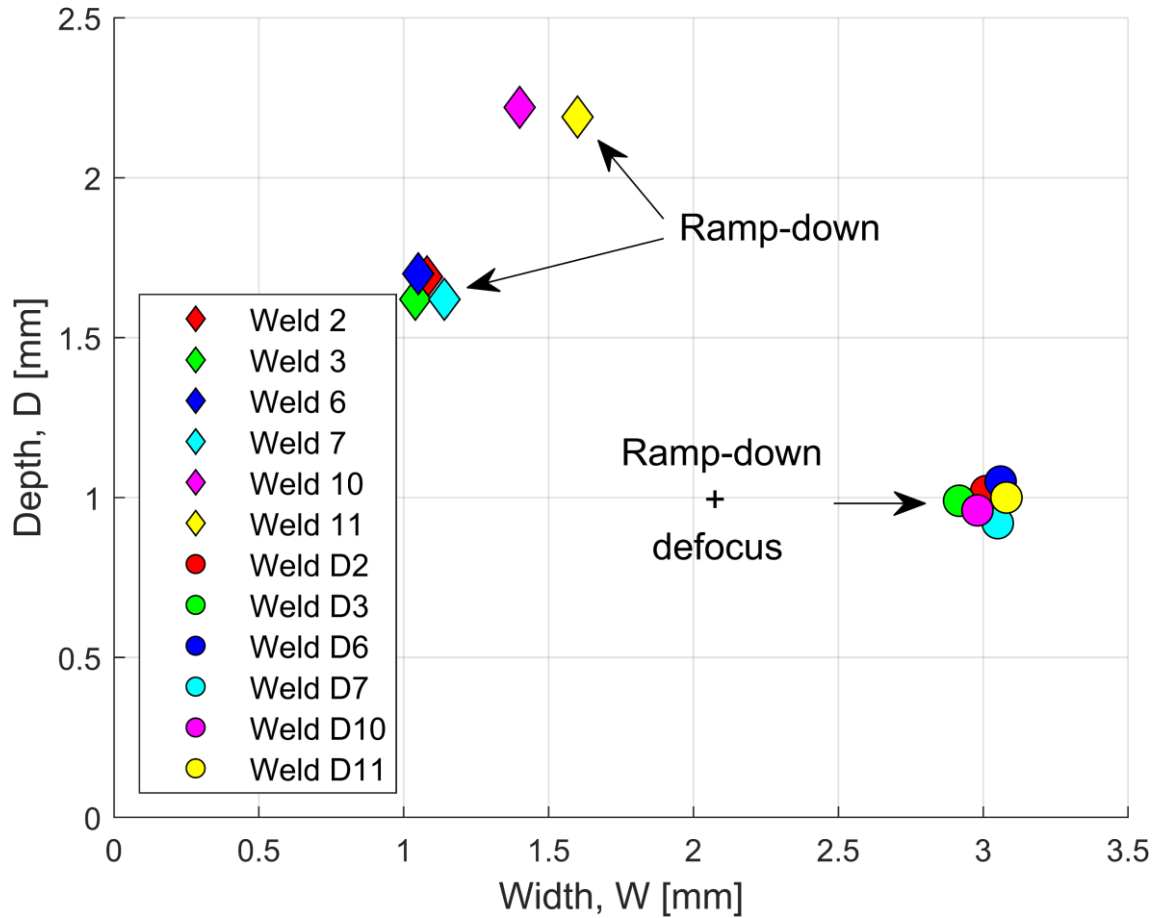


Figure 4-18: Weld termination point measurements

4.3.2.3 Weld root sagging

The effect of the different set of welding parameters and termination regimes on the formation of root sagging or root dropout is shown in Figure 4-19. In the laser power ramp-down termination regime the surface of the weld root is smooth and relatively flat where full penetration ceases, as shown by Weld 2 and Weld 3, despite using two different distances of laser power ramp-down. Both these welds used the lowest laser power and welding speed parameter configuration. However, when a higher laser power and weld speed is used, as is the case with Weld 10 and Weld 11, root sagging is present despite welding in the 2G horizontal position. The severity of root sagging is reduced when laser power ramp-down is combined with laser defocusing termination regime. The sagging at the weld root leads to a noticeable weld surface dropout or undercut and coincides with the peaks above a D/W ratio of 2, as discussed and shown previously in Figure 4-15 and Figure 4-16.

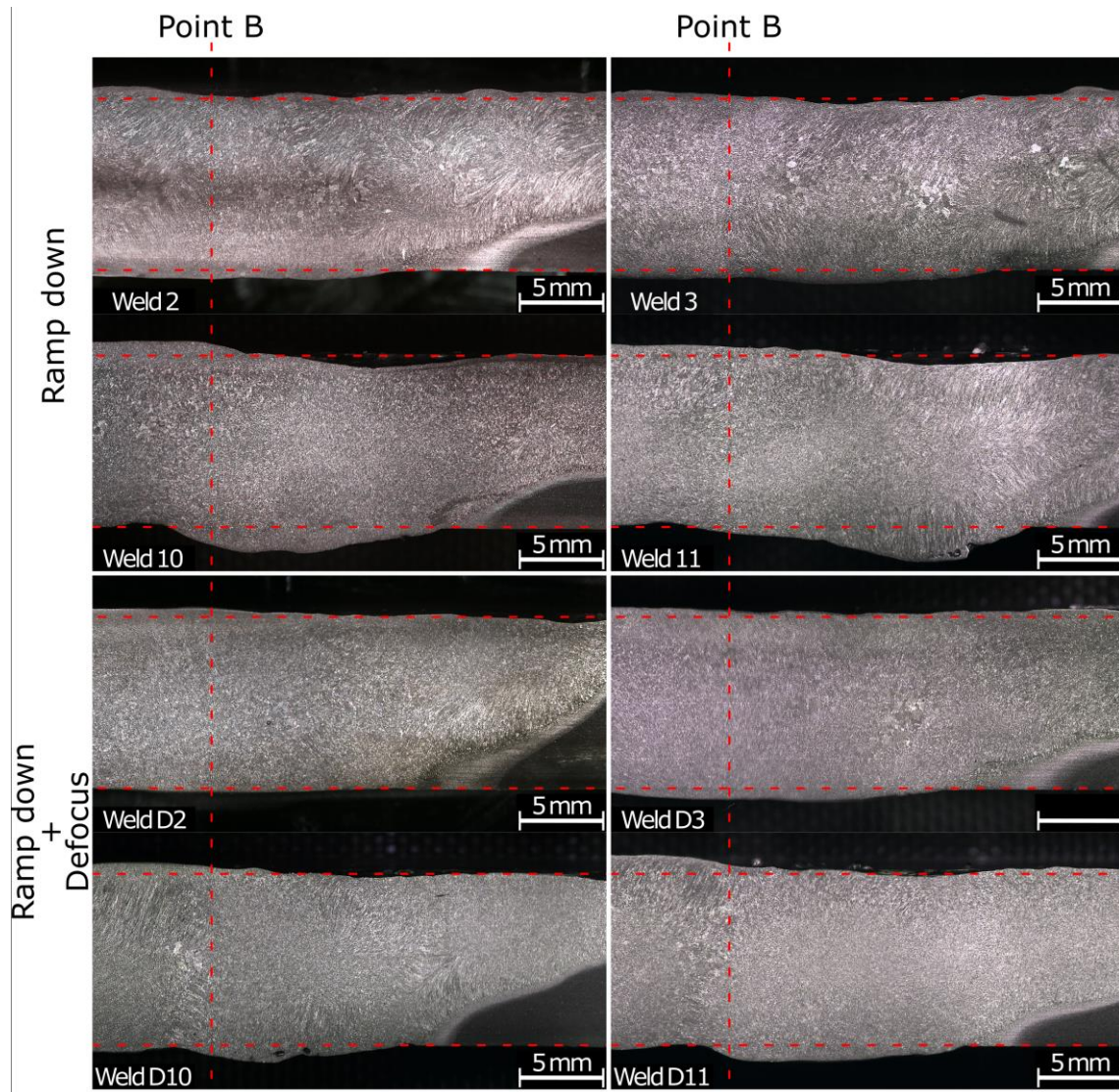


Figure 4-19: Longitudinal macrographs showing weld root sagging

4.4 Discussion

A combined discussion of the effect of the different termination regimes from each experiment is presented. The focus areas are on the weld profile, the weld root when transitioning from full penetration to partial penetration, and keyhole closure and the formation of weld craters at the laser termination point.

4.4.1 Effect of termination regimes on weld profile

Depending on the termination regime applied, a different weld termination profile is obtained. The change in penetration depth throughout the termination distance varies with laser power density, as shown in sections 4.3.1.4 and 4.3.2.1.

In the laser defocusing experiment, the penetration depth decreases following the same profile as the decrease in laser power density despite using different laser defocus angles and defocus rates. A change in D/W ratio is observed as the laser power density decreases below a value 0.8 kW/mm^2 , regardless of laser defocus angle and different interaction times, which varied between 196 – 376 ms. Assuncao et al. has shown that a transition from keyhole mode towards conduction mode welding regime occurs below a threshold power density, is dependent on the interaction time, and that these welding modes can be differentiated by the D/W ratio of the weld [141]. The change in D/W ratio below a power density of 0.8 kW/mm^2 for all three laser defocus angles correlates with a change in laser welding mode, from laser keyhole welding, towards conduction mode welding. Although, the D/W ratio where the transition takes place is higher than the values shown by Assuncao et al., the interaction times of these welds are significantly higher due to the increased laser spot diameter during defocusing. The shallow weld profiles below a power density of 0.3 kW/mm^2 have a D/W ratio less than 0.6 like those of conduction mode welds.

In the laser power ramp-down and combined termination regime experiment, the change in weld profile is consistent for a range of different welding and termination parameters and distances for both termination regimes. The decrease in penetration depth for both termination regimes follow the same power density profile for different parameter configurations, as shown in Figure 4-3. Therefore, the use of laser power density to control the termination of the laser

keyhole and weld depth are possible for both laser defocusing and laser power ramp-down terminations regimes under a variety of welding conditions.

During laser power ramp-down, the linear decrease of penetration depth and weld width gives a relatively constant D/W ratio indicating that the volume of liquid metal reduces linearly with laser power. The decrease in laser power and volume of liquid also results in a higher cooling rate. There is no indication that a transition from keyhole mode towards conduction mode welding regime occurs as the D/W ratio remains high, as shown in Figure 4-15, and because of the surface depression leading up to the termination point, as shown in Figure 4-17. Whereas, in the combined termination regime, a clear transition in welding mode is observed when the D/W ratio falls below 1 and the weld width begins to stabilise, as shown in Figure 4-16. The power density when the D/W ratio falls below 1 range from 0.6 – 0.8 kW/mm² for all the samples shown in Figure 4-16, which is consistent with the observations of the weld profile made in the laser defocusing experiment.

4.4.2 Effect of termination regimes on weld root defects

In steady-state laser welding, the formation of root defects, such as weld root sagging is typically associated with the downward flow of the melt and the effects of gravity and surface tension acting on the melt at the weld root [142,143]. The likelihood of root sagging occurring increases when welding plate thicknesses of 10 mm and above [143], or when full penetration is achieved, but there is insufficient laser power applied to maintain an open keyhole root, as shown by Haug et al. [144]. When terminating a full penetration, steady-state laser keyhole weld, it is inevitable that a transition occurs from full penetration - open keyhole, to a partial penetration - closed keyhole. Therefore, the region where full penetration ceases can be prone to root defects, such as root sagging. Root sagging may also lead to weld top surface dropout or undercut which requires repairing. The root sagging and corresponding drop in the weld surface is due to the molten metal flowing around the closing keyhole bottom as full penetration ceases, and then solidifying. Therefore, there is insufficient material near the weld surface resulting in the weld surface dropout or undercut.

In the laser defocusing termination experiment, welds were conducted in 8 mm thick plates, and root sagging was not observed during steady-state welding or when full penetration ceases during the termination regime. However, several different weld root surfaces were obtained depending on the laser defocusing parameters used. It was shown in Figure 4-7, that the point where full penetration ceases depend on the laser power density and interaction time. When defocusing at a high laser defocus angle (resultant low laser beam speed), the workpiece experiences more laser energy within a given region and time frame due to the increased interaction time. The increased heat where full penetration ceases may be beneficial for avoiding root sagging defects. However, extensive heating may occur, leading to over penetration and a wide weld root within a small region if incorrect defocusing parameters are applied. Therefore, depending on the workpiece thickness, welding speed, and material type, different laser defocusing rates should be applied. The laser defocusing termination regime should be slow enough to avoid keyhole collapse and root defects but not too slow to minimise remelting or overheating of the weld overlap region.

In the laser power ramp-down experiment, root sagging defects were observed at the transition from full penetration to partial penetration depending on the termination regime and welding parameters used, as was shown in Figure 4-19. The severity of root sagging appears to increase when using welding parameters with a lower heat input, as shown in Figure 4-20. Welds 2 and 3 has a heat input of 1.1 kJ/mm at steady-state and decreases to 0.8 kJ/mm when full penetration ceases, showing no signs of root sagging. However, Welds 10 and 11, which exhibits root sagging defects starts with a heat input of 0.7 kJ/mm and decreases to 0.5 kJ/mm when full penetration ceases.

The observations of root sagging occurrence with low heat input is contradictory to the results shown by Gook et al. [130], but is supported by the findings shown by Haug et al. [144] and Suder et al. [145]. Gook et al. attributed the root sagging defects to the increased heat input or slow ramp-down of laser power. However, results from both Haug et al. and Suder et al. showed that root sagging can be avoided when a higher laser power or arc power, in the case of HL-AW, is applied during steady-state welding. The increased heat input maintains the surface

tension forces and redirects the flow of molten metal behind the rear keyhole and towards the weld surface, reducing the molten metal at the weld root. The welding parameters and welding position (i.e. 2G horizontal welding position) used in the steady-state region and termination regime in this study does differ from the welding parameters and setup used in the experiments carried out by Gook et al. [130]. Therefore, it is possible that the cause of root sagging could be attributed to both the increase in and lack of heat input when transitioning from full penetration to partial penetration welding and further study is necessary to determine this. The effect of gravity also needs to be considered.

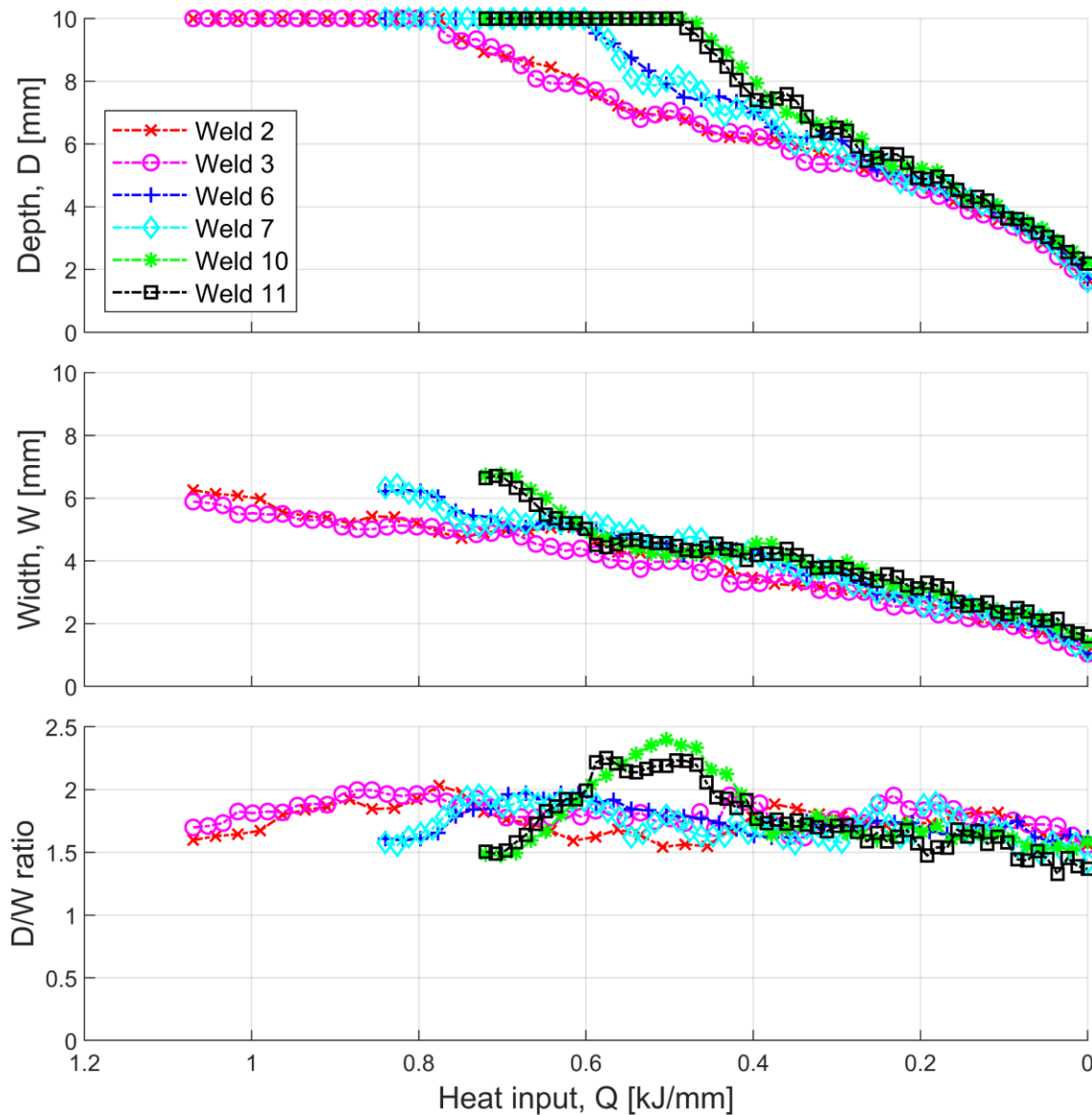


Figure 4-20: Change in weld profile with calculated heat input during laser power ramp-down termination regime

In the combined termination regime, a reduction in weld root sagging was observed, which can be explained by the marginal increase in heat input, as shown in Figure 4-21, because of the slower beam speed when laser defocusing. An increase in heat input of 0.05 – 0.1 kJ/mm in the combined termination regime when full penetration ceases can be observed when comparing Figure 4-21 to Figure 4-20, for each respective weld samples. The effects of laser defocusing on melt flow dynamics and heat transfer to the root of the keyhole is also likely to be different and may be beneficial for reducing the severity of root sagging defects.

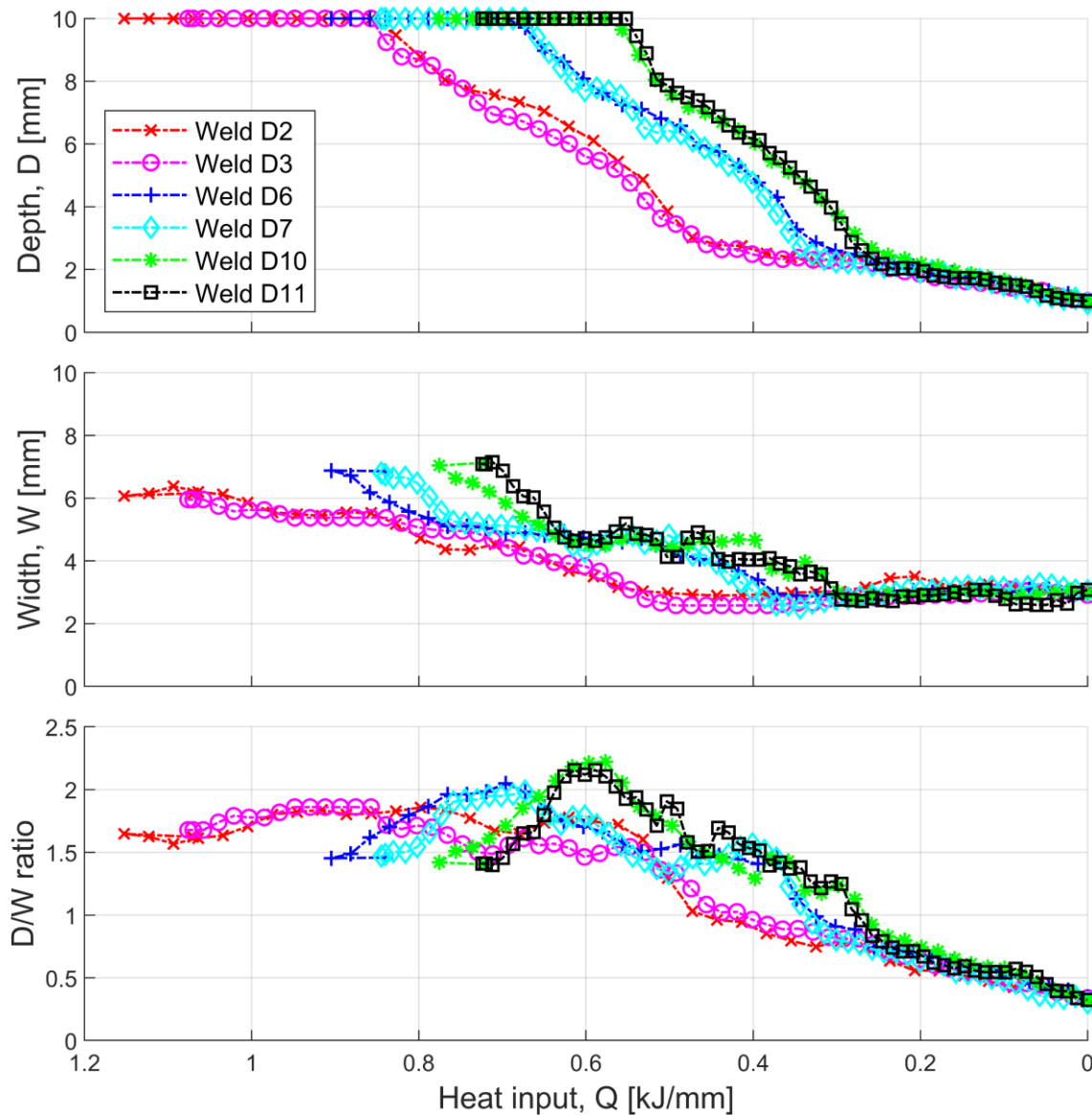


Figure 4-21: Change in weld profile with calculated heat input during combined laser power ramp-down and laser defocusing termination regime

4.4.3 Effect of termination regimes on weld crater formation

Successful laser termination without keyhole collapse, weld craters and cracking could be achieved using a variety of different weld parameters and termination regimes. Weld crater formation can be associated with specific laser parameters, and weld pool geometries depending on the termination regime applied.

In the laser defocusing termination regime, collapsed weld craters always occurred when the laser terminated at a laser power density of 0.85 kW/mm^2 . However, the likelihood decreases when the laser terminates at a lower power density of 0.2 kW/mm^2 , as shown in Figure 4-4 and Figure 4-5. Other defects, such as solidification cracking, was observed near the collapsed weld crater, as shown in Figure 4-8. Cracks are likely to form because of the high solidification stresses and cooling rate associated with the weld geometry. However, when the laser continued defocusing to a larger spot size diameter, the change in weld geometry and cooling rate prevented cracking from occurring.

Weld craters and surface depressions also occurred at the laser termination point in the laser power ramp-down termination regime regardless of the parameters set used. However, the formation of weld craters is prevented by using a combination of laser power ramp-down and laser defocusing termination regime, as shown previously in Figure 4-17. In the laser power ramp-down regime, the surface depression leading up to the termination point is a result of the molten metal flowing behind the laser spot as it traverses. Therefore, the small and narrow melt pool at the termination point has insufficient molten metal when solidification takes place, leading to the formation of a weld crater.

The combination of both termination regimes results in a lower power density but higher interaction time throughout laser termination distance. The lower power density leads to a reduction in vaporisation and penetration depth, whereas, the increasing interaction time, associated with the increase of beam spot size diameter, results in a wider melting area. The increased melting of the workpiece surface leading up to the termination point provides a wider and stable melt pool and a slower solidification rate. Therefore, a smooth and flat weld termination point is obtained due to sufficient molten metal upon solidification.

4.4.4 Summary of different laser termination regimes

Laser defocusing, laser power ramp-down, and a combined termination regime approach has proven successful for laser keyhole termination without significant defects. Depending on the laser termination regime applied, different weld terminations can be obtained. In summary, the results from this chapter indicate that the laser defocusing termination regime is more suitable for the prevention of weld crater formation and the formation of other defects during laser keyhole termination. When laser defocusing is combined with laser power ramp-down, it also decreases the severity of root sagging defects at the transition from full penetration to partial penetration in plates of 10 mm thickness.

The laser defocusing termination regime results in an increased heat input during laser termination due to the method of achieving laser defocusing as mentioned in section 4.2.2.1. The increase in heat input and laser spot diameter during laser termination increases the melting of the workpiece surface, giving a different weld profile and providing more molten metal throughout the termination distance and at the termination point during solidification. On the other hand, the laser power ramp-down termination regime results in the opposite behaviour. Both the heat input and the amount of molten metal throughout the termination distance and at the laser termination point is reduced. The differences in heat input and weld profile between the two laser termination regimes result in different cooling rates and this may affect the microstructural development and mechanical properties throughout the laser termination region. To reduce or limit the increase in heat input when applying the laser defocusing termination regime (using the laser head traverse approach), a lower defocus angle or an increase in travel speed should be applied. However, an increase in laser heat input was also found to be beneficial in mitigating root sagging defects when leaving full penetration and transitioning to partial penetration welding.

Both laser termination regimes appear to be flexible for the given range of laser termination distances and termination rates studied. However, further study is required to determine how the termination regimes and thermal cycles affect the weld overlap start/stop region and defect formation.

4.5 Conclusions

The effect of laser defocusing, laser power ramp-down, and a combination of both laser termination regimes on laser keyhole closure and laser termination related defects have been presented in this chapter.

- The formation of weld craters at the laser termination point can be prevented by using a combination of laser power ramp-down and laser defocusing termination regimes. The combination of both termination regimes enables successful keyhole closure by transitioning from full penetration keyhole mode towards partial penetration conduction mode welding without defects. Sufficient molten metal is necessary to fill the weld crater during laser termination and is provided by the increased melting of the workpiece surface due to the increased laser spot diameter during laser defocusing.
- The change in weld profile during the application of either laser termination regime depends primarily on the power density and end laser spot diameter.
- When laser defocusing is applied, a transition from keyhole mode welding towards conduction mode welding regime occurs below a laser power density of 0.8 kW/mm^2 , or below a D/W ratio of 1 within the range of interaction times studied. However, this transition does not occur in the laser power ramp-down termination regime.
- Sufficient heat input is necessary when transitioning from full penetration to partial penetration to avoid root sagging defects. A higher heat input maintains the surface tension forces and redirects the flow of molten metal behind the rear keyhole and towards the weld surface

Chapter 5

Laser keyhole initiation and termination related defects: Effect of inter-pass temperature and laser defocusing termination regime on weld overlap start/stop region

5.1 Introduction

The previous chapter investigated the effect of different laser termination regimes on the formation of laser termination related defects for longitudinal welds. The impact of intersecting welds and laser initiation and termination at the weld overlap start/stop region needs further investigation to enable the use of laser keyhole welding for circumferential welding applications.

In this chapter, the influence of inter-pass temperature on laser keyhole weld initiation and termination at the weld start/stop region were investigated. Different inter-pass temperatures at the weld overlap start/stop region were achieved by replicating different pipe diameters and using the residual heat from the first weld seam. The inter-pass temperature and thermal cycle are vital as they control the microstructure and mechanical properties, and for some steels, a higher temperature is needed to achieve good weld properties. The focus is to identify the formation of defects during laser termination at the weld overlap start/stop region and how different inter-pass temperatures and solidification rates affect laser keyhole termination defects.

Two sets of experiments were conducted to investigate the effect of inter-pass temperature on the weld start/stop region achieved using abrupt laser termination, and using a laser defocusing termination regime.

Parts of this chapter has been written into a paper that has been accepted and published in the *International Journal of Advanced Manufacturing Technology*.

Lai WJ., Ganguly S., Suder W. Study of the effect of inter-pass temperature on weld overlap start-stop defects and mitigation by application of laser defocusing. International Journal of Advanced Manufacturing Technology. Springer Nature; 2021; : 117–130. Available at: DOI:10.1007/s00170-021-06851-8

5.2 Methodology

5.2.1 Experimental set-up

The difference between the two experiments regarding set-up and parameters are shown in Table 5-1. The laser power and laser travel speed, were calculated using the *Power Factor Model* as proposed by Suder and Williams to achieve full penetration [140].

For the laser defocusing termination regime experiment, welds took place on as received plates without removal of the mill scale and some changes to the welding parameters were made. A significantly low travel speed was investigated in the laser defocus termination regime experiment as this would increase the likelihood of keyhole collapse due to the large volume of liquid metal surrounding the narrow laser keyhole, according to the literature in 2.3.2.1. The plate condition and welding parameters used is to test the worst-case welding scenario to study the effect of melt pool flow dynamics on defect formation during the laser defocusing termination regime.

Table 5-1: Experimental set-up and parameters for each experiment

Differences:	Experiment:	
	Abrupt laser termination	Laser defocus termination regime
Welding parameters:		
<i>Laser power, P, [kW]:</i>	4.65	3.30
<i>Laser travel speed, v, [m/min]:</i>	0.50	0.25
<i>End laser spot diameter, $\varnothing_{End}$, [mm]:</i>	0.6	0.6 3.0 6.0
Plate differences:		
<i>Surface finish:</i>	Machined	As received
<i>Length x Width x Thickness, [mm]:</i>	200 x 60 x 8	300 x 85 x 7.7
<i>Weld seam section length</i>		
$L_{\overline{AB}} L_{\overline{BC}} L_{\overline{CD}}$, [mm]:	38 106 44	80 80 80
Replicated circumferential welds:		
<i>Pipe diameters, D_{Eipe}, [m]:</i>	0.60 0.25 0.10	7.0 0.1
<i>Circumference weld time, t_{circ}, [s]:</i>	226.2 94.3 37.7	5277.9 75.4
<i>Calculated delay time, t_{delay}, [s]¹:</i>	195.6 63.7 7.1	5209.3 6.8

¹ A $t_{DA} \approx 8$ s and 11 s was used in the calculation for the t_{delay} in the abrupt laser termination and laser defocus termination experiments, respectively.

To measure the inter-pass temperature, two K-type thermocouples were spot welded onto the top surface of the plates, approximately 10 mm on either side of the projected weld seam centreline, equidistant from points B and C. These were connected to an oscilloscope to record the temperature profile during the first weld pass, and weld overlap of the second weld pass. The plates were then clamped horizontally in place using a fixture in the 2G welding position, as shown in Figure 5-1.

In the subsequent laser defocusing termination experiment, the temperature measurement process was simplified. Only one thermocouple was attached to the plate and it was connected to a digital hand-held device, which was observed using a CCTV camera.

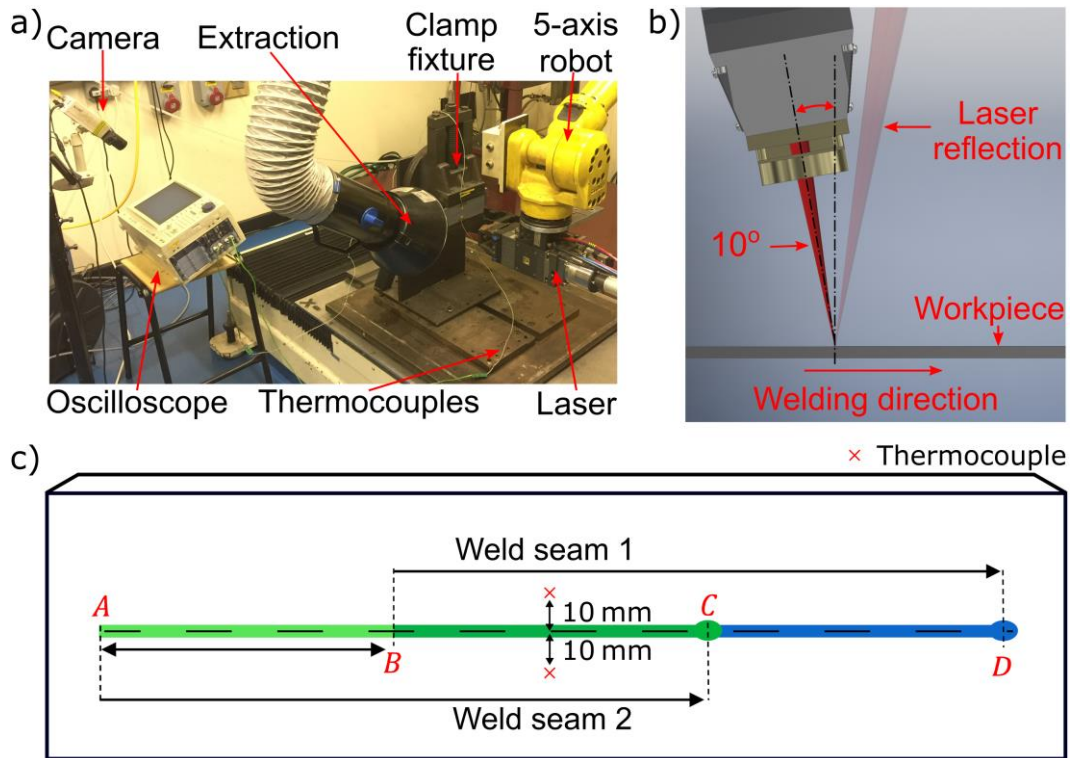


Figure 5-1: a) Experimental set-up, b) Schematic of laser head angle, c) location of thermocouples

5.2.2 Experimental approach

5.2.2.1 Abrupt laser termination

To compare and determine the effect of the different inter-pass temperatures on the weld overlap start/stop region, no control of the laser initiation or termination was implemented. The laser initiates instantaneously at full power and terminates abruptly from full power to no emission.

5.2.2.2 Laser defocusing termination regime

Only two pipe diameters were replicated in this experiment. Firstly, an extreme diameter of 7 m to achieve an inter-pass temperature corresponding to room temperature and is like the large diameters of offshore wind monopiles was considered. Secondly, the same diameter used in the abrupt termination experiment of 0.1 m as was used, giving an inter-pass temperature of 190 °C.

The laser defocusing termination regime was carried out using the approach described in section 3.2.3. All three different end laser spot diameters were applied for each replicated pipe diameter resulting in six samples.

5.2.2.3 Inter-pass temperature measurements

The processed temperature measurements for the three welds in the abrupt laser termination experiment are shown in Figure 5-2. A difference in the peak temperature for the first weld pass between the three welds is observed and this is due to the accuracy of the thermocouple location from the weld centreline. However, the importance of this study is the residual heat or inter-pass temperature, which is the temperature the plate cool downs to before the second weld seam takes place. The inter-pass temperature is, therefore, the minimum recorded value before the temperature increases again when the second weld pass takes place. The residual heat from the first weld seam will affect the second weld seam from point A to point C and this will be investigated accordingly.

The inter-pass temperature observed for the replicated pipe diameter of 0.1 m in the laser defocusing termination regime experiment was 190 °C as mentioned previously.

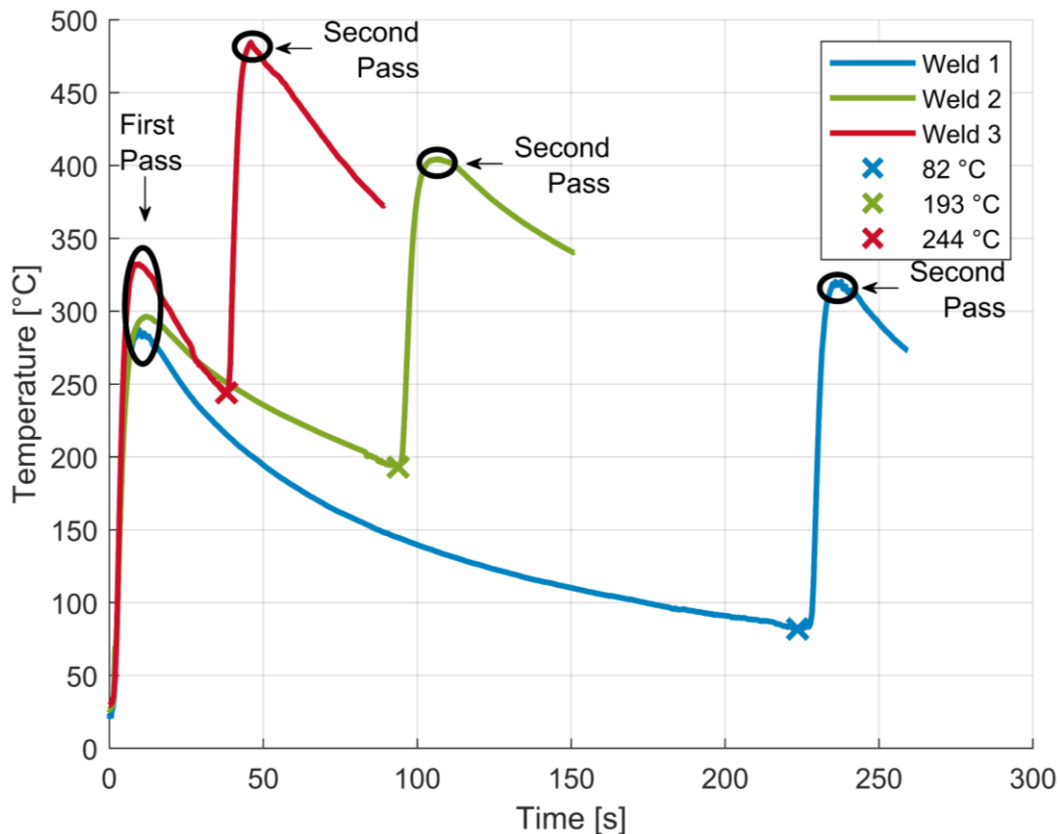


Figure 5-2: Temperature profile measurements of each weld sample from abrupt laser termination experiment

5.3 Results

5.3.1 Abrupt laser termination

The results shown in this section focus on the effect of inter-pass temperature on the weld at different replicated sections of a circumferential weld and on the formation of defects related to abrupt laser keyhole initiation and termination in the weld start/stop region. Results of the abrupt laser keyhole initiation and termination points of a typical longitudinal weld (point A and D, respectively) is also shown for comparison.

5.3.1.1 Effect of inter-pass temperature on weld profile

The top and root surface of the weld samples are shown in Figure 5-3. There are observable defects at the termination point of each weld sample, which will be highlighted in more detail in section 5.3.1.4.

The weld seam sections, $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$, of each weld sample appear identical to each other despite the variation in inter-pass temperature. The only noticeable difference is the increase in the amount of discolouration on the plate, surrounding the second weld seam, as the inter-pass temperature increases.

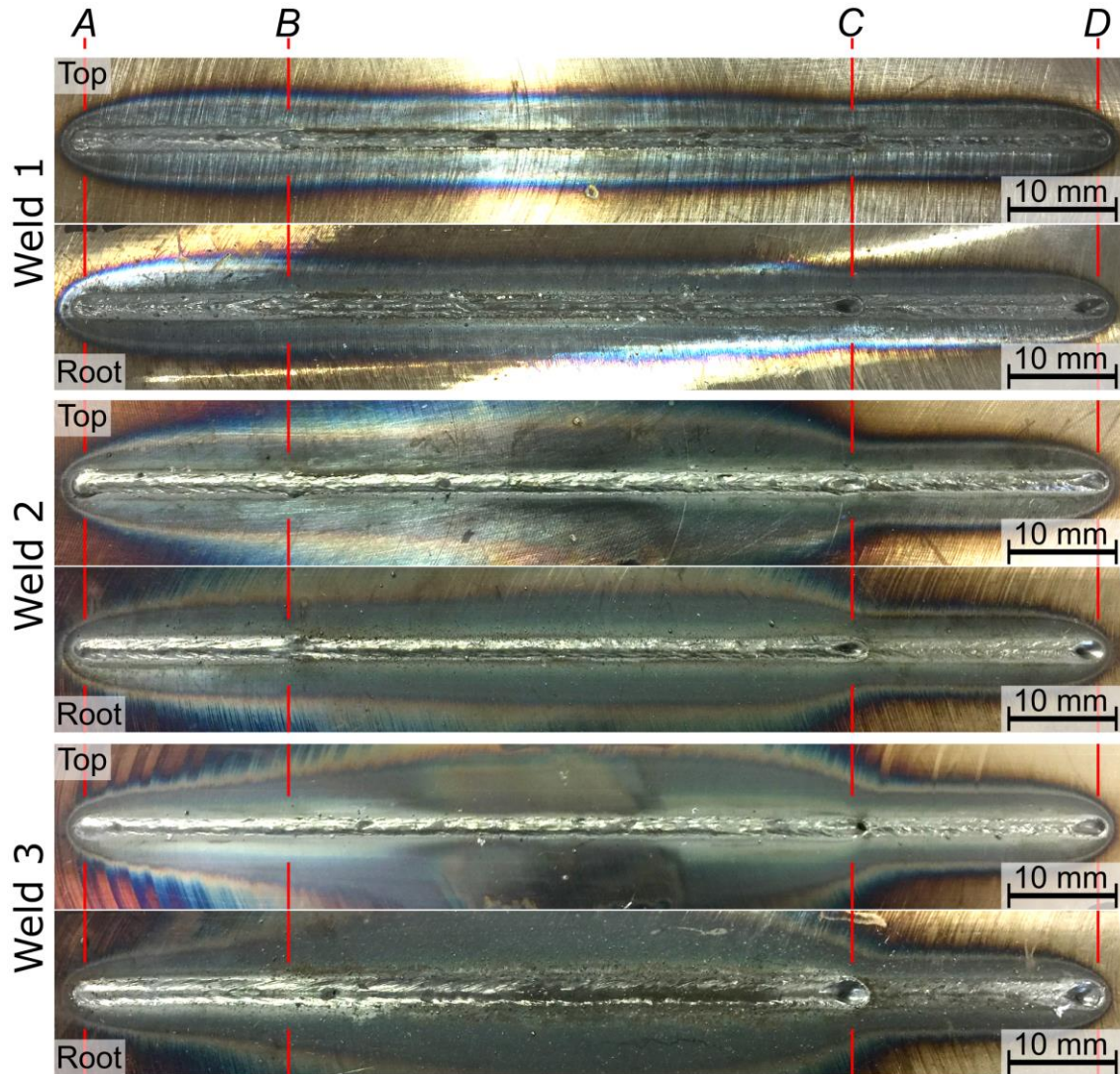


Figure 5-3: Top and root surface of each weld sample

Figure 5-4 shows the cross-sectional transverse macrographs, cut from the middle of the weld seam sections $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$ for each weld sample. The transverse macrograph of $\overline{CD}$ for all three weld samples were made with identical parameters on plates at room temperature. Despite identical parameters and welding conditions, a slight variation is observed between the weld profile geometry from each weld sample of section $\overline{CD}$. The variation in weld profile geometry applies across the whole weld seam for each weld sample, respectively. However, comparison between weld seam sections of the same weld sample can still be made.

When comparing the weld profile of section $\overline{CD}$ to $\overline{AB}$ and $\overline{BC}$, of each weld sample respectively, the size of the HAZ changes because of the increased residual heat. In weld sample 3, where the shortest delay time was applied, the second weld seam and weld start/stop region experienced the highest inter-pass temperature due to the residual heat from the first weld seam. The size of the HAZ at the weld start/stop region (transverse macrograph $\overline{BC}$) is, therefore, significantly larger. On the other hand, the FZ of each respective weld sample remains similar despite the increase in inter-pass temperature and the weld being re-welded at the weld start/stop region.

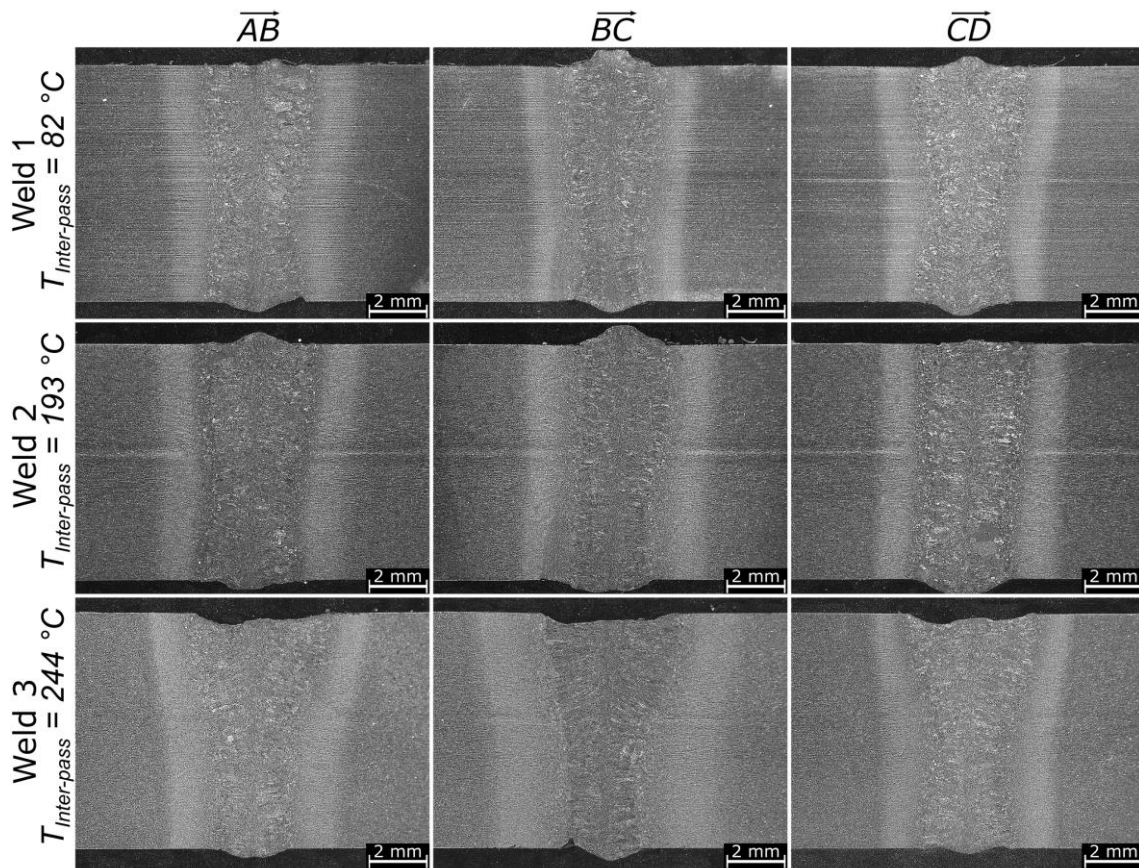


Figure 5-4: Transverse macrographs from the middle of each weld seam section

5.3.1.2 Effect of inter-pass temperature on weld microstructure

Figure 5-5 shows the micrographs of the FZ that were taken at the centre of the welds for each weld seam section from Figure 5-4. Micrographs of sections $\overline{CD}$ show a combination of pearlite with different morphologies of ferrite phases, such as grain boundary ferrite (GBF), polygonal ferrite (PF), and acicular ferrite (AF), and Widmanstätten ferrite (WF). Sections $\overline{AB}$ are similar in microstructure, however, in weld sample 2 and 3, there is some influence of the higher inter-pass temperature. The microstructure at the FZ shows more diffusion-controlled phases occurring. The amount of pearlite decreases while ferrite proportion increases with increasing inter-pass temperature. At the weld overlap start-stop region (section $\overline{BC}$), where the inter-pass temperature was at its maximum, there is a significant increase in size and volume fraction of ferrite phases, when compared with section $\overline{CD}$. In the weld overlap start-stop region of weld sample 3, the microstructure is predominantly ferrite.

