



Xichen Wang

Investigation of wire-based laser directed energy deposition (DED)
process for high-resolution submillimetre features

School of aerospace, transportation and manufacturing
PhD in Manufacturing

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Academic Year: 2024 - 2025

Supervisor: Professor Stewart Williams
Associate Supervisor: Dr. Gonalo Rodrigues Pardal
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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

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Abstract

In this thesis, the feasibility of manufacturing submillimetre-scale wall features using 250 W to 500 W and 1.00 kW to 2.79 kW laser power, from a 1.0 mm small beam to 1.5 mm – 3.0 mm large beams was investigated. The D-ratio correlates the beam diameter with wire diameter was introduced for deposition performance and wire position sensitivity discussion.

The study firstly reveals the possibility of fabricating defect-free, smooth surface appearance and submillimetre-scale wall features using 500 W of laser power with large laser beam diameters of 1.50 mm to 2.00 mm (D-ratio of 2.50 to 3.33) without the plume interference. It was found that using a larger beam size can enhance the chance of deposition success due to enough specific point energy applied, a relatively lower but even distribution of the power density, and less energy discrepancy projected on wire and substrate, as a result, increase in the possibility of deposition success.

This study also successfully applied 2.79 kW of high-level laser power and a large beam size of 3.00 mm (D-ratio of 5.00) to build the millimetre-scale wall features at a fast processing speed. It was found that fast processing speed, large laser beam size, and high-level laser power enable the chance of feeding more material into the melt pool, meanwhile, a larger D-ratio is needed for preventing the wire position sensitivity introduced back. A deposition rate of 400 g/h was achieved by using a 0.6 mm diameter wire and still exhibits the potential of fabricating submillimetre-scale wall features with the deposition rate potentially reaching 750 g/h, which is comparable to the conventional power-based laser DED process of 600 g/h.

Finally, the possibility of applying FLMIPs in the wire-based laser directed energy deposition regime was revealed, but the comprehensive feasibility of applying these parameters in the wire-based laser directed energy deposition regime needs to be further investigated.

These imply that wire-based laser DED process is capable of manufacturing submillimetre-scale features with good performance at relatively large beam

sizes and has the potential to achieve competitively high deposition rates in submillimetre-scale features to satisfy the rapid manufacturing requirements in the additive manufacturing regime.

Keywords:

Laser wire additive manufacturing; thin-wall structure; high resolution; 316L stainless steel; large laser beam size; interaction time; specific point energy; power density, surface energy density; WFS to TS ratio.

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List of Abbreviations

AM	Additive Manufacturing
BD	Beam Diameter
CNC	Computer Numerical Control
CW	Continuous Wave
DED	Directed Energy Deposition
EI	Energy Input
EMA	Energy per unit Mass on the unit of Area of the substrate
Esp	Specific Point Energy
FLMIPs	Fundamental Laser Material Interaction Parameters
h-PD	High Power Density
IT	Interaction Time
LP	Laser Power
PBF	Powder Bed Fusion
PD	Power Density
p-PD	High peak-Power Density
SS	Stainless Steel
Surface ED	Surface Energy Density
TS	Travel Speed
WAAM	Wire Arc Additive Manufacturing
WEBAM	Wire Electron Beam Additive Manufacturing
WFS	Wire Feed Speed
WLAM	Wire-based Laser Additive Manufacturing
2D	Two dimensions
3D	Three dimensions

1 Introduction

1.1 Background

Metal Additive Manufacturing (AM) has been the focus in the academic and industrial fields and has exhibited prosperous development and investigation trends for many years. Metal AM techniques have many advantages over traditional manufacturing methods, such as short lead time, design flexibility, and reduced material waste (S. W. Williams et al., 2016). Nowadays, many metal AM techniques have become gradually mature, such as powder bed fusion (PBF) processes, wire arc additive manufacturing (WAAM). These techniques are adopted by industries in many fields, such as aerospace, manufacturing, nuclear, and medical (Mbodj et al., 2021) to satisfy the requirements of rapid manufacturing and different scales under different application regimes.

Manufacturing features at the submillimetre-scale are essential for industries such as manufacturing and medicine, including applications such as aerospace turbine blades, medical implants, or relevant bone-replacing components (Kaljevic & Demir, 2022; C. Wei et al., 2019). Currently, the laser-based PBF process is generally adopted as the main technique to manufacture high-resolution, complex submillimetre features because of the small powder sizes (15 – 50 μm) and relatively small laser beam sizes (30 – 100 μm) (Coroado et al., 2021; G. Gong et al., 2021; J. Liu & Wen, 2022), which help enable the precise energy control. However, powders are hard to recycle and easily suffer from contamination (Feenstra et al., 2021). Health and safety issues are also challenges for the PBF process (Oliari et al., 2017), especially when it comes to powder toxicity, the inflammable and explosive possibility of the powders (Gupta et al., 2021). This is due to the typical 20 - 50 μm of powder particle sizes (Kaljevic & Demir, 2022; S. Wei et al., 2017) which could cause the potential danger and hazard to the operators and the environment (Mok, Bi, Folkes, & Pashby, 2008). In addition, the PBF process is difficult to achieve multi-material components fabrication due to cross-contamination between the different powders used (Bandyopadhyay & Heer, 2018; Feenstra et al., 2021), and the deposition rate of the conventional PBF process is as low as 480 g/h (Z. Li et al., 2022). Powder-

based directed energy deposition (DED) process, however, can improve the deposition rate significantly and can achieve complex functional graded materials (Feenstra et al., 2021) and multi-material parts fabrication (Svetlizky et al., 2021), but the weaknesses of the deposits such as lower resolution due to the relatively larger melt pool (up to several centimetres) (Z. Li et al., 2022) and a larger layer thickness (0.5 mm) (Yao et al., 2022; Zhong et al., 2015; Z. Li et al., 2022); poorer surface quality and lower dimensional accuracy compared to PBF process (Möhring et al., 2022) still limit the process application.