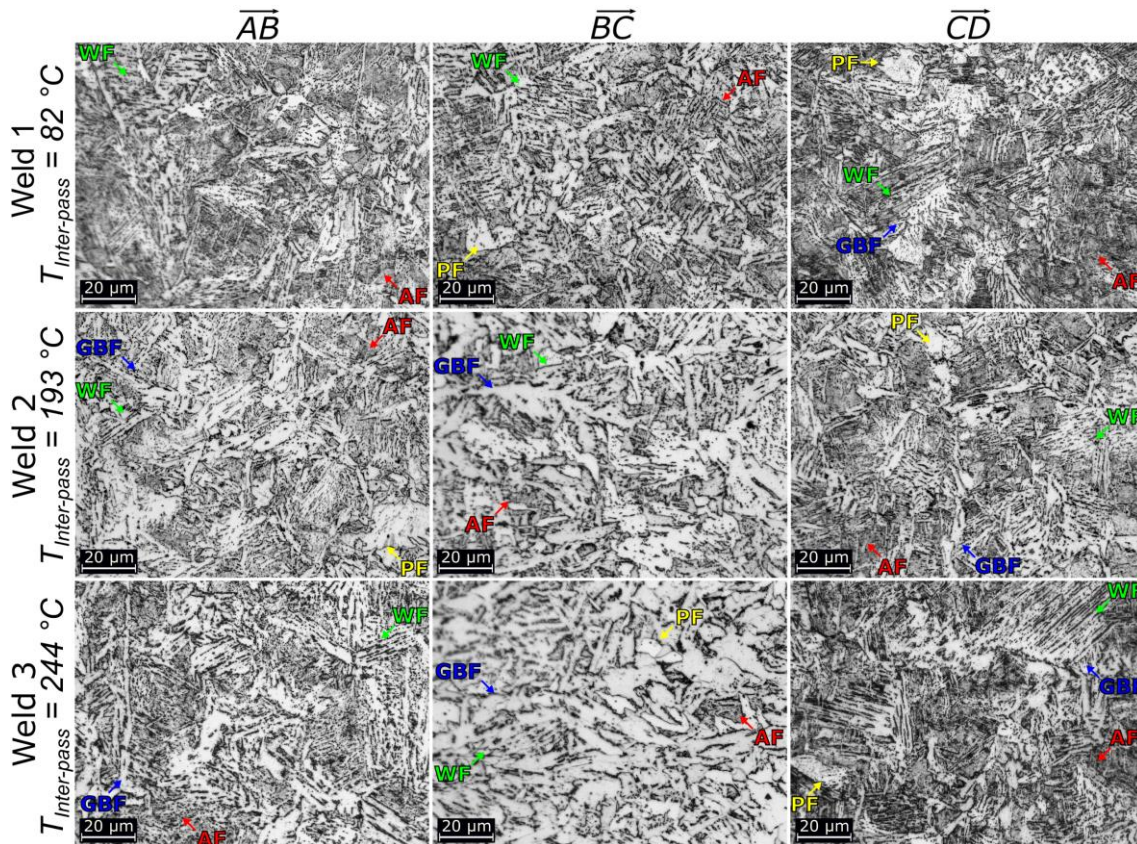


Figure 5-5: Transverse micrographs of the FZ from each weld seam section

5.3.1.3 Effect of inter-pass temperature on weld micro-hardness

Micro-hardness profiles across the weld centreline, along the mid-thickness of the transverse macrographs from Figure 5-4 were measured.

Figure 5-6 shows the micro-hardness profiles of $\overline{AB}$ and $\overline{CD}$ from each weld sample. The micro-hardness profile and values shown are typical of welds made in S355 steels and are well below the maximum acceptable value of 350 HV [7]. The minor variation in the micro-hardness profiles of weld seam sections of $\overline{CD}$ is expected despite identical parameters due to the variation in weld profile as previously mentioned. However, a small decrease in hardness across the weld can be observed when comparing $\overline{AB}$ with $\overline{CD}$ of each weld sample, respectively. The small decrease in hardness seen in sections $\overline{AB}$ of each weld sample is due to the influence of inter-pass temperature on the weld microstructure, as was observed in Figure 5-5.

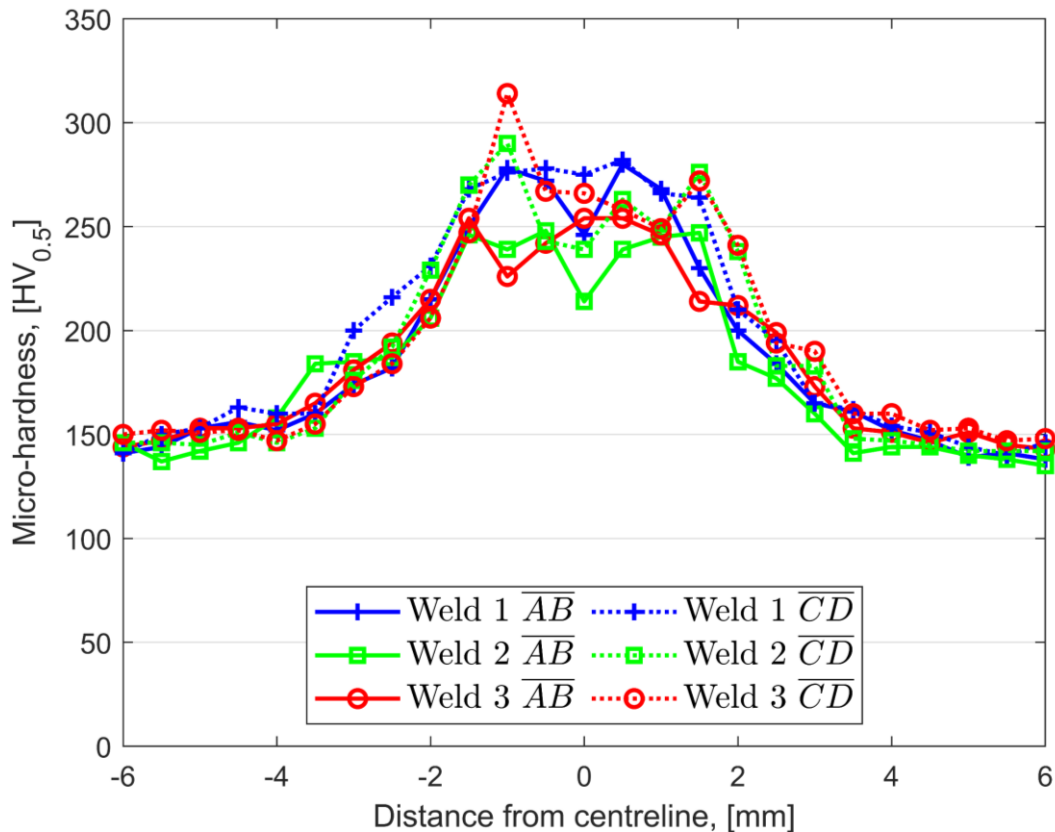


Figure 5-6: Micro-hardness profile at the mid-thickness across the weld centreline of weld seam sections $\overline{AB}$ and $\overline{CD}$ from each weld sample

Figure 5-7 shows the micro-hardness profiles of $\overline{BC}$ from each weld sample compared with the average micro-hardness profile of $\overline{CD}$. The impact of the different inter-pass temperatures at the weld overlap start-stop region is shown. A significant decrease in hardness across the weld is observed when the weld overlap experienced the highest inter-pass temperature. There is little difference in hardness at the centreline of the three weld samples as there is no significant difference in cooling profile at the fusion zone as compared with the HAZ.

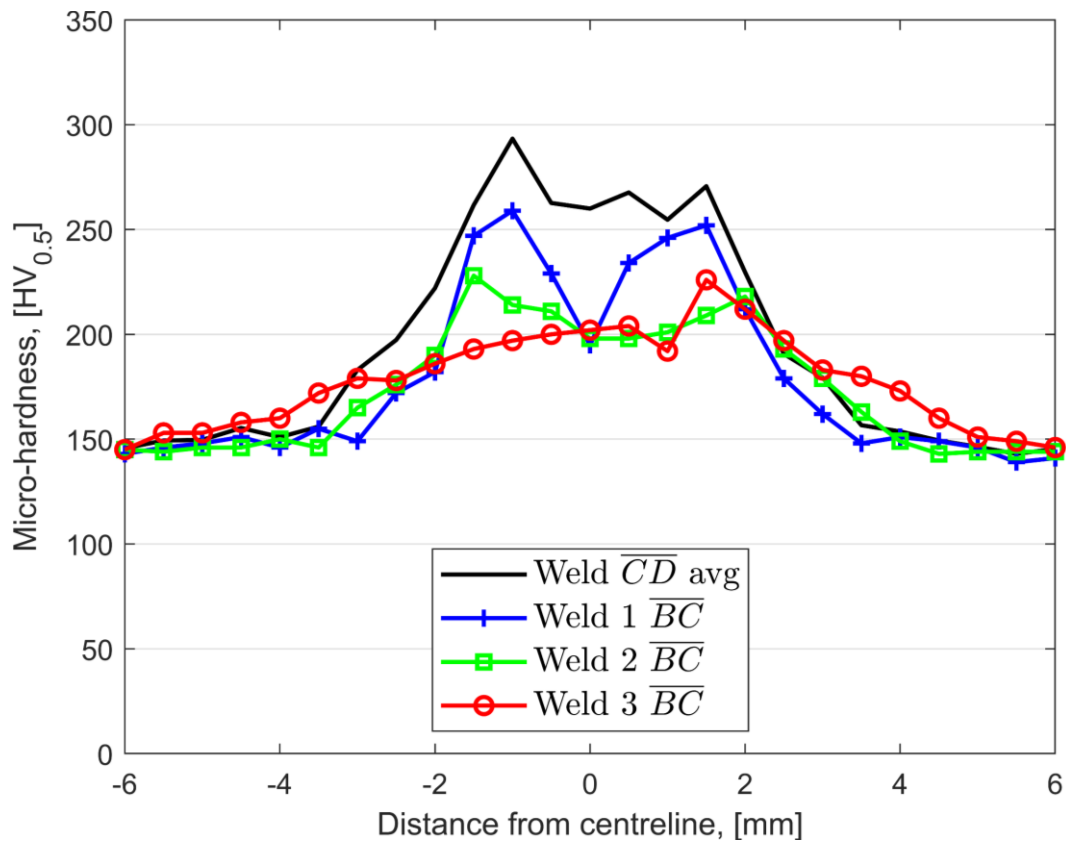


Figure 5-7: Micro-hardness profile at the mid-thickness across the weld centreline of weld seam sections $\overline{BC}$ of each weld sample

The decrease in hardness is more obvious when comparing the average hardness across the FZ of each weld seam section of each weld sample. The weld overlap start/stop region, $\overline{BC}$, has the lowest hardness, followed by the second weld, $\overline{AB}$, and finally the first weld, $\overline{CD}$. An average of the FZ hardness, 1.5 mm either side of the weld centreline was calculated, and the values are shown in Table 5-2. It shows that the hardness of the weld metal FZ of section $\overline{AB}$ and $\overline{BC}$ decreases with increasing inter-pass temperature. The average

hardness in the FZ of section $\overline{BC}$ of weld sample 2 and 3 correlates with the amount of GBF and PF observed in the weld microstructure in Figure 5-5.

Table 5-2: Average FZ micro-hardness of each weld seam section and weld sample

Weld sample	$\overline{AB}$	$\overline{BC}$	$\overline{CD}$	Percentage change	
				$\overline{CD}$ to $\overline{AB}$	$\overline{CD}$ to $\overline{BC}$
Weld 1	260.6	237.4	272.7	-4.5	-12.9
Weld 2	239.7	208.4	261.4	-8.3	-20.3
Weld 3	241.4	202.4	267.6	-9.8	-24.5

5.3.1.4 Effect of inter-pass temperature on abrupt laser initiation and termination at the weld start/stop region

Previously, Figure 5-3 showed the top and root surface of each weld sample. Upon visual inspection of the laser initiation and termination points, it was observed that defects were present only at the termination points in the form of weld craters or cavities on both surfaces. In comparison, the laser initiation points only had slight weld reinforcement and no other visible defects.

Longitudinal macrographs of each laser initiation and termination points from each weld sample are shown in Figure 5-8. Points A and D represent the initiation and termination of a typical longitudinal weld. On the other hand, points B and C represent the initiation and termination of a circumferential weld intersection. Point B is where the initiation point is overlapped by the intersecting weld at the weld overlap start/stop region.

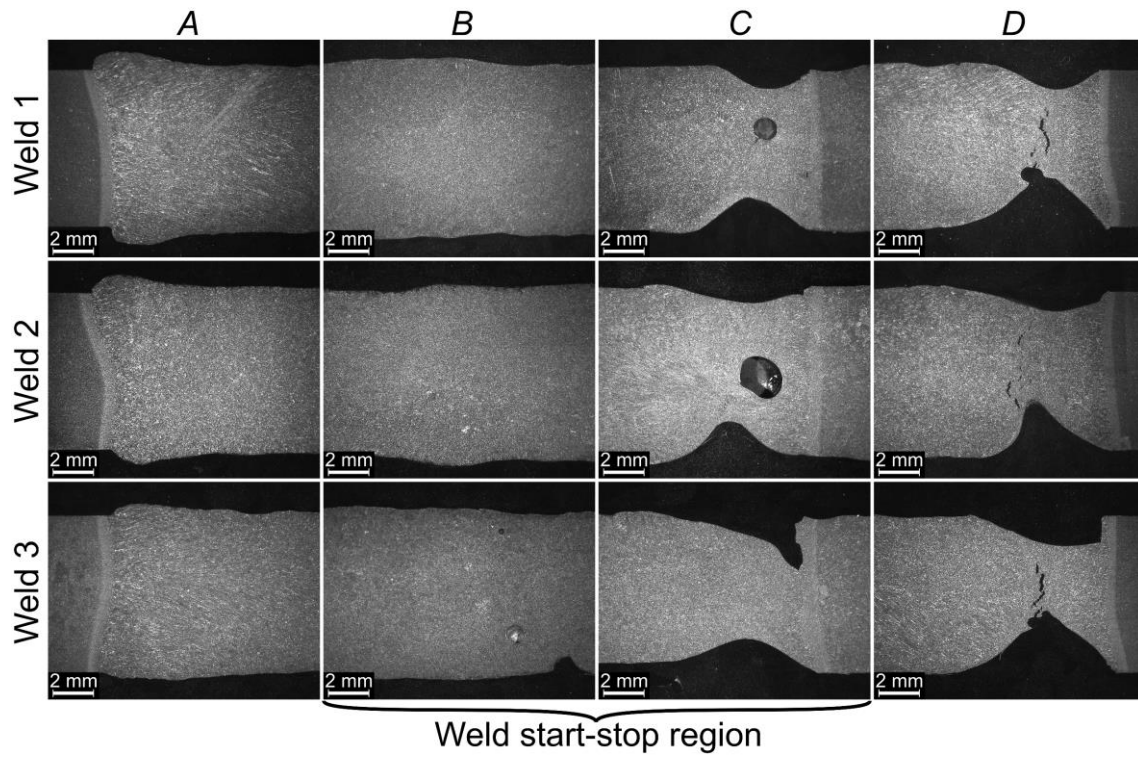


Figure 5-8: Longitudinal macrographs of the initiation and termination points of each weld sample

Point A – Abrupt laser initiation point

Point A represents the initiation point of a longitudinal weld. There are few defects apart from the weld reinforcement which was noticeable from the visual inspection and longitudinal macrographs from all weld samples.

Point D – Abrupt laser termination point

Point D represents the termination point of a longitudinal weld. The defects observed are identical despite the small variation in the weld profiles mentioned previously. Significant underfill in the form of deep weld craters or cavities are present on both the top and root surface at point D as was observed from the visual inspection. Solidification cracking perpendicular to the weld and through the thickness of the plate is also visible between the top and root weld craters.

Point B – Weld overlap of an abrupt laser initiation point

At point B where the laser initiation point (point B) is re-welded by the second weld seam, the weld reinforcement is re-melted and redistributed resulting in a more uniform transition in the weld surface. There are no observable defects at point B in weld samples 1 and 2, however, in weld sample 3 there is a pore and root underfill present. The location of the porosity and root undercut/void observed is about 4 - 5 mm after the laser initiation point of the first weld seam and not directly under the laser initiation point.

Point C – Abrupt laser termination on top of a previous weld

At point C, weld craters or cavities are still present and still rather severe like at point D, however there is no solidification cracking in either weld samples. In weld samples 1 and 2, a large pore is present, and the size of the pore is larger in weld sample 2, which had a higher inter-pass temperature than weld sample 1. On the other hand, there is no pore present in weld sample 3, which had the highest inter-pass temperature. However, the top surface crater geometry of weld sample 3 differs significantly.

5.3.2 Laser defocusing termination regime

The results shown in this section focus on the effect of laser defocusing termination regime on the weld start/stop region and on laser keyhole termination related defects, and how this varies at a different inter-pass temperature.

5.3.2.1 Effect of laser defocusing on weld start/stop region weld profile

Visual inspections of the top surface of the weld start/stop region for each weld sample showed typical weld crater defects at point C in all weld samples regardless of laser termination regime and inter-pass temperature. The application of laser defocusing at the weld overlap also causes surface ripples to form on the top weld surface at a certain distance into the laser defocus as shown by Figure 5-9.

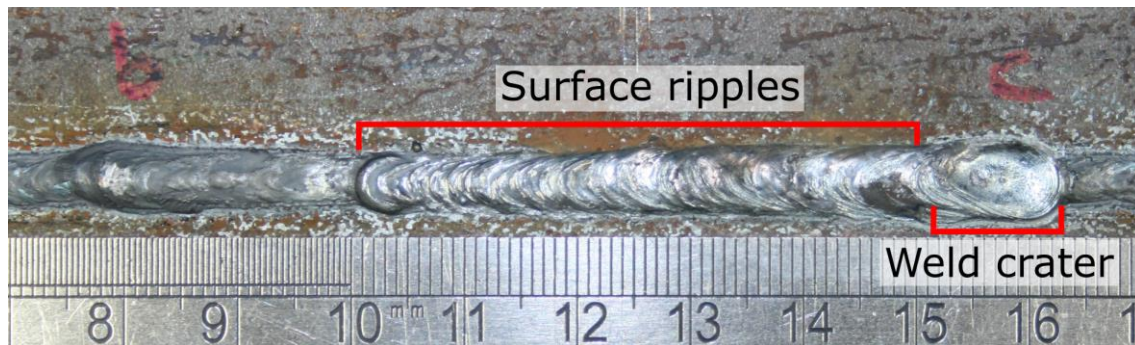


Figure 5-9: Top surface of the weld overlap start/stop region where laser defocusing termination regime was applied

Figure 5-10 shows the longitudinal macrographs in-between points B and C where full penetration ceases due to laser defocusing. The HAZ of the second weld seam has again been highlighted. There are no observable internal defects, such as porosity within this region, indicating that keyhole collapse was avoided and that a stable, successful keyhole closure was achieved.

The transition from full penetration to partial penetration and resulting change in penetration depth when laser defocusing is steeper with higher laser end spot diameters. The penetration depth begins to stabilise after a certain point of defocusing, however, the stabilised penetration depth also coincides with the formation of the surface ripples on the top of weld surface.

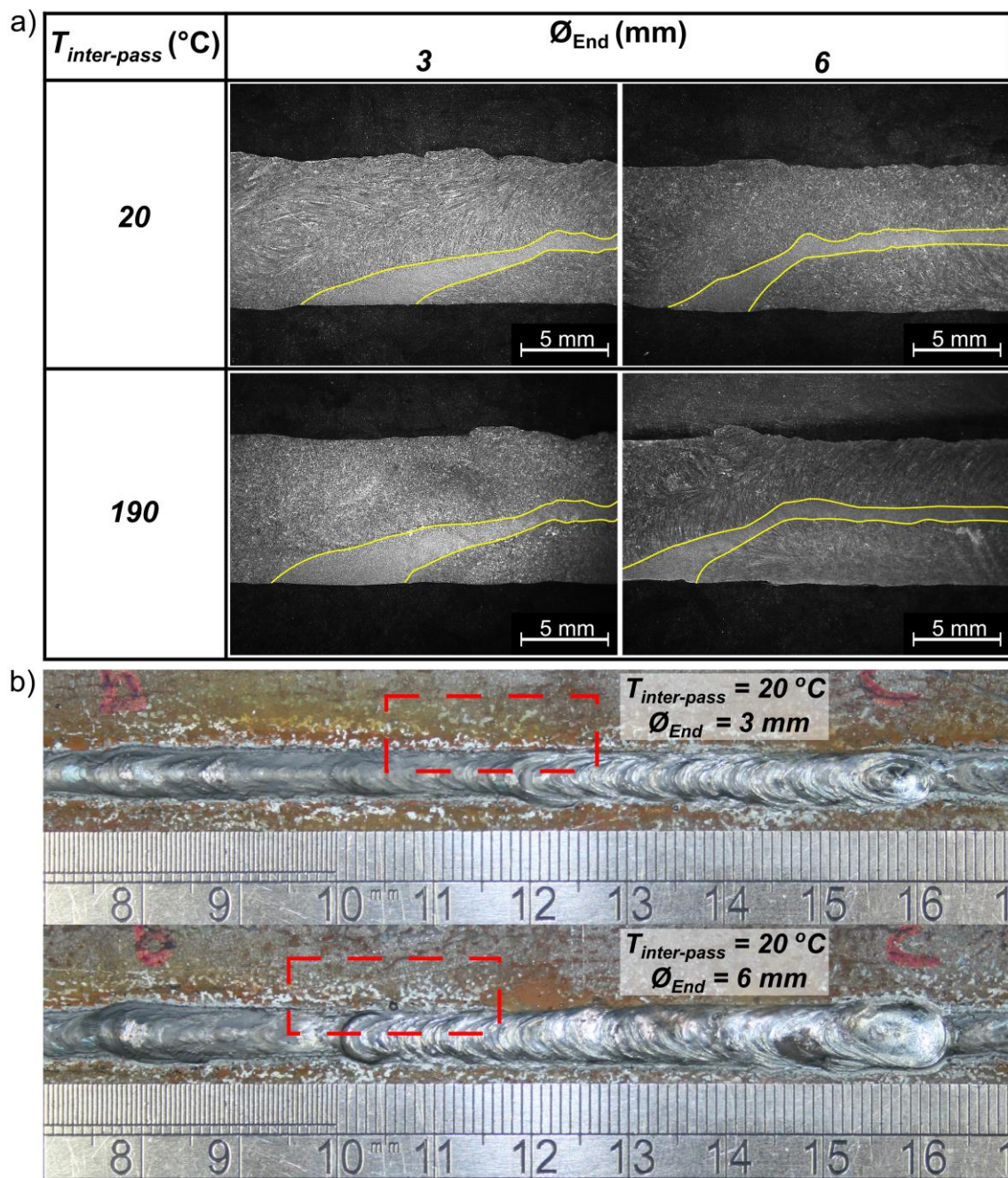


Figure 5-10: a) Longitudinal macrographs of weld transition to partial penetration due to laser defocusing, b) location where macrographs were taken indicated by dashed line rectangles

5.3.2.2 Effect of laser defocusing on weld start/stop region micro-hardness

Figure 5-11 shows a visual representation of the micro-hardness profiles projected on top of the corresponding traverse cross-sectional macrographs that were taken from the weld overlap of each weld sample.

The reference weld with no laser defocus has a similar weld and micro-hardness profile as the weld seam sections of $\overrightarrow{BC}$ shown in Figure 5-4 and Figure 5-7, respectively, from the previous experiment. There is a negligible effect of the higher inter-pass temperature on the micro-hardness for the reference weld.

The effect of the laser defocusing on the weld profile can be clearly observed by the two different weld areas, which corresponds with the two weld seams. The HAZ of the overlapping second weld seam can be clearly distinguished from the previous weld seam and increases in size at higher inter-pass temperatures. The micro-hardness profiles through thickness, therefore, varies as a result. At the top of the weld, an increase in hardness can be observed at the coarse-grained HAZ between the liquid-solid boundary and the HAZ of the second weld seam overlap. The material here experiences high temperatures below the melting point and subsequent rapid cooling. However, at a higher inter-pass temperature, the micro-hardness profile at the top of the weld does not see an increase and is more uniform instead. A higher overall hardness is seen in the middle and bottom traverse of the welds where defocusing was applied when compared with the reference welds with no defocusing applied. An overall reduction of 6%, 4.6% and 0.87% for a $\varnothing_{End}$ of 0.6 mm, 3 mm, and 6 mm respectively is seen when comparing an inter-pass temperature of 20°C to an inter-pass temperature of 190°C.

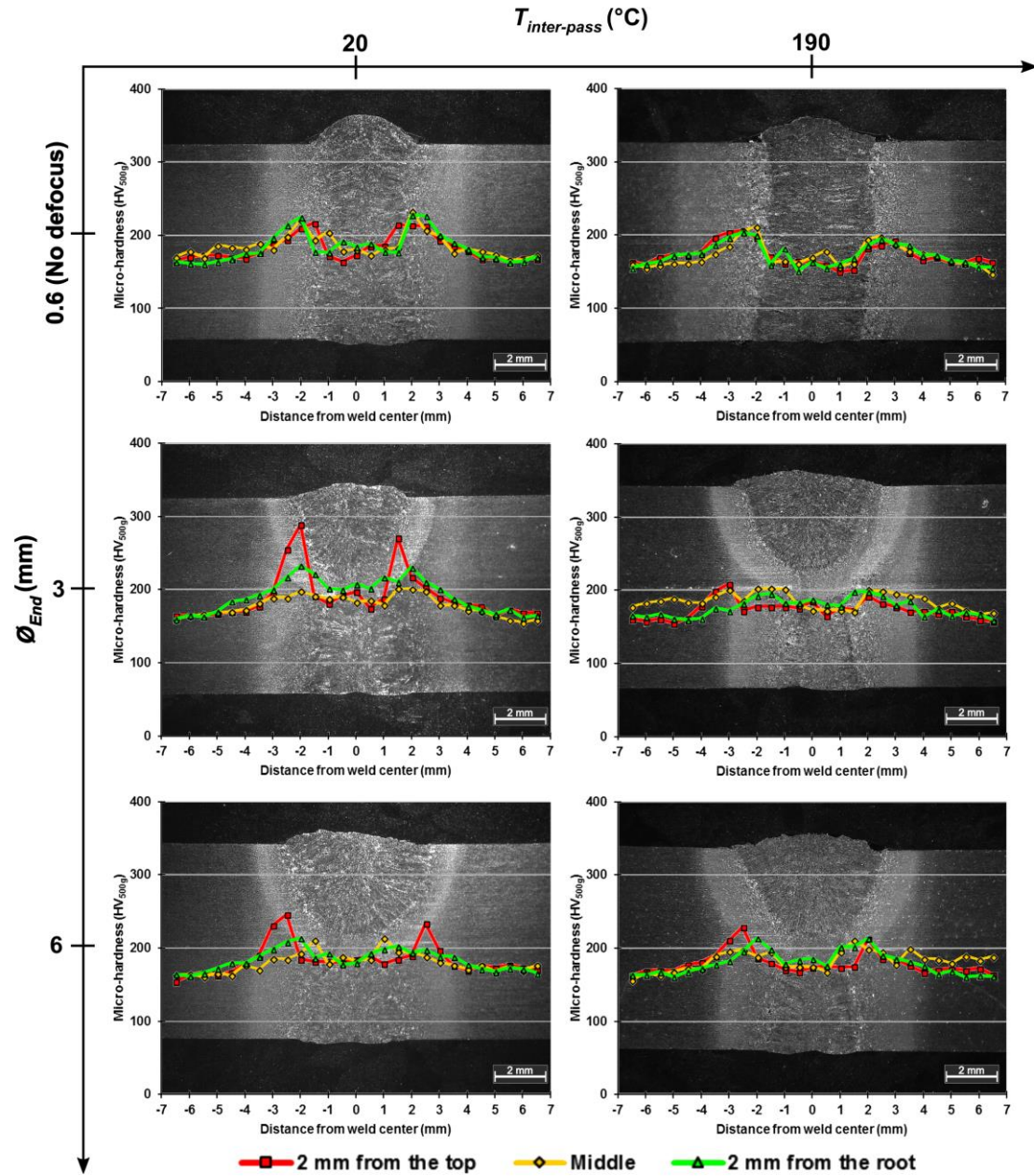


Figure 5-11: Micro-hardness profiles projected onto transverse macrographs of the weld overlap for each weld sample

5.3.2.3 Effect of laser defocusing on weld start/stop laser termination

Figure 5-12 shows the top surface and longitudinal macrograph of the termination for each set of laser end spot diameters and inter-pass temperatures. Weld samples where $\varnothing_{End} = 0.6$ mm are reference weld samples where no defocusing was applied and the laser terminates abruptly. The HAZ of the second weld seam has been highlighted to show the difference in weld profile and penetration depth. Evidently an increase in the end laser spot diameter at the termination point leads to an increase in the weld crater width and length, which also increases with increasing inter-pass temperature. In general, laser defocusing gives nice weld termination points without severe defects.

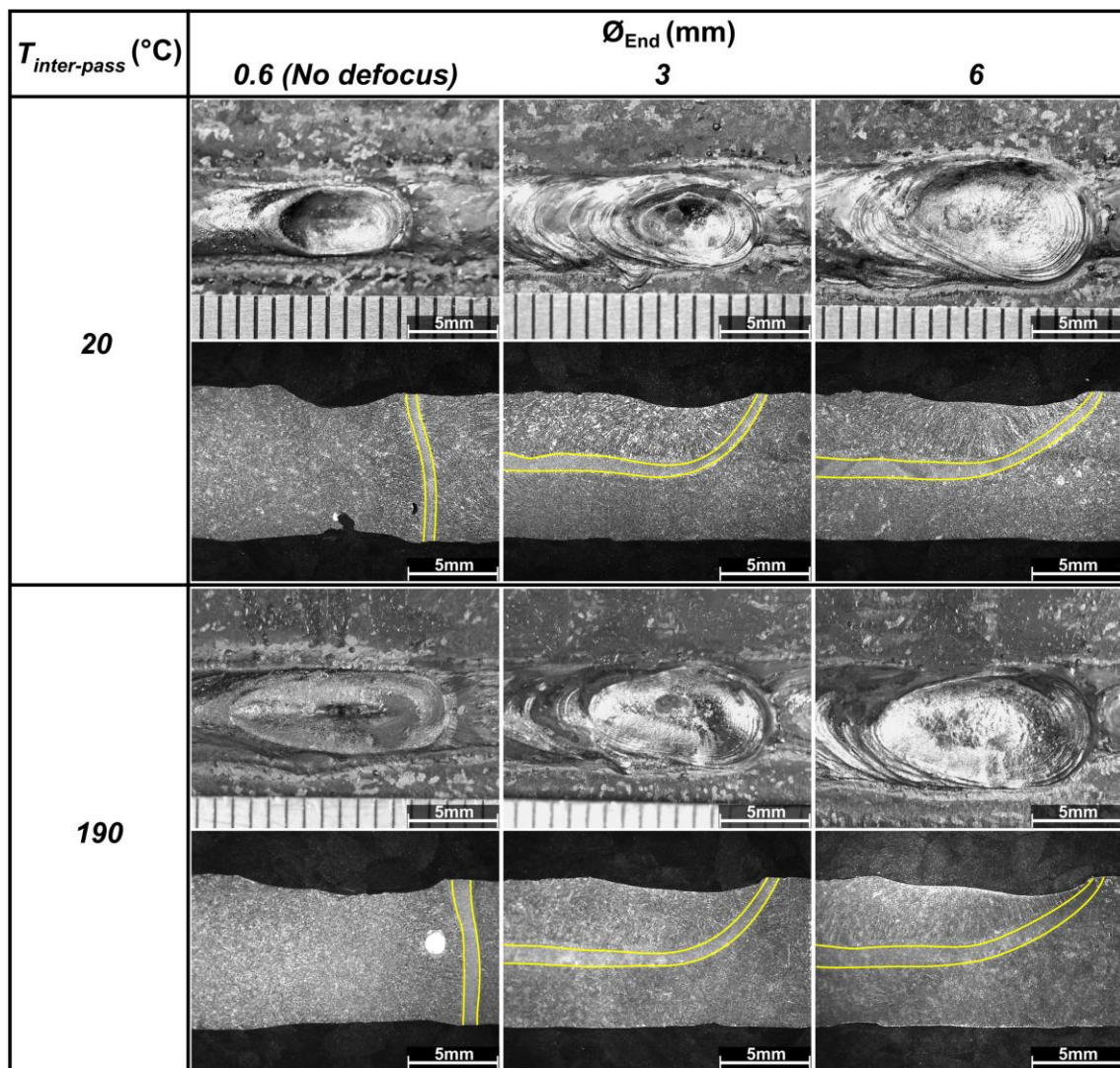


Figure 5-12: Top surface and longitudinal macrograph of termination point C at different laser defocus end spot diameters and inter-pass temperatures

Similar termination defects, such as pores and weld craters are present at point C in the reference weld samples. However, these defects are less severe when compared with the termination point C of the previous abrupt laser termination experiment shown in Figure 5-8 due to the change in weld parameters. No internal defects, such as porosity or cracking, are present at the termination point where laser defocusing was applied. However, weld craters in the form of a surface depression, like that of arc welding, remains at the laser termination point despite the application of laser defocusing.

5.4 Discussion

5.4.1 Abrupt laser termination

5.4.1.1 Effect of inter-pass temperature on weld overlap

Small variations in weld profile geometry due to minor inaccuracies of the laser focal spot alignment with the plate surface was observed, as shown in Figure 5-4. The undercut visible at the top surface across all weld seam sections of weld sample 3 is a result of the focal spot misalignment.

The inter-pass temperature increases the maximum temperature experienced and slows down the cooling rate of the second weld pass, as was observed from the temperature measurements in Figure 5-2. As the material is exposed to different temperature profiles throughout the replicated circumferential weld seam, each weld seam section differs.

The effect of inter-pass temperature on the weld profile and HAZ was highlighted in Figure 5-3 and Figure 5-4, where an increase in inter-pass temperature led to an increase in the size of the HAZ at the weld overlap. The increased size of the HAZ is because the workpiece was already hot (preheated) when the weld overlap took place. Therefore, less laser energy is required to melt the material and the extra thermal energy either contributed to an increase in penetration or was transferred to the material instead. The laser power was kept constant to maintain consistency within these experiments but ideally at high inter-pass temperatures, the laser power should be decreased at the weld overlap. The higher temperatures and slower cooling rates at the weld overlap also result in a

microstructure with softer and coarser phases, such as large GBF and PF in the weld metal FZ. The effect of the inter-pass temperature on the microstructure is also reflected in the weld micro-hardness profiles, where the hardness decreases with increasing inter-pass temperature. Excessively high inter-pass temperatures may unfortunately lead to a loss in mechanical strength and hardness and is detrimental to the weld toughness. Therefore, the thermal cycle and cooling rate need to be controlled at the weld overlap, especially for offshore steel structural applications.

5.4.1.2 Effect of inter-pass temperature on abrupt laser initiation and termination related defects

Abrupt laser keyhole initiation (point A and B)

The slight weld reinforcement at point A is caused by a combination of thermal expansion of the weld metal, and the rapid solidification of the molten material that flowed behind the laser keyhole as the laser begins its traverse, as shown in Figure 5-8. Typically, a gradual ramp up of laser power over a small distance is used to initiate laser welds but was not applied to maintain similar welding conditions. At point B, which represents the initiation of a circumferential weld, the weld reinforcement is less significant and there is little to no defects present because of welding over a laser weld initiation point. The likely cause of the small pore in weld sample 3 after the initiation point is due to gas entrapment from the bottom of the keyhole during solidification, and the undercut/void at the root is an indication of this. To mitigate such defects, the laser power should be decreased proportionally during the start of the weld overlap depending on the resultant inter-pass temperature.

Results for both laser initiation points at the start of a weld or when overlapped indicate that it is not a major problem in laser keyhole welding when using the set of parameters studied within this chapter. However, this is not the case for laser keyhole termination, where more attention is necessary.

Abrupt laser keyhole termination (point C and D)

At point C and D where the laser terminates abruptly, there are unacceptable defects present. During laser termination, the keyhole collapses in on itself and rapidly solidifies leaving behind the weld craters on both the top and root surface. The cracks observed at point D, which represents the termination of a longitudinal weld, suggests that there are significant solidification stresses present due to the rapid solidification, thermal gradient, and shrinkage stresses caused by the difference in weld and parent metal.

At point C, the termination point of a circumferential weld, is less susceptible to cracking due to the similar microstructure and thermal gradient (lower thermal stresses). The pore or void at point C is a typical defect that occurs because of keyhole collapse, gas entrapment and rapid solidification of the collapsed keyhole. At high inter-pass temperatures, the solidification rate would reduce, allowing time for gases to escape and for the molten metal to fill any voids caused by the keyhole collapse. This was observed in weld sample 3, where there was no pore or void in the weld, but a difference in the top surface crater geometry. The different top surface crater geometry indicates that there was sufficient time for the pore or void to surface and escape and for the molten metal to fill the void before solidification.

The change in circumference being welded and resulting inter-pass temperature has little effect on the prevention of laser keyhole termination related defects when the laser is terminated abruptly. The results indicate that keyhole collapse and closure is dependent on and driven by keyhole dynamics and that the effect of the thermal cycle is minimal. However, the inter-pass temperature does affect the microstructural development and hardness profile, which needs to be considered to achieve the desired mechanical properties.

The observed results also show that abrupt laser keyhole initiation is less susceptible to defects compared to abrupt laser keyhole termination. Abrupt laser keyhole termination results in an unfilled keyhole cavity or void unless a robust strategy is adopted to fill the keyhole cavity during laser termination.

5.4.2 Laser defocusing termination regime

5.4.2.1 Effect of laser defocusing on weld start/stop region weld profile

The application of laser defocusing termination regime at the weld overlap allows for the laser to transition from keyhole mode towards conduction mode laser welding due to the reduction in laser power density. The region where the weld leaves full penetration due to laser defocusing shows no significant defects at the root, as was shown in Figure 5-10. However, from this point onwards, where the penetration depth begins to stabilise, the melt pool flow becomes erratic resulting in ripples in the weld surface. The formation of surface ripples is due changes in the melt pool flow direction and dynamics due to the change in melt pool size and aspect ratio. From literature, changes in flow direction and melt pool dynamics that causes surface ripple behaviour are affected by surface active elements, shielding gas, and material chemical composition. Therefore, it is necessary to investigate the effect of these phenomena. The surface ripples are also unacceptable as the irregular surface roughness are stress concentrators and are detrimental to the fatigue life of the weld and structure.

There are no observable internal defects throughout the weld overlap, such as porosity, which suggests that successful keyhole closure is achievable using laser defocusing termination regime and keyhole collapse is avoided. Typically, at such low welding speeds, laser defocusing is not recommended as it increases the amount of molten metal.

5.4.2.2 Effect of laser defocusing on weld start/stop region micro-hardness

The change in weld profile due to laser defocusing is like that of a multi-pass weld and the difference in hardness across the two weld profiles reflects this. Control of the inter-pass temperature and laser defocusing termination regime is essential as the micro-hardness profile is dependent on these factors. Excessive cooling between the completion of the weld seam may occur If the circumference of the workpiece is significantly large or the welding speed too slow. As a result, this may induce hard microstructural phases in the weld overlap start-stop region.

5.4.2.3 Effect of laser defocusing on weld start/stop laser termination

When the laser terminates after defocusing, a shallow depression at the termination point in the form of a weld crater remains due to the laser terminating at the full laser output. There are marginal differences in the appearance of the weld crater when terminating using laser defocusing at a higher inter-pass temperature. The higher thermal energy within the material leads to increased melting and this is observed by the increased size of the melt pool and HAZ resulting in a slightly larger weld crater upon laser termination.

Underfill defects at the root surface of the termination point are eliminated as the weld is no longer in full penetration due to the reduction in penetration. Therefore, there is no vaporisation pressure to cause metal expulsion at the root as with full penetration welds.

5.5 Conclusions

In this study, the effect of inter-pass temperature, achieved by replicating different weld circumferences on flat plates of 8 mm thick S355 structural steel plates, on microstructure and weld overlap start/stop defects were investigated.

- Within this study, there were no significant laser initiation defects apart from excess weld reinforcement when initiating at full laser power. However, when the laser initiation point is overlapped by the second weld seam, the weld reinforcement is reduced.
- It was identified that abrupt laser termination causes more significant defects, such as underfills in the form of deep weld craters, pores and solidification cracking when compared with abrupt laser initiation.
- Laser keyhole termination points are susceptible to cracking due to significant solidification stresses because of the large thermal gradient and difference in microstructure between the weld metal and parent metal that occurs in longitudinal welds.

- In circumferential welds, the similar microstructure and residual heat between the start section of the weld and the new termination point prevents cracking from occurring, however, this is still dependent on the thickness and circumference of the workpiece being welded.
- Laser termination related defects are present regardless of the inter-pass temperature indicating that keyhole closure and collapse is dependent on keyhole and melt pool dynamics rather than the metallurgical aspects, such as the thermal cycle. However, the inter-pass temperature does affect the microstructural development and hardness profile. Therefore, the thermal cycle and cooling rate need to be controlled at the weld overlap, especially for offshore steel structural applications.
- Successful laser keyhole closure was achieved through the application of a laser termination regime. No internal defects, such as porosity or voids were present indicating that the keyhole closed gradually without collapsing. The penetration depth and keyhole gradually reduced, leaving a small depression in the form of a shallow weld crater on the top surface which indicates that further optimisation of the process parameters is required to fully achieve a defect free laser circumferential weld.
- Although successful keyhole closure was achieved using the laser defocusing termination regime, the formation of surface ripples was observed. The changes in melt pool size and melt pool dynamics and flow direction lead to the formation of these surface ripples when the penetration depth began to stabilise at a certain aspect ratio. Therefore, further investigation on the effect of melt pool dynamics, melt flow direction and factors affecting these phenomena is required. Also, this indicates that using laser defocusing termination regime at slow weld speeds is not advisable or further control and modifications are necessary.

Chapter 6

Effect of laser termination regime and material chemical composition on weld overlap start/stop region

6.1 Introduction

It has been shown in the previous chapters that melt pool dynamics can differ during laser termination due to changes in the melt pool size and aspect ratio depending on the laser termination regime applied. Melt pool dynamics and flow direction are affected by surface active elements and the material chemical composition during welding and behaves differently for different materials.

Structural steel grades used throughout Europe are classified based on yield strength, impact energy requirements, and the method of manufacture, specified in the standard BS EN 10025 [132]. The composition of these steel grades is limited to a maximum weight percentage of specific elements with a wide tolerance. Therefore, the chemical composition for the same structural steel grade varies significantly and can have varying amounts of alloying elements between batches. These differences can affect laser weldability and in particular laser termination due to changes in melt pool behaviour.

In this chapter, the application of laser power ramp-down and laser defocusing termination regimes, on the weld start/stop region, were studied on different batches of S355J2+N steel plates. The different plate batches have slightly different chemical composition due to variations in the alloying elements. The major differences in chemical content between the three different plate batches is the amount of carbon, manganese, and silicon. The purpose of this study was to distinguish how the different termination regimes affect the weld overlap and how they are impacted by the variation in chemical composition for the same steel grade.

Parts of this chapter has been written into a paper that has been accepted and published in the *Journal of Manufacturing Processes*.

Lai WJ., Ganguly S., Suder W. Study on effect of laser keyhole weld termination regimes and material composition on weld overlap start-stop defects. Journal of Manufacturing Processes. Elsevier; October 2020; 58(October): 416–428. Available at: DOI:10.1016/j.jmapro.2020.08.012

6.2 Methodology

Two separate experiments were conducted within this chapter. Firstly, the effect of the two different laser termination regimes were studied to understand how the process parameters affect laser termination and defect formation within the weld overlap start/stop region. Secondly, the effect of varying chemical composition of S355J2+N grade structural steels on the two laser termination regimes was studied following on from the results from the first experiment.

6.2.1 Experimental set-up

Three different batches of S355J2+N grade structural steels used in this experiment were tested externally using optical emission spectroscopy analysis, and their composition is shown in Table 6-1. For one weld sample in experiment 1, a 100 % argon shielding gas at 35 l/min was applied using a cross-jet air-knife across the top surface of the weld start/stop region during the application of a laser defocusing termination regime.

Table 6-1: External optical emission spectroscopy chemical analysis of S355J2+N plate variations

Plate	Wt. %													N ²	O ²
	C	Mn	Si	S	P	Cu	Ni	Cr	Mo	Al	V	Nb	Ti	(ppm)	(ppm)
L	0.08	0.92	0.01	0.01	0.01	0.03	0.03	0.03	<0.01	0.05	<0.01	0.03	0.02	18	15
M	0.17	1.44	0.34	0.013	0.014	0.01	0.03	0.02	<0.01	0.02	<0.01	<0.01	<0.01	36	12
N	0.15	1.49	0.5	<0.005	0.016	0.03	0.05	0.03	<0.01	0.04	<0.01	<0.01	<0.01	33	5

Micrographs of each plate batch are shown in Figure 6-1 and only plate L were used in experiment 1. Plates were cut and machined to 300 x 120 x 8 mm to remove mill scale and cleaned with acetone prior to welding. After the first weld seam, the plate was left to cool to room temperature before cleaning with acetone to ensure there were no contaminants on the weld bead during the weld overlap.

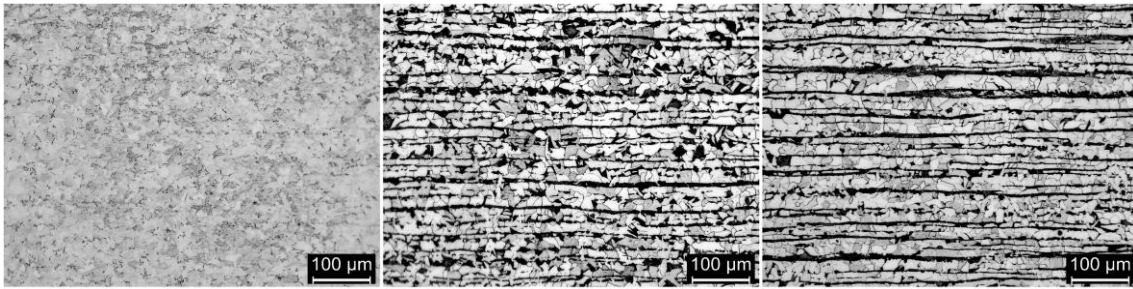


Figure 6-1: Micrographs of different S355J2+N plate batches, from left to right: Plate L, Plate M, Plate N

6.2.2 Experimental approach

The experimental approaches used in this chapter for replicating circumferential welds onto flat plates and laser defocusing and laser power ramp-down termination regimes can be found in sections 3.2.1 to 3.2.4.

6.2.2.1 Welding procedure and parameters

In previous chapters, it was found that a lower angle during laser defocusing (longer weld overlap distance) reduced or limited the increase in heat input at the weld overlap due to maintaining a similar travel speed of the beam in the welding direction. Therefore, two weld overlap distances ($\overline{BC}$) of 40 mm and 80 mm were considered to achieve a high and low rate of termination in experiment 1. Only an 80 mm weld overlap was used in experiment 2.

Circumferential weld overlaps following the approach given in section 3.2.1 were achieved using two overlapping weld seams of 160 mm. This allowed each weld seam section, $\overline{AB}$, $\overline{BC}$ and $\overline{CD}$, to have an equal length of 80 mm. The second weld seam was reduced to 120 mm to achieve a weld overlap of 40 mm.

Welding parameters were selected from a series of trial welds that provided full penetration with uniform top and root surface quality. A laser power of 3.8 kW and travel speed of 0.5 m/min provided the best weld quality based on visual inspections. However, an increase in laser power to 5.2 kW at the same travel speed was required to achieve full penetration with uniform top and root surface quality in experiment 2 due to the different composition of the steel plates.

6.2.2.2 Weld termination regimes

The different parameters applied for each laser termination regime at the weld overlap for each experiment is shown in Table 6-2. The travel speed of the laser head during both laser power ramp-down and laser defocusing termination regimes was kept at 0.5 m/min. The change in speed of the laser beam in the welding direction during laser defocusing can be calculated using equation 3-6, given in section 3.2.3. The range of the speed of the beam in the welding direction is also shown in Table 6-2.

Table 6-2: Termination parameters for each experiment

Experiment:	Termination parameters:		
	Laser termination power,	End laser spot diameter,	Speed of beam in welding direction,
	P_{End} , [kW]:	$\varnothing_{\text{End}}$, [mm]:	v_{beam} , [m/min]
Experiment 1			
<i>Laser power ramp-down:</i>	3.8, 1, 0.5, 0	0.6	0.5
<i>Laser defocusing:</i>	3.8	1.2 - 4.2	0.39 – 0.51
Experiment 2			
<i>Laser power ramp-down:</i>	0	0.6	0.5
<i>Laser defocusing:</i>	3.8, 5.2	4.2	0.39 – 0.51

Different laser termination powers and end laser spot diameters were used to investigate the relationship and effect of laser power density and melt pool size on weld crater formation. The change in laser power density for each termination regime over an 80 mm distance has been calculated based on a top-hat beam profile and is shown in Figure 6-2. Actual values of laser power density calculated for laser defocusing will differ as the beam profile changes from a top-hat profile to a gaussian distribution.

In experiment 2, selected weld parameters from experiment 1 for an 80 mm weld overlap were replicated onto the three different batches of steel plates.

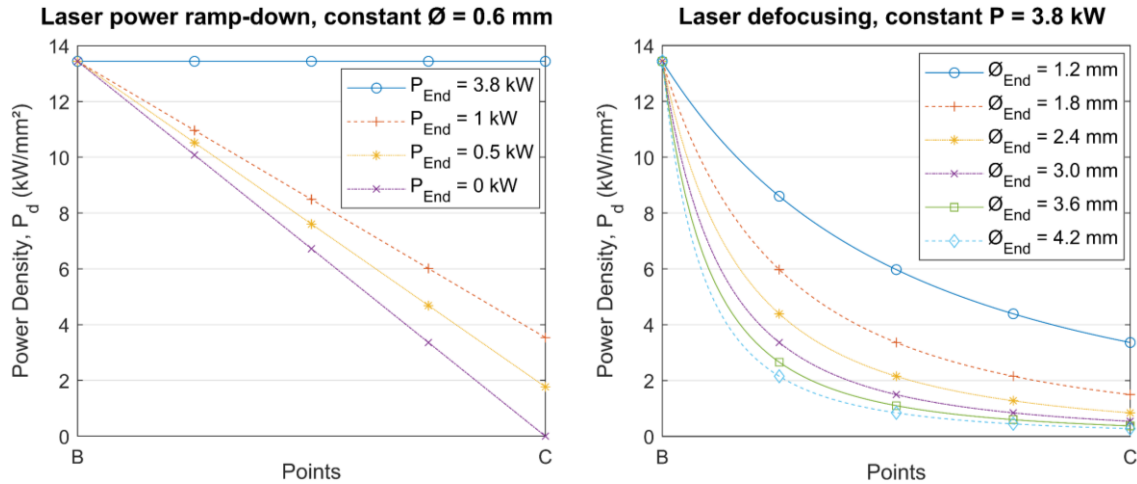


Figure 6-2: Change of laser power density for each termination regime

6.2.2.3 Weld sample analysis and crater geometry measurements

Photographs of the plate surface and X-ray radiography of weld samples were taken prior to cutting and weld sampling. Both longitudinal and transverse macrographs were taken from critical regions and points along the weld samples.

The weld profile of weld craters with a cavity were measured, as shown in Figure 6-3 using. The weld cavity profile was projected onto the macrograph as a “path” in Inkscape, a free and open-source vector graphics editor software. The path is made up of several line segments and nodes and these nodes were exported as X-Y coordinates using an open-source extension and processed using MATLAB.

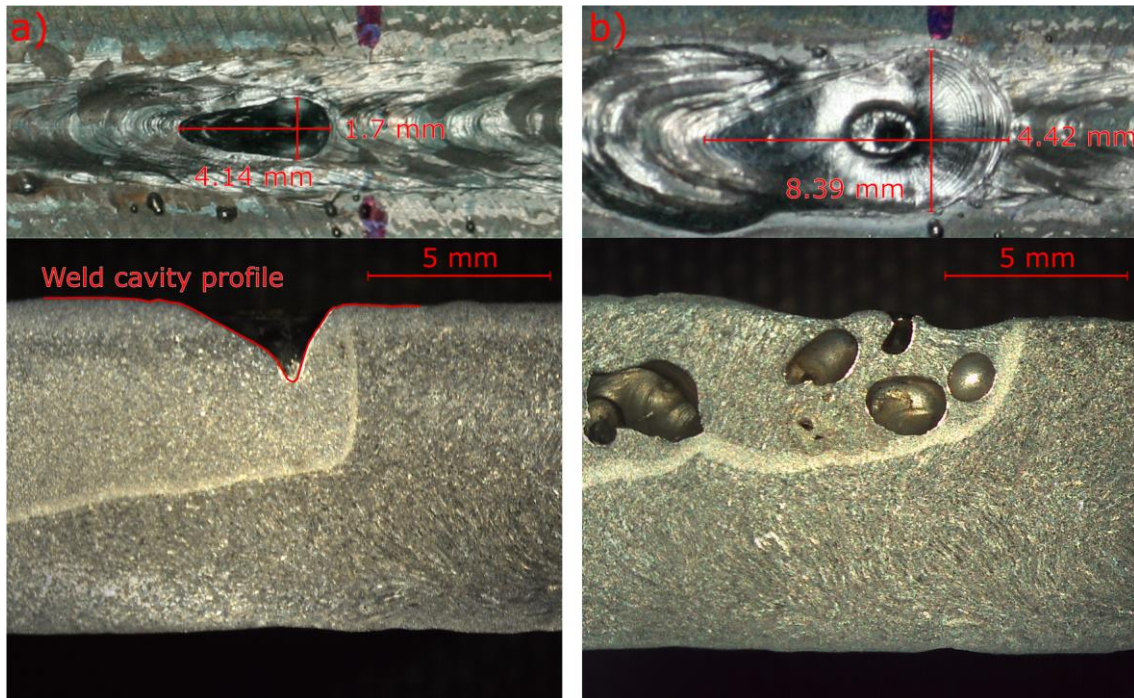


Figure 6-3: Illustration of weld crater geometry measurements, a) crater with cavity, b) crater with surface depression and porosity

6.2.2.4 Tensile tests with digital image correlation (DIC)

In experiment 1, tensile tests using DIC was conducted to measure the local strain distribution across specific weld seam sections of each termination regime. The set-up and procedure of the tensile tests is described in section 3.4.2. One weld sample from each laser termination regime was selected and replicated for tensile testing. Therefore, two sets of tensile specimens for each termination regime were obtained. Weld samples of laser power ramp-down to 0 kW were labelled as A1 and B1 followed by the location the tensile specimens were taken from. For example, the tensile coupon A1-AB corresponds with a laser power ramp-down to 0 kW from the weld overlap section. Weld samples of the laser defocusing to an end spot diameter of 3 mm were labelled as A2 and B2.

Fractography of the tensile specimen fracture surface was performed using Scanning Electron Microscope (SEM) by technical staff.

6.3 Results

6.3.1 Experiment 1: effect of different laser termination regimes on weld overlap start/stop region

6.3.1.1 Reference weld – abrupt laser termination

A reference weld was conducted where the laser terminates abruptly at point C for comparison purposes. Figure 6-4a shows the top weld surface and x-ray image of the reference weld highlighting where any internal defects occurred and the locations where macrograph samples were taken. Figure 6-4b shows the longitudinal macrographs of each point, and transverse macrographs of each weld seam section between each point. As parameters were kept constant apart from the changes at the weld overlap, all weld areas outside of the weld start/stop region, such as point A and D, and weld seam sections $\overline{AB}$ and $\overline{CD}$, are identical to the reference weld.

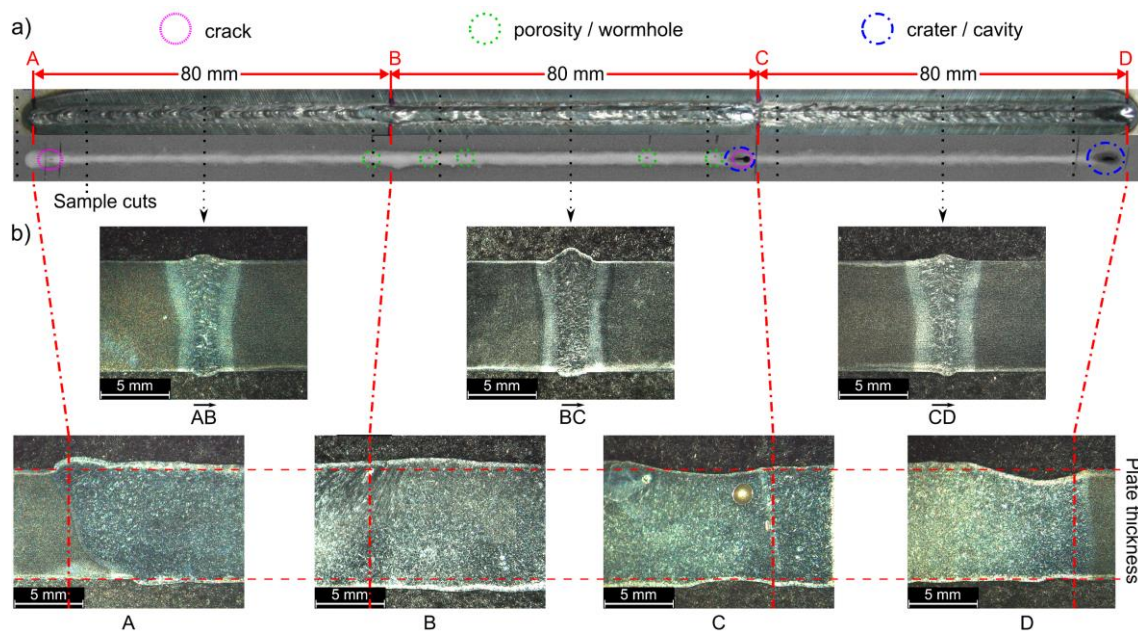


Figure 6-4: Reference weld, a) weld top surface and x-ray images, b) longitudinal and transverse macrographs from specific locations

Defects due to abrupt laser termination, such as weld crater/cavities, porosity, and solidification cracking, can be seen from the weld surface and x-ray image of the reference weld. In several weld samples, the x-ray images highlighted the presence of centreline solidification cracking just after the laser initiation point A,

although this was not captured in the longitudinal macrograph. At point B, there is no indication of solidification cracking, however, there is the presence of porosity prior to or just after the laser initiation in some weld samples. Porosity is also observed randomly within the weld overlap of the reference weld and within the weld seam sections of $\overline{AB}$ and $\overline{CD}$ of the other weld samples.

6.3.1.2 Laser power ramp-down termination regime

Photographs of the weld top surface and x-ray images of the weld start/stop region of each weld sample are shown in Figure 6-5. The x-ray images showed no cracks at point B, only the presence of porosity in some weld samples. There is also an increase in weld reinforcement and width at point B where the laser initiation point was overlapped.

From point B to point C, a gradual reduction in the width of the second weld seam can be observed from the weld top surface. The presence of porosity throughout the weld overlap also appears to reduce when compared with the reference weld.

At the laser termination point C, weld craters and cavities occur unless the laser power is ramped down to 0 kW over 80 mm. However, though there was no weld crater, a string of porosity prior to the laser termination point C was present. When the laser power is ramped down to 0 kW over 40 mm, a small pore and depression in the surface, no deeper than 0.3 - 0.4 mm remains.

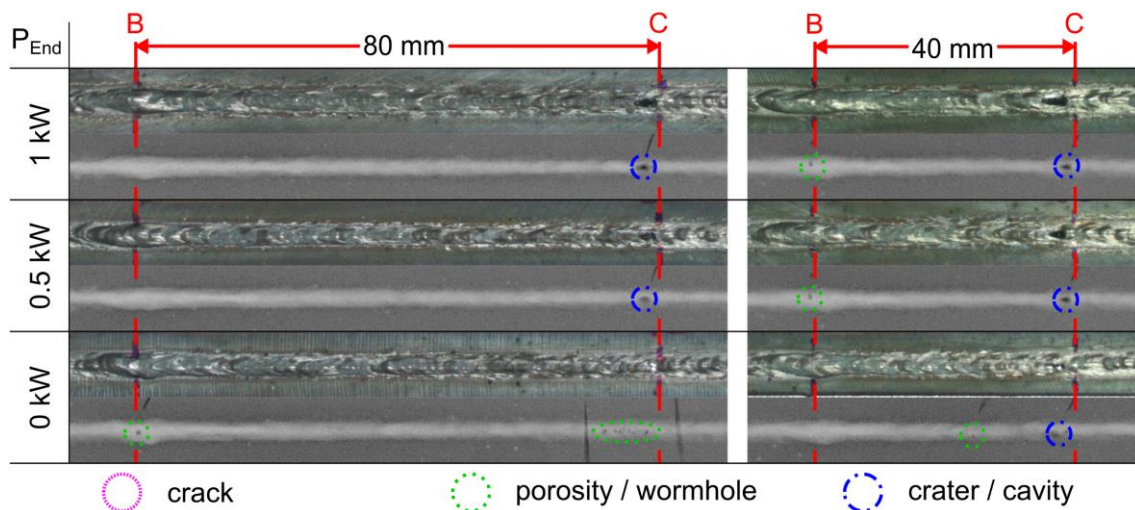


Figure 6-5: Weld top surface and x-ray image of weld start/stop region using laser power ramp-down termination regime

Longitudinal macrographs of the 40 mm weld start/stop region samples are shown in Figure 6-6. The weld craters/cavities at point C are more evident and the size and depth reduces with reducing end laser termination power. There are no defects, such as root sagging, where full penetration ceases and a gradual linear reduction in penetration depth is observed. The weld overlap region is relatively smooth and stable apart from the surface irregularity at the termination point.

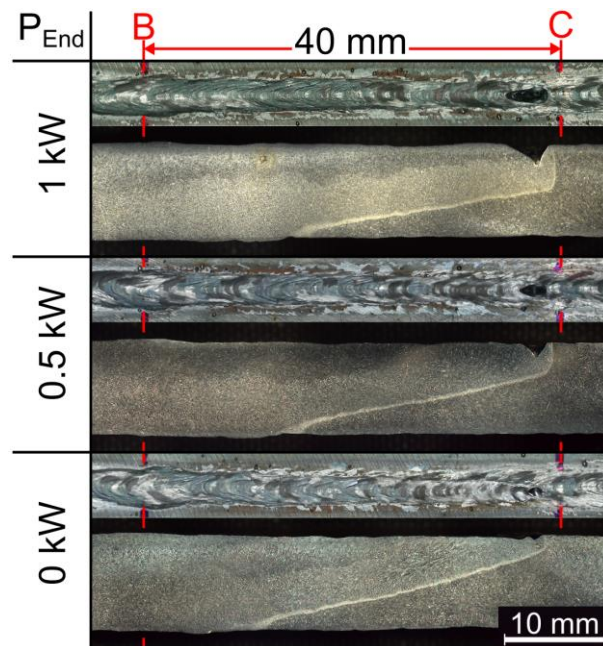


Figure 6-6: Weld top surface and longitudinal macrographs of weld start/stop region using laser power ramp-down termination regime over 40 mm

6.3.1.3 Laser defocusing termination regime

Figure 6-7 shows the top surface and x-ray images of the weld start/stop region of each weld sample. The x-ray images show no internal defects at point B. The top surface of the weld samples shows that the width of the second weld seam increases with increasing end laser spot diameter as the laser defocuses from point B to point C. Surface ripples are also observed after a certain distance of laser defocusing prior to laser termination when defocusing to an end spot diameter of 3 mm and above. Two different severity of porosity are present at different areas of the weld overlap depending on the end laser spot diameter.

Random pores can be seen throughout the weld overlap like in the laser power ramp-down termination regime. However, severe porosity, in the form of porosity clusters, appears below the surface ripples. The surface ripples and geometry of the porosity clusters indicate that melt pool instability could be the source of these defects.

At point C, weld craters or cavities are still present when laser defocusing to an $\varnothing_{\text{End}} = 2.4$ mm and below. When the laser is defocused to an $\varnothing_{\text{End}} = 3$ mm or above, there are no weld craters or cavities present. However, the formation of porosity clusters prior to point C occurs as previously mentioned.

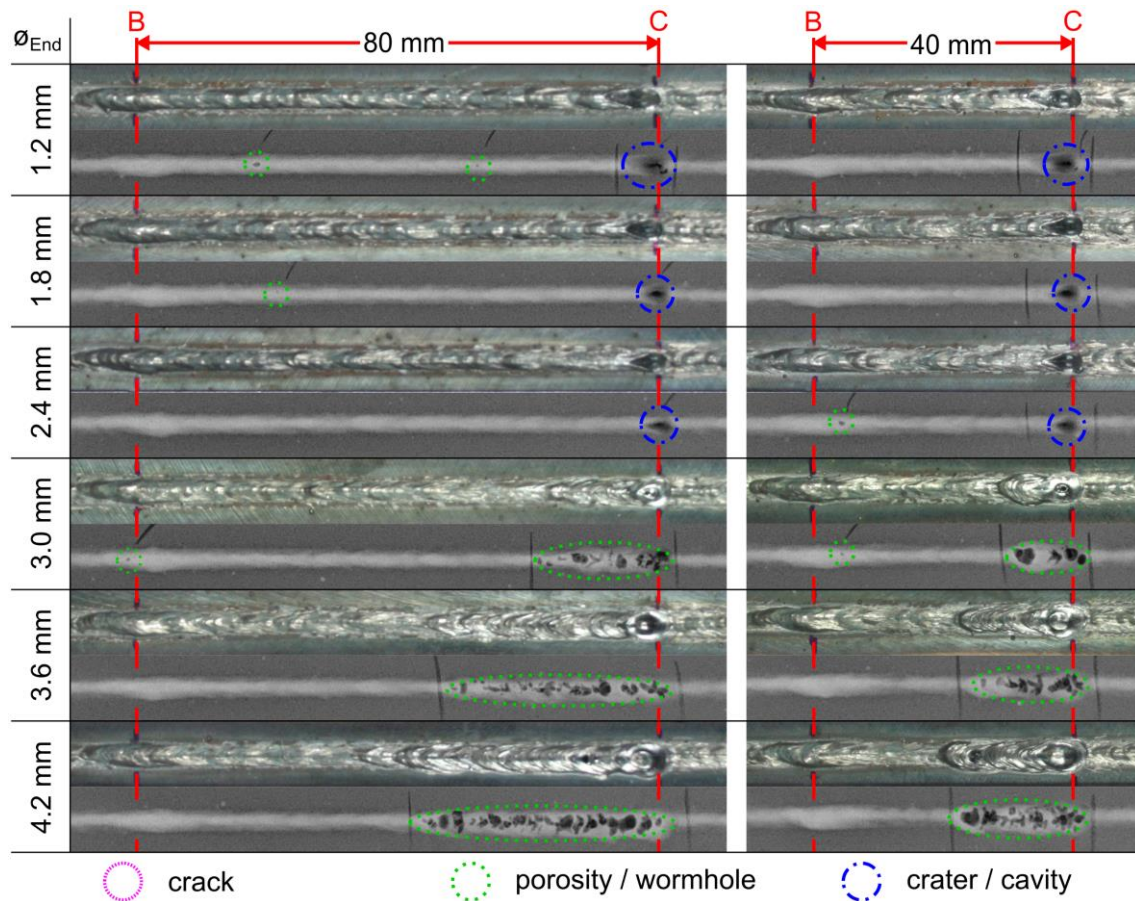


Figure 6-7: Weld top surface and x-ray image of weld start/stop region using laser defocusing termination regime

Longitudinal macrographs of the 40 mm weld start/stop region samples are shown in Figure 6-8. The weld cavities and porosity clusters can now be more closely observed. When laser defocusing to a $\varnothing_{\text{End}} = 1.2$ mm, there is still full penetration at point C and weld cavities and craters can be observed on both the top and root surface. A crack is also visible at between the top and root craters. The overall size of the weld cavities at point C decreases with increasing $\varnothing_{\text{End}}$. There are no defects, such as root sagging, when full penetration ceases and the change of penetration depth follows a parabolic trend until it stabilises at a certain penetration depth, corresponding with the change in laser power density during laser defocusing shown in Figure 6-2.

The porosity cluster formation that was previously highlighted only occurs when the penetration depth begins to stabilise as can be seen from the weld profile. The location where the porosity clusters and surface ripples began to form were correlated with the laser spot diameter and it was found that they only form when the spot diameter reached a value of 2.4 mm and above. The power density and interaction time at this point in the laser defocus is approximately 0.84 kW/mm² and 300 ms, respectively.

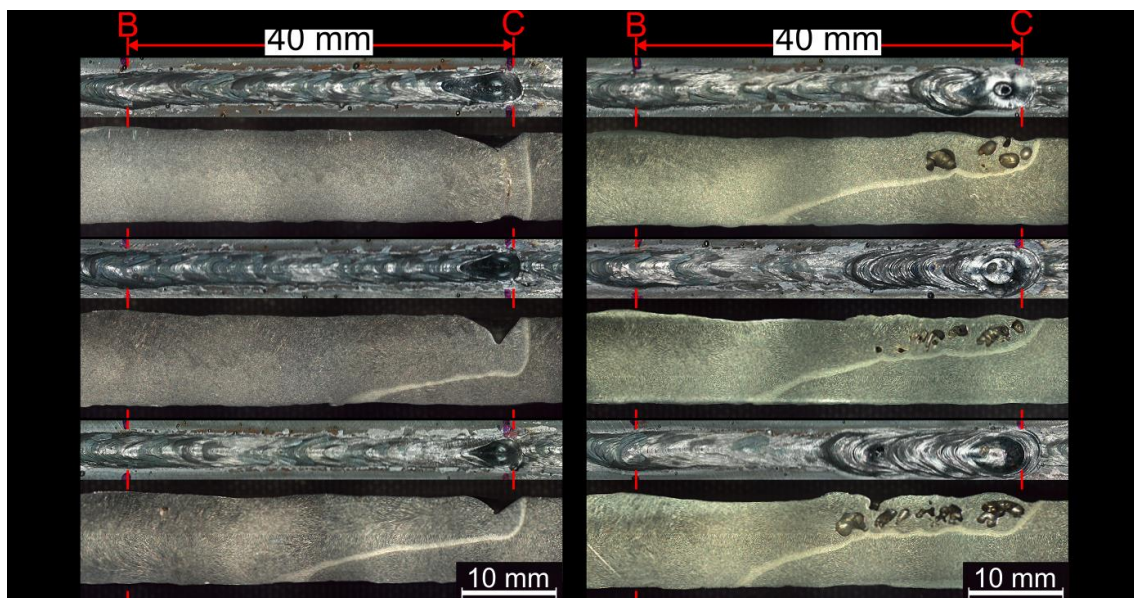


Figure 6-8: Weld top surface and longitudinal macrographs of weld start/stop region using laser defocusing termination regime over 40 mm

Figure 6-9 shows repeated weld samples of laser defocusing to an end spot diameter of 3 mm over a 40 mm weld start/stop overlap region with and without shielding gas applied. The surface ripples and porosity cluster formation decrease when shielding gas is added, however, a large pore remains at the laser termination point C. The addition of shielding gas is beneficial for maintaining melt pool stability during laser defocusing.

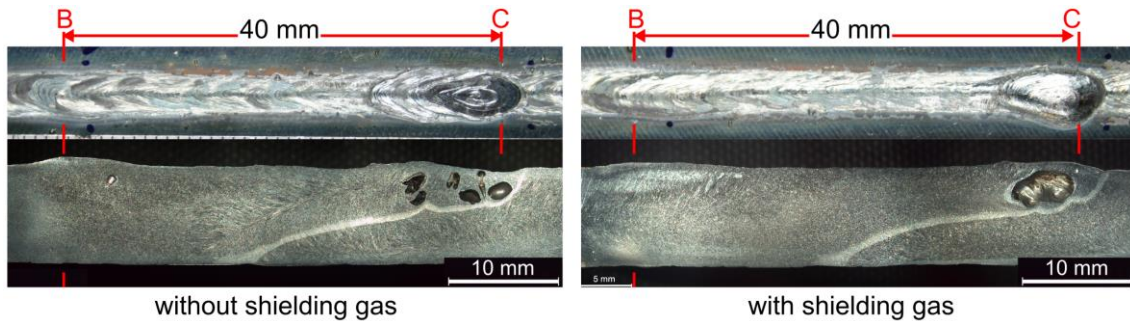


Figure 6-9: Weld top surface and longitudinal macrograph of weld start/stop region using laser defocusing termination regime to $\varnothing_{\text{End}} = 3 \text{ mm}$ over 40 mm

6.3.1.4 Weld crater geometry

The weld crater length and width at the termination point C from each weld sample were measured from Figure 6-5 and Figure 6-7. These measurements were then correlated with the calculated laser power density and interaction time, as shown in Figure 6-10.

A clear difference is observed when comparing the weld crater length and width of each termination regime. A linear correlation between laser power density and the weld length and width, independent of interaction time, was observed during the laser power ramp-down termination regime. As P_{End} decreases, the size of the weld crater also decreases. Whereas, for the laser defocusing termination regime, only the weld crater length decreases linearly, whilst the weld crater width remains constant with reducing power density and increasing interaction time. However, when the power density reduces below 84 kW/mm^2 and the interaction time increases above 300 ms (defocusing above a $\varnothing_{\text{End}} = 2.4 \text{ mm}$), there is a drastic change in both the weld crater length and width.

The rate of laser power ramp-down, which varies depending on the weld overlap distance, does not appear to affect the weld crater length or width. However, there is a variation in the weld crater length and width with the rate of laser defocusing applied, especially when defocusing above $\emptyset_{\text{End}} = 2.4$ mm.

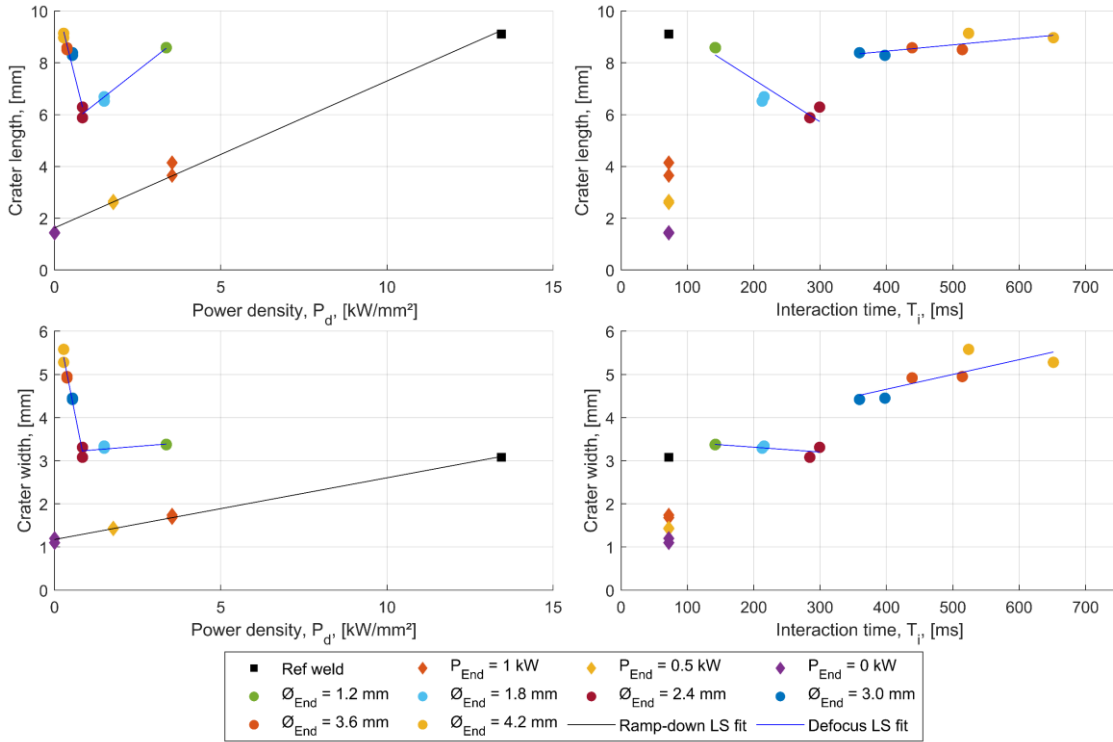


Figure 6-10: Weld crater length (top) and width (bottom) variation with laser power density (left) and interaction time (right) for each weld sample

Figure 6-11 shows the weld crater or cavity profiles taken from the longitudinal macrographs of the 40 mm weld start/stop regions using the procedure described in section 6.2.2.3. The profiles of the weld samples when laser defocusing above a $\emptyset_{\text{End}} = 2.4$ mm were not included due to the occurrence of the porosity clusters.

The overall size and depth of the weld crater at the termination point decreases with decreasing P_{End} in the laser power ramp-down termination regime. A similar relationship is also observed with the laser defocusing termination regime. However, when $\emptyset_{\text{End}} = 1.2$ mm a shallow weld crater is observed at the top surface. The weld crater profile of $P_{\text{End}} = 1$ kW and $\emptyset_{\text{End}} = 1.2$ mm shows a similar crater depth, which correlates with the similar calculated laser power density of 3.16 kW/mm² and 3.15 kW/mm², respectively.

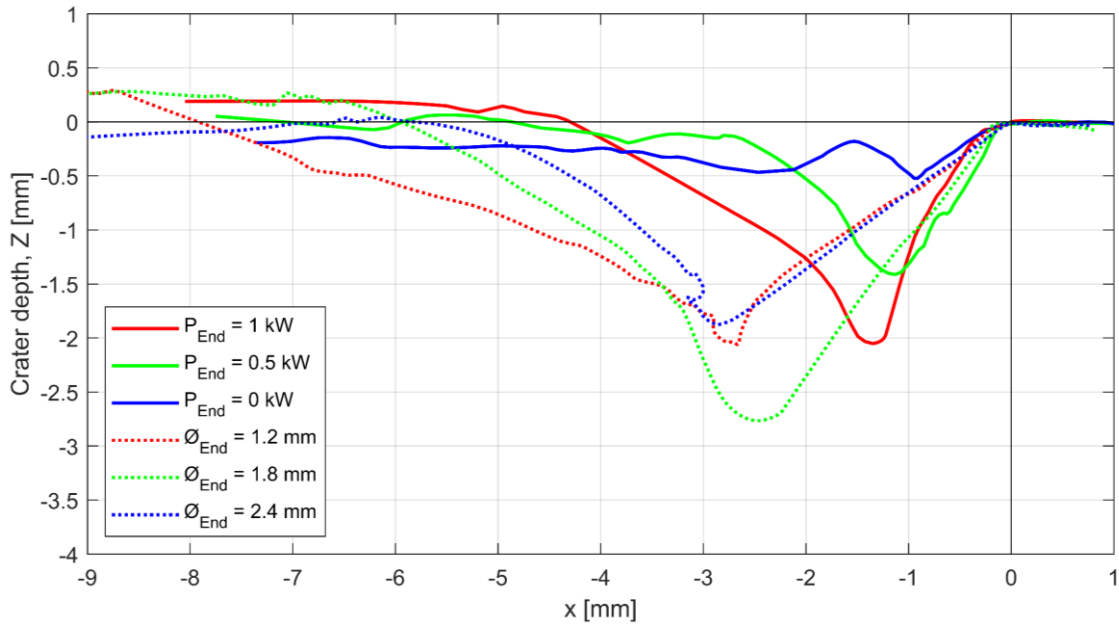


Figure 6-11: Weld crater/cavity profiles of the longitudinal macrographs of 40 mm weld overlap samples

6.3.1.5 Tensile test with DIC

The methodology, set-up and procedure for the tensile test using DIC is described in section 3.4.2. A total of 16 tensile specimens from different locations of the weld samples, were tested.

All tensile specimens fractured after necking at the base metal regardless of the termination regime or location of the specimens. Some tensile specimens containing porosity defects in the weld metal region (point C of laser defocusing weld samples) also fractured in the base metal, as shown in Figure 6-12 .

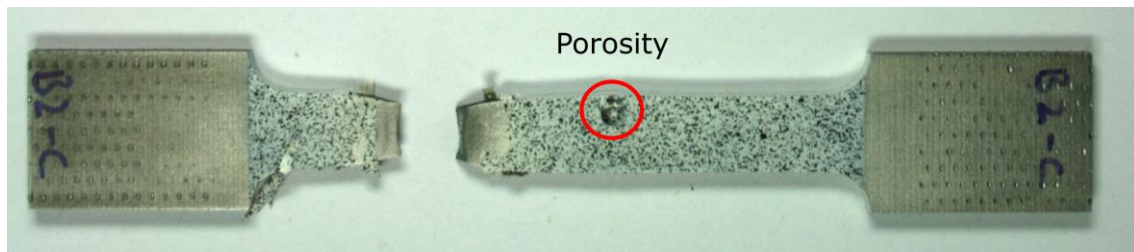


Figure 6-12: Tensile specimen of point C of the laser defocus weld sample showing porosity defect

The global stress-strain of each tensile specimen from the different regions of the weld samples are shown in Figure 6-13. Some tensile specimens have significantly lower elongation due to problems with the paint flaking off as the specimens began necking, as explained in section 3.4.2.2. Therefore, the iterations of the tensile test following the loss of paint were not included regarding elongation.

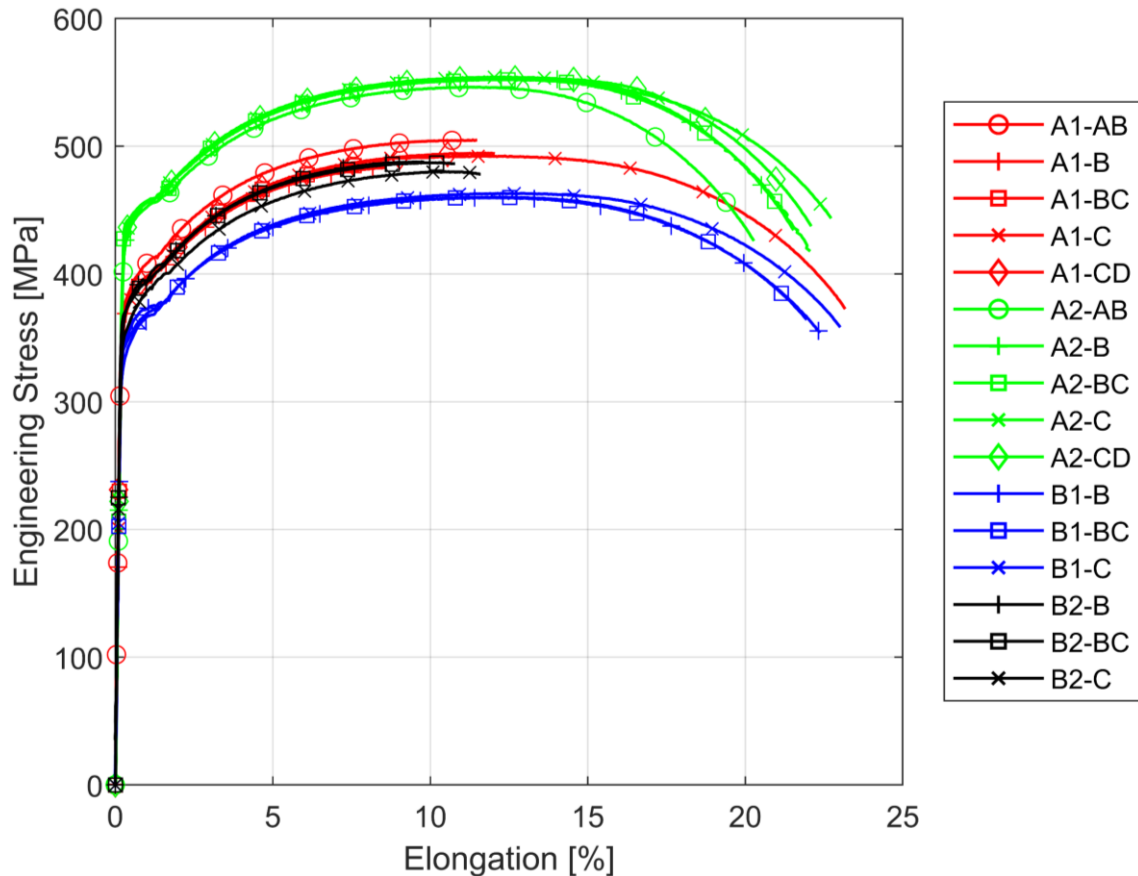


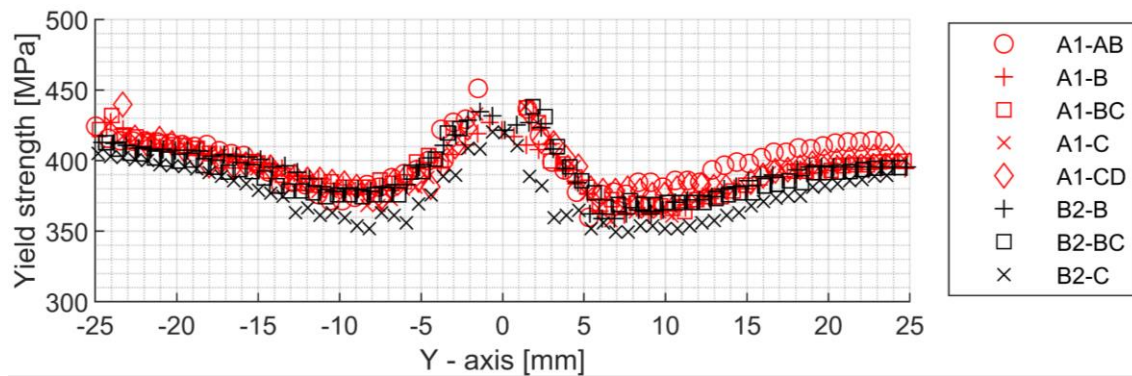
Figure 6-13: Global stress-strain of laser power ramp down (A1 and B1) and laser defocusing (A2 and B2) tensile specimens

There is a noticeable difference in tensile properties between the weld samples rather than between the different sections of the weld samples. The mean and standard deviation of the tensile properties (where measurable) has been calculated for each weld sample and is given in Table 6-3. Weld samples A1 and B2 are similar, whereas A2 and B1 weld samples show a difference in mechanical properties. Therefore, there is no significant difference with the termination regime applied but rather a difference in behaviour due to the plates.

Table 6-3: Tensile properties of each weld sample

Weld sample	YS [MPa]	UTS [MPa]	Elongation [%]
<i>Laser power ramp-down</i>			
A1	375 ± 5	493 ± 8	-
B1	344 ± 8	461 ± 2	22 ± 0.6
<i>Laser defocusing</i>			
A2	436 ± 5	552 ± 4	22 ± 0.7
B2	367 ± 11	485 ± 5	-

The local yield strength across each specimen from the two similar weld samples (A1 and B2) is shown in Figure 6-14. The results indicate that there is little impact of the laser termination regime and weld start/stop overlap region on the mechanical properties as previously stated.

**Figure 6-14: Local yield strength across tensile specimen of laser power ramp down (A1) and laser defocusing (B2)**

The DIC results and yield strength map of the termination point C from each laser termination regime is shown in Figure 6-15. The results are similar for both termination regimes regarding local yield strength distribution across the weld region. The effect of the pore in the laser defocusing specimen B2-C can be seen from the strain and yield strength contour maps. The presence of the pore in the weld metal led to local stress concentrations due to the non-uniform application of stress at that point. Despite the pore defect, the tensile specimen still fractured at the base material as the strength of fusion zone of the laser weld has much higher strength than the parent metal.