Wire-based laser DED process is also limited to high-resolution features due to the intrinsic characteristic of the wire diameter, which is significantly larger than the powder dimensions; this naturally causes a larger melt pool to accommodate the wire and resulting in a relatively higher average layer height and wider width (Z. Li et al., 2022). However, the superior characteristics of the cleaner working environment (Abioye et al., 2013), easier for manufacturing multi-material structures than powder-based processes (Bandyopadhyay & Heer, 2018), cheaper raw material (Oliari et al., 2017), less possibility of entrapping gas and forming porosities in the deposits (Svetlizky et al., 2021); a nearly 100% wire capture efficiency (Svetlizky et al., 2021), and easier accessible availability (more abundant) of the wire than powder (Mbodj et al., 2021) contribute to the promising investigation of wire-based laser DED for manufacturing high-resolution submillimetre features.

In laser-based additive manufacturing processes, laser beam size plays a very critical role, which can affect the deposition performance significantly. In the PBF process, researchers generally use small laser spot sizes (30 μm to 100 μm) (J. Liu & Wen, 2022) to ensure the energy can be accurately delivered to and projected on the material. Recently, some researchers have focused on using large beam sizes (compared with powder sizes) in the PBF process to reduce the total scanning time thus enhancing productivity (Beam size: 240 μm) (Makoana et al., 2018); stabilising the melt pool by exploring the conduction heating regime to depress the vaporization threshold (Beam size: 500 μm) (Sow et al., 2020). However, currently, there is little research focusing on using large laser beams in

wire-based laser DED processes to fabricate submillimetre features, which can be more controllable for the laser operation than the small laser beams. The effect of large beam sizes on deposition performance and the feasibility of manufacturing submillimetre features using large beams is still not clear. In addition, the wire-based laser DED process is sensitive to the variation of processing conditions such as wire position relative to the substrate (Miranda et al., 2008), wire tip position relative to the melt pool, wire feed rate, and laser beam size (Abioye et al., 2013). To reduce the sensitivity of these processing conditions, using large beam sizes for the wire-based laser DED process should be explored. Thus, this dissertation topic mainly focuses on the investigation of using large laser beam sizes (here, defined as ≥ 1.5 mm) for additive manufacturing of high-resolution submillimetre features with good performance. To cater for the rapid manufacturing requirements in additive manufacturing, the study is also extended to the high deposition rate wire-based laser DED process for millimetre to submillimetre-scale features manufacturing. The fundamental laser material interaction parameters (FLMIPs) which have been used in the welding regime analysis are also applied to this wire-based laser DED process to evaluate the deposition performance. The concept is shown in Figure 1-1.

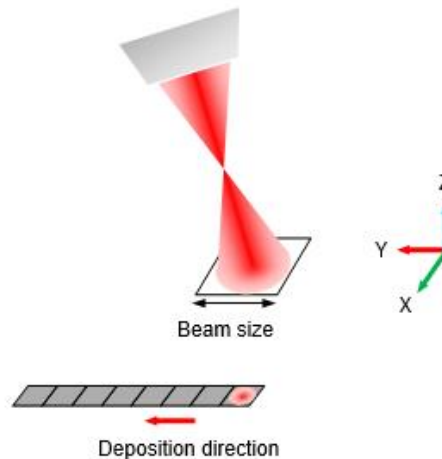


Figure 1-1 Schematic of the concept of sectioning the deposit to a beam-sized length.

The main purpose is to section the whole bead into several beam-size length parts and focus on one individual part to analyse the deposition performance, and this small part analysis can represent the whole bead length performance.

1.2 Hypothesis

Defect-free, net-shape submillimetre-scale wall features can be manufactured using the wire-based laser DED process under larger beam diameters using the continuous waveform lasers, thereby avoiding high power density beams, and prompting operating in the conduction regime with greater process tolerance for the wire position.

1.3 Aim and objectives

1.3.1 Aim

Validate the hypothesis: successfully use wire-based laser DED process with large laser beams to manufacture defect-free, high-resolution submillimetre wall features with stable performance and extend it to high deposition rates.

1.3.2 Individual objectives

- Assess the current approach of wire-based laser DED for submillimetre wall features using a 1.0 mm laser beam.
- Applying larger laser beam sizes (≥ 1.5 mm) to identify the relationship between the laser beam size with the wire diameter for stable performance, identify the process window and the limitation of the large beam boundary, and optimise the wall features' deposition performance.
- Extend the process to higher deposition rates via higher levels of laser power and faster processing speeds to build the wall features, so final parts can be printed.