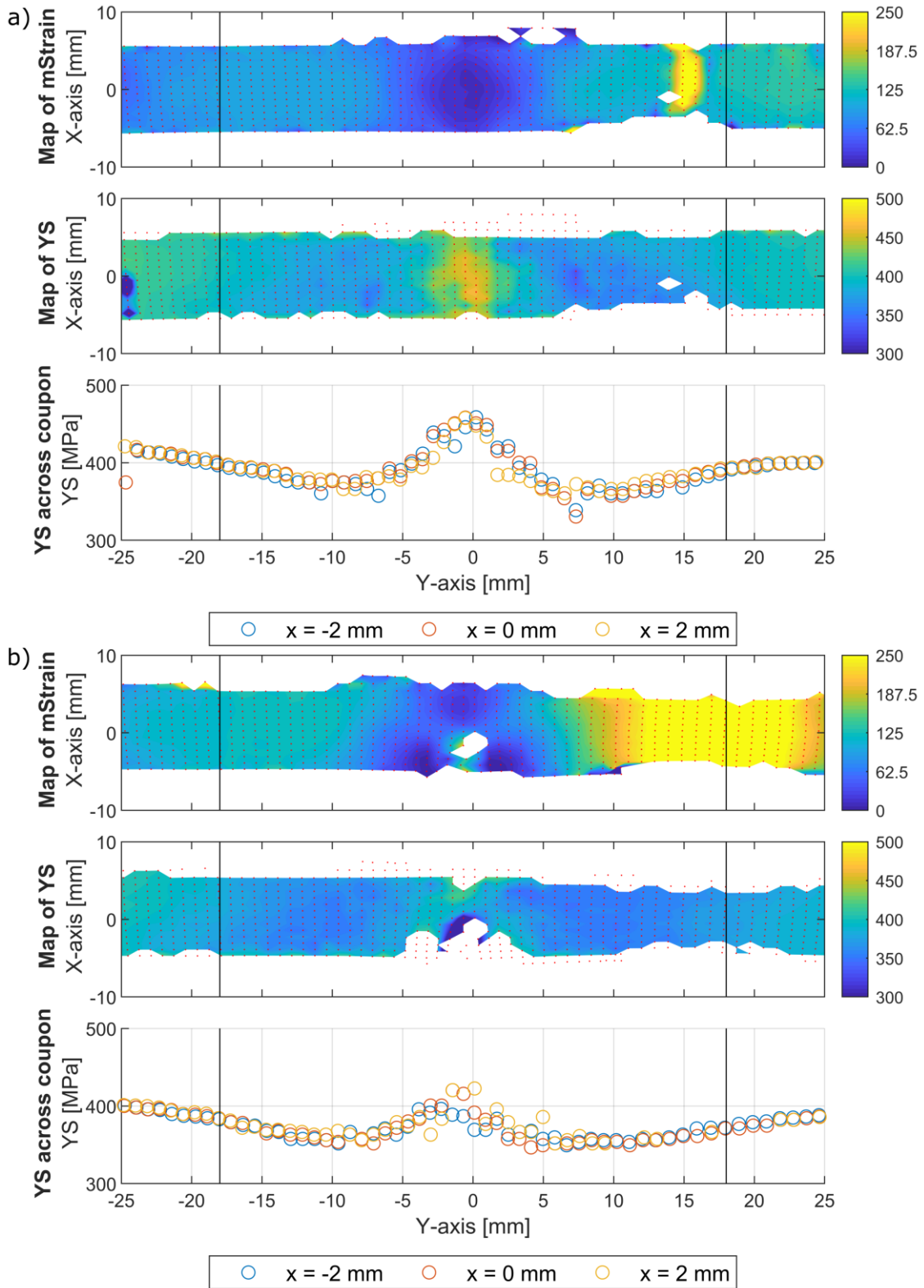


Figure 6-15: Contour maps of strain and yield strength, and the local yield strength across tensile specimens, a) Laser power ramp-down (A1-C) and b) Laser defocusing (B2-C)

Fractography

Figure 6-16 shows SEM images of the rupture surfaces from the specific tensile specimens of weld samples A1 (laser power ramp-down to 0 kW) and B2 (laser defocusing to an end laser spot diameter of 3 mm).

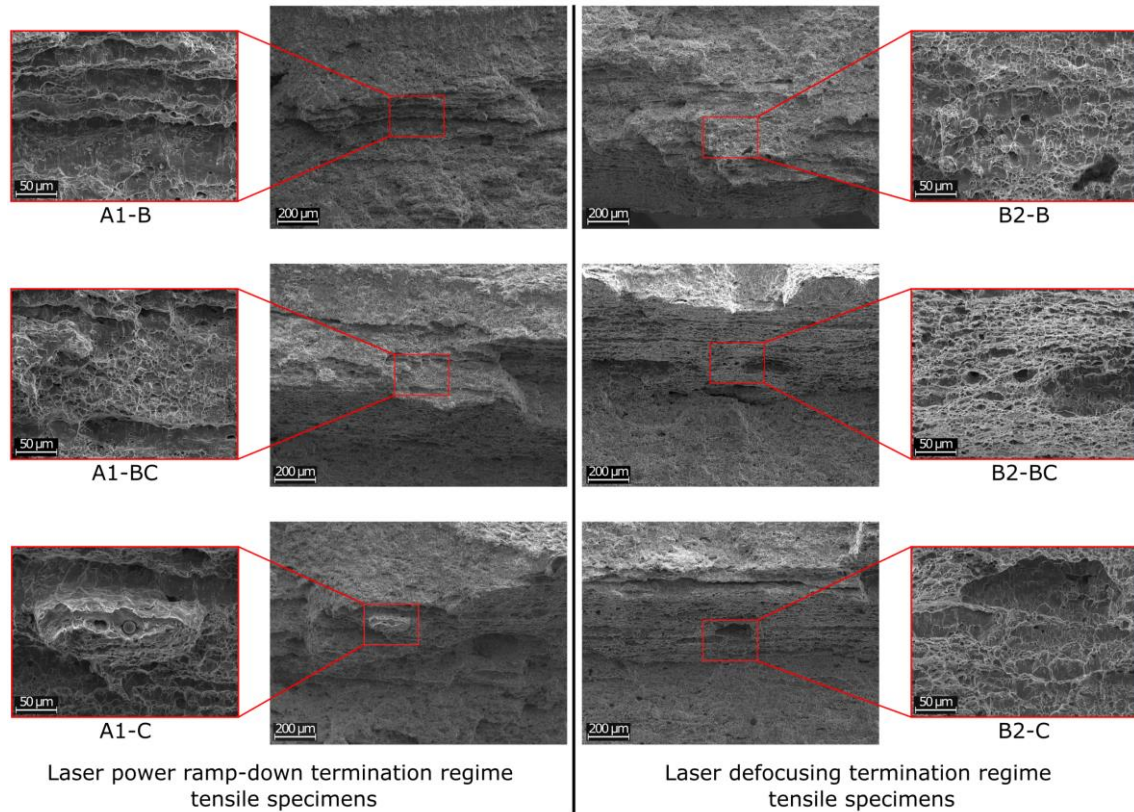


Figure 6-16: Rupture surfaces of specimens from each weld sample section

The rupture surface of each specimen is of the base material, away from the weld zone. Layers due to the plate manufacturing process can be observed from the SEM images. All rupture surfaces of the tensile specimens showed ductile behaviour. A spherical inclusion can also be observed in specimen A1-C.

6.3.2 Experiment 2: effect of varying plate composition on different laser termination regimes at the weld overlap start/stop region

6.3.2.1 Reference weld – abrupt laser termination

Reference welds where the laser terminates abruptly were conducted on each different steel grade plate batch using both sets of welding parameters. Figure 6-17 shows the top and root surface of the weld start/stop overlap region for these reference welds. Whilst full penetration was achieved in plate L, a loss of penetration was observed in plates M and N for the same welding parameters. Therefore, an increase in laser power of 37 % at the same weld speed, was required to attain full penetration with good weld surface quality without defects, such as undercuts and root sagging. A significant amount of slag formation is visible on the weld surface of plates M and N, whereas plate L shows no visible slag formation. The x-ray images showed no presence of porosity in the reference welds of plates M and N.

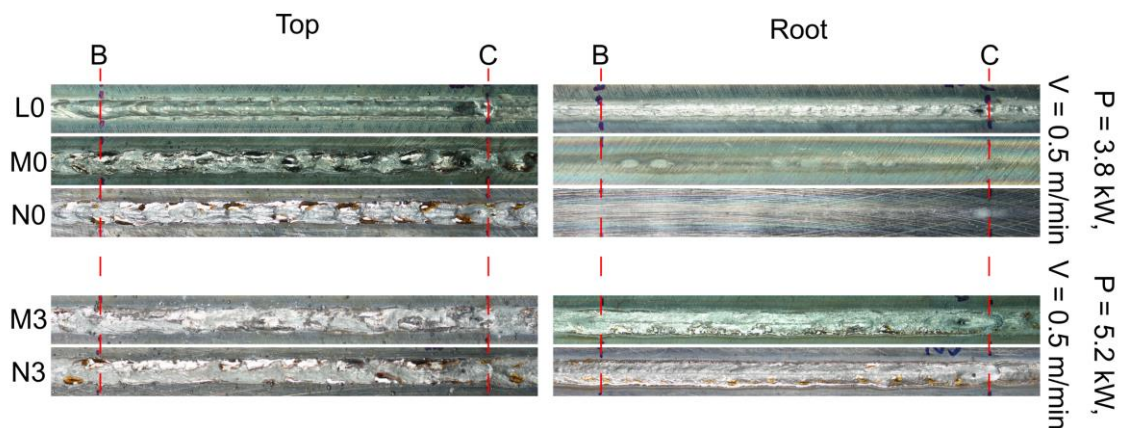


Figure 6-17: Top and root surface of the 80 mm weld start/stop region of the reference welds conducted on different plate batches

Figure 6-18 shows the transverse macrographs of the reference welds taken from the weld seam section between point A and B. The lower penetration depth and different weld profile in plates M and N when compared with plate L can be seen. Once full penetration is achieved in plates M and N, the weld profile also varies. The top and root of the weld is significantly wider than the centre, having the appearance of a goblet or wine glass. The top of the weld of plate N is slightly wider than in plate M.

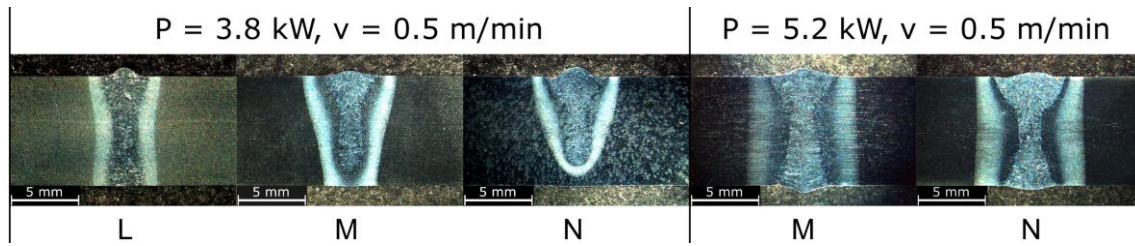


Figure 6-18: Transverse macrographs of weld seam section $\overline{AB}$ from each reference welds performed on different plate batches

6.3.2.2 Laser power ramp-down termination regime

Figure 6-19 shows the weld surface, x-ray image and longitudinal macrograph of the weld overlap start/stop region from each weld sample on plates M and N. No string of porosity was observed near the termination point of weld cases M2 and N2, unlike with the previous case in plate L. Unfortunately, in weld case M2, a surface crater formed during the laser power ramp-down termination regime. When full penetration welds were achieved on plates M and N using the second set of weld parameters, there were no internal defects at the weld start/stop region or the termination point C, as weld case M5 and N5 shows. However, there is a small amount of root sagging and weld reinforcement at the root of point B.

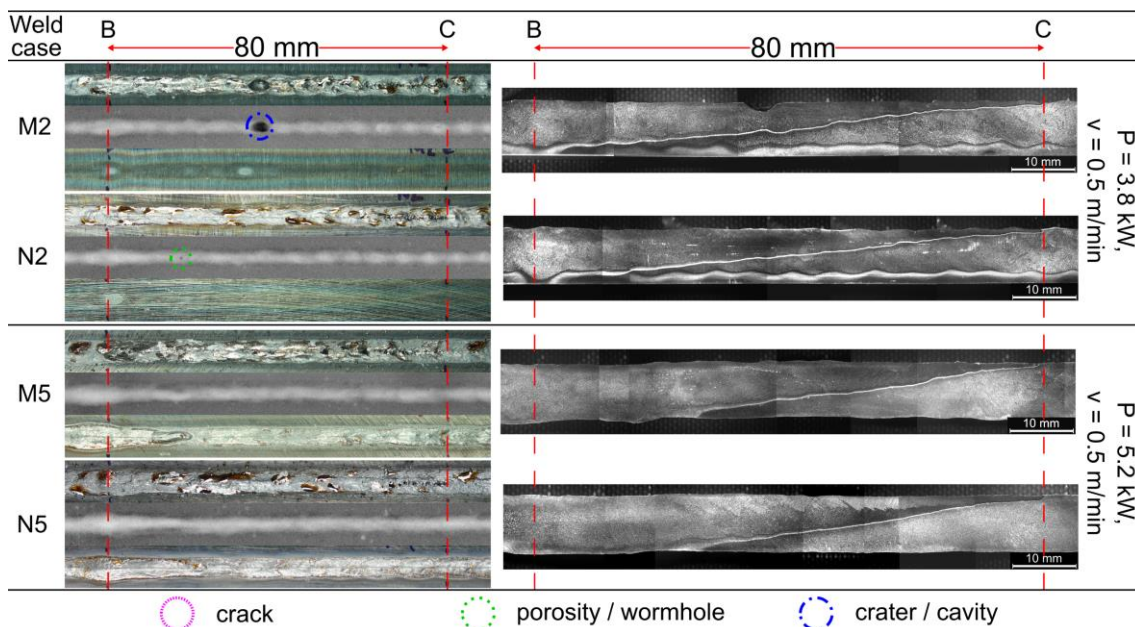


Figure 6-19: Weld top surface, x-ray image, weld root surface and longitudinal macrograph of each weld overlap start/stop region using laser power ramp-down termination regime

6.3.2.3 Laser defocusing termination regime

Figure 6-20 shows both weld surface, x-ray image and longitudinal macrograph of the 80 mm weld start/stop region from each weld sample and plate. The repeated weld case, L1, is identical to the laser defocus regime to $\varnothing_{\text{End}} = 4.2$ mm from experiment 1 shown in Figure 6-7. The severity of the porosity clusters is now emphasised by the longitudinal macrograph. However, when using the same laser defocusing parameters on plates M and N (weld case M1 and N1), there is no porosity cluster formation or surface ripple behaviour as was seen in weld case L1. When full penetration was achieved in plates M and N (weld case M4 and N4), there is no porosity cluster formation either. However, small amounts of porosity present at the edge of the weld beads near the termination point C in plates M and N were observed. No root defects were visible when full penetration ceases in weld case M4 or N4. The point where full penetration ceases also differs slightly from weld case M4 to N4.

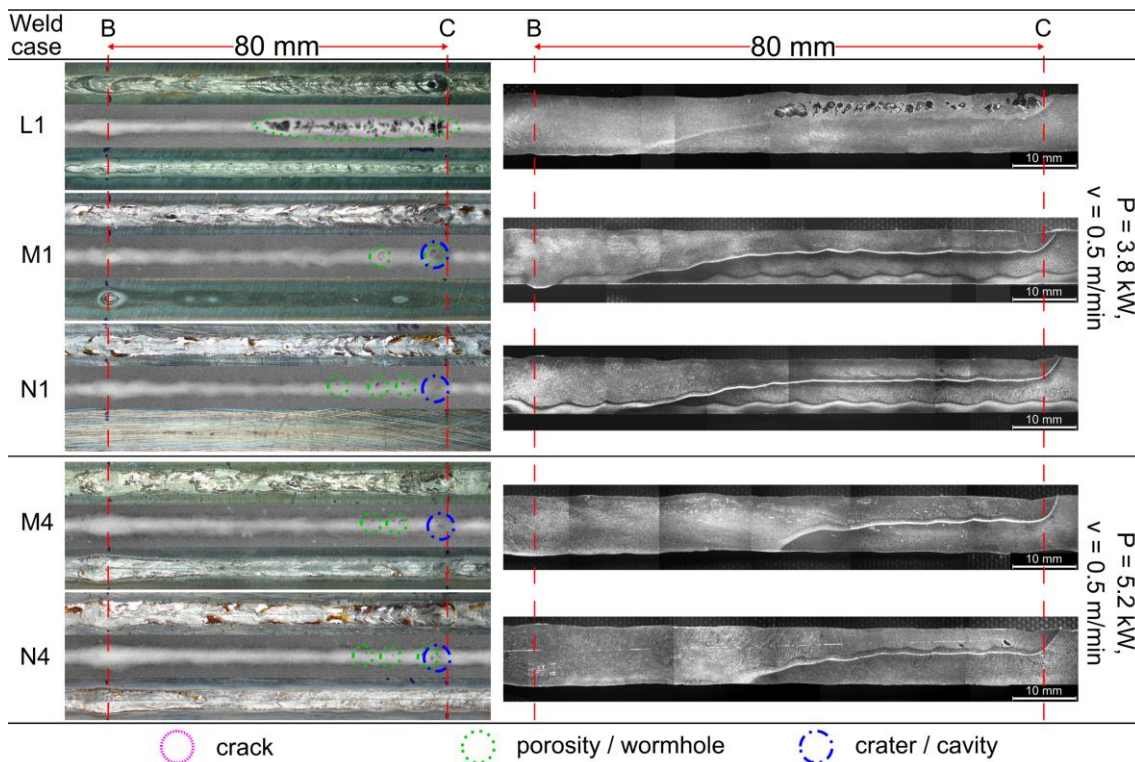


Figure 6-20: Weld top surface, x-ray image, weld root surface and longitudinal macrograph of each weld overlap start/stop region using laser defocusing termination regime

Analysis of the videos from each laser defocus weld sample gives insight into the different melt pool behaviour that occurs between the different plate batches. Figure 6-21 shows compiled video frames at specific time intervals of the weld overlap start/stop region for each weld case. Laser defocusing begins at 0 s and the melt pool and weld plume has been highlighted. The video of weld case L1 showed that the melt pool became longer and appeared more turbulent at 2.0 s when compared with weld case M1 and N1. At 3.0 s, a significant difference between the melt pool and plume of each weld case can be observed. The melt pool surface begins to fluctuate, and surface ripples form upon solidification in weld case L1, whereas the melt pool remains stable for weld case M1 and N1. The weld plume also becomes more dispersed in weld cases M1 and N1. In weld case L1, the weld plume is still tall and constricted. At 5.1 s into the video (1 s before laser termination), the weld plume for weld case L1 is still tall, and the melt pool still turbulent with lots of movement. On the other hand, videos of weld cases M1 and N1 showed that the melt pool was more stable throughout the laser defocusing termination regime and weld overlap.

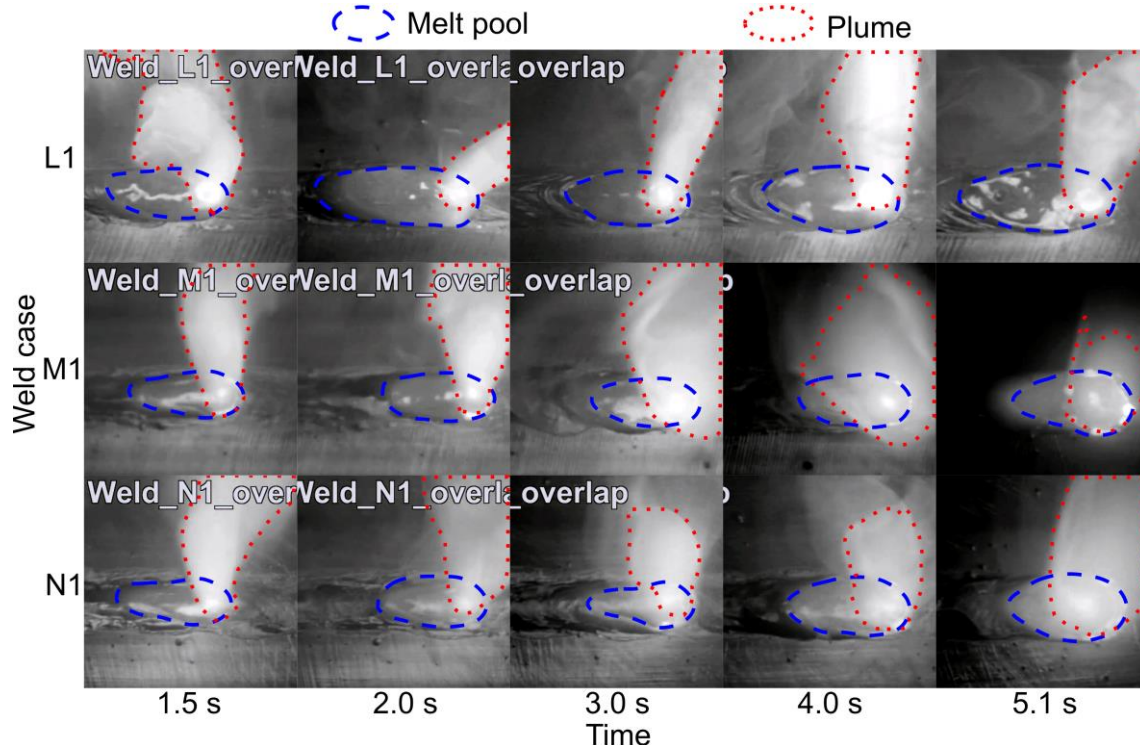


Figure 6-21: Video frame close-up at different time intervals during laser defocusing termination regime with melt pool and weld plume highlighted

6.4 Discussion

6.4.1 Effect of termination regime on weld start/stop region

6.4.1.1 Effect of weld overlap on crack formation at laser initiation point

The formation of cracks at point A can be attributed to the shrinkage stresses due to the change in weld bead shape and penetration, as shown in Figure 6-22. At point B, the laser initiation point is re-melted by the second weld seam, redistributing the molten metal, and eliminating any cracks that may have formed. The weld profile of the second weld seam is more uniform as a result, which leads to less shrinkage stresses and prevents the formation of cracks during solidification. Both termination regimes used in this study were applied gradually and showed no issues when overlapping the initiation point of the first weld seam.

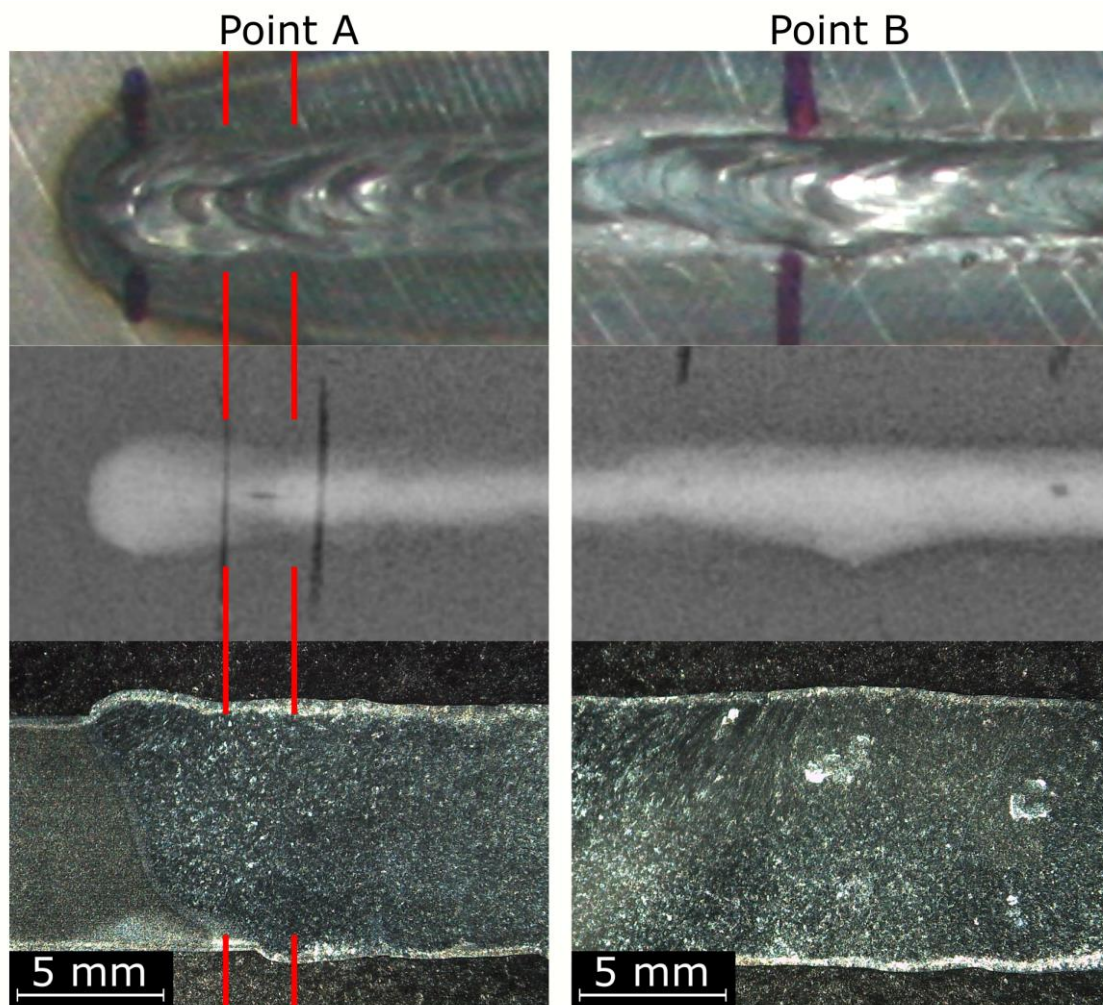


Figure 6-22: Point A and B images from Figure 6-4 highlighting solidification crack

6.4.1.2 Effect on weld profile, weld depth and mechanical properties

The change in weld profile and penetration depth for both termination regimes correlates well with the change in laser power density profile, as shown in Figure 6-2. A clear dependence of penetration depth on laser power density despite the increasing laser spot diameter during laser defocusing was observed. However, a stabilisation in penetration depth was observed during laser defocusing, which occurred when the laser power density reached a value of 84 kW/mm². The stabilisation in penetration depth despite continued decrease of laser power density shows that a transition occurs, and a different mechanism is governing the penetration depth and melt pool dynamics. Note that during laser defocusing, the laser spot diameter and interaction time continuously increases. Therefore, the stabilisation in penetration depth is related to the increase in interaction time beyond a calculated value of 300 ms. The change in mechanism governing the penetration depth indicates a change in laser welding regime, from laser keyhole mode welding towards conduction mode welding.

The mechanical properties across the different locations of the tensile specimens of each weld sample showed little variation unless there was the presence of defects. The results highlighted a bigger difference in mechanical properties between plate batches rather than due to welding or the different termination regimes applied at the weld overlap start/stop region.

6.4.1.3 Effect on weld crater formation

Figure 6-10 and Figure 6-11 showed how the weld crater geometry varied between the two termination regimes when applied over a 40 mm distance. The formation of weld craters during laser termination is a result of the rapid solidification of the melt pool. Therefore, it is not surprising that there is a correlation between the weld crater geometry with laser power density as the power density determines the amount of material melted. The distance (i.e., rate) of laser power ramp-down or laser defocusing applied also affects weld crater formation as there was no weld crater when laser power ramp-down to 0 kW was applied over 80 mm. Several other factors, such as the material and chemical composition also affect laser termination and the formation of weld craters.

6.4.2 Impact of plate composition on laser welding and termination

Two out of the three plate batches showed a significant variation in chemical composition and behaved differently when undergoing laser weld processing. Plate L had significantly less carbon, manganese, and silicon content when compared with plates M and N, as was shown in Table 6-1. Both manganese and silicon are key deoxidisers used in steelmaking and will affect the amount of dissolved oxygen in the molten material. The melt pool flow behaviour is, therefore, likely to be affected as the incorporation of oxygen from the atmosphere when welding is likely to be larger in plate L if no shielding gas is used due to the lower concentration of deoxidisers.

6.4.2.1 Effect on weld penetration during steady-state laser welding

Plate L, which had lower concentrations of deoxidisers, experienced a higher penetration depth when compared to plate M and N. The lower concentration of deoxidisers can lead to the potential of oxygen intake and reaction from the atmosphere. Oxygen concentration above a certain percentage can lead to a positive temperature gradient of surface tension and increases the fluidity of the melt pool. The changes in Marangoni flow and surface tension effects can lead to an increase in penetration depth. However, some authors considered these effects to be negligible in laser keyhole welding [103,104]. These experiments used much lower power and welding speeds as compared to the experiments carried out by Ribic et al. and Zhao et al. Hence Marangoni flow and surface tension would affect the flow behaviour and penetration and cannot be neglected. The possibility of carbon monoxide formation owing to the higher amounts of dissolved oxygen in the melt pool leading to increased pressure within the keyhole and therefore, increased penetration is also valid. On the other hand, the higher concentrations of manganese and silicon in plates M and N promotes slag formation in the form of Manganese Oxide and Silicon Dioxide. The formed slag protects the melt pool from oxygen ingress which results in the opposite behaviour for both Marangoni flow and, carbon monoxide formation. Manganese and silicon also reduce the viscosity of the molten metal, which can disturb the laser keyhole and would contribute to the lower penetration depth as well.

6.4.2.2 Formation of porosity cluster defects during laser defocusing

The porosity clusters and surface ripples shown in Figure 6-20 only formed when laser defocusing on plate L and was not present in plate M or N despite identical welding parameters. The increase in melt pool size during laser defocusing can lead to melt pool instability due to the increased melt flow and interaction with oxygen from the atmosphere. The surface ripples and porosity cluster are an indication of melt pool instability and correlates with the transition in mechanisms that govern the penetration and melt pool dynamics as was discussed in section 6.4.1.2. When laser defocusing beyond a certain distance, the penetration depth begins to stabilise, and the formation of the melt pool is driven by conduction rather than vaporisation. The increase in interaction time from this point forwards has a significant effect on the thermal energy within the melt pool and would be capable of increasing the reaction of carbon with the dissolved oxygen to form CO, leading to the formation of porosity.

It is evident, that there is a significant effect of deoxidisers on the formation of the porosity clusters during laser defocusing as plates M and N, which had higher concentrations of deoxidisers, did not exhibit any porosity cluster formation. The effect of the plate chemical composition on the melt pool was shown by the video frames in Figure 6-21. A closer analysis of the video frame at 5.1s, for plate L, shown in Figure 6-23, shows the instability of the melt pool and captures the moment a gas bubble disturbs the melt pool surface. It appears that the formed gases within the melt pool are trying to escape, and in doing so, disturbing the surface tension, and causing the melt pool to collapse when they break through the liquid surface. The escaping gases, coupled with the collapse of the melt pool, can promote further gas entrapment and porosity formation.

To avoid the formation of porosity during steady-state laser welding, and especially during the application of laser defocusing termination regime, of mild steels it is recommended to use materials with a higher proportion of deoxidisers. Steels with more deoxidisers are more tolerant to changes in melt pool dynamics and flow during the application of either laser termination regime studied within this chapter. Therefore, the choice of laser termination regime also depends on the material chemical composition.

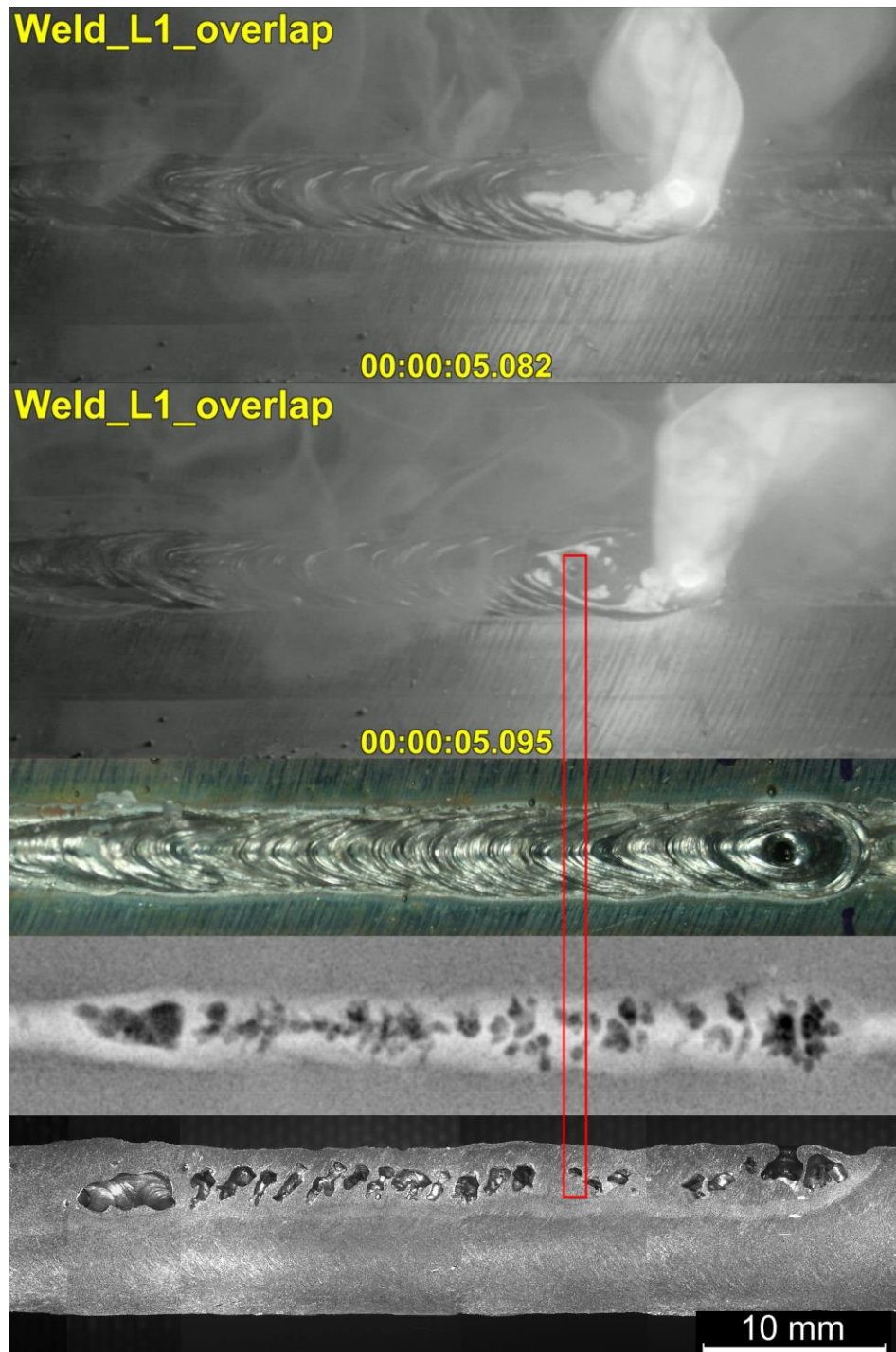


Figure 6-23: Video frame comparison with plate top surface, x-ray image and macrograph, highlighting melt pool instability and porosity formation

6.5 Conclusions

The investigation of the effects of two different laser termination regimes, laser power ramp-down and laser defocusing, on the weld start/stop region, on different chemical composition mild steel plates were studied in this chapter.

- Successful prevention of defects, such as porosity, cavities, cracks, and craters, associated with the abrupt termination of the laser source and keyhole collapse is possible by applying either termination regime.
- Differences in the mechanical properties at the weld overlap start/stop region varied more with the plate composition rather than the termination regime applied.
- Laser power ramp-down is easier to apply but can result in an abrupt change to the applied heat and weld profile when leaving full penetration. Whereas laser defocusing maintains the heat applied and results in a smoother keyhole closure and weld profile transition, but if done incorrectly can induce melt pool instability and porosity.
- The different amounts of deoxidising elements in low alloy carbon steels, such as manganese and silicon, affect oxygen ingress and slag formation in the melt pool during laser processing. These phenomena can affect the keyhole and melt pool dynamics, such as vaporisation recoil pressure, Marangoni flow and surface tension effects, resulting in melt pool instability, gas entrapment, and porosity formation, and differences in weld penetration depth. The severity of these phenomena on defect formation is increased by the larger melt pool during laser defocusing as compared with laser power ramp-down termination regimes, leading to the formation of porosity clusters.

- Application of either laser termination regimes on mild steel with higher concentrations of deoxidisers, such as manganese and silicon, can lead to successful, defect-free circumferential weld overlap start/stops.
- Variation in the chemical composition of structural steel grades needs to be more tightly controlled for laser welding applications as they have a significant effect on weld melt pool behaviour and defect formation. The presence of deoxidising elements is essential to prevent gas formation and thereby, porosity.

Chapter 7

Hybrid laser-arc welding: Weld stability and effect of weld termination at weld overlap start/stop region

7.1 Introduction

In previous chapters, the formation of laser keyhole termination defects was studied, and it was found that they were mainly due to the collapse of the keyhole and rapid solidification of the melt pool when the laser was terminated abruptly. To mitigate these defects, different laser termination regimes, such as laser power ramp-down and laser defocusing were studied. Both laser termination regimes gradually reduced the keyhole depth prior to laser termination, greatly reducing the occurrence of keyhole collapse. In this chapter, the effect of the arc in steady-state hybrid laser-arc welding (HL-AW) and during HL-AW termination was studied.

There can be several challenges in autogenous laser welding of thick section structural steels, such as insufficient weld quality, high aspect ratio and narrow welds, high solidification rates and sensitive joint fit-up tolerance, to name a few. These challenges can be overcome by adopting a hybrid laser welding process, such as HL-AW. HL-AW offers higher quality welds with deeper penetration when compared with autogenous laser welding. The addition of filler wire via the arc source allows for the weld morphology and profile to be controlled. Therefore, weld metal strength equal or higher than the parent metal can be achieved. Typically, joints formed by the melting of parent alloys alone is normally insufficient for thermo-mechanical processing manufactured structural steels.

These benefits make the process highly applicable for the welding of thick sections and can compensate for any inaccuracies during weld preparation. Although filler wire can be added during laser welding alone, it is difficult and inefficient to melt the filler wire and maintain deep penetration. Unfortunately, there is still limited applications of HL-AW for circumferential welding applications. Majority of termination defects in deep penetration welds are related to keyhole instability, which is typically associated with the laser. However, understanding of both laser and arc stability and termination phenomena in hybrid welding is necessary. To enable the use of HL-AW for circumferential welding applications, the effect of combined process parameters during steady-state, weld initiation and weld termination at the weld overlap start/stop region was investigated.

Gas metal arc welding (GMAW) can be broken down into two main metal transfer modes or types, short circuiting, and spray transfer. Only short circuiting and a variant of spray transfer, pulsed spray, is capable of welding in all positions and are suitable for circumferential welding in hybrid configuration. Therefore, in this chapter two representative process variants of short circuiting and spray transfer were studied. The process variants studied are Cold Metal Transfer (CMT), an advanced GMAW short-circuiting metal transfer mode from Fronius, and Pulsed Metal Inert Gas (P-MIG) spray transfer mode. Both these process variants from Fronius are self-adaptive and have improved control and stability of the current by automatically adjusting both the voltage and current for a given WFS to maintain stable metal transfer at reduced heat inputs. In the case of the Fronius CMT system, when using the CMT variant, the wire retracts when short circuiting occurs which improves the droplet transfer and detachment.

In this chapter, a parametric study was conducted in HL-AW using two different GMAW process variants, CMT and P-MIG. The effect of different welding parameters on weld process stability and weld penetration depth were studied.

Further studies on the hybrid weld process termination at the weld overlap start/stop region was also performed. Different aspects of laser and arc termination procedures were incorporated and the effect of these on the weld profile and formation of weld termination defects were investigated.

7.2 Methodology

7.2.1 Experimental set-up

7.2.1.1 Hybrid laser-arc welding

The laser was coupled with a Fronius CMT advanced 4000R power source which was operated in either CMT or P-MIG process variants. The Fronius CMT power source is a self-adaptive power source which adjusts the arc parameters based on the programmed WFS to maintain a stable weld deposition. The arc source was integrated with the Fanuc robot, allowing it to be controlled using the Fanuc teach pendant. A prefabricated 3-axis torch holder with a rotational X-axis was connected to the Fanuc robot, as shown in Figure 7-1. The laser was positioned perpendicular to the workpiece with the arc torch trailing behind the laser at an angle of 35° opposite to the welding direction (i.e., arc pushing or arc trailing configuration). A triangular groove was machined into the top of the gas shroud of the arc torch to allow the laser beam to reach the weld zone. A contact tip to workpiece distance (CTWD) of 17 mm was used for all the hybrid welds with a separation distance of 2 - 2.5 mm between the laser spot and tip of the filler wire.

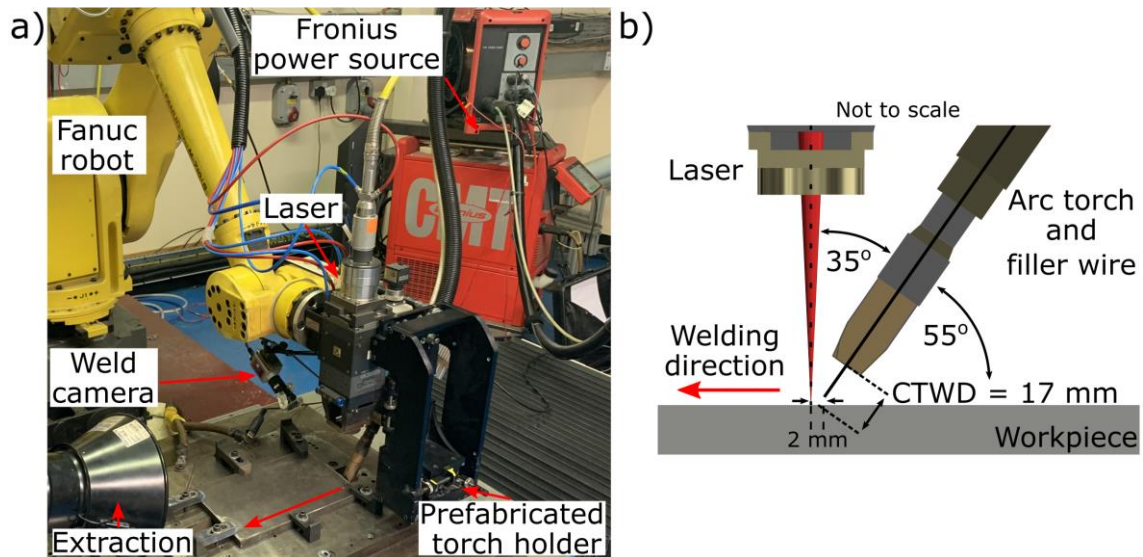


Figure 7-1: Hybrid laser-arc welding, a) experimental setup, b) schematic diagram

BOC argon heavy shield mixture containing 20% CO_2 was used as the shielding gas for the GMAW process. The shielding gas was delivered through the welding torch and the flow rate was set at 20 l/min.

SupraMIG Ultra 1 mm wire manufactured by Lincoln Electric was used as the filler wire in the HL-AW experiments. The chemical composition of the wire is shown in Table 7-1.

Table 7-1: Chemical analysis of SupraMIG Ultra filler wire

Wt. %											
C	Mn	Si	S	P	Cu	Ni	Cr	Mo	Al	Ti	Zr
0.079	1.670	0.940	0.020	0.011	0.011	0.013	0.039	0.010	0.003	0.010	0.002

As-received plates were cut to dimensions of 300 x 250 x 15 mm (length x width x thickness) and cleaned with acetone prior to welding.

A Weldmon AMV 4000 data logger was used to acquire the arc voltage and current during welding.

7.2.2 Experimental approach

7.2.2.1 Parametric study of hybrid laser-arc welding

Welds were performed using autogenous laser, CMT and P-MIG GMAW process variants, and a combination of these HL-GMAW. Firstly, autogenous laser weld trials were conducted to obtain laser powers that gave a penetration depth of approximately 7 mm at fixed welding speeds where possible and within the limits of the equipment. The obtained laser parameters from the autogenous laser trial welds were used in the HL-GMAW welds along with different wire feed speeds (WFS) for the two GMAW process variants.

The parameters for the HL-GMAW used in this parametric study are shown in Table 7-2. GMAW and HL-GMAW welds using both process variants were conducted with the arc torch in the arc pushing configuration, as shown in Figure 7-1. The maximum WFS is limited by the choice of process variant. The maximum WFS that can be applied is 9.8 m/min and 22.5 m/min for CMT and P-MIG process variants, respectively. Therefore, four different WFS values were investigated for each process variant were in this study.

Table 7-2: Welding parameters used in HL-GMAW parametric study

Parameters	Value
<i>Laser power, P, [kW]:</i>	4, 5, 6.7, 8
<i>Welding speed, v, [m/min]:</i>	0.5, 1, 2, 4
<i>Laser energy input, Q_{Laser}, [kJ/mm]</i>	133, 83, 55.8, 33.3
<i>CMT WFS, WFS_{CMT}, [m/min]:</i>	2, 4, 6, 8
<i>P-MIG WFS, WFS_{P-MIG}, [m/min]:</i>	5, 10, 15, 20

7.2.2.2 Hybrid laser-arc weld overlap start/stop termination study

In the study of hybrid weld termination at the weld overlap start/stop region, a laser power of 5 kW and a welding speed of 1 m/min was used for all welds. WFS of 6 and 5 m/min for CMT and P-MIG, respectively, was used. These parameters provided similar penetration depths and were selected from the previous parametric study.

For the weld termination regime, laser power ramp-down along with different arc ‘finish slopes’ (reduction of arc current when terminating) were investigated over a weld overlap distance of 40 mm. A special 2-step trigger was used which turns the arc on or off and allows for a start and finish slope to be applied when the trigger is pressed (controlled by a digital output on the Fanuc teach pendant). The start and finish slopes are controlled by specific parameters, such as the start and finish current as a percentage, duration of the start and finish current, and the slope duration.

An example of the parameter screen setup from the Fronius RCU5000i remote control MIG/MAG synergic welding manual is given in Figure 7-2. A slope duration must be applied using this arc trigger program; therefore, a minimum value of 0.1 s was used. Reference welds without start and finish slopes were conducted with the start and finish current at 100 %, slopes of 0.1 s, and a current duration of 0.1 s. These parameters ensured that the arc initiates and terminates at 100 % current with the special 2-step trigger option.

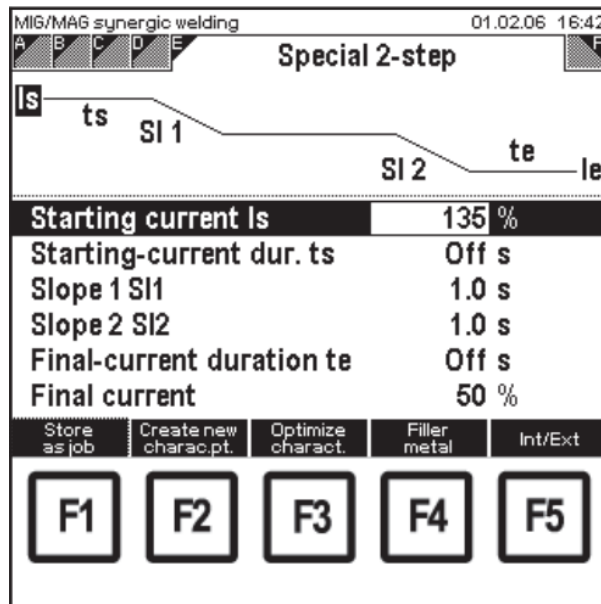


Figure 7-2: Example of Fronius RCU5000i remote control MIG/MAG synergic welding: “Special 2-step” screen [146]

For this study, only laser power ramp-down and the arc finish slopes were applied. The final current and final current duration were kept constant at 50 % and 0.1 s, respectively. Different laser power ramp-down distances and arc finish slope durations (named as “slope 2” in Figure 7-2) prior to the termination point (point C) were applied. The laser power ramp-down was programmed to ramp to 0 kW. The arc slope duration is equivalent to a certain arc finish slope distance at the set welding speed of 1 m/min. A schematic example HL-GMAW termination parameter at the weld overlap start/stop region is shown in Figure 7-3.