2 Literature review

2.1 State-of-the-art wire-based laser DED

Metal AM has developed rapidly in recent decades due to the high demand for rapid fabrication in the medical, automobile, and aerospace sectors (Bandyopadhyay & Heer, 2018), etc. Many types of metal AM techniques are adopted to create complex parts which are difficult to create by conventional manufacturing methods. A variety of metal AM processes gives the design of complicated features more freedom, from one material to many materials, from large scale to submillimetre scale without the need to frequently use complicated and costly tooling. To date, metal AM can be classified into PBF processes and DED processes (Moeinfar et al., 2022). DED processes can be classified into wire-based and powder-based types further based on the types of feedstock. Wire-based DED (w-DED) processes, owing to the significantly higher deposition rate compared with the PBF processes, become very attractive in the industrial and academic fields. To date, wire-based DED can be classified into wire-based arc DED (also called Wire Arc Additive Manufacturing (WAAM)), wire-based electron beam DED (also called Wire Electron Beam Additive Manufacturing (WEBAM)), and wire-based laser DED (also called Wire Laser Additive Manufacturing (WLAM)) (DebRoy et al., 2018). The WAAM process is more suitable for medium to large-scale component fabrication with low and medium complexity (S. W. Williams et al., 2016). For example, Ti-6Al-4V spars and landing gears, steel wind tunnel models as mentioned in (S. W. Williams et al., 2016). WLAM, nevertheless, due to the availability to achieve accurate energy delivery control by laser, becomes a good candidate for fabricating features with better surface finishing (Syed et al., 2005), also the deposition environment is cleaner without metal dust pollution (Xu et al., 2017) compared with the arc-based process which has attracted many scholars' attention already. Nowadays, the two mainstreams of the WLAM configurations are classified based on the wire feeding manner, i.e., off-axis feeding or coaxial feeding (Chen et al., 2022). The coaxial feeding manner is quite a recently developed technology, which generally places the wire perpendicular to the workpiece and in the centre of the ring-shaped

annular beam or multi-laser beams. The principle of the coaxial feeding configurations and the corresponding working mechanisms are shown in Figure 2-1 (a) - (d). Coaxial feeding is regarded as a direction-independent process, which means the factor of the angle between the wire nozzle and the laser beam is removed. As a result, this factor does not exist in the coaxial feeding processes and cannot affect the deposition performance. Therefore, the coaxial feeding technique is widely adopted in the additive manufacturing regime by many researchers currently due to its many advantages and convenience over the off-axis feeding method. The off-axis method is relatively older, being used extensively in welding applications.