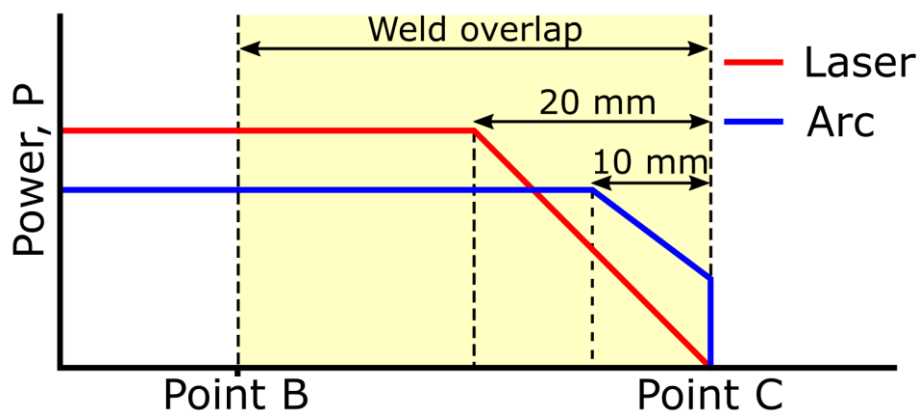


Figure 7-3: Example schematic of HL-GMAW termination using a 20 mm laser power ramp-down distance and a 10 mm arc finish slope distance

The welding parameters used for the HL-AW termination regime study is shown in Table 7-3. Reference welds of autogenous laser and GMAW only for each process variant were conducted using the different weld termination parameter configurations. No shielding gas was applied with the autogenous laser welds.

Table 7-3: Welding parameters used in HL-GMAW termination regime study

Parameters	Value
<i>Laser power ramp-down distance, L_{Ramp}, [mm]</i>	0, 10, 20, 40
<i>Arc finish slope duration, t_{slope}, [s]</i>	0, 0.1, 0.6, 1.2
<i>Arc finish slope distance, L_{slope}, [mm]</i>	0, 1.67, 10, 20

7.2.3 Sample analysis

7.2.3.1 Weld profile measurements

Weld profile measurements of the penetration depth, weld width, and weld reinforcement (bead height) was taken from the transverse cross-sectional macrographs of all weld samples using Axiovision. An example of the weld profile measurements is shown in Figure 7-4.

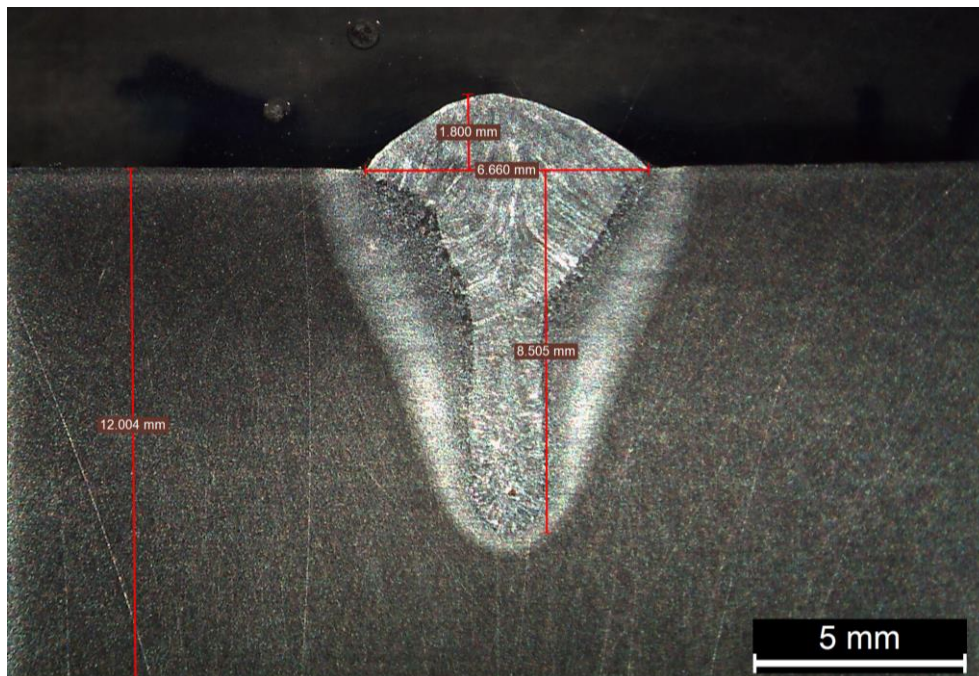


Figure 7-4: Example of transverse cross-sectional macrograph weld profile measurements

7.2.3.2 Laser scanning surface topography

In the hybrid laser-arc weld overlap start/stop termination study, laser scanning of the weld overlap start/stop region was conducted using a Romer Absolute Arm with integrated scanner from Hexagon [147]. The purpose of the surface topography was to analyse and compare the effect of the different HL-GMAW termination regimes on the weld profile of the weld overlap start-stop region.

The laser scan of the weld beads generates several coordinate-based data points that require processing. The “Learning Edition” of Verisurf, a model-based inspection and measurement software [148] was used to process and analyse the scanned data as it is free for academic purposes. A 3D mesh profile of the weld bead was generated from the data points which can then be compared with a CAD (computer aided design) file. However, for surface topography purposes within this chapter, a CAD of the substrate was generated from the data points itself and the 3D mesh profile of the weld bead was compared against it. Exporting the analysed data was not possible using the Learning Edition of the Verisurf software. Therefore, a graphical solution using Inkscape, a digital image processing software was used. A line path comprising of several nodes was projected onto the image of the weld profile, exported as XY coordinates, and then plotted using MATLAB. A graphical schematic of each step is shown in Figure 7-5. The colour bar and histogram show the deviation of the weld bead from the substrate in millimetres.

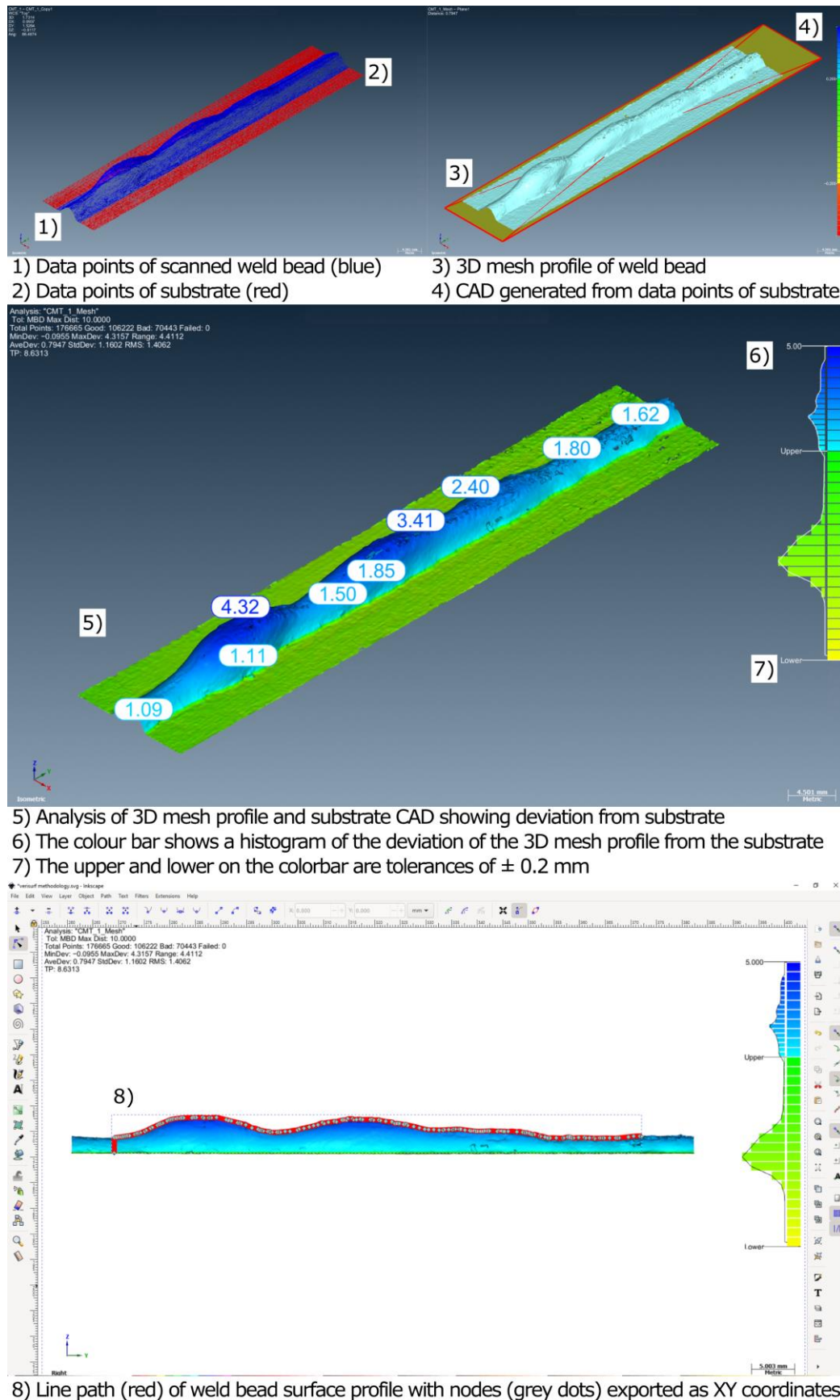


Figure 7-5: Processing of laser scanned weld overlap using Verisurf and Inkscape

7.3 Results

7.3.1 Parametric study of hybrid laser-arc welding

7.3.1.1 Effect of laser-arc interactions on melt pool stability

Figure 7-6 shows the weld top surface and cross-sectional macrographs of autogenous laser, GMAW and HL-AW welds obtained using the minimum and maximum welding speeds and WFS. Larger transverse cross-sectional macrographs of all weld samples are shown in Figure 7-9 and Figure 7-10.

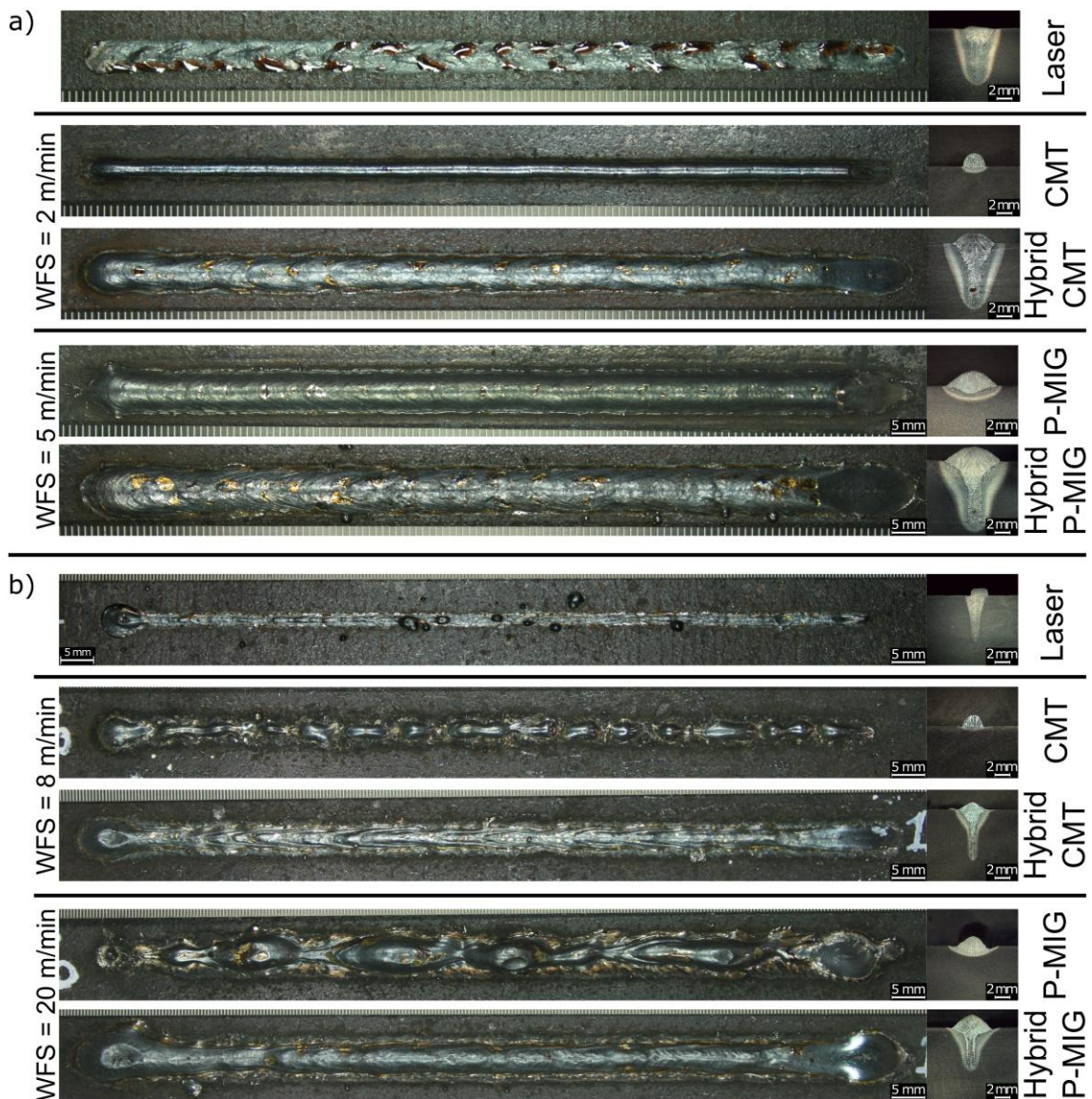


Figure 7-6: Autogenous laser, GMAW and HL-GMAW weld surfaces and transverse cross-sectional macrographs, a) $P = 4 \text{ kW}$, $v = 0.5 \text{ m/min}$, b) $P = 8 \text{ kW}$, $v = 4 \text{ m/min}$

At a welding speed of 0.5 m/min, autogenous laser and arc welds using either CMT or P-MIG process variants with the lowest WFS parameters appear to be stable and smooth, as shown in Figure 7-6. The laser weld profile shows a deep penetrative weld with no observable internal defects. Welds obtained using CMT and a low WFS of 2 m/min gives a small bead with little penetration and high weld toe angle, which is not practical for welding purposes. On the other hand, P-MIG with a WFS of 5 m/min provides a much wider bead and a more suitable weld toe angle and penetration depth. In HL-GMAW, both hybrid CMT and hybrid P-MIG weld beads at a welding speed of 0.5 m/min appear less stable when compared with the GMAW weld beads obtained using CMT and P-MIG, respectively. The instability in both HL-GMAW welds at a welding speed of 0.5 m/min is evident from the waviness of the weld bead, spatter, and porosity that is present at the root of the weld.

At a higher welding speed of 4 m/min all weld beads are intermittent, indicating that the welding process is unstable. In autogenous laser welding, the weld becomes narrow, and a significant amount of spatter occurs resulting in an uneven weld surface. In GMAW, it becomes impossible to deposit a stable weld bead at such high welding speeds despite using the highest WFS for either process variant due to the lack of heat. The weld beads for both process variants show intermittent deposition of filler material and in the case of P-MIG, humping behaviour was observed. However, when the power sources are combined, it is possible to achieve better welds at much higher welding speeds compared with each individual welding process. Although the HL-GMAW welds are still unstable with the parameter configurations used, the welds have better weld reinforcement and weld shape as compared to autogenous laser welding. The additional heat from the laser in HL-GMAW improves the distribution of the filler material to the melt pool and solidification behaviour of the weld metal when compared with GMAW only.

The stability of GMAW can be monitored from the arc voltage and current waveform via an AMV. The waveforms for both GMAW and HL-GMAW welds for the two different process variants, CMT and P-MIG, are shown in Figure 7-7 and Figure 7-8, respectively.

Stability of CMT and Hybrid CMT waveforms

The differences in CMT weld stability at different WFS and welding speeds can be clearly seen in Figure 7-7. At 0.5 m/min the droplet transfer is consistent at both WFS but the short circuit duration with a WFS of 8 m/min is very short and is like that of P-MIG. However, at a welding speed of 4 m/min the droplet transfer becomes intermittent with longer periods of short circuiting and arcing occurring. The long periods of short circuiting and arcing behaviour at a weld speed of 4 m/min correlates with the intermittent weld bead shown previously in Figure 7-6b. Overall, CMT appears to be stable across the whole range of WFS studied. It is particularly stable at a WFS of 4 m/min and 6 m/min, and at low welding speeds. However, the welding process becomes increasingly unstable at higher welding speeds.

Small differences in weld stability can be observed from the waveforms when comparing CMT with hybrid CMT welds. At a welding speed of 0.5 m/min there is little difference between CMT and hybrid CMT welds with a WFS of 2 m/min. However, at a higher WFS of 8 m/min the voltage of the hybrid CMT weld becomes slightly irregular when compared with CMT.

At a welding speed of 4 m/min, there is little improvement in the droplet transfer in hybrid CMT when using a WFS of 2 m/min. With a WFS of 8 m/min, the droplet transfer becomes more regular when comparing hybrid CMT with CMT alone.

The combination of the laser and arc source in hybrid CMT reduces the stability slightly across all the WFS and welding speeds studied when compared with CMT alone. Both CMT and hybrid CMT welds appear to be more stable at WFS below 6 m/min and at lower welding speeds.

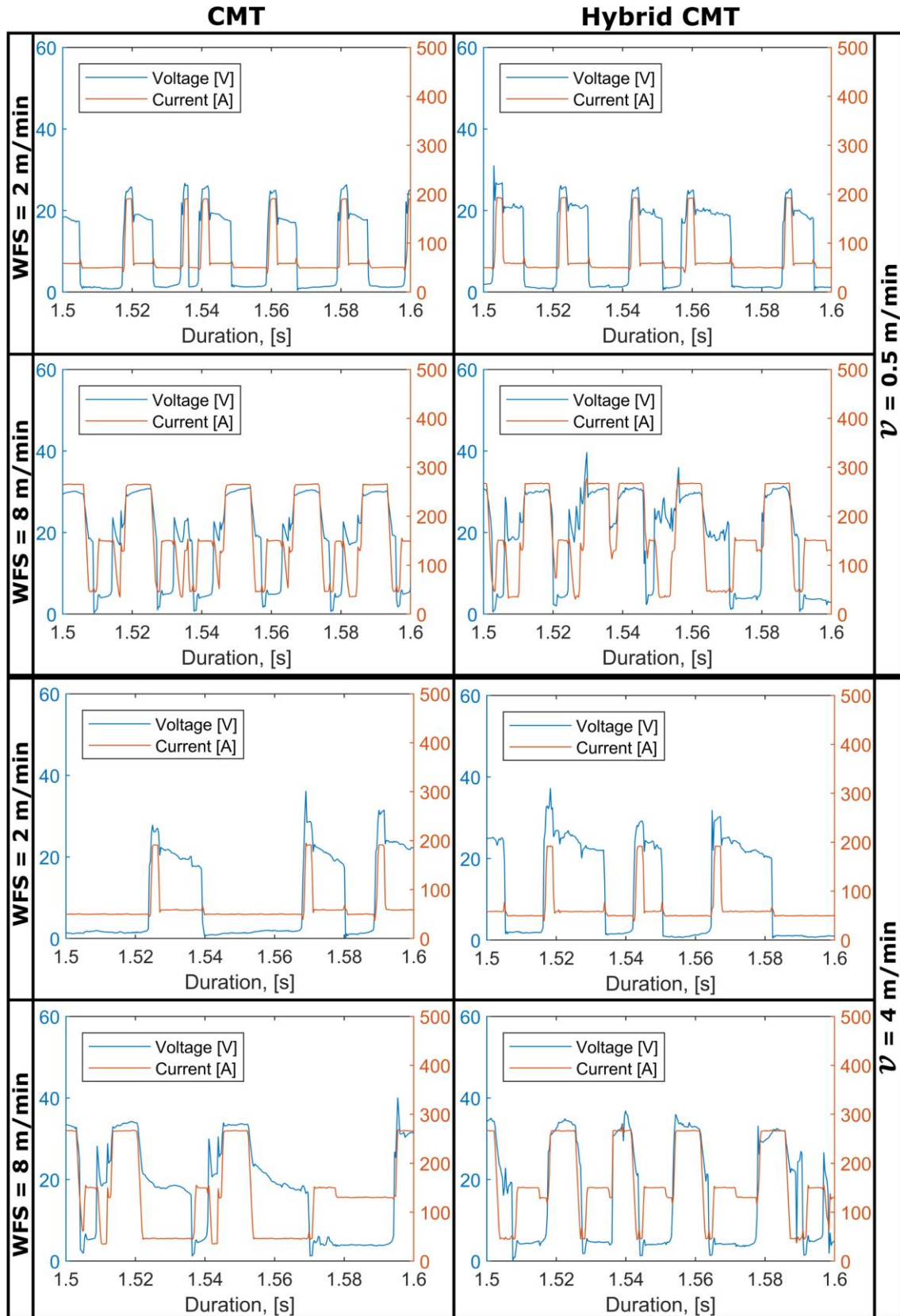


Figure 7-7: CMT and Hybrid CMT waveforms at different WFS and welding speeds

Stability of P-MIG and hybrid P-MIG waveforms

In P-MIG, the waveforms shown in Figure 7-8 appear to be more stable and regular at a high WFS compared with low WFS for both welding speeds. However, as was shown previously in Figure 7-6b, the P-MIG weld bead at a welding speed of 4 m/min and WFS of 20 m/min was not stable. Although online monitoring of the waveform during welding indicated the arc was relatively stable, the melt pool flow and solidification can differ significantly. Occurrences of short circuiting was also observed at both low WFS and high welding speeds. P-MIG appears to be most stable at higher WFS of 15 m/min at welding speeds ranging from 0.5 – 2 m/min, or at a WFS of 20 m/min at a welding speed of 0.5 - 1 m/min.

When the laser is coupled with P-MIG at low welding speeds, the arc becomes less stable when compared with P-MIG alone. However, at welding speeds above 2 m/min, the addition of the laser improves the arc stability and droplet transfer behaviour significantly. The stability of the melt pool also improves with increasing WFS in hybrid P-MIG according to the arc waveform.

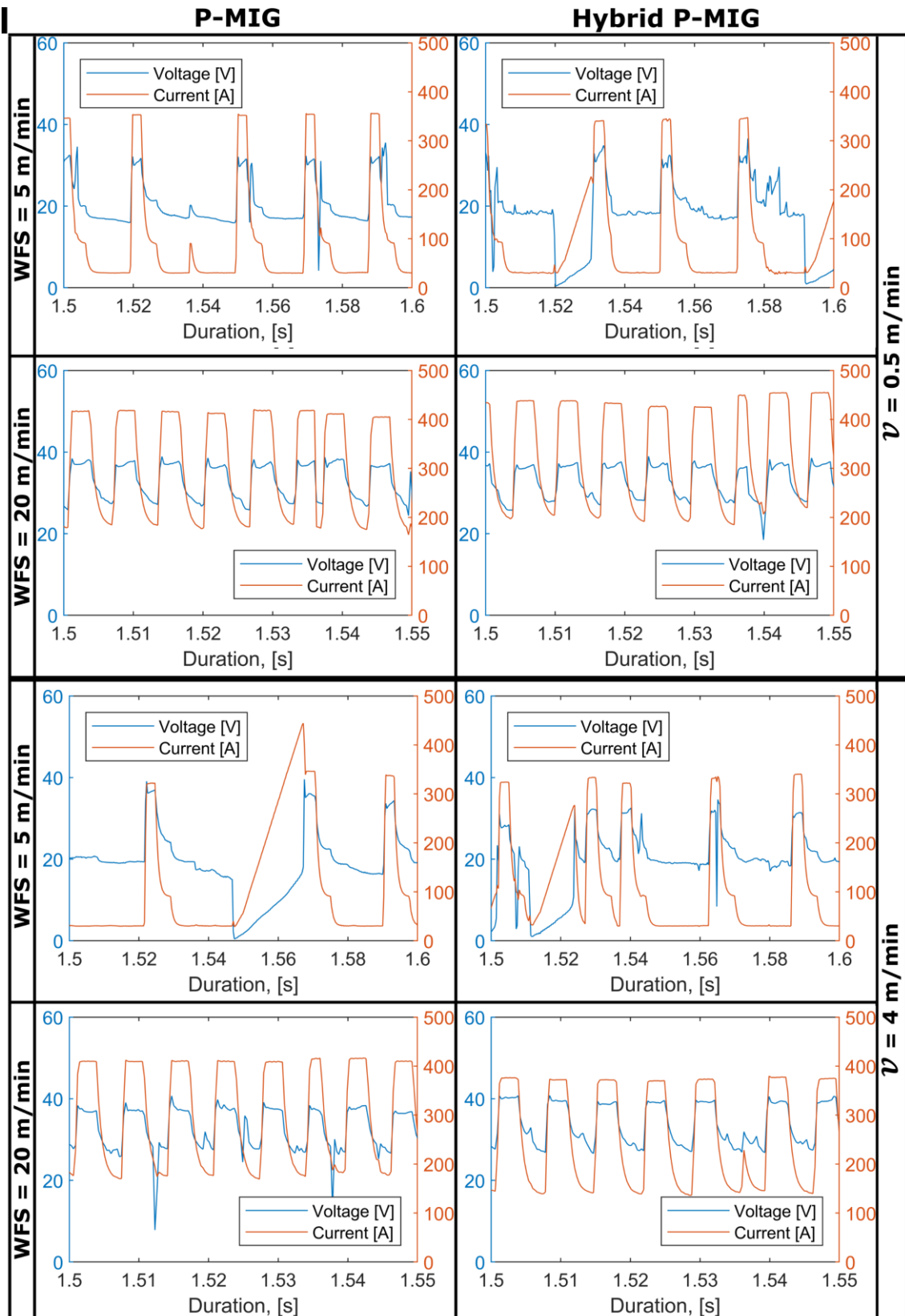


Figure 7-8: P-MIG and Hybrid P-MIG waveforms at different WFS and welding speeds

7.3.1.2 Effect of arc on laser weld profile and penetration in HL-GMAW

Figure 7-9 and Figure 7-10 show the transverse cross-sectional macrographs of welds conducted with a range of parameters in GMAW and HL-GMAW using CMT and P-MIG, respectively. Reference autogenous laser welds are also included for comparison purposes.

CMT and hybrid CMT

In Figure 7-9, the effect of WFS for each parameter when using CMT in GMAW and HL-GMAW is shown. In CMT, as the WFS increases, the weld depth, width, and reinforcement increase. It was observed that welds become unstable and intermittent when using a welding speed of 2 m/min unless a WFS of 8 m/min was used. At a welding speed of 4 m/min, it was not possible to weld regardless of the WFS used.

The addition of CMT with laser in hybrid CMT improves the weld profile of autogenous laser welds significantly. The weld depth, width and reinforcement all increase with the addition of CMT when comparing autogenous laser welds with hybrid CMT welds for the same parameter configuration. However, solidification cracking or shrinkage cavities and porosity was observed at the weld root in several hybrid CMT weld samples. At welding speeds of 2 m/min and above, the hybrid CMT welds show signs of minor undercuts.

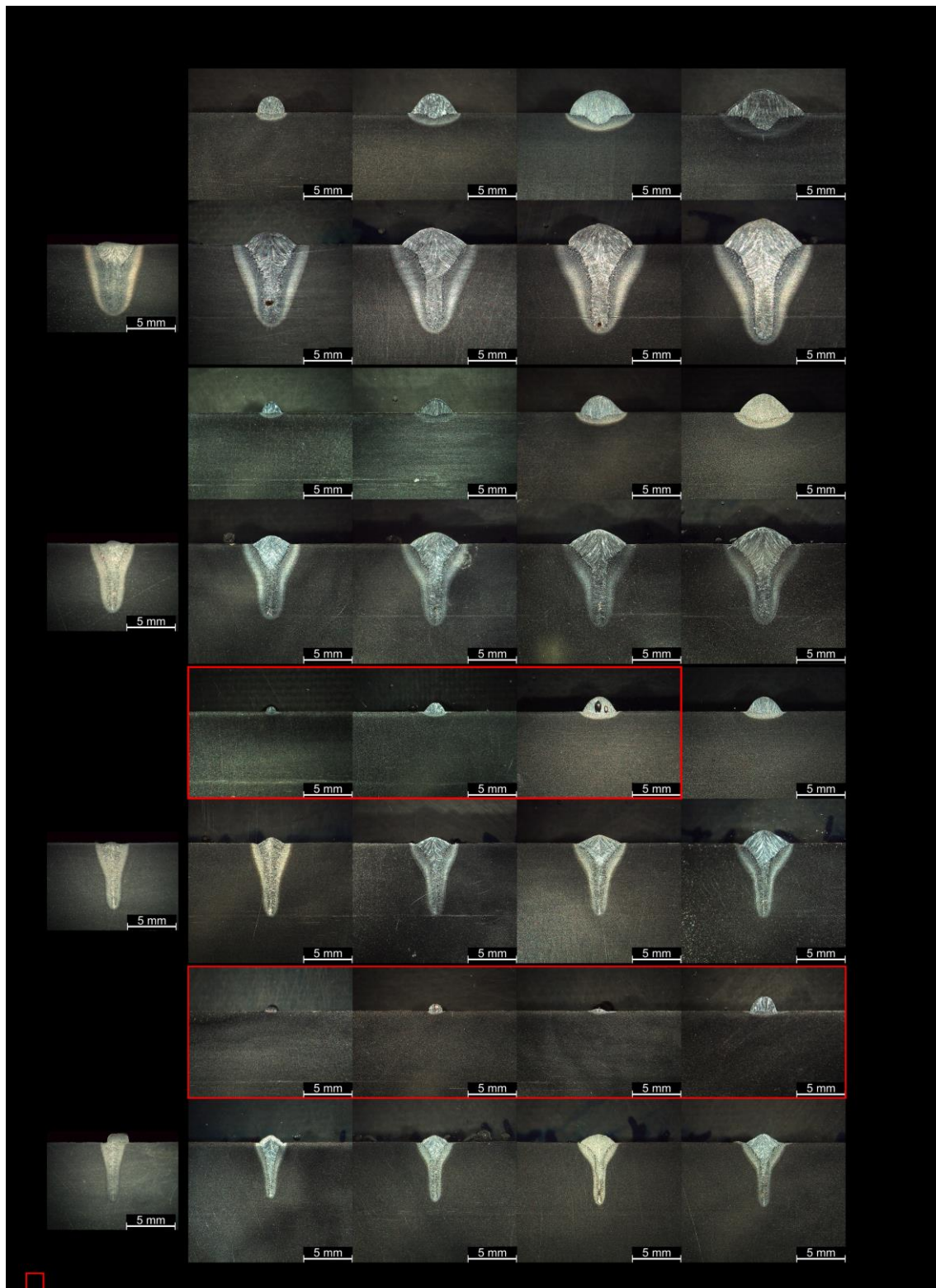


Figure 7-9: GMAW and HL-GMAW transverse cross-sectional macrographs of welds achieved using CMT

P-MIG and hybrid P-MIG

Figure 7-10 shows the effect of WFS for each parameter configuration when using P-MIG for GMAW and HL-GMAW. Much larger and wider weld beads with deeper penetration were obtained with P-MIG when compared with the CMT welds due to the larger achievable WFS resulting in more material deposited and higher electromagnetic force and heat input.

Like CMT, P-MIG welds also become unstable when using a welding speed of 2 m/min. However, the opposite to CMT occurs where the welds are more stable at lower WFS in P-MIG but becomes unstable due to humping defects at higher WFS.

A significant increase in penetration depth is observed when combining P-MIG with laser in hybrid P-MIG, especially at lower welding speeds. Similar keyhole root defects like those seen in hybrid CMT were observed in hybrid P-MIG. These root defects occur more frequently at low WFS in hybrid P-MIG.

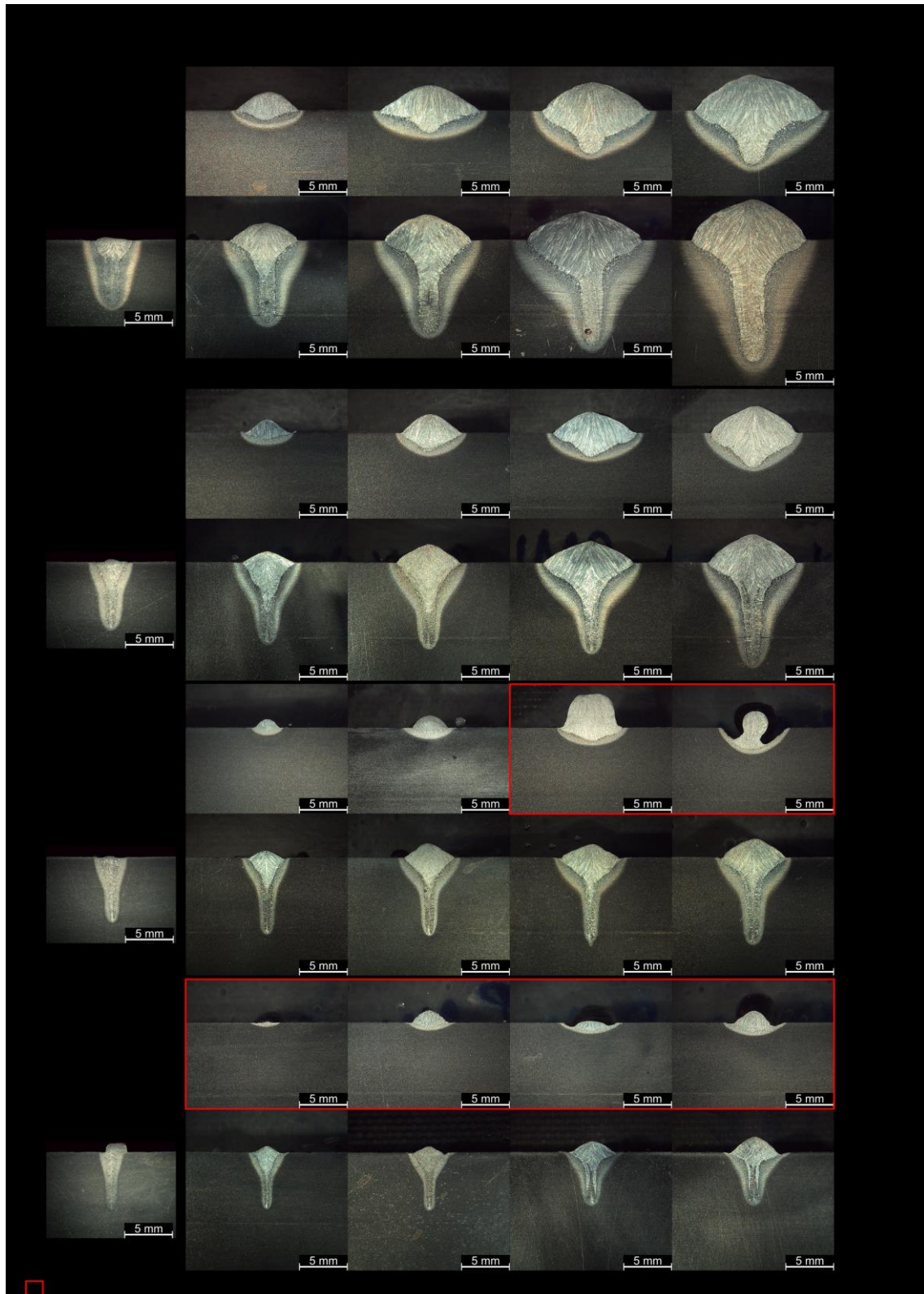


Figure 7-10: GMAW and HL-GMAW transverse cross-sectional macrographs of welds achieved using P-MIG

Effect of arc heat input on weld profile

The influence of the arc source on autogenous laser welds in HL-GMAW can be determined by observing the changes to the weld profile due to the increase in arc heat input. Differences in the weld profile between autogenous laser welds and HL-GMAW were measured and calculated for the following figures. The arc heat input can be calculated by averaging the arc power captured by the Weldmon AMV and dividing by the welding speed, as shown in equation 7-1.

$$\text{Arc heat input, } Q_{Arc}, (kJ/mm) = \frac{\sum_{i=1}^n \text{Arc voltage}_i \times \text{Arc current}_i}{n \times \text{Welding speed}} = \frac{\sum_{i=1}^n V_i \times A_i}{n \times v} \quad 7-1$$

Where n is the total number of sample data captured by the Weldmon AMV.

Weld profile measurements were taken using the method shown in section 7.2.3.1

Penetration depth

Figure 7-11 shows how the penetration depth of the autogenous laser welds (≈ 7 mm) increase due to the additional heat input and electromagnetic force from the arc source in HL-GMAW for a range of welding parameters.

It can be clearly seen that the increase in penetration depth follows a parabolic curve and is dependent on the heat input from the arc rather than the process variant used. However, the amount of heat input applied is dependent on the range of WFS that can be used, which is limited by the choice of process variant.

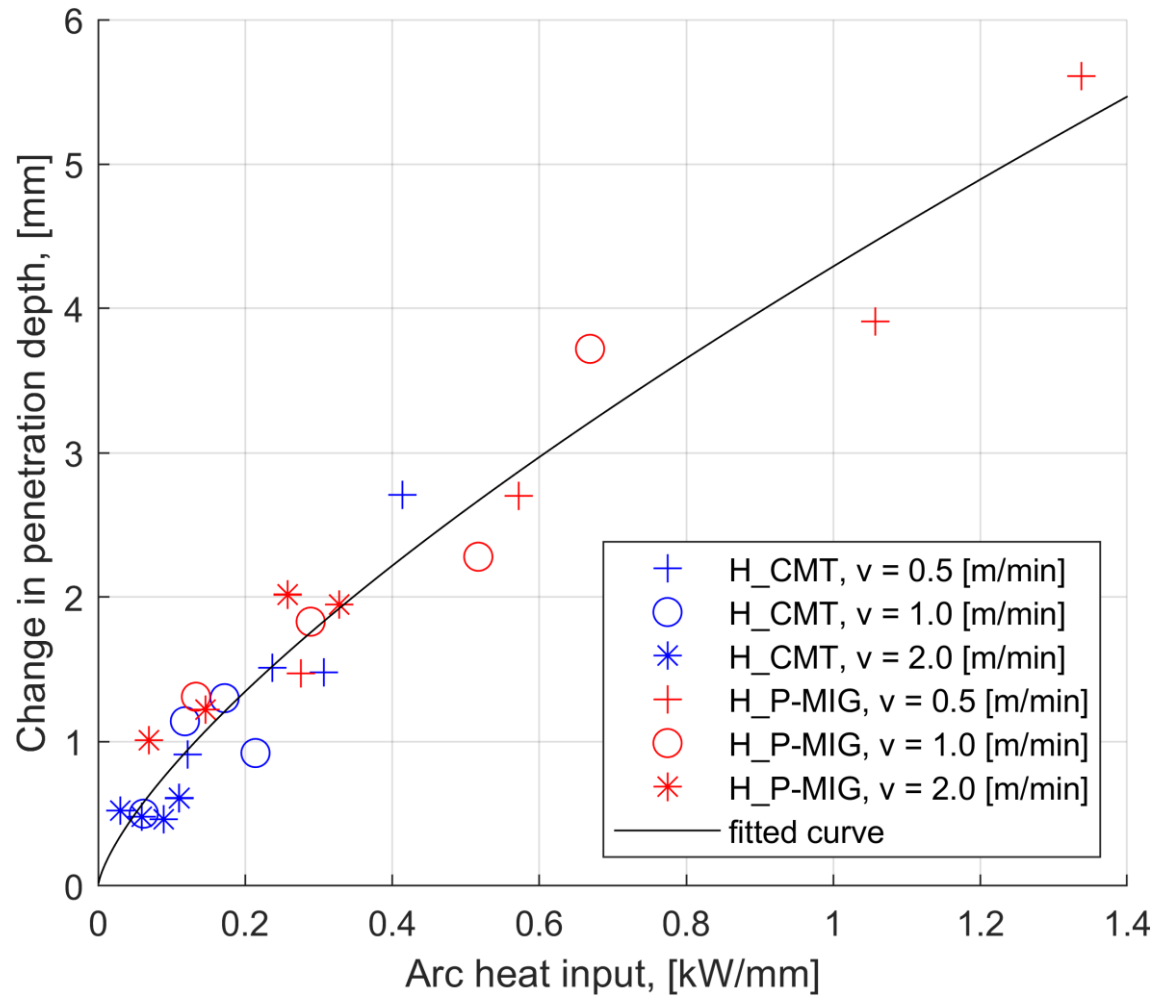
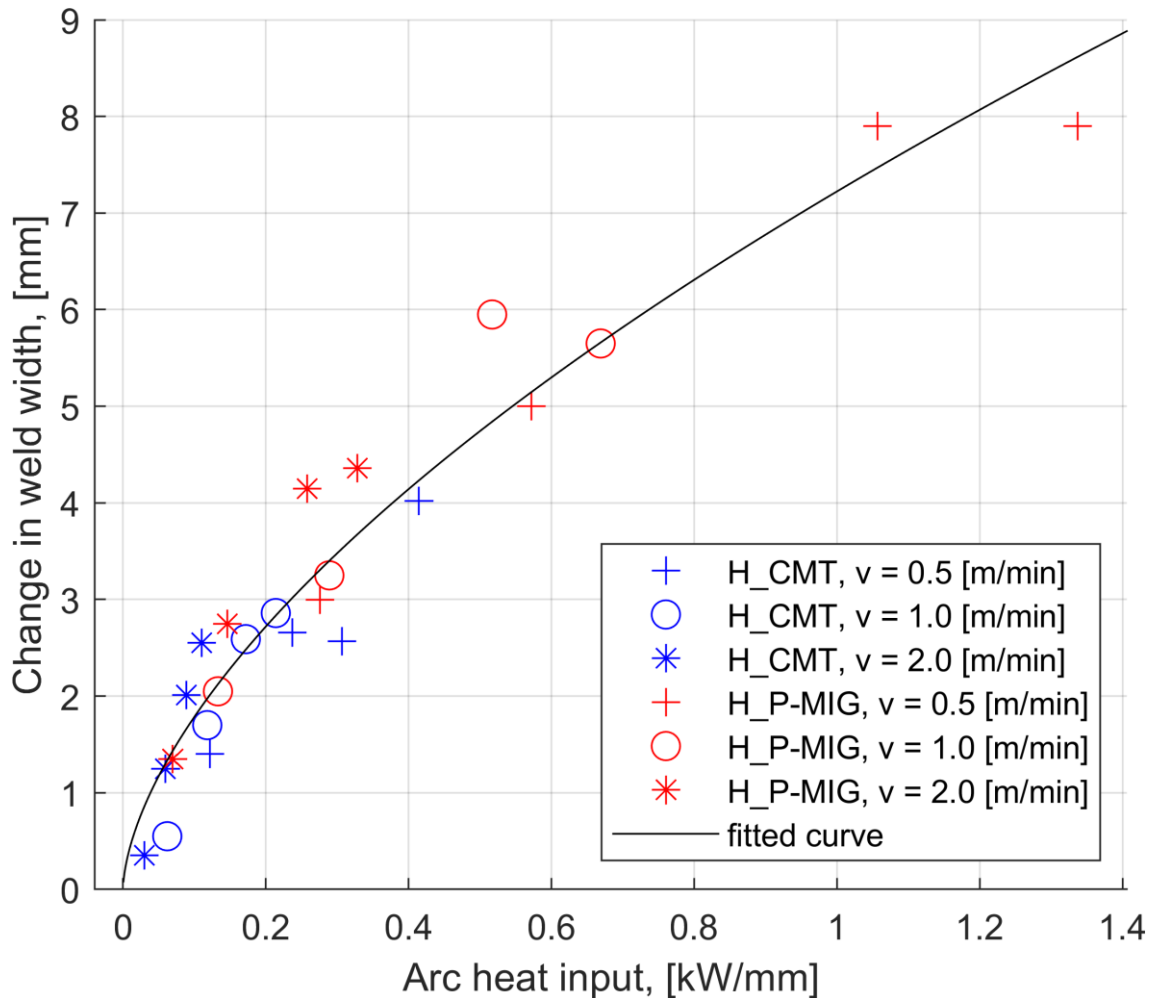


Figure 7-11: Effect of arc heat input on penetration depth in HL-GMAW

Weld width

A similar trend on the weld width is observed in Figure 7-12. The increase in heat input from the arc source also results in an increase in weld width in HL-GMAW. Even when the applied arc heat input is low, there is a significant increase in the weld width due to the addition of filler metal and increase in melting area due to the arc processing zone.



Weld reinforcement

The same trend is observed when looking at the effect of the additional arc heat input on weld reinforcement (bead height), as shown in Figure 7-12 Figure 7-13.

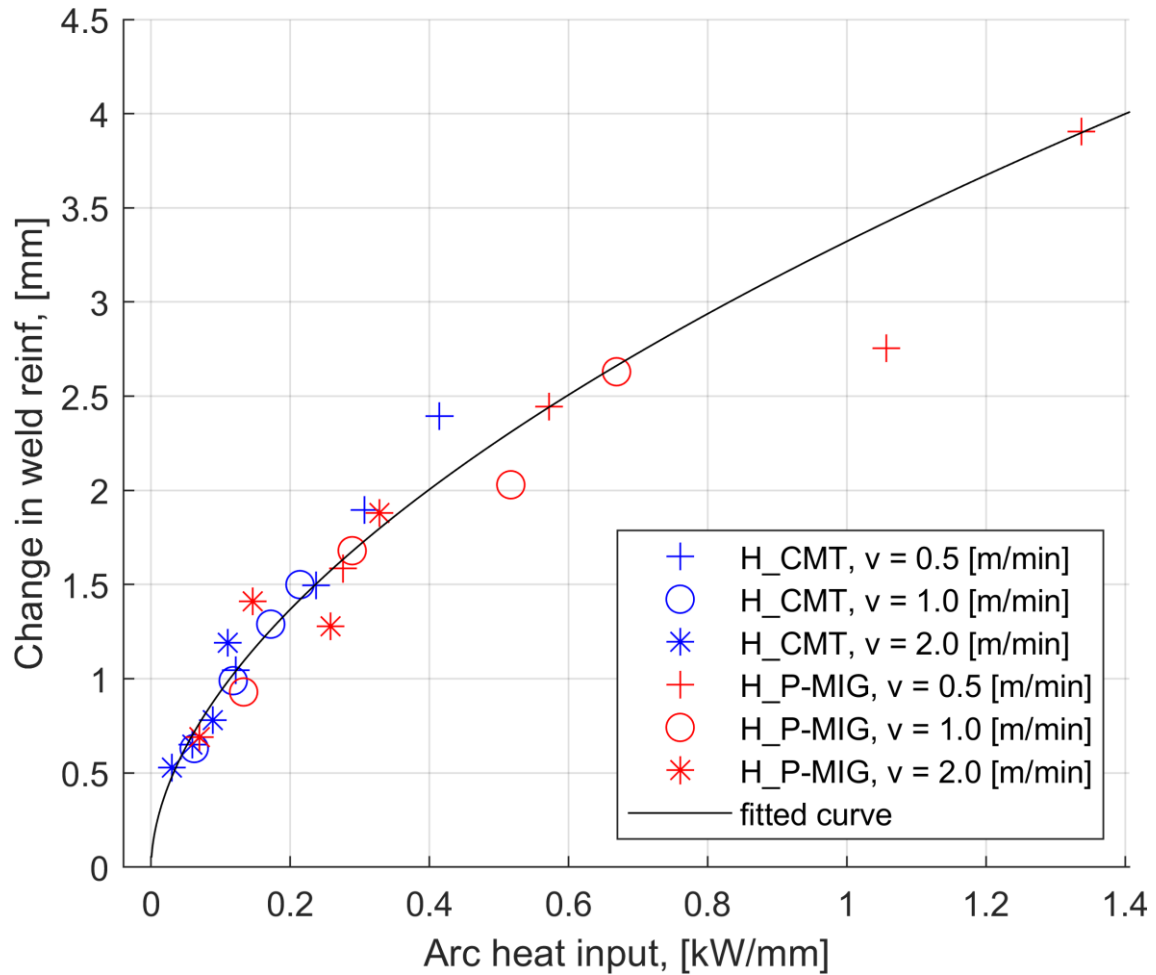


Figure 7-13: Effect of arc heat input on weld reinforcement in HL-GMAW

7.3.2 Hybrid laser-arc weld overlap start/stop terminations

In this section, autogenous laser and HL-GMAW weld overlaps were conducted with different laser power ramp-down and arc finish slope distances prior to weld termination. A laser power of 5 kW, welding speed of 1 m/min and WFS of 6 and 5 m/min for CMT and P-MIG, respectively, was used.

7.3.2.1 Effect of hybrid termination on weld overlap start/stop surface

The following figures in this section are obtained from the laser scanning of the top surface of the weld overlap start/stop. The colours highlight the deviation of the weld bead from the substrate as explained in section 7.2.3.1.

Autogenous laser

Weld craters with a depth below the substrate surface (shown in red) occur when no laser power ramp-down or ramp-down over 10 mm is applied, as shown in Figure 7-14. A small and shallow surface depression remains at the laser termination point when the laser power ramp-down distance is increased to 20 mm and above. Small amounts of spatter are visible on the weld surface with the set of laser power and welding speed used. The amount of weld spatter across the weld overlap decreases with increasing laser power ramp-down distance.

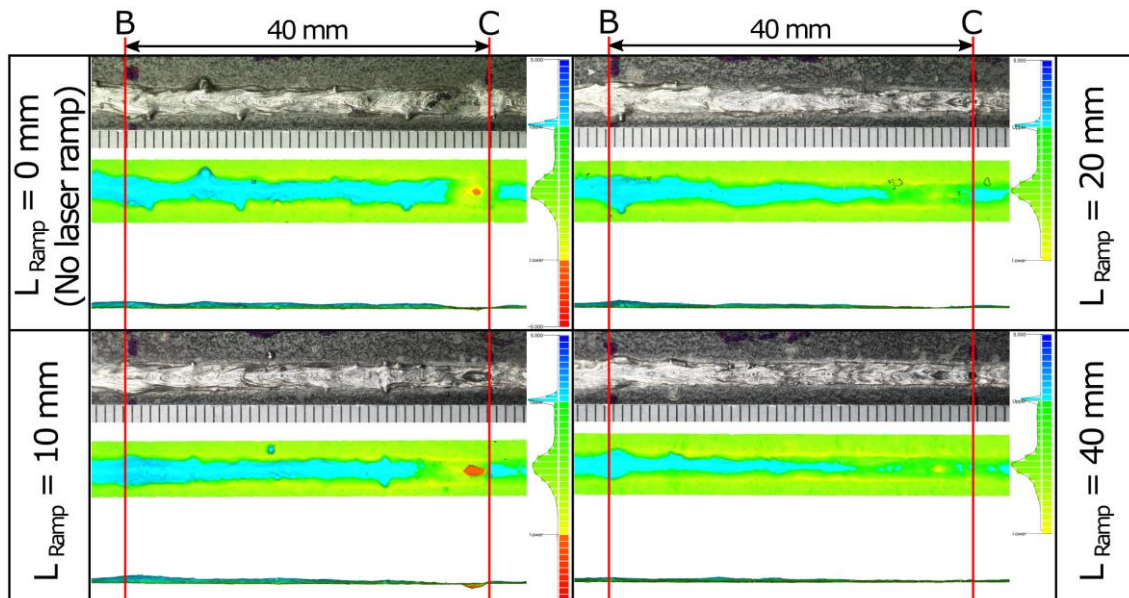


Figure 7-14: Autogenous laser weld overlap top and side surface profiles at different laser power ramp-down distances

CMT and hybrid CMT

The weld overlap start/stop regions of CMT and hybrid CMT welds are shown in Figure 7-15.

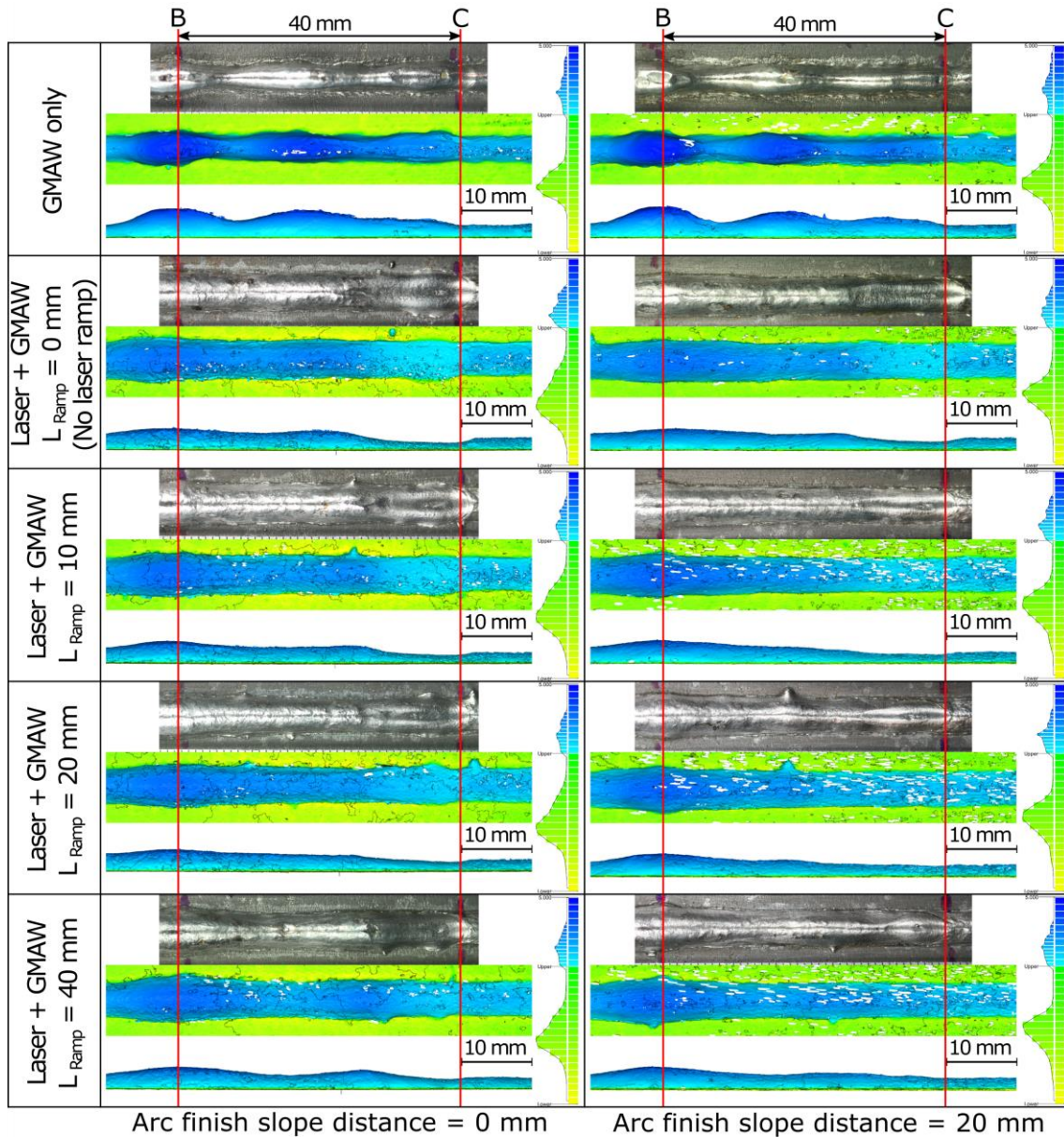


Figure 7-15: GMAW and HL-GMAW weld overlap top and side surface profiles at different L_{Ramp} and arc finish slope distances using CMT, $P = 5 \text{ kW}$, $v = 1 \text{ m/min}$, $WFS = 6 \text{ m/min}$

Weld reinforcement and weld humping are visible at the weld overlap region when using CMT only. The weld reinforcement is especially severe at point B, where the initiation of the weld is overlapped by the second weld seam, and at the middle of the weld overlap.

When the laser is introduced in hybrid CMT, the weld reinforcement at point B decreases and the weld bead is more uniform across the whole weld overlap region. These differences in weld reinforcement for CMT and hybrid CMT is shown more clearly in Figure 7-16. A small decrease in weld reinforcement followed by a small increase is observed between 10 – 30 mm from point B when a L_{Ramp} of 40 mm is applied in hybrid CMT when compared with no laser ramp.

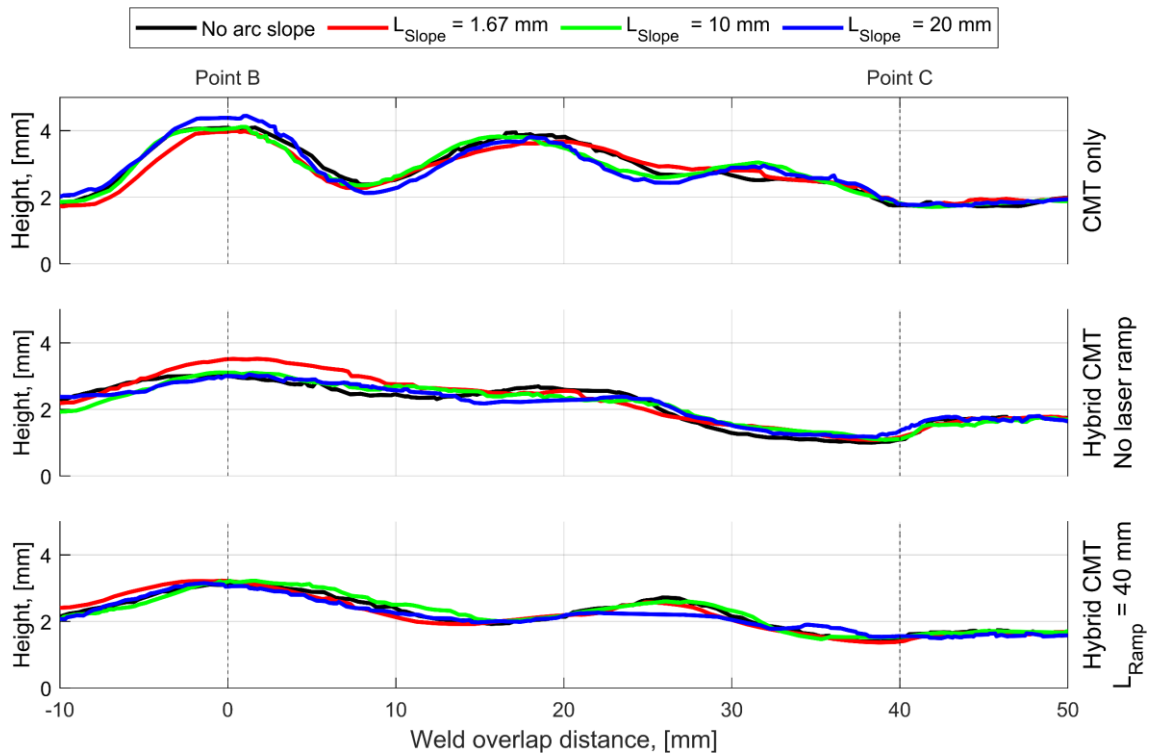


Figure 7-16: Effect of arc finish slope distance on weld overlap surface profile for CMT only, hybrid CMT with no laser ramp, and hybrid CMT with $L_{\text{Ramp}} = 40$ mm

There is a small influence of the arc slope distance (L_{Slope}) on the surface profile at the termination point C when using CMT for both GMAW and HL-GMAW, as shown in Figure 7-16. In CMT only, no weld crater is observed at the termination point regardless of the L_{Slope} used. However, in hybrid CMT with no laser ramp, large weld craters and surface depressions at the termination point C (relative to the rest of weld bead) are present. An increase in L_{Slope} decreases the depth of the surface depression at point C marginally. When a L_{Ramp} of 40 mm is applied, the weld crater and surface depression is mitigated, and increasing the L_{Slope} improves the overall weld overlap profile. Clearly the main influence on the weld overlap profile and weld crater formation is the laser power ramp-down.

The effect of the laser power ramp-down distance in hybrid CMT on the weld overlap surface profile is shown more clearly in Figure 7-17. As L_{Ramp} increases, the size of the weld crater and surface depression reduces. The waviness in weld reinforcement at the weld overlap when a L_{Ramp} of 40 mm is applied is more apparent when compared with the other L_{Ramp} distances, as shown in Figure 7-17 when no arc slope is applied.

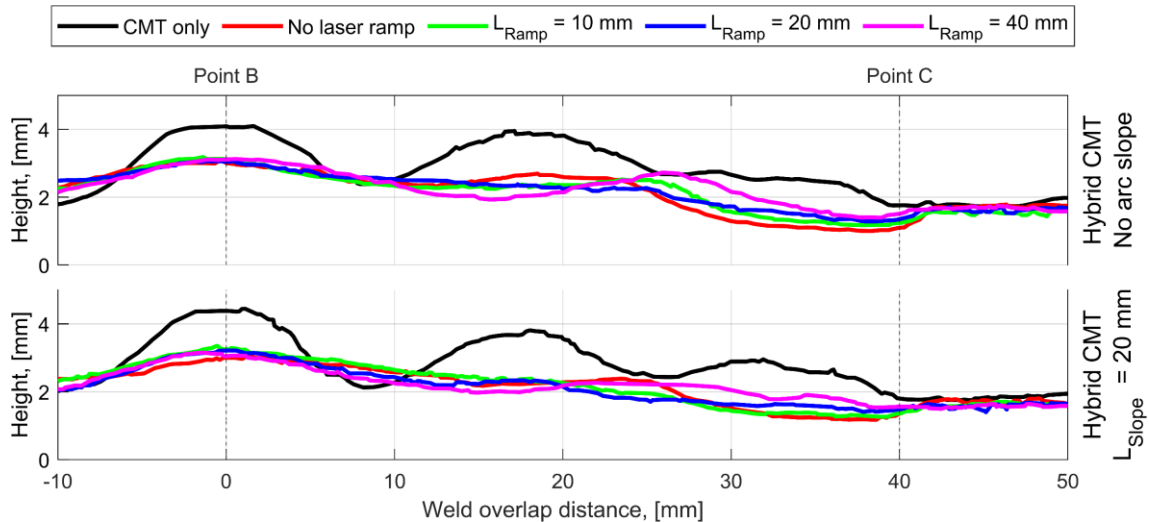


Figure 7-17: Effect of laser power ramp-down distance on weld overlap surface profile for hybrid CMT with no arc slope and hybrid CMT with $L_{\text{Slope}} = 20$ mm

P-MIG and hybrid P-MIG

Figure 7-18 shows the P-MIG and hybrid P-MIG weld overlap start/stop regions. Compared with CMT only, the P-MIG only weld overlap region has considerably less weld reinforcement at point B and is more uniform across the weld overlap despite the similar WFS used. However, there is also a significant amount of spatter when using the P-MIG when compared with the CMT in both GMAW and HL-GMAW.

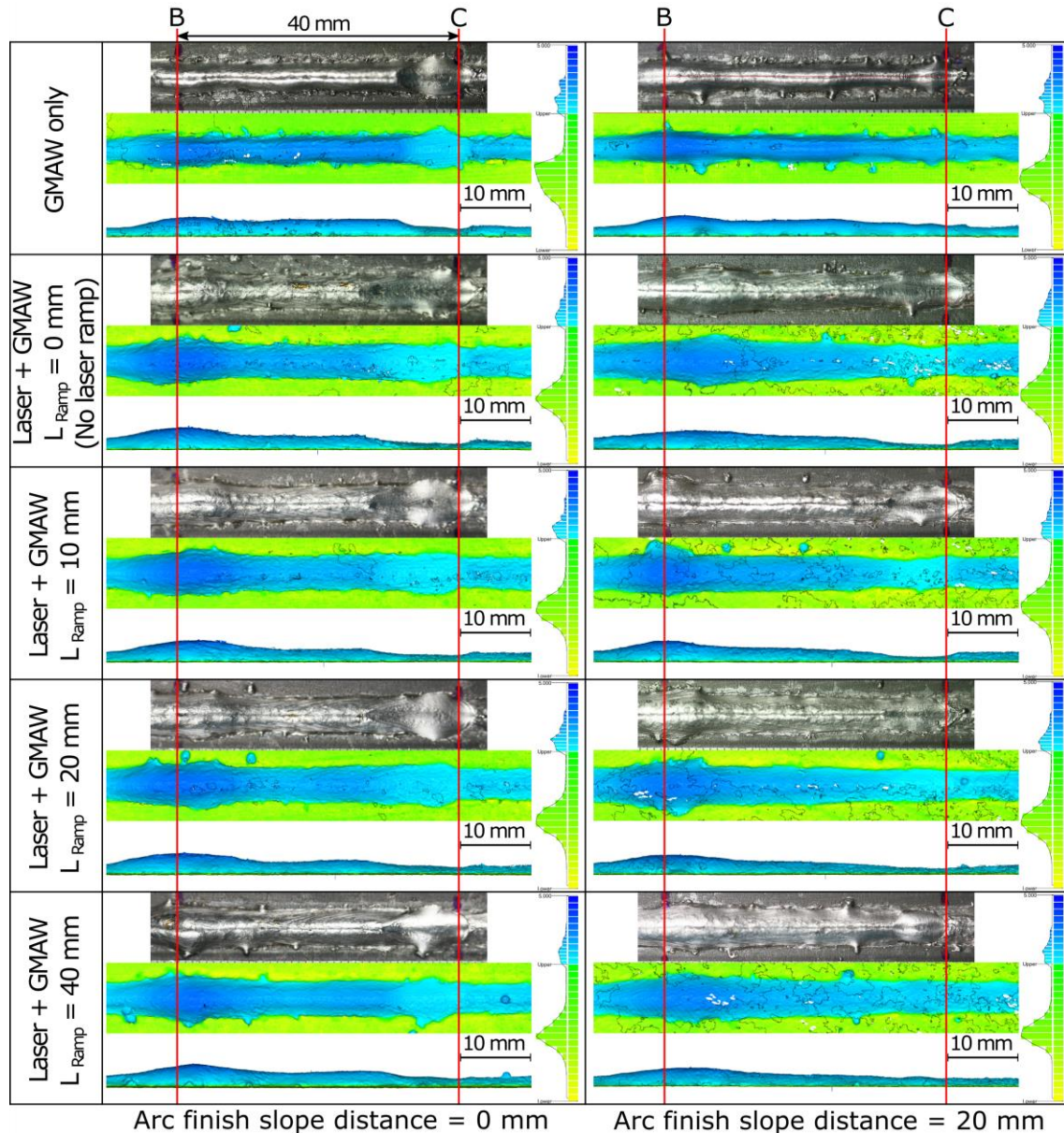


Figure 7-18: GMAW and HL-GMAW weld overlap top and side surface profiles at different L_{Ramp} and arc finish slope distances using P-MIG, P = 5 kW, v = 1 m/min, WFS = 5 m/min

The differences in weld reinforcement and surface profile when using P-MIG in GMAW and HL-GMAW is shown in Figure 7-19. In P-MIG only, a weld crater and surface depression remain at the termination point C when no arc finish slope is applied. However, when an L_{Slope} of 1.67 mm or above is applied, the weld crater is filled and mitigated. On the other hand, in hybrid P-MIG, there is also a small influence of L_{Slope} on the weld crater surface profile, much like in hybrid CMT.

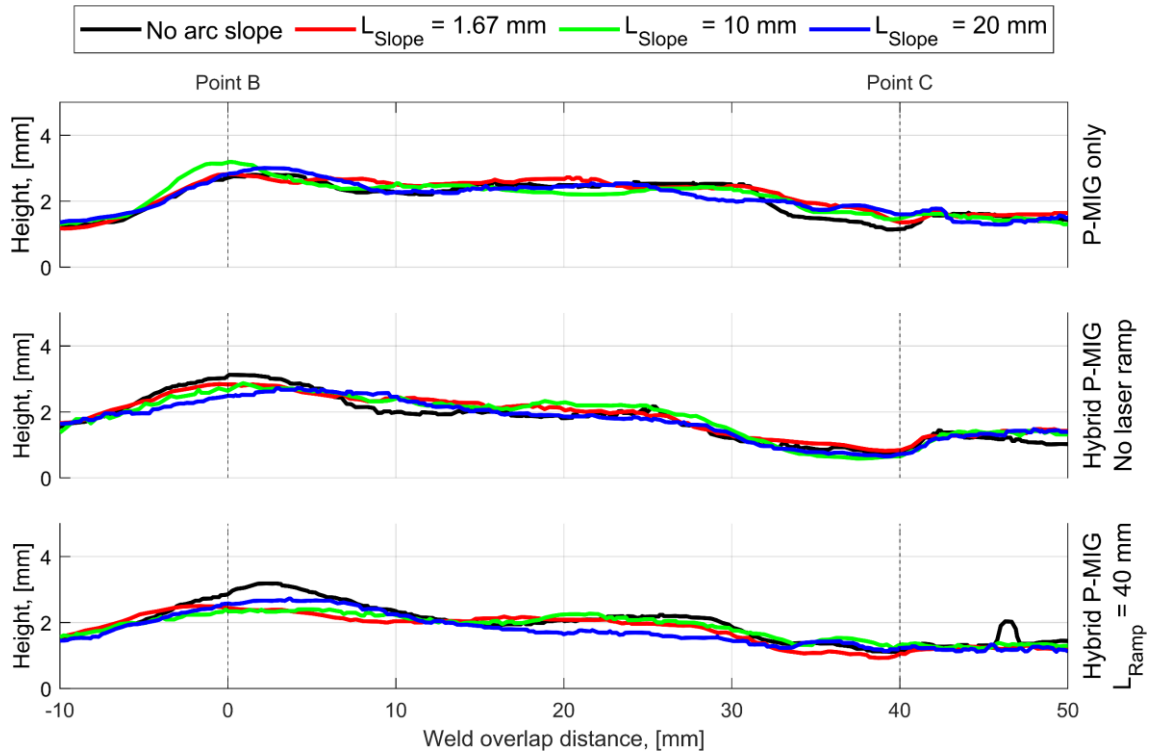


Figure 7-19: Effect of arc finish slope distance on weld overlap surface profile for P-MIG only, hybrid P-MIG with no laser ramp, and hybrid P-MIG with $L_{\text{Ramp}} = 40$ mm

The effect of L_{Ramp} in hybrid P-MIG on the weld overlap surface profile is shown in Figure 7-20. Like hybrid CMT, as L_{Ramp} increases, the size of the weld crater and surface depression reduces. The weld crater and surface depression at point C is completely mitigated when using an $L_{\text{Ramp}} = 40$ mm with a $L_{\text{Slope}} = 20$ mm.

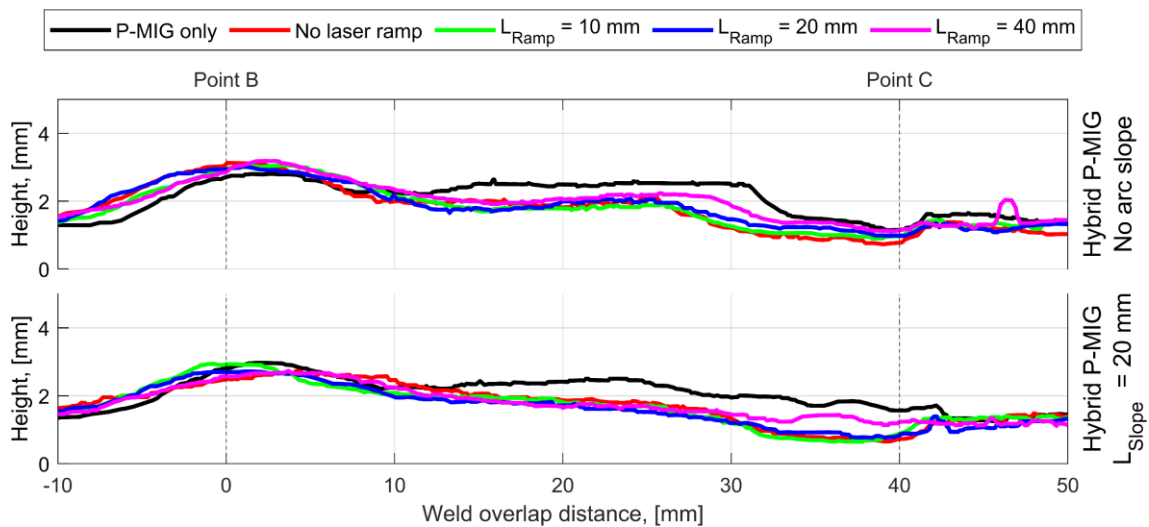


Figure 7-20: Effect of laser power ramp-down distance on weld overlap surface profile for hybrid P-MIG with no arc slope and hybrid P-MIG with $L_{\text{Slope}} = 20$ mm

7.3.2.2 Effect of hybrid termination on weld overlap start/stop weld profile and defect formation

Autogenous laser

Longitudinal macrographs of autogenous laser weld overlap start/stop regions without laser power ramp-down (abrupt laser termination) and with laser power ramp-down over 40 mm is shown in Figure 7-21. The weld sections before point B and after point C of both weld samples show the steady-state, single weld pass areas. These areas are mostly free from defects apart from some small pores.

At point B, an increase in penetration can be seen in the first weld pass when the laser initiates. In the weld overlap area, between points B and C, a small increase in penetration depth and shrinkage cavity defects can be observed. These shrinkage cavity defects continue across the whole weld overlap area when no laser power ramp-down is applied. However, when laser power ramp-down is applied (over 40 mm in this case), the shrinkage cavity defects are only present at point B. No defects are observed when the penetration depth reduces at the weld overlap region when laser power ramp-down is applied.

At point C, a large keyhole cavity, weld crater and porosity are observed due to the abrupt termination of the laser. However, when laser power ramp-down is applied, no defects are observed at the termination point C.

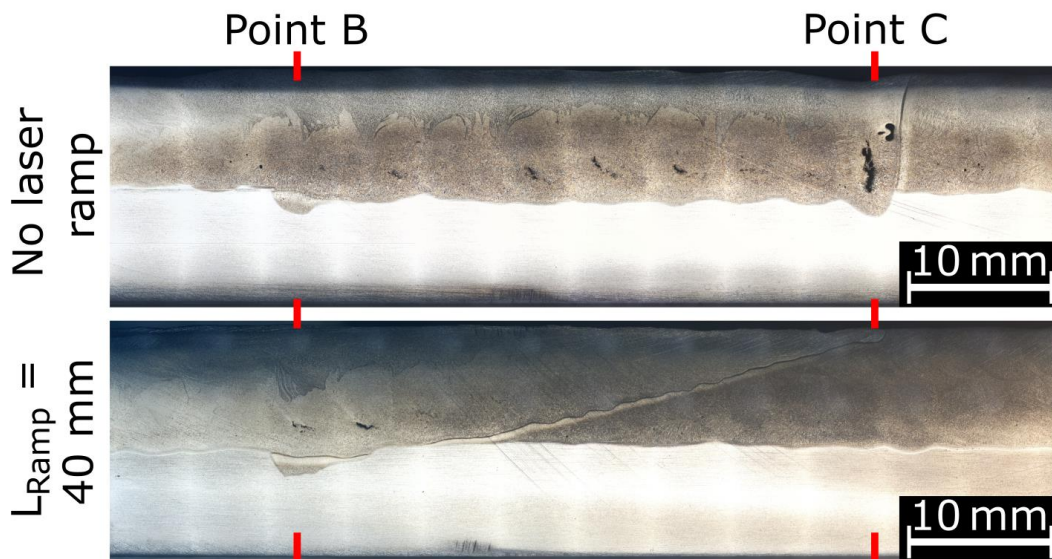


Figure 7-21: Longitudinal macrographs of autogenous laser weld overlap start/stop regions achieved with different L_{Ramp}

Hybrid CMT

Figure 7-22 shows the longitudinal macrographs of hybrid CMT weld overlap start/stop regions for a range of L_{Ramp} and no arc finish slope. An increased amount of porosity at the weld root is observed in the steady-state areas in hybrid CMT when compared with autogenous laser welds.

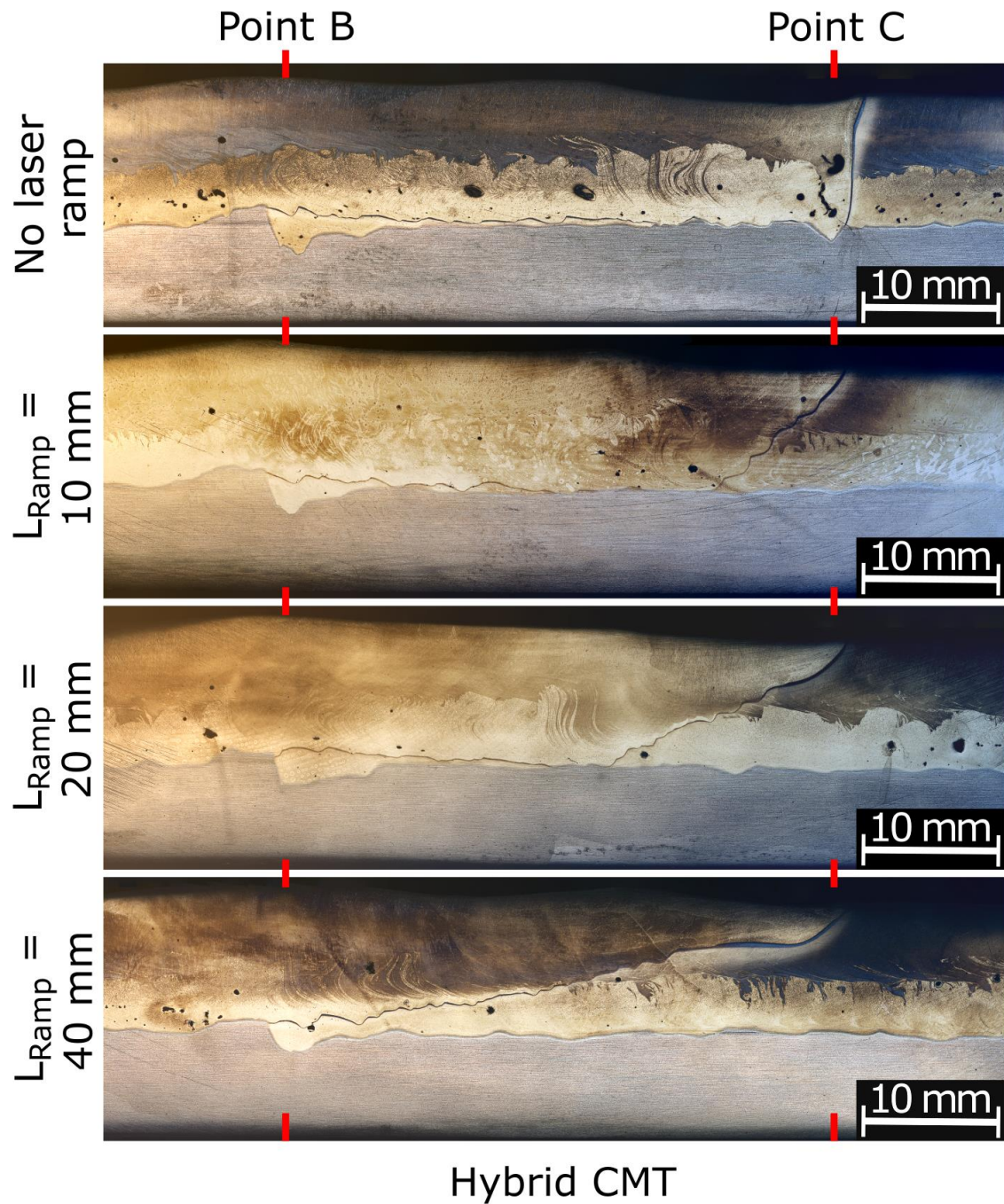


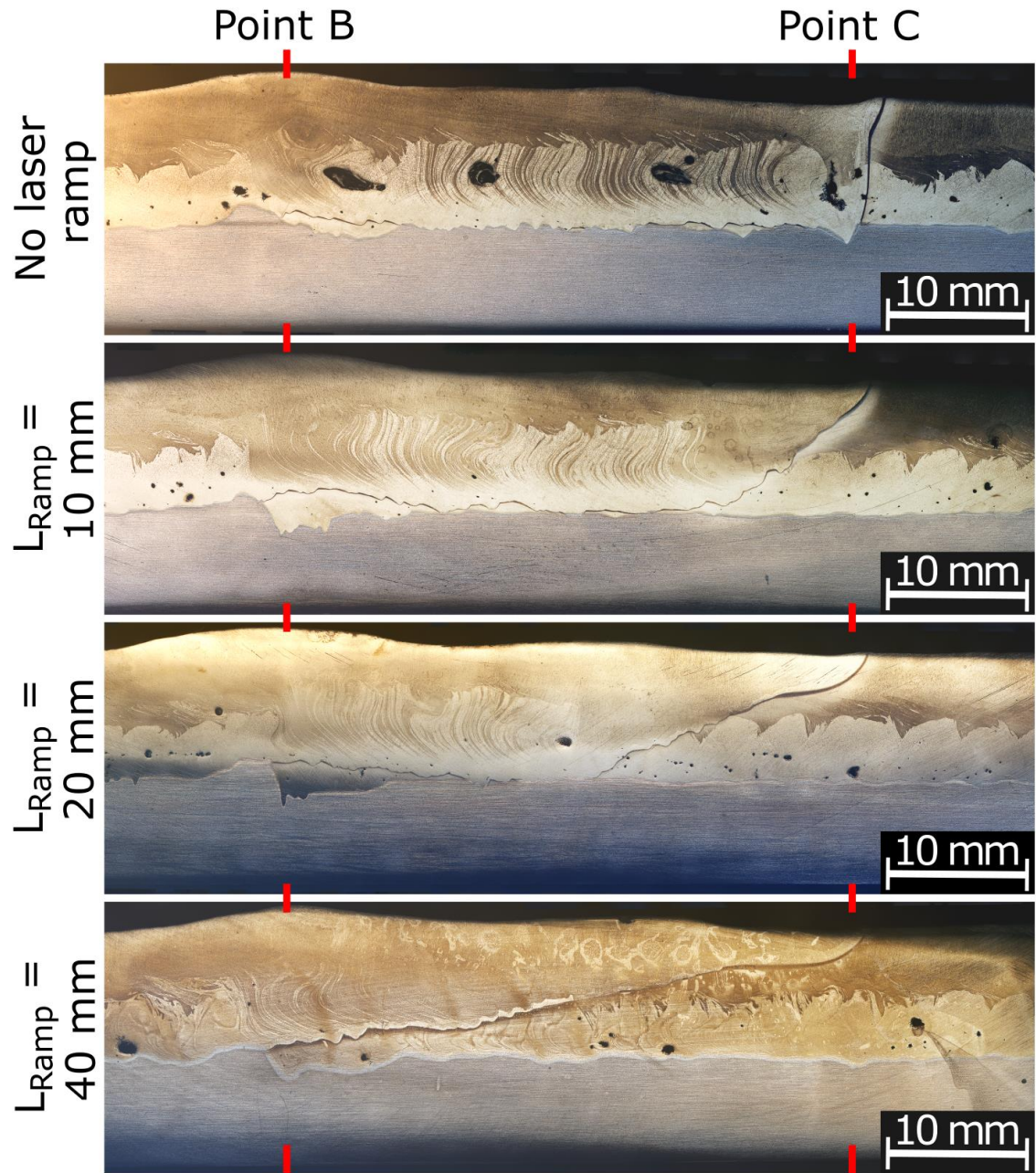
Figure 7-22: Longitudinal macrographs of hybrid CMT weld overlap start/stop region achieved with different L_{Ramp} and no arc finish slope

Similar shrinkage cavity defects and large pores are visible in the hybrid CMT weld overlap start/stop region, between points B and C, when no laser ramp is applied. However, the occurrence of these defects appears less frequently and less severe in the other weld samples despite the same parameters, apart from where the laser power ramp-down was applied (where the penetration depth reduces). In the regions of the weld samples where laser power ramp-down is applied, the formation of both porosity and shrinkage cavity defects decreases.

At point C where no laser ramp was applied in Figure 7-22, a shrinkage cavity defect and a large pore can be seen due to the abrupt termination of the laser and arc source. However, when a laser power ramp-down is applied over 5 mm, only a small pore remains. When a laser power ramp-down distance of 10 mm and above is applied, no defects at the termination point were observed.

Hybrid P-MIG

Figure 7-23 shows the longitudinal macrographs of hybrid P-MIG weld overlap start/stop regions for a range of L_{Ramp} with no arc finish slope applied. The results observed in the hybrid P-MIG weld samples are very similar to the hybrid CMT weld samples. Similar defects, such as shrinkage cavity and porosity defects, at the weld overlap and termination point C are also present in the hybrid P-MIG weld samples when no laser ramp is applied. When laser power ramp-down is applied in hybrid P-MIG, little to no defects were observed in the regions where the penetration depth reduced.



Hybrid P-MIG

Figure 7-23: Longitudinal macrographs of hybrid P-MIG weld overlap start/stop region achieved with different L_{Ramp} and no arc finish slope

7.4 Discussion

7.4.1 Parametric study of hybrid laser-arc welding

7.4.1.1 Effect of laser-arc interactions on melt pool stability and weld profile

It was shown in section 7.3.1.1 that the stability of GMAW and HL-GMAW can be observed from the arc waveform and that they are affected by the WFS and welding speed. In GMAW, both CMT and P-MIG process variants are stable depending on the welding parameters used. However, in HL-GMAW, the factors and variables affecting the stability of the melt pool increases. The effect of laser power, welding speed, and WFS was studied using both CMT and P-MIG process variants in HL-GMAW.

Hybrid CMT

In hybrid CMT, melt pool instability was observed from the arc waveforms for all WFS and welding speeds studied apart from when using a WFS of 2 m/min and a welding speed of 0.5 m/min, despite the low amount of spatter. Video analysis of the hybrid CMT welds show that the melt pool instability is due to the laser keyhole and vapour plume being disturbed by the periodic change of forces from the arc when the arc ignites and short-circuits, as shown in Figure 7-24.

At a low WFS of 2 m/min, the re-ignition of the arc and sudden increase in arc pressure exerts a force on the molten metal, causing small surface ripples to form. These small surface ripples and oscillations typically do not affect the laser keyhole significantly. However, during the dip transfer short circuit cycle, the small increase in molten metal and surface ripples led to molten metal flow towards the laser keyhole, resulting in melt ejection and spatter due to interaction with the laser keyhole and vapour plume.

At a higher WFS of 8 m/min, the re-ignition of the arc exerts a larger force on the molten metal, pushing it away from the arc and towards the front of the laser keyhole. When the arc short circuits, the sudden decrease in arc pressure and balance of hydrodynamic forces causes the molten metal to flow back towards the centre of the melt pool. The oscillating flow of molten metal disturbs the laser keyhole opening, resulting in melt ejection and spatter due to interaction with the vapour plume, as shown in Figure 7-24.

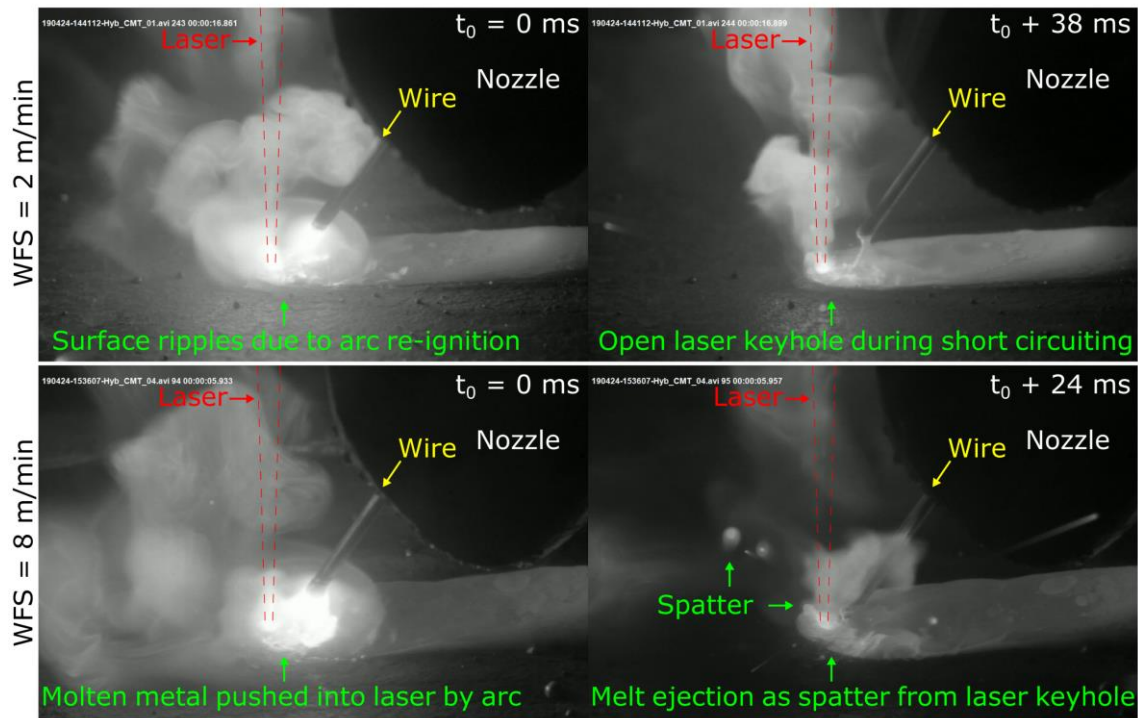


Figure 7-24: Video frame grabs showing hybrid CMT with different WFS, $P = 4$ kW, $v = 0.5$ m/min

At high welding speeds, the same phenomena occur where the re-ignition of the arc causes surface ripples and spatter to form across the range of WFS studied, as shown in Figure 7-25. However, an unstable phenomenon called wire chopping was observed at a WFS of 8 m/min, as shown in Figure 7-25. Wire chopping is where the wire melts prematurely but not completely and subsequently detaches as the next cycle of peak current occurs, as explained by Bunaziv et al. [120]. The wire chopping appeared to occur after the short-circuiting phase due to the proximity and interaction between the wire and molten metal surface. The increase in heat energy from the laser may also exacerbate the wire chopping phenomenon. Bunaziv et al. also observed this wire chopping phenomena when using hybrid laser - pulsed CMT. The authors found that wire chopping occurred more frequently with high welding speeds above 0.8 m/min, arc torch trailing configuration, and with pulsed CMT. The authors also found that wire chopping occurrence decreases when using a pulsed arc process variant and higher WFS due to the increased arc length. In these experiments, the wire detached onto the melt pool below resulting in an uneven weld surface upon solidification, as shown previously in Figure 7-6.