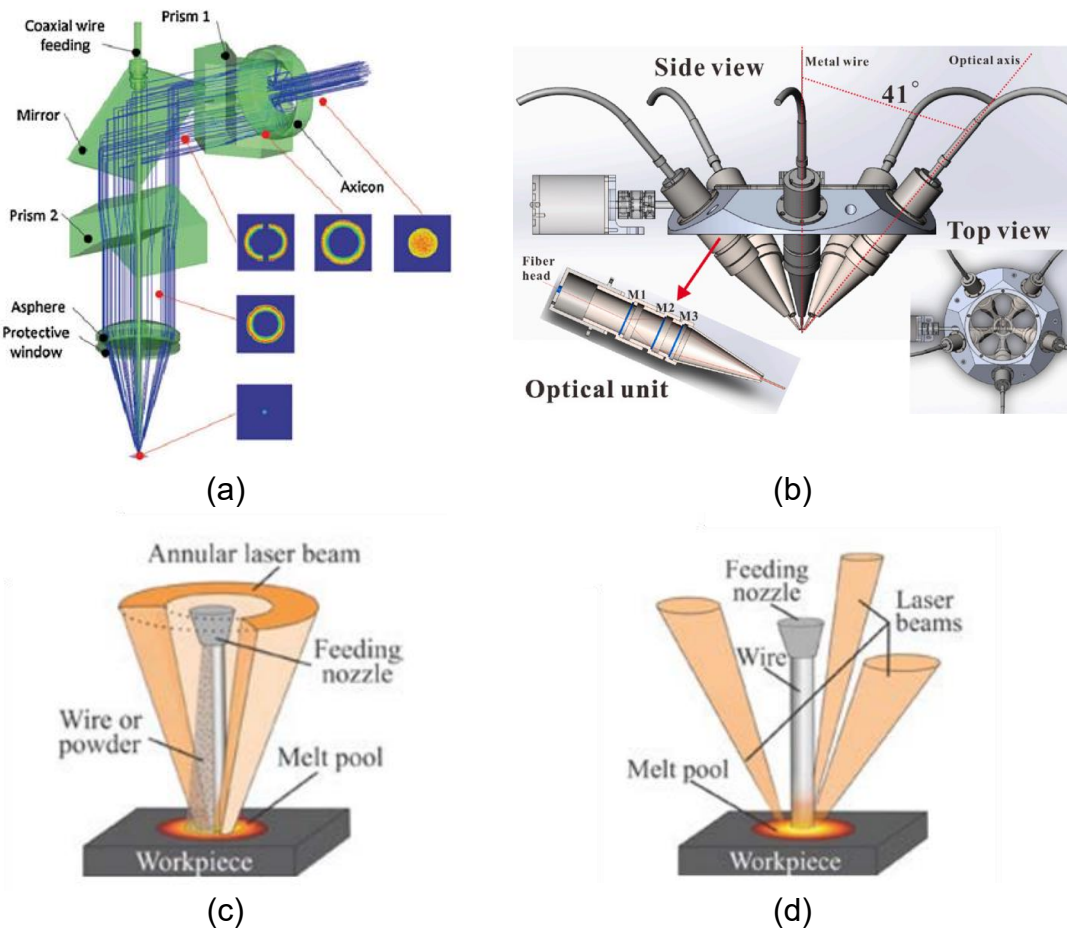


Figure 2-1 Principle of the coaxial feeding configurations of (a) ring-shaped annular beam (Motta et al., 2018), and (b) multiple laser beams case (X. Ding, Ma, et al., 2022). Schematic of working mechanisms of (c) the ring-shaped annular beam, and (d) multiple laser beam case (Govekar et al., 2018).

Compared with the wire-based arc process which has been developed to a relatively mature level, the wire-based laser DED process is located in a relatively new development phase and an immature and infant level (Y. Ding et al., 2018), and the initial concept and setups were naturally derived from the cladding facilities (Oliari et al., 2017; Syed et al., 2005). Thus, an off-axis feeding manner was adopted in the initial phase (Henri et al., 2012; Mok, Bi, Folkes, & Pashby, 2008). Currently, the off-axis wire feeding manner is still used because once the best configuration, such as the feeding angle and the position of the wire feed nozzle are identified, good deposition performance can be achieved. Beyond that, the integrated design of the off-axis feeding setup is relatively cost-effective and simple (Kaljevic & Demir, 2022) when compared to coaxial feeding as the coaxial setup needs specialised equipment.

Wire-based laser DED technology has many extra factors besides the general or common system parameters (power, wire feed speed, travel speed) in the process that need to be studied when compared with arc-based processes, such as laser beam diameter, laser incident angle, laser wavelength and etc. All of these parameters can be categorised as primary input phase parameters, which can affect the different deposit results (output) directly from geometry, appearance, properties, etc, perspectives. On the contrary, parameters that are not directly related to the energy input (Ayoola, 2015) but still exhibit a critical impact on the deposition performance can be defined as secondary input phase factors (introduced in the latter context).

The variety of combinations of primary input factors will cause different processing operation envelopes, making the investigation of the process window based on each set of parameters more complicated. Thus, processing at different laser beam sizes at different feeding positions and angles, combined with a feasible range of system parameters to have quality deposits is the main focus at the initial investigation stage and even till now. (Mok, Bi, Folkes, & Pashby, 2008) studied the laser power and travel speed effects on geometries using a 2 mm x 7 mm rectangular laser beam processed at the focal position and found that the width of the deposit is mainly controlled by laser power; travel speed dominated

the height more than laser power. Front feeding was assumed as an ideal method which can perform the highest smooth deposits (Kim & Peng, 2000; B. Li et al., 2021; Mok, Bi, Folkes, & Pashby, 2008; Syed et al., 2005). Better surface quality was achieved by front and side feeding than rear feeding, but the uneven edges of both sides caused by the molten metal liquid flow sideward due to the side feeding caused the bead to be not as smooth as the front feeding method (Mok, Bi, Folkes, & Pashby, 2008). However, (Xiao et al., 2002) reported that back feeding of the filler wire in CO₂ laser welding of aluminium is more efficient and stable, and claimed that the best wire feed direction is a material-dependent situation, a good deposition performance of the chosen material can be achieved via choosing proper wire feeding direction and the corresponding wire position. Wire feeding angle is found to be important (Syed et al., 2005) in the wire-based laser DED process, a maximum deposition rate was achieved at a 45° angle with front feeding (Mok, Bi, Folkes, & Pashby, 2008), a similar conclusion of the highest deposition weight and the best laser absorptivity at 45° was reported in (Huang et al., 2021). (Syed et al., 2005) specified an angle range of 20° – 60° for front feeding can achieve quality deposits instead of a specific angle, and reported that a lower angle could lift and misalign the wire once the melt pool solidified, a higher angle can cause more ripples to appear. (Abioye et al., 2013) applied 42 ±1 degree of the wire feeder angle with front feeding to ensure the wire tip is located at the centre of the melt pool.

Therefore, currently, the wire feeding position and angle for the off-axis feeding are still not fixed, and these factors could depend on the system, material and application, but it seems that most of the researchers agree that the front feeding with a 20° to 60° feeding angle can achieve relatively satisfactory results.