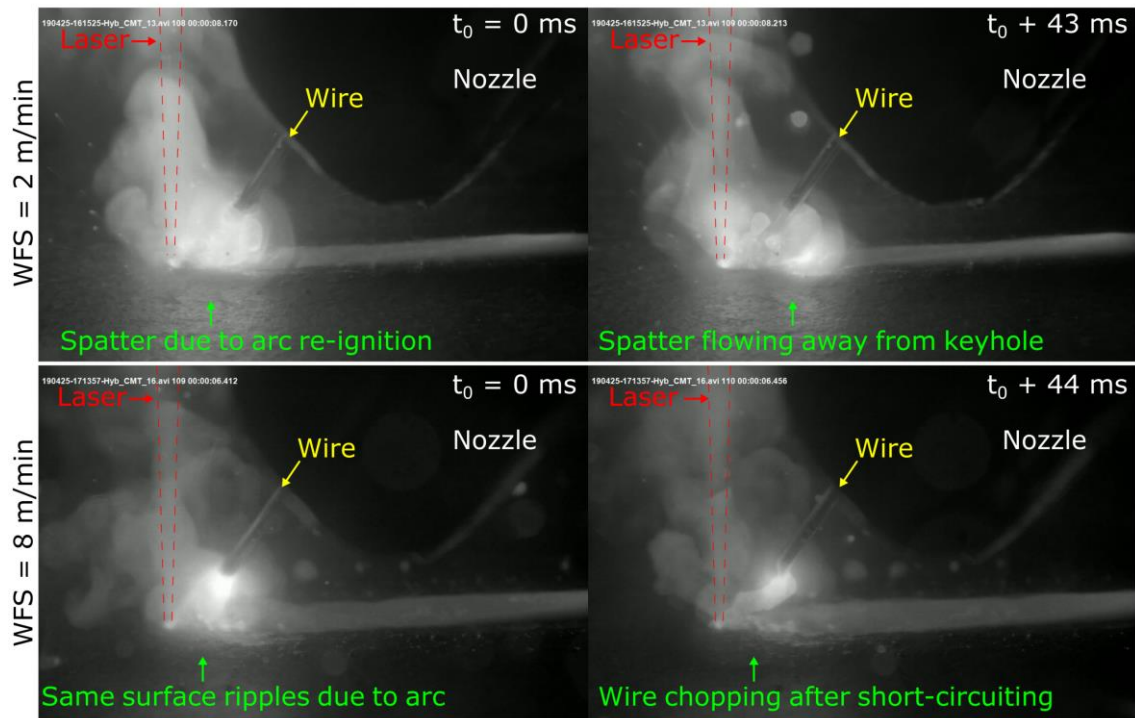


Figure 7-25: Video frame grabs showing hybrid CMT with different WFS, $P = 8$ kW, $v = 4$ m/min

In hybrid CMT, the welding process and melt pool was found to be unstable for many of the welding parameters studied according to the arc waveform and spatter observed from the videos despite many of the welds showing uniform and defect free weld surface profiles. The instability observed was also evident as porosity defects at the weld root in several weld samples, as shown previously by the transverse cross-sectional macrographs in Figure 7-9. Although CMT is known for its high weld quality and process stability in GMAW, the interactions of the dip transfer and short-circuiting phenomena with the laser keyhole and vapour plume can cause instabilities to occur in hybrid CMT. These instabilities can result in keyhole collapse and porosity at the weld root, as was observed in this study and shown previously in Figure 7-9. However, several authors, such as Bunaziv et al. [120], Frostevarg et al. [123], and Li et al. [149] have shown that hybrid CMT produces more stable welds with less defects when compared with other arc process variants. Welds without spatter were observed by the different authors when using the arc leading configuration as compared with arc trailing due to less interaction between the droplets and laser keyhole opening.

Hybrid P-MIG

In hybrid P-MIG, the stability of the melt pool appears to increase with WFS and current when observing the arc waveforms and videos. Video analysis of hybrid P-MIG welds show that at low WFS of 5 m/min, the melt pool instability is caused by the arc pulsing and droplet impingement on the laser keyhole, resulting in a surface ripples and a large volume of spatter, as shown in Figure 7-26. The formation of surface ripples on the melt pool due to droplet impingement in GMAW was also shown through numerical modelling of the fluid flow by Hu et al. [150]. The instability and surface ripples caused by the droplet impingement on the melt pool surface may also lead to and cause keyhole instability and collapse. Keyhole collapse resulting in weld root porosity was evident from Figure 7-10 at low WFS and welding speed.

At a higher WFS of 20 m/min, the increase in current, electro-magnetic force, and arc pressure results in a large depression in the surface of the molten metal and an increased laser keyhole opening. In both GMAW and HL-GMAW, the size of the surface depression is dependent on the WFS, due to the arc current, and welding speeds as was shown by Guen et al. [151]. The droplets of molten filler wire are fed directly into the open keyhole without disturbing the laser, resulting in significantly less spatter and a larger and more stable melt pool. An increase in keyhole stability with increasing arc power (higher WFS) was also observed by Xu et al. in HL-GMAW of aluminium [152].

However, at higher welding speeds, the surface depression and laser keyhole opening reduces when compared with low welding speeds at the same high WFS. Therefore, the laser keyhole opening is disturbed by the droplet impingement, causing melt pool instability and spatter, like at low WFS.

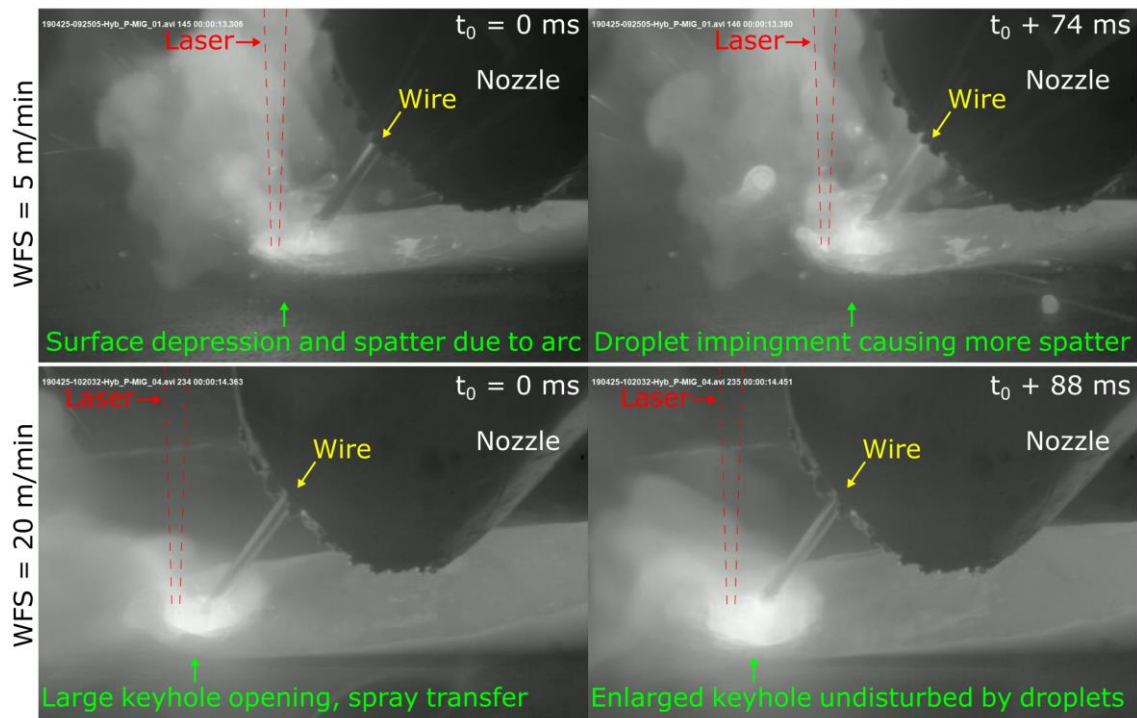


Figure 7-26: Video frame grabs showing hybrid P-MIG with different WFS, $P = 4$ kW, $v = 0.5$ m/min

For hybrid P-MIG, melt pool stability increases with WFS due to the increased electro-magnetic force and arc pressure creating a larger surface depression and the increasing the size of the laser keyhole opening. The increased laser keyhole opening minimises the effect of droplet impingement. The various interactions and synergic effect of the combination of a laser and arc source has been well reported in literature [115,116,121–124], as discussed in section 2.4.1. The combination of the laser and arc also increases the heat applied, allowing the arc to work better at higher welding speeds and improving droplet transfer and melt pool stability, as supported by the results from this study. Unlike hybrid CMT, hybrid P-MIG maintains a constant arc and droplet transfer mechanism, reducing melt pool instability.

7.4.1.2 Effect of arc on laser weld profile and penetration in HL-GMAW

In section 7.3.1.2, the change in weld profile of autogenous laser welds due to the addition of an arc source in HL-GMAW operated in either CMT or P-MIG process variants was shown. Improvements in both weld penetration and weld quality was observed when comparing HL-GMAW welds with autogenous laser welds. Despite the differences in droplet transfer mechanism between CMT and P-MIG, the effect of both process variants on the weld profile can be correlated to the additional heat input and electro-magnetic force supplied by the arc source.

An increase in penetration depth, weld width, and weld reinforcement was observed with the increase in additional heat input from the arc source, as was shown previously in Figure 7-11, Figure 7-12, and Figure 7-13, respectively. Therefore, the increase in weld dimensions is dependent on the increase in arc current, heat input, and electro-magnetic force rather than the process variant. However, the choice of process variant does affect the range of WFS that can be used due to limitations of the power source selected. Therefore, the range of additional heat input from the arc source and WFS under specific welding parameters, i.e., welding speed, depends on the process variant used.

The additional thermal energy from the arc source in HL-GMAW is not the only factor that contributes to the increase in weld dimensions. Other factors, such as the synergic effect of the laser and arc, arc pressure, droplet impingement forces and larger volume of metal also affect the melt pool dynamics and weld dimensions [117,151]. The large increase in weld penetration observed in hybrid P-MIG when using a high heat input ($v = 0.5$ m/min, WFS = 20 m/min) shown previously in Figure 7-10 was due to several different phenomena. As shown previously in Figure 7-26, an increase in surface depression and laser keyhole opening due to the increase in electro-magnetic forces and arc pressure was observed. The larger laser keyhole opening combined with the surface depression allows the laser beam to penetrate deeper into the workpiece without loss of energy, increasing the laser efficiency and resulting in a deeper penetration depth. The larger keyhole opening also enables the droplets of filler to enter the melt pool without disturbing the laser, increasing keyhole stability assuming that the dynamic forces are balanced and maintained.

7.4.2 Hybrid laser-arc weld overlap start/stop terminations

Section 7.3.2 showed the effect of different laser power ramp-down and arc finish slope distances on the weld overlap start/stop region surface, weld profile and the effect on defect formation within this area in HL-GMAW. The welding parameters were kept constant apart from the changes applied during the weld termination regime at the weld overlap start/stop region. A laser power of 5 kW, welding speed of 1 m/min, and a WFS of 6 m/min and 5 m/min, was used for hybrid CMT and hybrid P-MIG welds, respectively.

7.4.2.1 Effect of hybrid weld termination on weld overlap start/stop surface

Differences in weld surface profile was observed between GMAW and HL-GMAW weld overlaps achieved using CMT and P-MIG process variants, as shown previously in Figure 7-16 and Figure 7-19, respectively. These differences were due to variation in arc voltage, current and WFS at the weld overlap depending on the process variant used for both GMAW and HL-GMAW, as shown by the locally weighted average plots in Figure 7-27 and Figure 7-28, respectively.

In CMT, a small increase followed by a small decrease of arc voltage, current and WFS was observed in the second weld pass as it transitioned across the initiation point of the first weld pass (point B), as shown at the left of Figure 7-27. As the weld overlap occurs, the self-adaptive power source would adjust the WFS accordingly due to the change in arc voltage or arc length because of the weld reinforcement of the first weld pass. The change in WFS and amount of deposited material at the weld overlap explains the varying weld reinforcement at the weld overlap.

In P-MIG, the WFS for both the first and second weld pass was relatively constant, as shown in Figure 7-27. Therefore, the amount of deposited material from point B to point C would also be constant, showing little variation in the weld overlap as was observed. To maintain a uniform weld profile at the weld overlap start/stop region in GMAW, a suitable arc start slope and arc finish slope should be applied when the second weld pass overlaps the initiation of the first weld pass (point B), especially when using CMT process variant.

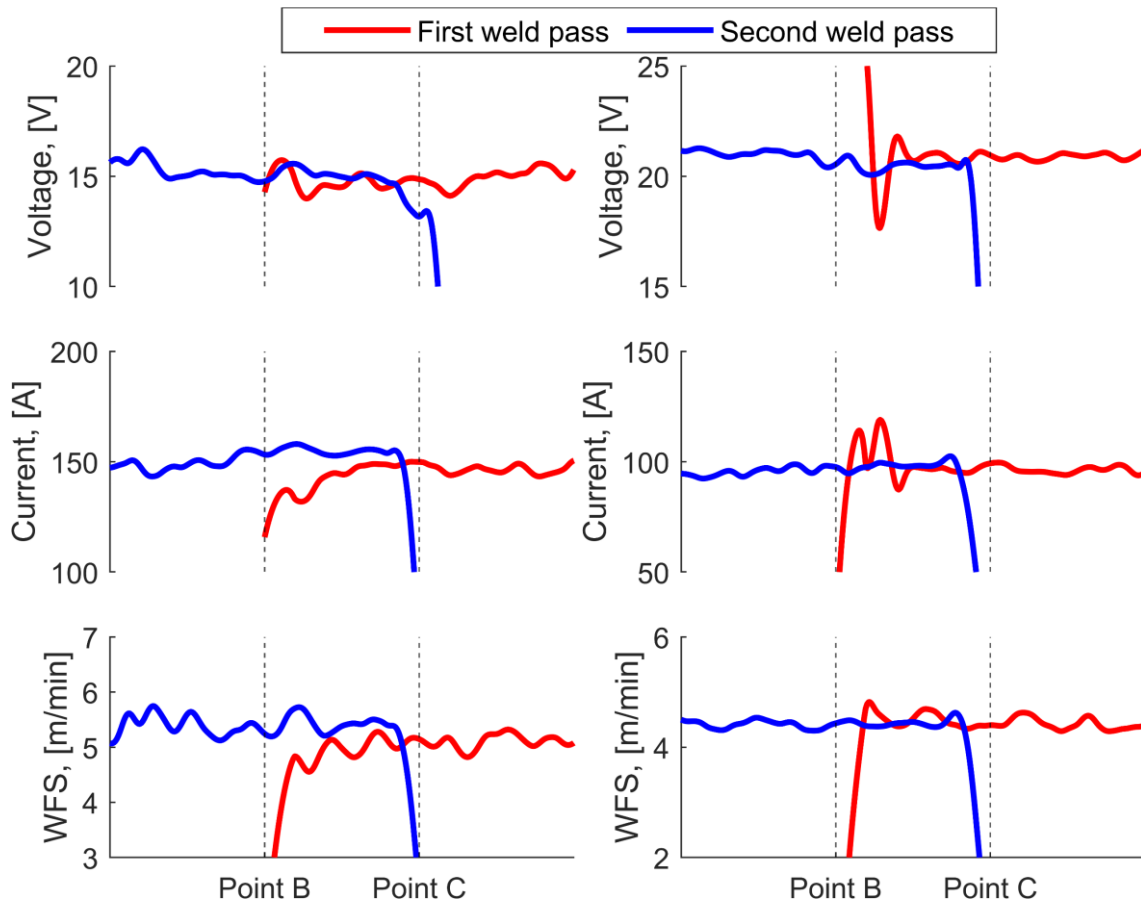


Figure 7-27: Locally weighted average of arc waveform data of GMAW weld overlap with an $L_{\text{slope}} = 1.67$ mm, left) CMT only, right) P-MIG only

In HL-GMAW, the arc voltage was relatively constant across the weld overlap but the arc current and WFS varied accordingly to adjust for the change in weld reinforcement at the weld overlap due to the first weld pass, as shown in Figure 7-28. The weld reinforcement of HL-GMAW is less than GMAW when using the same arc parameters, as was shown previously in Figure 7-16 and Figure 7-19 for CMT and P-MIG, respectively. Therefore, the self-adaptive power source made less adjustments and the WFS varies less at the weld overlap in HL-GMAW when compared with GMAW. To achieve a flush or level weld profile at the weld overlap and at the steady-state areas, adjustments to the weld initiation and termination should be applied.

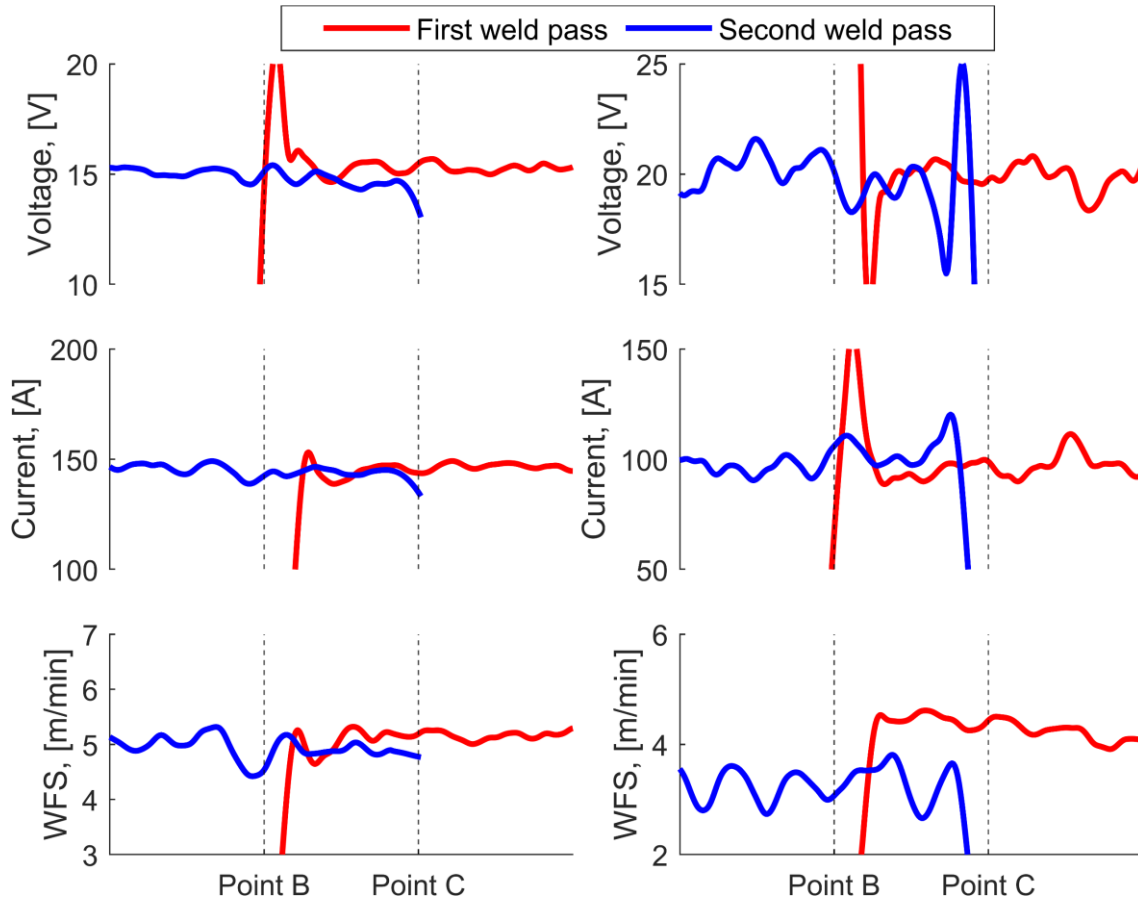


Figure 7-28: Locally weighted average of arc waveform data of HL-GMAW weld overlap with no laser ramp and a $L_{\text{slope}} = 1.67$ mm, left) hybrid CMT, right) hybrid P-MIG

In both hybrid CMT and hybrid P-MIG, weld craters and surface depressions at the termination point C remain unless a combination of laser power ramp-down and arc finish slope is applied. The size of the weld crater and surface depression reduces more with the increase in laser power ramp-down distance rather than the increase in arc finish slope distance for both hybrid CMT and hybrid P-MIG, as shown previously in Figure 7-17 and Figure 7-20, respectively. The weld crater size is an indication of the melt pool size prior to solidification. Therefore, the data obtained from these experiments show that there is a greater dependence of the melt pool size on the laser power rather than the energy supplied by the arc source in HL-GMAW. The effect of the arc finish slope distance has little influence on the weld crater and surface depression size unless a laser power ramp-down distance of 40 mm is applied.

7.4.2.2 Effect of hybrid termination on weld overlap start/stop weld profile and defect formation

The effect of laser power ramp-down on the weld overlap profile and defect formation in partial penetration autogenous laser welding was shown in Figure 7-21. The presence of shrinkage cavity defects and porosity at the weld overlap and termination point (point C) is likely to be caused by the rapid solidification of molten metal and keyhole instability. The small increase in penetration depth and shrinkage cavity defects at the weld overlap region with no laser ramp compared with the steady-state areas (before point B and after point C) suggests that the laser keyhole is less stable when welding over and remelting a previous weld pass. The small increase in penetration depth followed by the increase in shrinkage cavity defects at the weld overlap suggests that they are both correlated. Typically, an increase in weld penetration when remelting a previous layer is observed in laser welding due to the increased laser absorption by the rough weld surface of the first weld pass. A reduction in shrinkage cavity defect formation was observed at the weld overlap when a laser ramp-down distance of 40 mm was applied. This indicates that the laser keyhole is more stable when the laser power and laser keyhole depth reduces when welding over and remelting a previous weld pass. In autogenous laser welding, a reduction in laser power and penetration depth at the weld overlap start/stop region is beneficial to prevent over-penetration and the formation of shrinkage cavity defects.

In HL-GMAW, porosity was observed at the weld overlap start/stop region when using either CMT or P-MIG process variants when no laser power ramp-down was applied. Whereas shrinkage cavity defects were only present at the weld termination point when the weld was terminated abruptly. Like in autogenous laser welding, the severity and occurrence of these defects decreased with the reduction in penetration depth at the weld overlap when laser power ramp-down was applied. Therefore, it is necessary that the weld overlap distance is minimised, and a laser power ramp-down termination regime applied as soon as the weld intersects to avoid porosity and shrinkage cavity defects in autogenous laser welding and HL-GMAW weld overlap start/stops.

7.5 Conclusions

In this chapter, a parametric study was conducted in HL-AW using two different GMAW process variants, CMT and P-MIG. The effect of different welding parameters on factors, such as the weld process stability and weld penetration depth were studied. Further studies on the hybrid weld process termination at the weld overlap start/stop region was also performed. Different aspects of laser and arc termination procedures was incorporated and the effect of these on the weld profile and formation of weld termination defects were investigated.

- The use of different GMAW process variants and welding parameters has a significant effect on the weld pool stability in HL-GMAW. When using CMT, the welds are more stable at low WFS and welding speeds. Whereas, when using P-MIG, the weld stability increases with WFS and welding speed.
- The main causes of melt pool instability in HL-GMAW, using either CMT or P-MIG process variants, are droplet impingement and arc pressure fluctuations resulting in melt pool surface ripples. The droplet impingement and surface ripples interact with the laser keyhole opening, resulting in melt ejection and spatter due to interaction with the vapour plume. The disturbance of the laser keyhole at the surface of the melt pool can lead to keyhole instability, and subsequent collapse, resulting in weld root porosity and in some cases, shrinkage cavity defects.
- The increase in weld dimensions, such as penetration depth, weld width and weld reinforcement (bead height) can all be correlated with the additional increase in arc heat input from the arc source when combining a GMAW source with a laser source in HL-GMAW. The process variant does not affect the weld dimensions significantly, but it does limit the arc heat input applicable by the power source due to limitations of the WFS that can be used.

- A significant increase in weld stability and penetration depth was observed in hybrid P-MIG when using a high WFS of 20 m/min at a welding speed of 0.5 m/min due to the increase in weld surface depression and laser keyhole opening. The increase in surface depression and laser keyhole opening is caused by the higher arc current and deposition frequency due to the high WFS, which leads to an increase in arc heat input, arc pressure, and electro-magnetic forces. The larger keyhole opening allows the laser to penetrate further into the workpiece, increasing the laser efficiency and resulting in a deeper penetration. The larger keyhole opening also allows for droplets of filler to enter the melt pool without disturbing the laser, increasing the stability of the melt pool and keyhole.
- An uneven weld surface with excess weld reinforcement at the weld overlap and weld intersection can occur if the WFS at the weld initiation and weld overlap are not controlled properly. It is typically more severe in GMAW when compared with HL-GMAW, especially when using the CMT process variant.
- In partial penetration autogenous laser keyhole weld overlap start/stops, porosity at the weld root and shrinkage cavity defects were observed at the weld overlap region and termination point when the laser was terminated abruptly. However, these defects were only present at the weld overlap region but not at the single-pass steady-state regions or in the weld regions where the penetration depth began to reduce with the reduction of laser power. In HL-GMAW, only porosity was observed in the weld overlap start/stop region, but shrinkage cavity defects were still present at the termination point when the weld was terminated abruptly.

- For successful HL-GMAW termination using either CMT or P-MIG GMAW variants, the gradual reduction and closure of the laser keyhole is necessary through the application of laser power ramp-down. An arc finish slope is also necessary if the main contribution to the penetration depth is achieved by the increase in arc heat input and to provide a level weld surface profile.

Chapter 8

Overall discussion

8.1 Summary of key findings and further recommendations

The main aim of this research project was to investigate the causes of laser keyhole weld overlap start/stop defects and propose process-based mitigation methods to eliminate such defects as outlined in section 1.2.

The following findings from each topic studied in each chapter within this thesis identifies the causes of laser keyhole termination related defects and discusses the effect of different mitigation methods. Recommendations for practical applications from each chapter are also included.

Although the welds conducted within this thesis are all bead-on-plate welds, the process dynamics, keyhole and melt pool dynamics would be transferable to both longitudinal and circumferential butt-joint welds. However, further considerations of the differences in stress distribution, cooling profile, and gravitational effects are necessary when transferring the outcomes to circumferential butt-welds conducted in 5G all position welding.

8.1.1 Influence of different laser termination regimes

A preliminary study of different laser termination regimes on the weld profile, keyhole closure, and weld crater formation of longitudinal welds were investigated and assessed in Chapter 4. The laser termination regimes applied in the study were laser defocusing, laser power ramp-down, and a combination of the two. The chapter provides an insight into the effect of the different laser termination regimes and highlights points for consideration when applying them.

- Both laser defocusing and laser power ramp-down termination regimes enable successful keyhole closure without any form of keyhole collapse when transitioning from full penetration keyhole mode towards partial penetration conduction mode welding. Successful laser weld terminations were achieved without significant defects, such as porosity and weld cavities and craters when using a variety of weld parameters.
- The change in weld profile, such as the penetration depth and weld width, during application of either termination regime depends primarily on the power density and end laser spot diameter. Therefore, control of the weld profile during laser termination is possible using different welding setups. When laser defocusing is applied, a transition from keyhole mode welding towards conduction mode welding regime occurs below a laser power density of 0.8 kW/mm^2 , or below a D/W ratio of 1 within the range of interaction times studied. However, this transition does not occur in the laser power ramp-down termination regime.
- Root sagging defects and weld surface dropout or undercut were observed when leaving full penetration in 10 mm thick plates when a laser power ramp-down termination regime was applied. These defects occur because of the melt flow and surface tension forces due to the lack of heat at the keyhole root and results in D/W ratio (depth-to-width ratio) above a value of 2, as discussed and shown previously in Figure 4-15 and Figure 4-16.

- The simplest method to mitigate these root sagging defects that occur when leaving full penetration is to use further optimised initial steady-state welding parameters with a higher heat input, i.e., higher power or lower welding speeds. These defects can also be mitigated by combining the laser power ramp-down termination regime with laser defocusing achieved by movement of the laser head. The combination of the two laser termination regimes results in a higher heat input due to the slower traverse of the laser beam when laser defocusing.
- However, the root sagging defects seen in Chapter 4 were from BOP welds conducted in the 2G welding position. In a butt joint weld or in a 1G or 5G welding position, the presence of a joint gap and gravity will have a significant influence and promote the formation of root sagging defects. Therefore, further research on root sagging defect mitigation when leaving full penetration with different joint gap distance and at different welding positions will be useful.
- Other benefits of combining the two laser termination regimes are that it improves the weld surface profile and prevents weld crater formation when compared with laser power ramp-down alone. Sufficient molten metal is necessary to fill the weld crater during laser termination and is provided by the increased melting of the workpiece surface due to the increased laser spot diameter during laser defocusing.

8.1.2 Effect of inter-pass temperature at weld overlap start/stop region

Chapter 5 investigates the effect of varying inter-pass temperatures, achieved by replicating different weld circumferences on flat plates, on weld microstructure and weld overlap start/stop defect formation. The causes of weld overlap start/stop defects in laser keyhole welding when the laser is initiated and terminated abruptly were identified in this Chapter. A laser defocusing termination regime was implemented to mitigate the laser termination defects.

- No significant laser initiation defects, such as porosity or spatter was observed when the laser was initiated at full power. However, excess weld reinforcement (protrusion of weld metal) was present due to the thermal expansion and movement of molten metal solidifying. When the laser initiation point is overlapped by the intersecting weld, the weld reinforcement is reduced, and the weld profile becomes more uniform. Therefore, laser initiation at full power does not pose a significant issue in circumferential welding but further control of the starting parameters and application of a laser power ramp-up would be beneficial to achieve a completely uniform weld overlap start/stop region.
- Abrupt laser termination results in more significant and severe defects, such as underfills in the form of deep weld craters, pores, and solidification cracking because of keyhole instability and collapse when compared with abrupt laser initiation.
- Laser termination defects were present regardless of the inter-pass temperature, indicating that keyhole collapse is driven by keyhole dynamics rather than the metallurgical aspects, such as the thermal cycle during abrupt laser termination.

- Different thermal cycles can lead to a reduced solidification rate, enabling entrapped gases from the collapsed keyhole to escape but it does not prevent the formation of weld underfill defects at the top and root surface. Higher inter-pass temperature would result in thermal cycles which could be detrimental for mechanical strength due to the formation of microstructure with softer and coarser phases. Therefore, the thermal cycle and cooling rate need to be controlled at the weld overlap, especially for offshore steel structural applications. For thick section welding, the use of preheat or post weld heat treatment may be necessary as well. These factors will also need to be considered.
- Successful laser keyhole closure was achieved through the application of a laser defocusing termination regime. No internal defects, such as porosity or voids were present indicating that the keyhole closed gradually without collapsing. The penetration depth and keyhole gradually reduced, leaving a small depression in the form of a shallow weld crater on the top surface which indicates that further optimisation of the process parameters is required to fully achieve a defect free laser circumferential weld.
- Although successful keyhole closure was achieved using the laser defocusing termination regime, the formation of surface ripples at the transition from full penetration keyhole mode towards partial penetration conduction mode welding was observed. Therefore, further investigation on the effect of melt pool dynamics, melt flow direction and factors affecting these phenomena is required.

8.1.3 Influence of deoxidising elements in steel composition

Findings from both Chapter 4 and Chapter 5 indicated that the transition from full penetration keyhole mode welding towards partial penetration conduction welding can cause melt pool instabilities, especially when the laser defocusing termination regime is applied. Therefore, to identify the cause of these melt pool instabilities, different S355 structural steel plates with a significant difference in elements that affect surface-active elements, such as oxygen were tested in Chapter 6. The effect of certain alloying elements on melt pool dynamics and surface tension flow was described previously in sections 2.6 and was also found to have a significant impact on the formation of weld overlap start/stop defects.

- The different amounts of deoxidising elements in low alloy carbon steels, such as manganese and silicon, affect oxygen ingress and slag formation in the melt pool during laser processing. These phenomena can affect the keyhole and melt pool dynamics, such as vaporisation recoil pressure, Marangoni flow and surface tension effects, resulting in melt pool instability, gas entrapment, and porosity formation. The severity of these phenomena on defect formation is increased by the larger melt pool during laser defocusing when compared with laser power ramp-down termination regimes, leading to the formation of porosity clusters.
- Application of either laser termination regimes on mild steel with higher concentrations of deoxidisers, such as manganese and silicon, can lead to successful, defect-free circumferential weld overlap start/stops. The weld overlap start/stop region obtained with these steel plates when applying the laser defocusing termination regime were more uniform and without surface ripple defects as compared with the welds observed previously in Chapter 5. Therefore, these surface ripple defects are caused by the opposing melt pool dynamics, Marangoni flow and surface tension effects when laser defocusing.

- The cause of porosity was associated with the change in melt pool dynamics and flow due to oxygen ingress. Although the effect of shielding gas on the porosity formation was simply tested for one case within this Chapter, it did affect the porosity formation and improve the weld surface profile a little. Therefore, further studies incorporating shielding gas and different plate compositions is suggested, especially during the application of different laser termination regimes.
- Variation in the chemical composition of structural steel grades needs to be more tightly controlled for laser welding applications as they have a significant effect on weld melt pool behaviour and defect formation. The presence of deoxidising elements is essential to prevent gas formation and thereby, porosity. Significant variation in chemical composition of different plate batches were also found to affect melt pool dynamics and result in varying weld penetration depth during steady-state welding when using the same process parameters.

8.1.4 Study of hybrid laser-arc weld termination regimes

In Chapter 7, the effect of different HL-GMAW parameters using two different GMAW process variants, CMT and P-MIG, on factors, such as the weld process stability and weld penetration depth were studied. Mitigation methods of hybrid laser-arc termination defects using different combinations of hybrid laser-arc termination regimes, such as laser power ramp-down and arc finish sloping (reduction of arc current prior to arc termination), were also investigated.

- The increase in weld dimensions, such as penetration depth, weld width and weld reinforcement (bead height) can all be correlated with the additional increase in arc heat input from the arc source when combining a GMAW source with a laser source in HL-GMAW. The process variant does not affect the weld dimensions significantly, but it does limit the arc heat input that can be applied by a power source due to limitations of the WFS that can be used. Therefore, the selection of the process variant to be used depends on the weld profile requirements, i.e., penetration depth and weld reinforcement.
- The main causes of melt pool instability in HL-GMAW, using either CMT or P-MIG process variants, are droplet impingement and arc pressure fluctuations resulting in melt pool surface ripples. The disturbance of the laser keyhole at the surface of the melt pool can lead to keyhole instability, and subsequent collapse, resulting in weld root porosity and in some cases, shrinkage cavity defects. When using CMT, the welds are more stable at low WFS and welding speeds. Whereas, when using P-MIG, the weld stability increases with WFS and welding speed.

- A significant increase in weld stability and penetration depth was observed when using the P-MIG variant with a high WFS of 20 m/min at a welding speed of 0.5 m/min in HL-GMAW. These welding parameters caused the laser keyhole opening to increase due to the combined effects of the higher arc energy input and arc pressure. The larger keyhole opening allows the laser to penetrate further into the workpiece and prevents any droplets of filler from disturbing the laser and vapour plume. The increased stability and penetration with these parameters are beneficial for thick-section structural welding applications.
- In HL-GMAW, only porosity was observed in the weld overlap start/stop region, but shrinkage cavity defects were still present at the termination point when the weld was terminated abruptly. Therefore, it is necessary that the weld overlap distance is minimised, and a laser power ramp-down termination regime applied as soon as the weld intersects to avoid porosity and shrinkage cavity defects in HL-GMAW weld overlap start/stops.
- Shrinkage cavity defects were not observed in any of the full penetration weld overlaps performed with autogenous laser keyhole welding in the previous Chapters apart from at the weld termination point. Therefore, it is likely that shrinkage cavity defects are more prevalent in partial penetration welds, as was also seen in Figure 2-5 in section 2.1.2, due to the higher solidification from the surrounding base metal.
- Successful HL-GMAW terminations with either CMT or P-MIG GMAW process variants are dependent on the gradual reduction and closure of the laser keyhole, which is made possible with the application of laser power ramp-down. Further studies of HL-GMAW termination regimes for a wider range of weld process parameters and working envelope is necessary.

8.2 Contributions and impact of findings

The contribution from this research provides a deeper understanding of the formation and mitigation of laser keyhole termination related defects in both autogenous laser and hybrid laser-arc welding processes. The following provides the main contributions and potential impacts from this research.

8.2.1 Weld parameters that affect weld profile during weld termination

The change in weld profile, such as the penetration depth and weld width, during application of either termination regime in autogenous laser keyhole welding depends primarily on the power density and laser spot diameter at the weld termination point. Therefore, control of the weld profile during laser keyhole termination is possible using a combination of different laser termination regimes and welding equipment setups. Models and algorithms could be developed using laser power density to determine the optimum laser termination regime parameters required for a given weld design specification or weld requirement.

In hybrid laser-arc welding, the weld profile is affected by both the laser and arc source, but also by the amount of deposited filler material. In Chapter 7, the findings show that successful weld terminations were possible using a combination of laser power ramp-down termination parameters for one set of steady-state welding parameters. However, it is necessary to develop the working envelope further, especially for the steady-state welding parameters where the significant increase in penetration depth was achieved via the increase in arc heat input. Therefore, the arc finish slope parameters would be more important for hybrid laser-arc weld termination when using welding parameters with a higher wire feed speed.

8.2.2 Impact of material chemical composition

The large range of maximum alloying elements in S355 structural steels can lead to significant weld variability and defect formation when it comes to laser welding processes due to oxygen ingress. From a manufacturing point of view, it may not be possible to follow set welding specifications using the same laser welding parameters on different batches of S355 plates because of this. Therefore, as mentioned previously, further study on shielding gas and different material chemical composition plates is suggested. Otherwise, the chemical composition and processing routes of structural steel grades need to be more stringent for laser welding applications as they have a significant effect on weld melt pool behaviour and defect formation. Precise control of the termination regime parameters and material chemical composition is also necessary to avoid the formation of other defects, such as root sagging and porosity formation.

In hybrid laser-arc welding, the addition of shielding gas and filler material via the arc source could be utilised to offset and mitigate the issues with the varying chemical composition of the structural steel plates observed in autogenous laser keyhole welding. Filler material with a larger percentage of deoxidising elements could be beneficial in mitigating the afore mentioned issues.

8.2.3 Successful weld terminations in weld overlap start/stops

Successful autogenous laser keyhole and hybrid laser-arc weld terminations were achieved using a range of weld termination regimes and parameters across a wide process window in structural steel plates between 8 – 12 mm thickness. Formation of weld overlap start/stop defects were identified, and process-based methods proposed to mitigate such defects.

High productive welding processes, such as laser keyhole and hybrid laser-arc welding of thick section structural steels can lead to increased productivity and manufacturing cost savings when compared with conventional arc welding processes. Therefore, the knowledge developed from this research would enable and promote the wider adoption of laser keyhole and hybrid laser keyhole welding applications for thick section structural steels.

Chapter 9

Conclusions and future work

In autogenous laser keyhole and hybrid laser-arc welding, the main cause of defects at the weld overlap start/stop region of a circumferential weld is keyhole instability and collapse followed by the rapid solidification of the melt pool, especially when the laser is terminated abruptly. Laser keyhole initiation related defects when initiating at full laser power does not pose a significant issue, especially in circumferential welding as the initiation point is overlapped by the intersecting weld seam. These weld overlap start/stop defects can be successfully mitigated by adopting a laser or hybrid laser-arc weld termination regimes for a range of different welding parameters.

The weld profile of the weld overlap start/stop region during laser termination depends on the laser power density and laser spot diameter for either laser power ramp-down or laser defocusing termination regimes. Therefore, more sophisticated models and control algorithms for laser keyhole weld termination regimes can be developed and be utilised for different optical setups using laser power density as a control variable. Further studies into process modelling of laser weld termination using different termination regimes is necessary and results from this research could provide a starting point.

The difference in weld profile and thermal cycle of the two laser termination regimes studied also affects the residual stresses. Therefore, further studies on the effect of different laser termination regimes on residual stresses is required as it may adversely affect the structural integrity and fatigue performance.

The chemical composition and percentage of deoxidising elements of steel plates can have a significant impact on laser processing and defect formation, especially during weld termination. An insufficient percentage of deoxidising elements in the base material can lead to oxygen ingress and slag formation, severely affecting the melt pool and flow dynamics, especially in the absence of appropriate shielding gas. The addition of filler with a higher percentage of deoxidising elements in hybrid laser-arc welding could be a solution to the variability in the plate material composition. However, further study is needed to investigate the effect of varying plate and filler material chemical composition in hybrid laser-arc welding.

Although the welded thicknesses of 8 – 12 mm within this thesis are not comparable to those used in the manufacture of offshore wind turbine support structures, it still provides a significant improvement regarding penetration depth and welding speed. Currently, the research and advancements in laser welding and hybrid laser-arc welding processes has shown that thicknesses of up to 60 mm and above is possible using various hybrid laser configurations or by using a narrow-gap and multi-pass welding approach. Therefore, the research from this thesis can facilitate and enable laser and hybrid laser-arc multi-pass welding approach for circumferential welding of thick section steels.

However, for significant thicknesses of 100 mm and above, it would be more productive and easier to utilise electron beam welding, which negates the need for multi-pass welding. Although, consideration regarding the vacuum or reduced pressure environment, preheating and the cooling rate would be required to avoid cracking and adverse microstructure in these thick welds. In the near future, a transition from conventional submerged arc welding to laser, hybrid laser-arc, or even electron beam welding may occur in the pursuit of welding thick section tubular steels with higher productivity for the offshore wind industry.

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$$D_{Focal_x} = \sin(\theta) \times D_{Focal} = 7.02 \text{ mm}$$

$$D_{Focal_y} = \cos(\theta) \times D_{Focal} = 39.83 \text{ mm}$$

The change in X direction due to the increase in focal length needs to be subtracted from the two weld overlap lengths to determine the position of the defocused laser in the X direction for each case:

$$\overrightarrow{OP_{1_x}} = L_{\overrightarrow{BC}} - D_{Focal_x} = 32.98 \text{ mm} \mid 72.98 \text{ mm}$$

The position of the laser in the Y direction is the same as the change in Y direction due to the increase in focal length for both weld overlap lengths:

$$\overrightarrow{OP_{1_y}} = D_{Focal_y} = 7.02 \text{ mm} \mid 7.02 \text{ mm}$$

The distance $\overrightarrow{OP_1}$ for both cases can now be calculated using the Pythagorean theorem:

$$\overrightarrow{OP_1} = \sqrt{\overrightarrow{OP_{1_x}}^2 + \overrightarrow{OP_{1_y}}^2} = 51.71 \text{ mm} \mid 83.14 \text{ mm}$$

The speed of the laser beam in the X welding direction can now be calculated:

$$v_{beam} = \frac{L_{\overrightarrow{BC}} \times v}{\overrightarrow{OP_1}} = 0.39 \text{ m/min} \mid 0.48 \text{ m/min}$$

Appendix B

Laser power ramp-down program

The following loop was developed to reduce the laser power at a specified rate when called. This sub-program runs in parallel with any other program.

Certain registry values and analogue and digital inputs and outputs are already programmed and used across multiple other programs. Therefore, to avoid corrupting the other programs, these values were not changed.

Comments for the different registry values and analogue inputs and outputs and how each line in the program works is also included.