Parallely, some research focuses on the secondary input parameters study such as gas flow rate (Bernauer et al., 2023; Kaljevic & Demir, 2022), ambient pressure in the vacuum chamber (X. Ding, Li, et al., 2022), global (X. Ding, Li, et al., 2022; Kaljevic & Demir, 2022) or local shielding (Bernauer et al., 2023; Schulz et al., 2019) environment, substrate thickness, etc. (Kaljevic & Demir, 2022) declared that the increase of argon flow rate in the enclosure leads to thinner wall samples

with a smooth surface appearance, which can be induced by the lower overall energy content caused by the less oxidation occurrence. (Bernauer et al., 2023) also reported that the deposit bead width is negatively related to the shielding gas flow rate due to the convection causing the increased cooling effect of the melt pool as a result of a lower melt pool temperature having a lower expansion of the melt pool and a higher surface tension of the molten material. On the contrary, no obvious variation in the relationship between the deposit bead height and gas flow rate. (X. Ding, Li, et al., 2022) reported as the ambient pressure decreased within the range of 1 Pa to 120 Pa in the vacuum chamber, the bead height and contact angle decreased, and the bead width increased accordingly, which is attributed to the decrease of ambient pressure that caused the reduction of plasma plume effect on laser loss, therefore, the molten pool size is larger, this observation was also reported in (J. Gong et al., 2021). Also, a lower ambient pressure resulted in better wetting behaviour and spreading ability due to less oxide generation resulting in less surface tension, as a result, good forming was achieved. (Schulz et al., 2019) claimed purging the gas or vacuuming the chamber is time and energy-consuming, local shielding can be a better candidate, however, local shielding is challenging for the high reactive materials such as grade 5 titanium (Ti-6Al-4V) (Schulz et al., 2019), biodegradable Magnesium (Kaljevic & Demir, 2022) due to the high oxygen affinity, therefore, the authors pointed out that using enlarged shielded area or reducing the heated area by optimising the process design and allowing the shielding gas fully cover the heated zone to solve the difficulty. (Bernauer et al., 2023) claimed local shielding is an economic shielding method. It is independent of the component size which allows the facility to possess more flexibility. To improve the effectiveness of the local shielding in the off-axis feeding manner (Figure 2-2 (a)), the authors designed a novel coaxial local shielding nozzle with internal cooling channels' optimisation fabricated by the PBF process (Figure 2-2 (b) - (d)).

The authors successfully fabricated oxide-free 304 stainless steel beads (Figure 2-3 (a)) with better surface appearance than the lateral shielding nozzle case (Figure 2-3 (b)) and also prevented mixing with the atmosphere without the limitation of the component size.

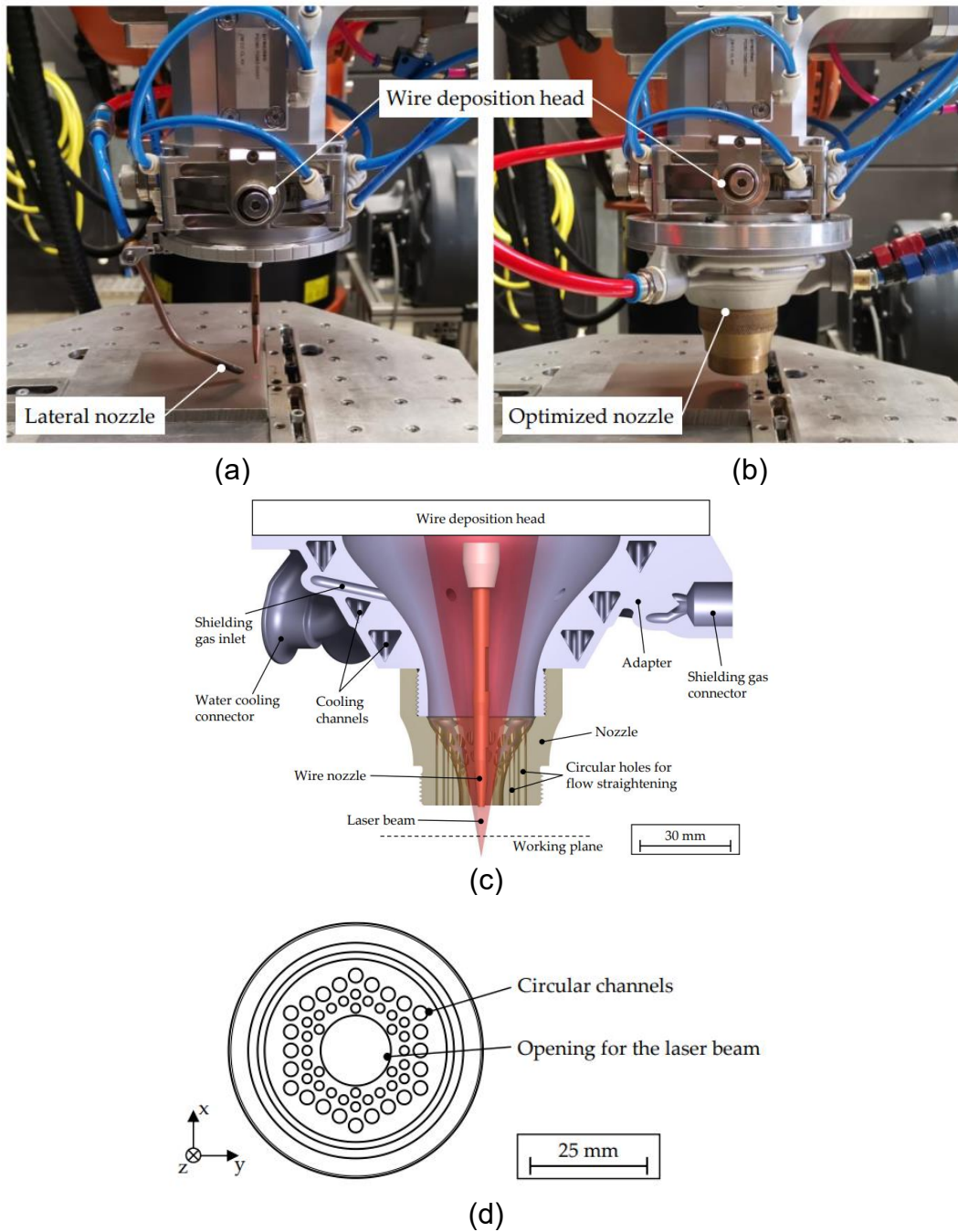


Figure 2-2 Configuration of (a) lateral shielding gas nozzle; (b) optimised coaxial shielding gas nozzle (Bernauer et al., 2023); (c) cross-sectional view of the design features of the optimised coaxial shielding gas device; (d) outlet geometry of the shielding nozzle with the circular channels.

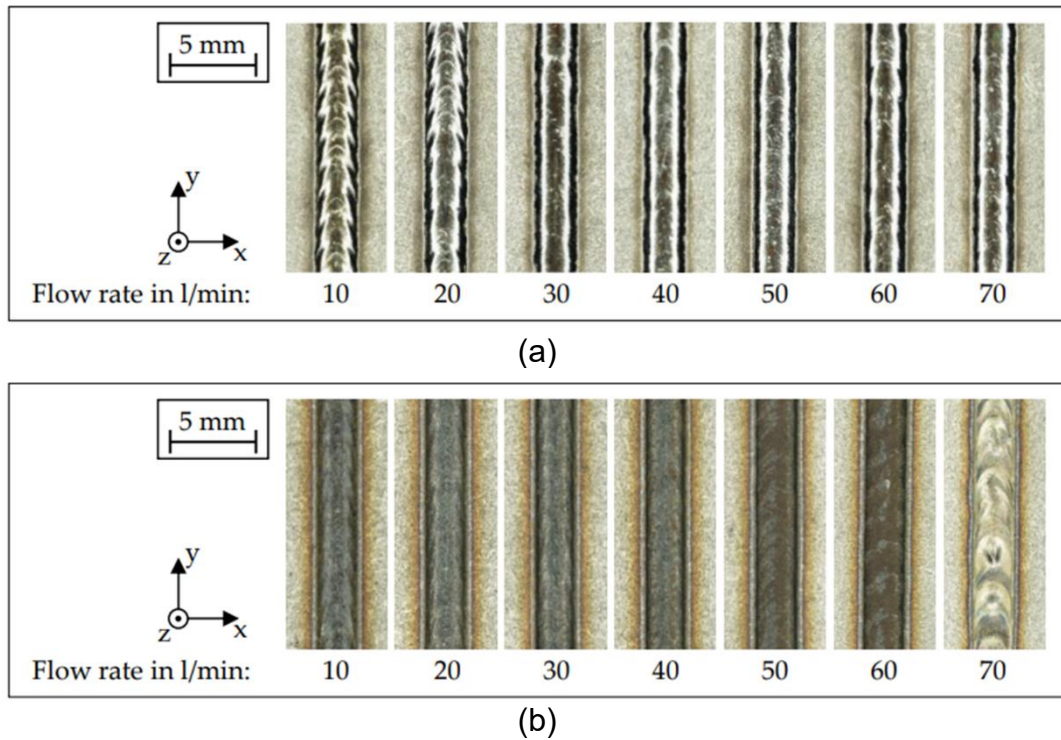


Figure 2-3 Surface condition of weld beads deposited with (a) the optimised local shielding nozzle; (b) the lateral local shielding nozzle.

Currently, various types of wire have been studied, among different elemental-based materials, titanium-based material attracts the most interest in the wire-based laser DED process due to its wide application in the aerospace industry (Z. Li et al., 2022). Many researchers took different materials as the starting point and focused on the output phase research from the perspective of mechanical properties, microstructures, morphologies, solidification behaviours (DeNonno et al., 2024; Xu et al., 2017) etc. (Xu et al., 2017) studied the morphologies, microstructures, and mechanical properties of the laser and 316L stainless steel wire deposition using 2.00 kW – 2.40 kW laser power with 0.8 mm diameter wire by 35 - 45-degree angle lateral feeding (front feeding) combined with 3.0 mm laser spot size. 3.0 mm/s to 9.0 mm/s of processing speed was used. Finally, a 3.3 mm single-layer bead width under low heat input and large wire feed rate conditions with smooth deposition performance was achieved; the bead width is larger but closer to the 3.0 mm laser beam size (Figure 2-4 (a)). And the effective wall widths with either wider than or narrower than the 3.0 mm laser beam size were achieved (Figure 2-4 (b)). This indicates that the wall width similar to the

beam size can be achieved, which gives a reference that if the researcher wants to achieve a specific bead or wall width, a similar size laser beam as the required bead or wall width could be used.