Program:

```

1:  R [53] = 90
2:  R [54] = 125.71
3:  R [55] = R [5]
4:  WAIT DO [32] = ON
5:  LBL [1]
6:  R [55] = R [55] - R [53]
7:  AO [5] = R [55]
8:  IF R [55] <= R [54], JMP LBL [2]
9:  WAIT 0.1(sec)
10: JMP LBL [1]
11: LBL [2]
12: DO [2] = OFF
13: DO [6] = OFF
14: WAIT DI [6] = OFF
15: DO [1] = OFF
16: WAIT DI [1] = OFF
17: DO [32] = OFF

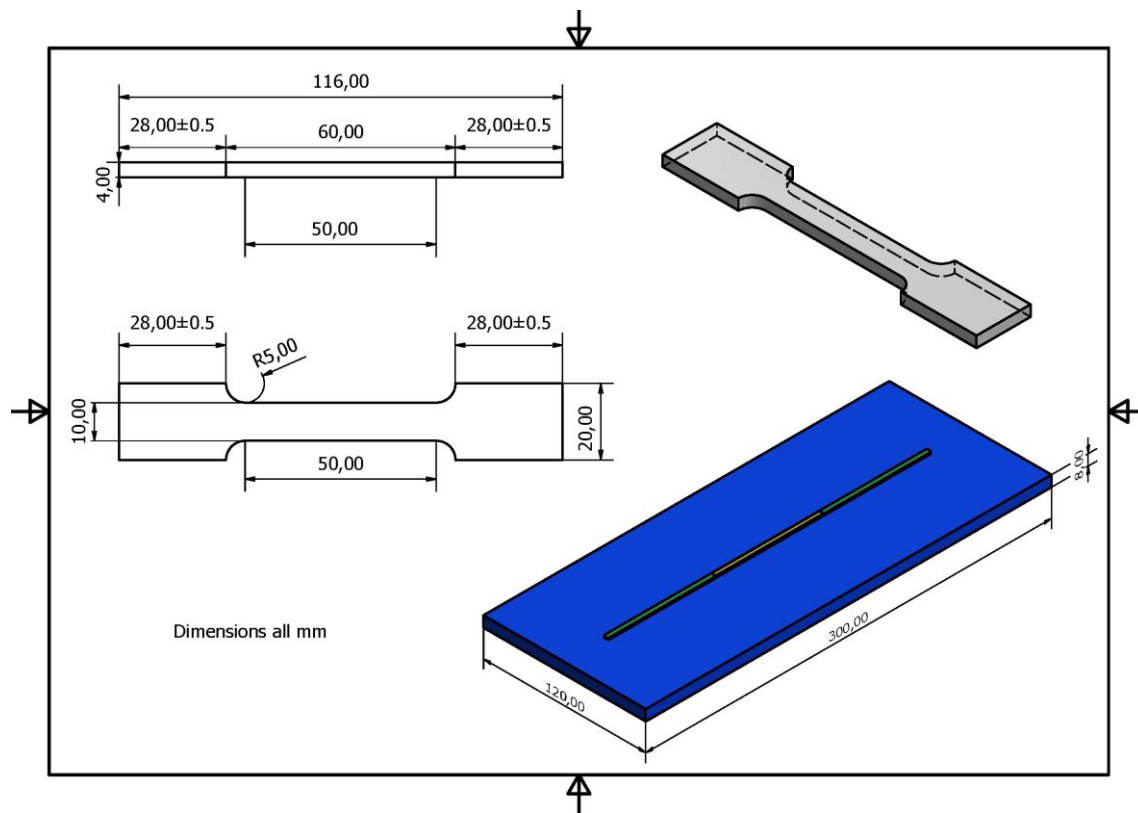
```

Comments:

- 1: R [53] is the analogue output value to reduce per loop, which is equivalent to a certain laser power.
- 2: R [54] is equivalent to 0 kW laser power. The value of 125.71 is the analogue output value and is a constant that is used to modify the registry value for the laser power output. Therefore, this has not been changed.
- 3: R [5] is the set laser power output used in other programs. To avoid changing this, an empty registry value, R [55] was used.
- 4: DO [32] is a digital output. The program only continues when this digital output is set to ON.
- 5: LBL [1] is the start of the loop
- 6: Reduces set laser power output registry value R [55] by the value set in R [53]
- 7: AO [5] is the analogue output value that is used by the laser power source.
- 8: IF function to terminate the loop and jump to LBL [2] when the set laser power output registry value reaches the set value in R [54]
- 9: Duration between loops, was set at 0.1 seconds to improve accuracy of the laser power reduction and output by allowing the laser source to adjust.
- 10: Jumps to LBL 1, restarts the loop
- 11: LBL [2] position IF function jumps too when conditions are met.
- 12: The following digital outputs is to turn off laser emission. DO [2] is the digital output to switch the laser ON or OFF

Appendix C

Tensile specimen design



Appendix D

Codes for tensile DIC data extraction and yield strength analysis

Global stress-strain

```

close all
clear all
clc
%% save variables at end of computation
% A1_B_variables.Stress = Stress;
% A1_B_variables.Elongation = Elongation;
% A1_B_variables.YieldStress_global = YieldStress_global;
% A1_B_variables.UTS_global = UTS_global ;
% A1_B_variables.elongation_rupture_global =
elongation_rupture_global;
% A1_B_variables.numfiles = numfiles;
% A1_B_variables.numpoint = numpoint;
% A1_B_variables.p = p;

% save ('A1-B_variables.mat','-struct', 'A1_B_variables')

%% Start new analysis
% Text file
filename = 'LOAD_A1-C.txt';

opts = detectImportOptions(filename);
opts.SelectedVariableNames = 'ReferenceStep_0';
load = table2array(readtable(filename,opts));
stepno = size(load,1);
numfiles = 700; % Number of steps
numpoint = 1100; % number of point extracted for the DIC data

% Extraction of data from the step files
stepdata = cell(1,numfiles);
for k = 1:numfiles
    stepname = sprintf('Step_%d.txt', k);
    opts = detectImportOptions(stepname);
    VariableNames = cellstr(opts.SelectedVariableNames);
    stepdata {1,k} = readtable(stepname,opts);
end
% Stress values
Stress=load(2:stepno)*1000/(4*10); % To be filed manually using the
load provided by the Istra software
[M,I] = max(Stress,[],1);
% numfiles = I;
E=210; % Young's modulus to be given by the user
%%Determintation of gauge length to use
initial_gauge_legnth=36; %To be determined by the code user (depend on
the specimen geomtery)
GL=1;
L=1;

number_gl=9; %needs to be an odd number number of gauge length
extracted (depend on the coupon width and the resolution of the DIC
data
z = 6; % Gauge length to plot

```

```

%% Open the text file.
% fileID = fopen(myfilename,'r');
X=zeros(numpoint,numfiles); % X coordinate of all points, for all
steps
XX=zeros(1,1,numfiles); % X coordinate of all points, distributed in
one matrix for each step
x=zeros(numpoint,numfiles); % pointer provided by Istra indicating the
relative position of each point in the x direction for each step
xx=zeros(numpoint,1); % x pointer for one step
Y=zeros(numpoint,numfiles);
YY=zeros(1,1,numfiles);
y=zeros(numpoint,1);
yy=zeros(numpoint,1);
% Data extraction
for H=1:numfiles
    Data=table2array(stepdata{1,H});
    Strain(:,H)=Data(1:numpoint,38); % Strain for all points and all
steps in one D matrix
    X(:,H)=Data(1:numpoint,3);
    xx(:,H)=Data(1:numpoint,1);
    Y(:,H)=Data(1:numpoint,4);
    yy(:,H)=Data(1:numpoint,2);
end
% Distribution of point in multi dimensional matrix (required to use
contourf function
for H=1:numfiles
    for i=1:numpoint
        XX(xx(i,H),yy(i,H),H)=X(i,H);
        YY(xx(i,H),yy(i,H),H)=Y(i,H);
        SStrain(xx(i,H),yy(i,H),H)=Strain(i,H);
    end
end
% Determination of matrix characteristics
numlines=max(xx);
numlines=numlines(numfiles);
numcolumn=max(yy);
numcolumn=numcolumn(numfiles);
clear F W
figure
g=1;
j=1;
%% Calculation of the YS for each point
for p=1:numlines
    for q=1:numcolumn
        A=mean(SSStrain(p,q,1:10));
        clear F plot_strain
        for t=1:numfiles
            W(t)=E*SSStrain(p,q,t)-E*(A+2);
            plot_strain(t)=SSStrain(p,q,t);
            if Stress(t) < W(t)
                F(t)= 0;
            else
                F(t)= Stress (t);
            end
        end
        YS(p,q)=max(F);
    end
end
if YS(p,q) >= (0.95*max(Stress)) % YS above 90% of the UTS measured
during this test will be removed to
% avoid numerical issues. The limit of 90% can be modified by the user

```

```

        YS(p,q)=NaN;
    end
    %% Results plotting
    % Especially when using the code for a new specimen, it is important
    to
    % check the aspect of the stress strain curve obtained. figures of 4 x
    4
    % plots will be provided by the code, the value of g indicates the
    plotting frequency
    if g==10000
        if j<=16
            subplot(4,4,j)
            plot(plot_strain,Stress,plot_strain,W)
            ylim([0 400]) % range of load obtained during the test
        title(['Position x=' num2str(XX(p,q,1)) ' y=' num2str(YY(p,q,1))])
        g=0;
        j=j+1;
        else
            j=1;
            figure('PaperPosition',[.2 .2 15 15])
            subplot(4,4,j)
            plot(plot_strain,Stress,plot_strain,W)
            ylim([0 600]) % range of load obtained during the test
            g=0;
            j=j+1;
        end
    else g=g+1;
    end
end
end
%% Remove non physical data
% Remove X and Y equal to 0
[R,P,Q]=size(XX);
for r=1:R
    for p=1:P
        for q=1:Q
            XXX(r,p,q)=XX(r,p,q);
            YYY(r,p,q)=YY(r,p,q);
            if XXX(r,p,q)==0
                if YYY(r,p,q)==0
                    XXX(r,p,q)=NaN;
                    YYY(r,p,q)=NaN;
                end
            end
        end
    end
end
[R,P]=size(YS);
for r=1:R
    for p=1:P
        if YS(r,p)==0
            YS(r,p)=NaN;
        end
        if SStrain(r,p,numfiles)==0
            SStrain(r,p,numfiles)=NaN;
        end
    end
end
end
end

```

```

%% Rotation and translation of the coordinate
% This is to obtain straight specimen in the map
[R,P,Q]=size(XX);
p=floor(P/2); % this centering is based on the centre line of the
sample disganted by the absciss p
% calculation of the rational matrix
X_a=min(YYY(:,p,1));
X_b=max(YYY(:,p,1));
Y_a=min(XXX(:,p,1));
Y_b=max(XXX(:,p,1));
A=(Y_b-Y_a)/sqrt((Y_b-Y_a)^2+(X_b-X_a)^2);
B=(X_b-X_a)/sqrt((Y_b-Y_a)^2+(X_b-X_a)^2);
Rot=[B,-A;A,B];
Rot=[1,0;0,1]; % To be used if no rotation is wanted
%% Calculation of the new coordinates
for i=1:numfiles
Cor=[X(:,i)';Y(:,i)'];
XY=Rot*Cor;
Xr(:,i)=XY(1,:); % new X as 1D matrix (all points, all steps)
Yr(:,i)=XY(2,:); % new Y as 1D matrix (all points, all steps)
end

XXr=zeros(R,P,Q); % reorganisation of the Xr with 1 dimention for each
step
YYr=zeros(R,P,Q); % reorganisation of the Xr with 1 dimention for each
step
for H=1:numfiles
for i=1:numpoint
XXr(xx(i,H),yy(i,H),H) = Xr(i,H);
YYr(xx(i,H),yy(i,H),H) = Yr(i,H);
end
end

%% Calculation tensile properties
% extraction gauge lentgh
n_gl=(number_gl-1)/2;
[R,P,Q]=size(YYr);
r=floor(R/2); %
p_1=floor(P/4)*3-1-n_gl; %first gauge length
p_2=floor(P/4)*3-1+n_gl; %last gauge length

while GL<initial_gauge_legnth
GL=sqrt((YYr(r-L,floor(P/2),1)-YYr(r+L,floor(P/2),1))^2+(XXr(r-
L,floor(P/2),1)-XXr(r+L,floor(P/2),1))^2);
L=L+1;
end
for p=p_1:p_2
total_length=sqrt((YYr(r-L,p,1)-YYr(r+L,p,1))^2+(XXr(r-L,p,1)-
XXr(r+L,p,1))^2);
if isnan(total_length)
else
for i=1:numfiles
Gauge_length(i,p)=sqrt((YYr(r-L,p,i)-YYr(r+L,p,i))^2+(XXr(r-L,p,i)-
XXr(r+L,p,i))^2);
end
end
end
Gauge_length=Gauge_length(:,p_1:end);

```

```

% Calculation elongation and YS for each gauge length
for p=1:number_gl
    clear F
    for i=1:numfiles
        Gauge_strain(i,p)=-(Gauge_length(1,p)-
        Gauge_length(i,p))/Gauge_length(1,p);
        Elongation(i,p)=-100*(Gauge_length(1,p)-
        Gauge_length(i,p))/Gauge_length(1,p);
    end

    row = find(Stress(:,1)>= 300);
    row = row(1,1);
    YM(:,p) = Stress(row,1)/Elongation(row,p);
    for i=1:numfiles
        W(i,p)=YM(1,p)*Elongation(i,p)-YM(1,p)*0.2;

    if Stress(i) < W(i,p)
        F(i)= 0;
    else F(i)= Stress(i);
    end
end
YieldStress_global(p)=max(F);
elongation_rupture_global(p)=Elongation(numfiles,p);
end
YieldStress_global
elongation_rupture_global
YS_global=mean(YieldStress_global)
Elongation_rupture_global=mean(rmmissing(elongation_rupture_global))
UTS_global=max(rmmissing(Stress))

Stress=Stress(1:numfiles);
for p=1:number_gl
    subplot(1,number_gl,p)
    plot(Elongation(:,p),Stress,Elongation(:,p),W(:,p))
    xlim([0 15])
    ylim([0 600])
    grid on
    grid minor
end
figure
fig = tiledlayout(1,1,'TileSpacing','Compact','Padding','Compact');
nexttile

Stress=Stress(1:numfiles);

plot(Elongation(:,z),Stress,Elongation(:,z),W(:,z))
xlim([0 25])
ylim([0 600])
xlabel('Elongation [%]')
ylabel('Engineering Stress [MPa]')

grid on
grid minor

%exportgraphics(fig,'Global_SS_example.png','Resolution',1000)

```

Contour map code

```
%Clear previous data
close all
clear all
clc

%Start new analysis
Loadfilename = 'LOAD_A1-C.txt'; % Name of text file
opts = detectImportOptions(Loadfilename);
opts.SelectedVariableNames = 'ReferenceStep_0';
Loadfile = table2array(readtable(Loadfilename,opts));
steps = size(Loadfile,1)-10;
numfiles = 410; % Number of steps to analyse

% Extraction of data from the step files
mydata = cell(1, numfiles);
for k = 1:numfiles
    myfilename = sprintf('Step_%d.txt', k);
    mydata{k} = importdata(myfilename);
end
% Finds lowest numpoint value of a step
datasize = zeros(size(mydata));
for k = 1:numfiles
    datasize(1,k) = size(mydata{1,k}.data,1);
end
% Variables (change accordingly)
numpoint = min(datasize); % Number of points extracted from the DIC
data
plotstep = numfiles; % Number of steps to plot on figure
alignx = 1.37; % Moves coupon in X direction
aligny = 50.4; % Moves coupon in Y direction
YSabove = 0.9; % Percentage limit of YS above UTS to disregard
(numerical errors)
YSbelow = 0.1; % Percentage limit of YS below UTS to disregard
(numerical errors)
a1 = 300; % YS lower limit
a2 = 500; % YS upper limit
b1 = 0; % Strain lower limit
b2 = 250; % Strain upper limit
theta = -0.5; % rotate coupon (degrees)
theta = degtorad(theta);
gauge = 36; % gauge length (mm)
E=210; % Young's modulus to be given by the user

% Stress values
Stress=Loadfile(2:numfiles+1)*1000/(4*10); % To be filed manually
using the load provided by the Istra software
%% Opens text files.
X=zeros(numpoint,numfiles); % X coordinate of all points, for all
steps
XX=zeros(1,1,numfiles); % X coordinate of all points, distributed in
one matrix for each step
x=zeros(numpoint,numfiles); % pointer provided by Istra indicating the
relative position of each point in the x direction for each step
xx=zeros(numpoint,1); % x pointer for one step
Y=zeros(numpoint,numfiles);
YY=zeros(1,1,numfiles);
```

```

y=zeros(numpoint,1);
yy=zeros(numpoint,1);

% Data extraction
for H=1:numfiles
Data=mydata{1,H}.data;
Strain(:,H)=Data(1:numpoint,38); % Strain for all points and all
steps in one D matrix
X(:,H)=Data(1:numpoint,3);
xx(:,H)=Data(1:numpoint,1);
Y(:,H)=Data(1:numpoint,4);
yy(:,H)=Data(1:numpoint,2);
end

% Distribution of point in multi-dimensional matrix (required to use
contourf function
for H=1:numfiles
for i=1:numpoint
XX(xx(i,H),yy(i,H),H)=X(i,H);
YY(xx(i,H),yy(i,H),H)=Y(i,H);
SStrain(xx(i,H),yy(i,H),H)=Strain(i,H);
end
end
% Determination of matrix characteristics
numlines=max(xx);
numlines=numlines(numfiles);
numcolumn=max(yy);
numcolumn=numcolumn(numfiles);
clear F W
figure
g=1;
j=1;
%% Calculation of the YS for each point
for p=1:numlines
for q=1:numcolumn
A=mean(SStrain(p,q,1:10));
clear F plot_strain
for t=1:numfiles
W(t)=E*SStrain(p,q,t)-E*(A+2);
plot_strain(t)=SStrain(p,q,t);
if Stress(t) < W(t)
F(t)= 0;
else
F(t)= Stress (t);
end
end
YS(p,q)=max(F);

if YS(p,q)>= (YSabove*max(Stress))% YS % above of the UTS measured
during this test will be removed to
% avoid numerical issues. The limit of 90% can be modified by the user
YS(p,q)=NaN;
end
if YS(p,q)<= (YSbelow*max(Stress))% YS below the UTS measured during
this test will be removed to
% avoid numerical issues. The limit of 90% can be modified by the user
YS(p,q)=NaN;
end

```



```

%% Results plotting
% Local stress-strain
% Especially when using the code for a new specimen, it is important
to
% check the aspect of the stress strain curve obtained. figures of 4 x
4
% plots will be provided by the code, the value of g indicates the
% plotting frequency

    if g==1000; % use high value to avoid plotting
        if j<=16
            subplot(4,4,j)
            plot(plot_strain,Stress,plot_strain,W)
            ylim([0 500]) % range of load obtained during the test
title(['Position x=' num2str(XX(p,q,1)) ' y=' num2str(YY(p,q,1))]);
            g=0;
            j=j+1;
        else
            j=1;
            figure('PaperPosition',[.2 .2 15 15]);
            subplot(4,4,j)
            plot(plot_strain,Stress,plot_strain,W)
            ylim([0 500]) % range of load obtained during the test
            g=0;
            j=j+1;
        end
    else g=g+1;
    end
end

end
%% Remove non physical data
% Remove X and Y equal to 0
[R,P,Q]=size(XX);
for r=1:R
    for p=1:P
        for q=1:Q
            XXX(r,p,q)=XX(r,p,q);
            YYY(r,p,q)=YY(r,p,q);
            if XXX(r,p,q)==0
                if YYY(r,p,q)==0
                    XXX(r,p,q)=NaN;
                    YYY(r,p,q)=NaN;
                end
            end
        end
    end
end

[R,P]=size(YS);
for r=1:R
    for p=1:P
        if YS(r,p)==0
            YS(r,p)=NaN;
        end
        if SStrain(r,p,numfiles)==0
            SStrain(r,p,numfiles)=NaN;
        end
    end
end
end
%% Rotation and translation of the coordinate

```

```

% This is to obtain straight specimen in the map
[R,P,Q]=size(XX);
p=floor(P/2); % this centering is based on the centre line of the
sample disganted by the absciss p
% calculation of the rational matrix
X_a=min(YYY(:,p,1));
X_b=max(YYY(:,p,1));
Y_a=min(XXX(:,p,1));
Y_b=max(XXX(:,p,1));
A=(Y_b-Y_a)/sqrt((Y_b-Y_a)^2+(X_b-X_a)^2);
B=(X_b-X_a)/sqrt((Y_b-Y_a)^2+(X_b-X_a)^2);
Rot=[cos(theta),-sin(theta);sin(theta),cos(theta)];
%% Calculation of the new coordinates
for i=1:numfiles
Cor=[X(:,i)';Y(:,i)'];
XY=Rot*Cor;
Xr(:,i)=XY(1,:)+alignx; % new X as 1D matrix (all points, all steps)
Yr(:,i)=(XY(2,:)+aligny).*-1; % new Y as 1D matrix (all points, all
steps)
end
XXr=zeros(R,P,Q); % reorganisation of the Xr with 1 dimension for each
step
YYr=zeros(R,P,Q); % reorganisation of the Xr with 1 dimension for each
step
for H=1:numfiles
for i=1:numpoint
XXr(xx(i,H),yy(i,H),H) = Xr(i,H);
YYr(xx(i,H),yy(i,H),H) = Yr(i,H);
end
end
% Remove points for which XXr=0 and YYr=0 at the final iteration
[R,P,Q]=size(XX);
for r=1:R
for p=1:P
if XXr(r,p,numfiles)==0;
XXr(r,p,numfiles)=NaN;
YYr(r,p,numfiles)=NaN;
end
if YYr(r,p,numfiles)==0;
XXr(r,p,numfiles)=NaN;
YYr(r,p,numfiles)=NaN;
end
end
end
[r,p,q]=size(XXr);
YS(r,p)=NaN;
%% Figure plotting
% The figures are plotted for the step final. to plot the figures at
another
% time step, numfiles needs to change in all contourf ans scatter
% functions
%% Maximum strain
figure
fig = tiledlayout(3,1,'TileSpacing','Compact','Padding','Compact');
nexttile
[Q,p]=contourf(YYr(:,:,plotstep),XXr(:,:,plotstep),SStrain(:,:,plotste
p),...
'LineColor','none');
colorbar;

```

```

hold on
scatter(Yr(:,plotstep),Xr(:,plotstep),5,'r. ');
line([-gauge/2 -gauge/2],[-10 10],'Color','k')
line([gauge/2 gauge/2],[-10 10],'Color','k')
xlim ([-25,25]);
ylim ([-10,10]);
p.LevelStep=1;
caxis([b1 b2]);
B=b2/4; % 8 = number of color marker (8x2=16 number of color in the
map)
colormap(parula(2*b2/B));
Strain_ticks=0;
for i=1:B+1
    Strain_ticks(i)=B*(i-1);
end
colorbar('Ticks',Strain_ticks);
% xlabel('Y-axis [mm]');
set(gca,'Xticklabel',[])
ylabel({'\fontsize{10}\bf Map of mStrain';'\fontsize{10}\rm X-axis
[mm]'});
%% Yield strength
nexttile
[C,h]=contourf(YYr(:,:,plotstep),XXr(:,:,plotstep),YS(:,:,), 'LineColor'
,'none');
hold on
scatter(Yr(:,plotstep),Xr(:,plotstep),5,'r. ');
line([-gauge/2 -gauge/2],[-10 10],'Color','k')
line([gauge/2 gauge/2],[-10 10],'Color','k')
colorbar
h.LevelStep=1;
caxis([a1 a2]);
A=a2/10; % 8 = number of color marker (8x2=16 number of color in the
map)
colormap(parula(4*a2/A));
YS_ticks=0;
for i=1:A+1
    YS_ticks(i)=A*(i-1);
end
YS_ticks(1)=0;
colorbar('Ticks',YS_ticks);
c.Label.String = 'YS[MPa]';
xlim ([-25,25]);
ylim ([-10,10]);
% xlabel('Y-axis [mm]');
set(gca,'Xticklabel',[])
ylabel({'\fontsize{10}\bf Map of YS';'\fontsize{10}\rm X-axis [mm]'});
%% Plot YS across the sample
[R,P,Q]=size(XXr);
nexttile
ans = YYr(:,:,plotstep);
p=floor(P/4)*3-1; % middle of the coupon (change accordingly)
for s=[p-2 p p+2]
    YS_plotting(:,2)=YS(:,s);
    YS_plotting(:,1)=YYr(:,s,plotstep);
    n=size(YS_plotting);
    n=n(1);
    for t=1:n
        if YS_plotting(t,2)<300;
            YS_plotting(t,2)=NaN;

```

```

end
end
scatter(YS_plotting(:,1),YS_plotting(:,2));

xlim ([-25,25]);
hold on
grid on
end
line([-gauge/2 -gauge/2],[a1 a2],'Color','k')
line([gauge/2 gauge/2],[a1 a2],'Color','k')
xlabel('Y-axis [mm]','FontSize',10);
ylabel({'\fontsize{10}\bf YS across coupon';'\fontsize{10}\rm YS
[MPa]'});
ylim([a1 a2])
legend ('x = -2 mm', 'x = 0 mm', 'x = 2 mm',...
        'Location','southoutside',...
        'NumColumns',3,...
        'FontSize',10)
%%
% exportgraphics(fig,'A1-CD_Contour_map.png','Resolution',1000)

```

Local stress-strain code (plots local stress-strain from specific points from the contour map)

```
% Points=[-2.52686,0.329334;7.61541,0.395743]
Plot_number=size(Points,1);
figure('PaperPosition',[.2 .2 15 15]);
for plot_nb=1:Plot_number
clear lookfor_matrix_X lookfor_matrix_Y YY_check XX_check W Xpoint
Ypoint F xx_plot yy_plot
%% How to plot the stress strained curve of a specific point on the
map
Ypoint_map=Points(plot_nb,1);
Xpoint_map=Points(plot_nb,2);
Coordinate_point_map=[Xpoint_map; Ypoint_map];

%% Remove the offset used to centered the coupon
Xpoint_R=Xpoint_map-alignx;
Ypoint_R=(Ypoint_map./-1)-aligny;
Coordinate_point_R=[Xpoint_R;Ypoint_R];

%% Remove the rotation
Coordinate_point=inv(Rot)*Coordinate_point_R;
Xpoint=Coordinate_point(1)
Ypoint=Coordinate_point(2)

%% look for this point in the initial data set
i=1;
for r=1:numlines
for q=1:numcolumn
if abs(XX(r,q,plotstep)-Xpoint)<0.007;
lookfor_matrix_X(i,1)=r
lookfor_matrix_X(i,2)=q
i=i+1;
end
end
end

I=i-1;
for i=1:I

YY_check(i,1)=YY(lookfor_matrix_X(i,1),lookfor_matrix_X(i,2),plotstep)
-Ypoint;
if abs(YY_check(i,1))<0.007;
xx_plot=lookfor_matrix_X(i,1);
yy_plot=lookfor_matrix_X(i,2);
end

end
%% Plot
for p=1:numlines
for q=1:numcolumn
A=mean(SSStrain(xx_plot,yy_plot,1:75));
clear F plot_strain
for t=1:numfiles
W(t)=E*SSStrain(xx_plot,yy_plot,t)-E*(A+2);
plot_strain(t)=SSStrain(xx_plot,yy_plot,t);
if Stress(t) < W(t)
```

```

        F(t)= 0;
    else
        F(t)= Stress (t);
    end
end
YS(p,q)=max(F);

if YS(p,q)>= (YSabove*max(Stress))% YS above 90% of the UTS measured
during this test will be removed to
% avoid numerical issues. The limit of 90% can be modified by the user
    YS(p,q)=NaN;
end
end
end
%% Results plotting
% Especially when using the code for a new specimen, it is important
to
% check the aspect of the stress strain curve obtained. figures of 4 x
4
% plots will be provided by the code, the value of g indicates the
% plotting frequency
fig
    subplot(1,Plot_number,plot_nb)

    plot(plot_strain,Stress,'o',plot_strain,W)
    ylim([0 600]) % range of load obtained during the test
title(['Position x=' num2str(Xpoint_map) ' y=' num2str(Ypoint_map)]);
xlabel('Engineering Strain')
ylabel('Engineering Stress, [MPa]')
xlim([0 150])
f=gcf
end

```

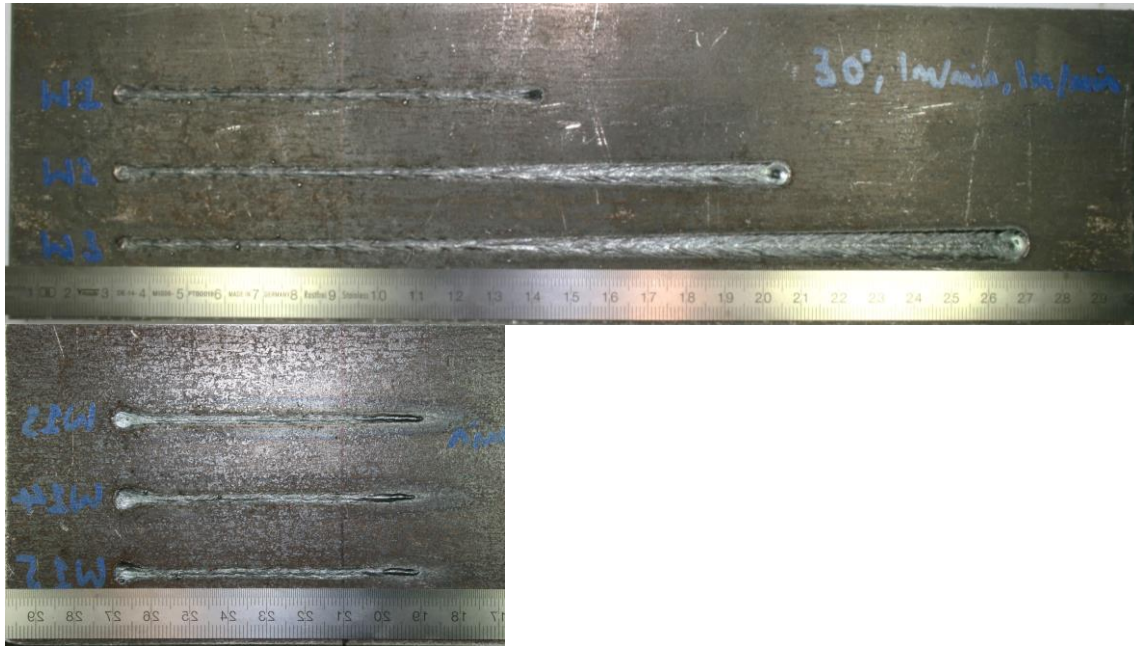
Appendix E

Top surface view of each parameter configuration used in the laser defocusing termination regime found in Chapter 4.

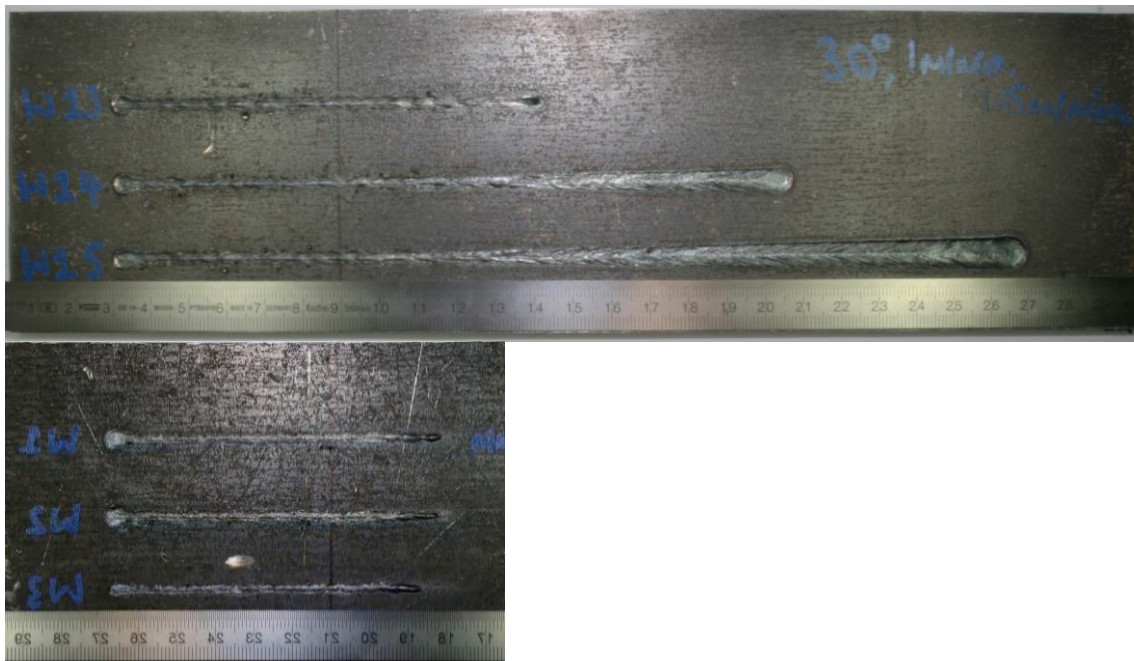
Constant parameters: $P = 6 \text{ kW}$, $v_{AB} = 1 \text{ m/min}$, $\varnothing_{End} = 3 \text{ mm}$, 6 mm , 9 mm

Root surface flipped horizontally to align with welding direction

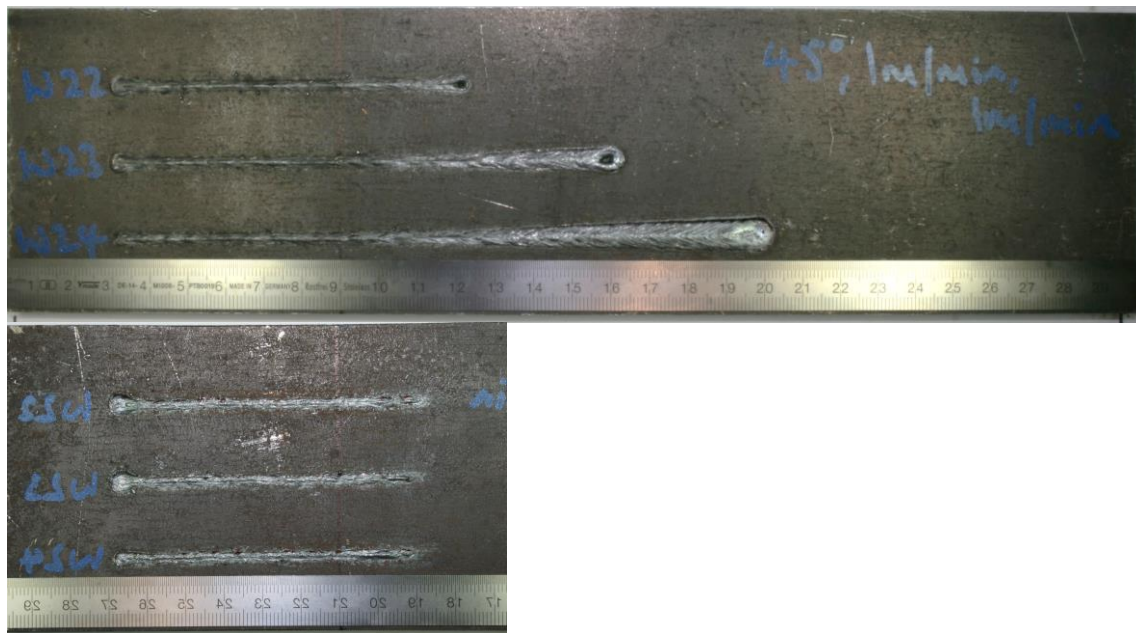
$\alpha = 30^\circ$, $v_{laserhead} = 1.00 \text{ m/min}$, $v_{Beam} = 0.95 \text{ m/min}$



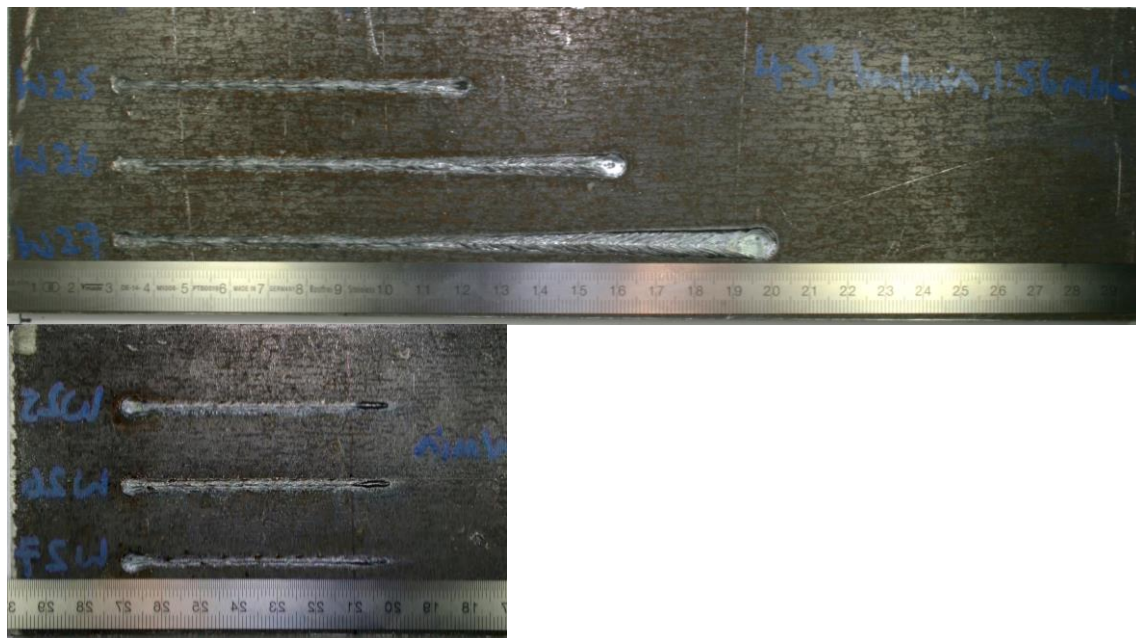
$\alpha = 30^\circ$, $v_{laserhead} = 1.15 \text{ m/min}$, $v_{Beam} = 1.10 \text{ m/min}$



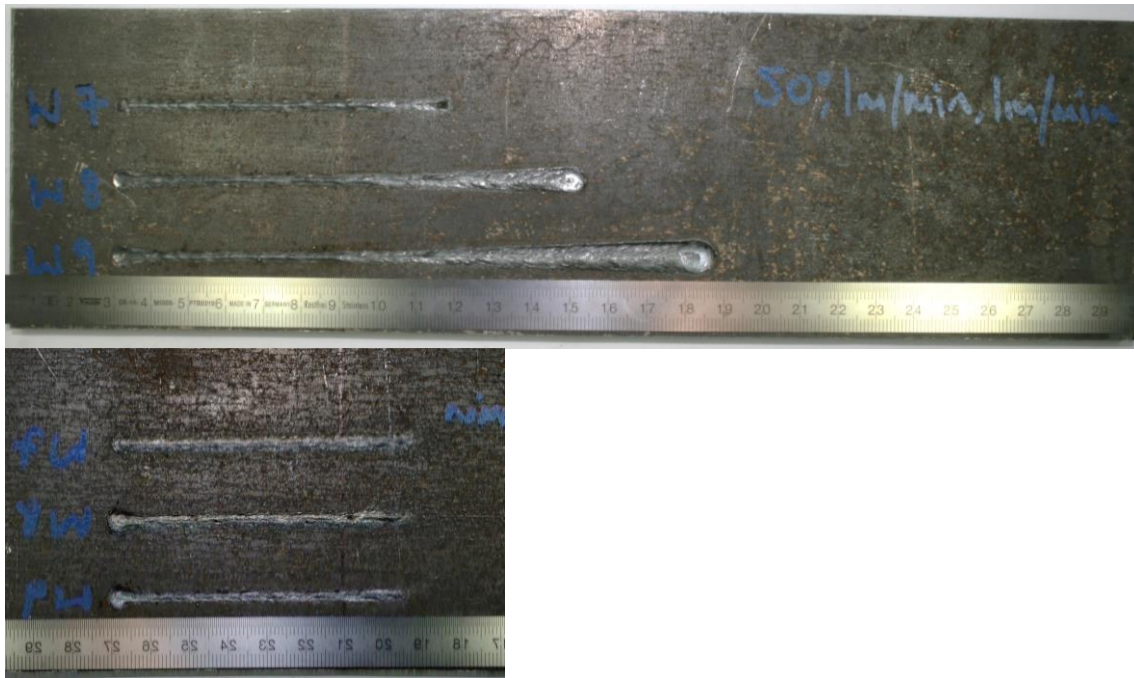
$\alpha = 45^\circ$, $v_{\text{laserhead}} = 1.00 \text{ m/min}$, $v_{\text{Beam}} = 0.86 \text{ m/min}$



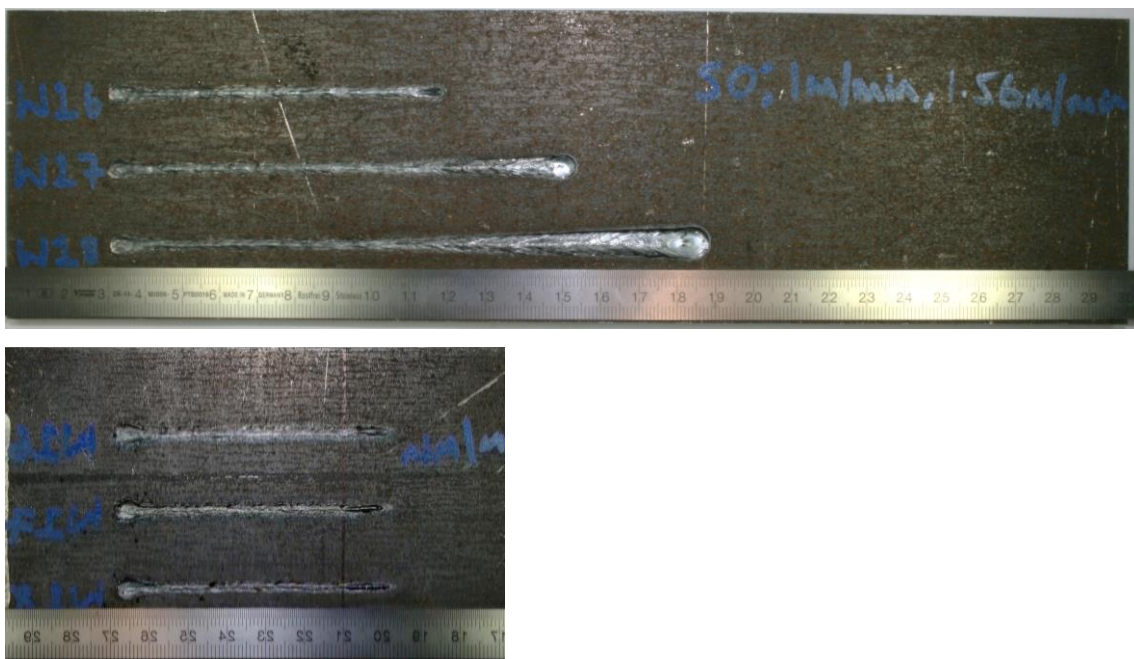
$\alpha = 45^\circ$, $v_{\text{laserhead}} = 1.56 \text{ m/min}$, $v_{\text{Beam}} = 1.30 \text{ m/min}$



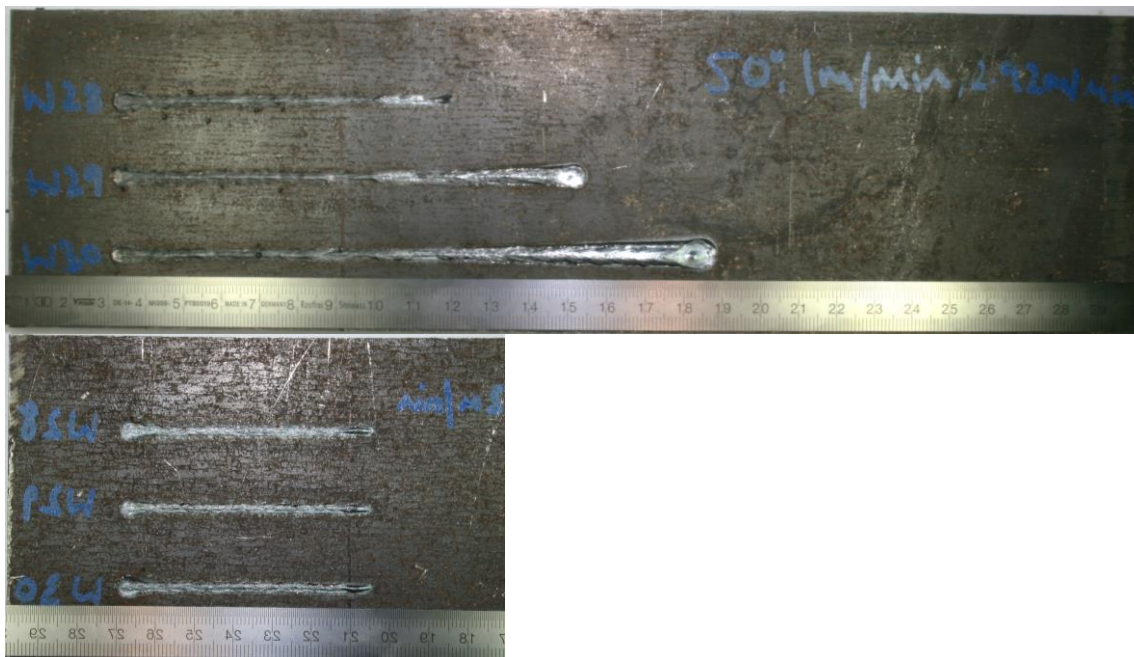
$\alpha = 50^\circ$, $v_{\text{laserhead}} = 1.00 \text{ m/min}$, $v_{\text{Beam}} = 0.78 \text{ m/min}$



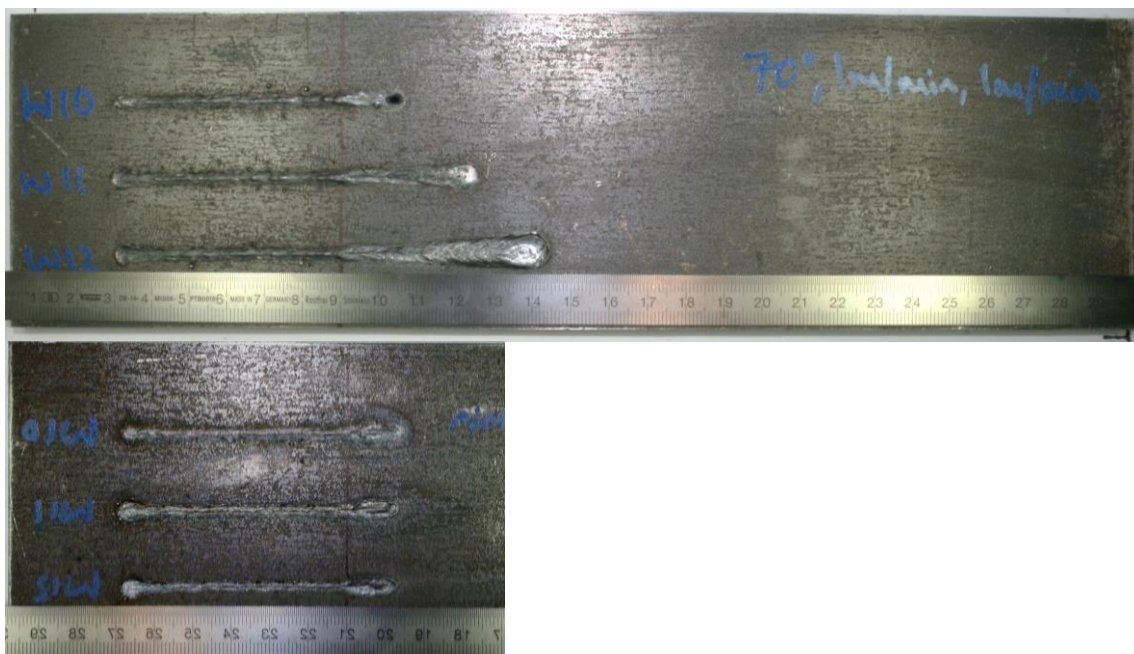
$\alpha = 50^\circ$, $v_{\text{laserhead}} = 1.56 \text{ m/min}$, $v_{\text{Beam}} = 1.21 \text{ m/min}$



$\alpha = 50^\circ$, $v_{\text{laserhead}} = 2.92 \text{ m/min}$, $v_{\text{Beam}} = 2.27 \text{ m/min}$



$\alpha = 70^\circ$, $v_{\text{laserhead}} = 1.00 \text{ m/min}$, $v_{\text{Beam}} = 0.51 \text{ m/min}$



$\alpha = 70^\circ$, $v_{\text{laserhead}} = 2.92 \text{ m/min}$, $v_{\text{Beam}} = 1.48 \text{ m/min}$