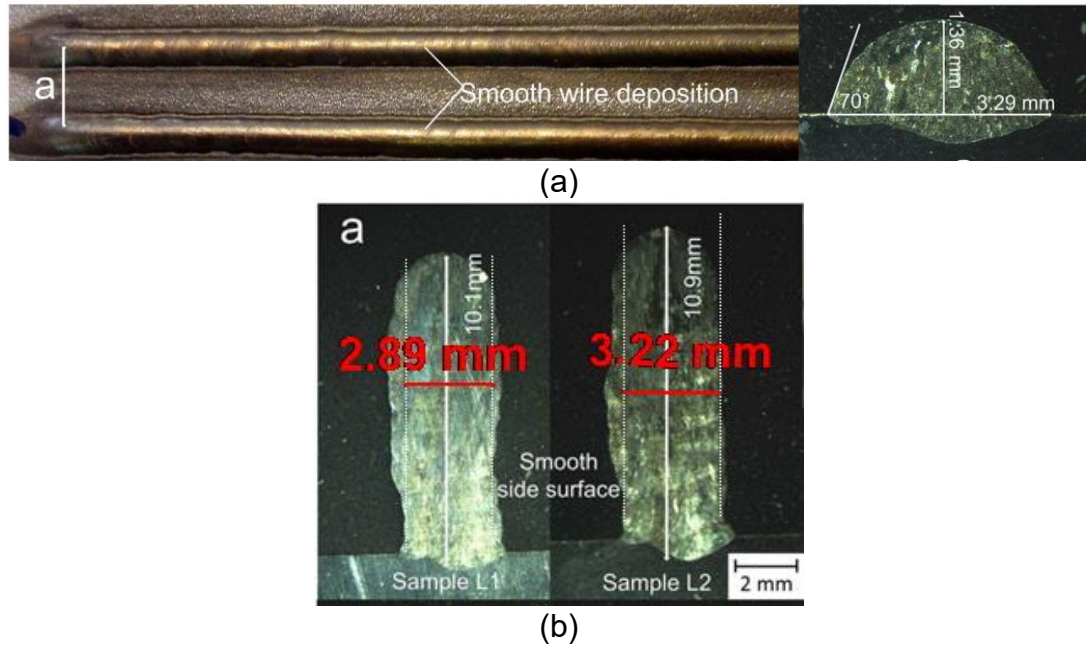


Figure 2-4 Images of (a) macroscopic morphology of 316L SS bead sample deposited with low heat input and large wire feed rate; (b) cross-sectional area of 10-layer samples with smooth side surface and corresponding effective width.

(Mok, Bi, Folkes, & Pashby, 2008) found that reducing the heat input either by increasing the travel speed at constant laser power or reducing the laser power at constant travel speed can achieve a higher hardness of Ti6Al4V. However, (Feenstra et al., 2021) claimed that the variation of processing parameters did not significantly influence the hardness of the Ti6Al4V single tracks. A similar finding in martensitic chrome-silica steel is made by (Biester et al., 2022), who pointed out that welding speed does not affect the microstructure evolution from the microstructure perspective, which reflects that the welding speed will not have an obvious impact on mechanical properties.

Meanwhile, some research focused on the post-output phase study, such as heat treatment (X. Ding, Ma, et al., 2022), and ultrasonic rolling (Kisielewicz et al., 2021), the measures in which phase mainly aim to improve the performance of the outputs; while some research put efforts into adding affiliated process equipment in the input phase to achieve resistive heating (Kisielewicz et al.,

2021), induction heating (Sang et al., 2022) of the materials, ultrasonic excitation of the melt pool (Heidowitzsch et al., 2023) to contribute to the improvements of the wire-based laser DED process outputs. (Kisielewicz et al., 2021) added a resistant preheating facility to heat the wire. During the deposition process, the laser absorption of the wire, process stability and metal fusion situations were improved; these improvements were also found by researchers (Kisielewicz et al., 2021). (Nie et al., 2016) pointed out that laser absorptivity can be enhanced to 15% after using a laser hot wire. (Sang et al., 2022) mentioned that when it comes to low-resistivity materials, resistance heating is unsuitable, which limits its wider application; alternatively, induction heating does not need to consider the resistivity concern, therefore, a wider range of materials can be applied. But only applying wire induction preheating can increase the temperature gradient which can maintain cold cracking in the deposits. Therefore, the authors preheated the 304 stainless steel wire and substrate together, which could improve the energy input and reduce the temperature gradient, thereby avoiding the generation of crack defects.

As laser-based research advances, coaxial wire-based laser DED with either an annular ring shape beam or with a several individual laser beams integrated configuration has been developed and has attracted significant research due to the advantage of direction independence (Kotar et al., 2019). Off-axis feeding was regarded as a non-stable and non-robust process for additive manufacturing (Govekar et al., 2018) because it is hard to achieve the uniform distribution of the laser radiation around both the wire and the substrate, which means that the off-axis deposition doesn't achieve similar conditions for all processing directions (Kotar et al., 2019; Zapata et al., 2022). On the contrary, the coaxial process can waive investigating the wire feeding angle relative to the laser beam, and the wire feeding direction. Therefore, avoids the uneven energy density distribution on the substrate and wire, which makes the deposition investigation more convenient to operate and more precise to control the laser energy input.

Additionally, beam shaping based on the optical component modifications can change the power distribution spatially and temporally (Mi et al., 2022). A

relatively more uniform energy density distribution with lower peak energy density can be achieved by introducing the annular laser beam profile. In this case, finer grains with equiaxed structure could be achieved under the same heat input due to the reduced thermal gradient (Chen et al., 2022), as shown in Figure 2-5 (a) and Figure 2-5 (b) compared with a conventional laser heat source Figure 2-5 (c) and energy density distribution Figure 2-5 (d). In this annular beam-shaped case, even the not fully melted wire-end can also be fed into the molten pool stably which can potentially provide the additional dendrite fragments acting as nucleates to prevent the columnar grain growth. Also, the coaxial wire-based laser DED process can enhance the energy utilisation rate, the required energy to fully melt the same amount of wire is less than the lateral feeding method for similar process parameters, as shown in the images of the cross-section of the single bead in Figure 2-6 (a), (b).

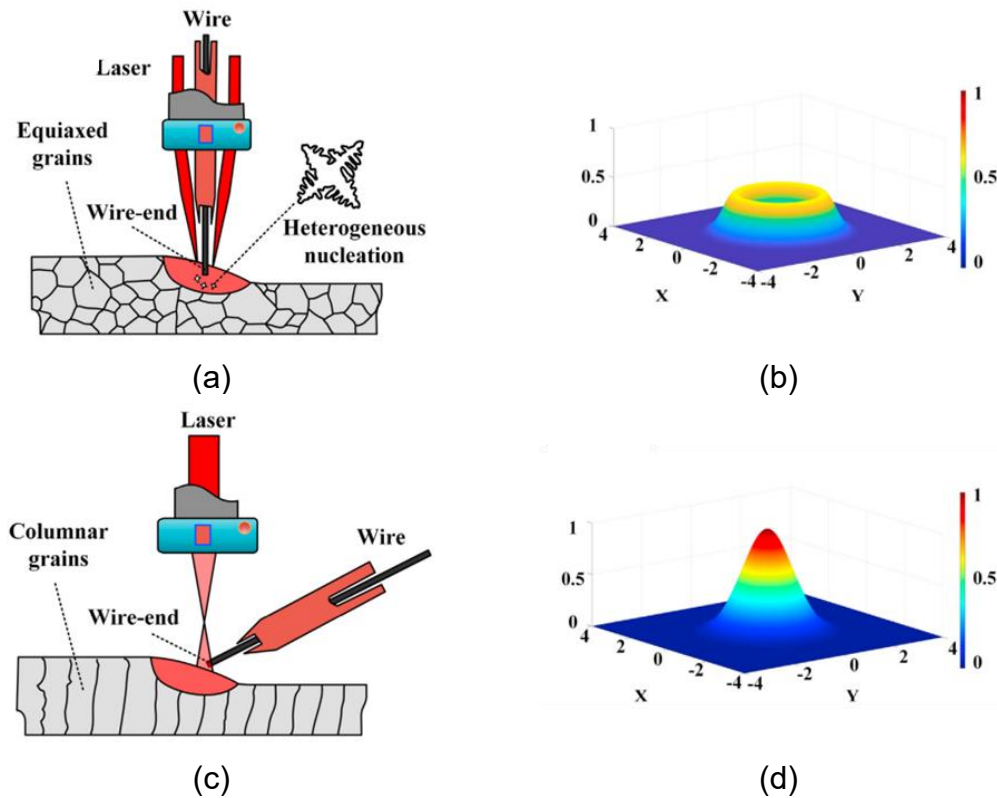


Figure 2-5 (a) Schematic of melting and solidification behaviour of using the coaxial feeding configuration; (b) calculated coaxial case laser beam energy distribution; (c) schematic of melting and solidification behaviour of using the lateral feeding configuration; (d) calculated lateral case laser beam energy distribution (Chen et al., 2022).

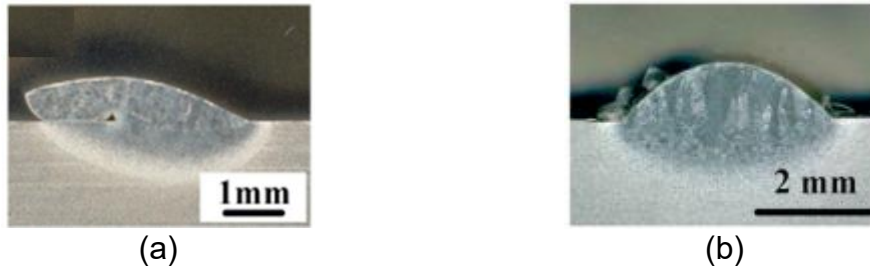


Figure 2-6 Images of (a) poor single bead profile formation using lateral case; (b) good bead profile formation using coaxial case under the same processing parameters with the same heat input (Chen et al., 2022).

The coaxial feeding method is well accepted as a direction-independent process because the wire and processing head are perpendicular to the workpiece. However, (Roch et al., 2023) investigated the effect of the laser head direction of three laser beams' coaxial configuration on bead geometry and penetration of Inconel 718 material. Figure 2-7 shows that different laser-material interaction patterns projected on the material can be formed based on the available rotational angle (travel direction is along the x-axis shown in the image).

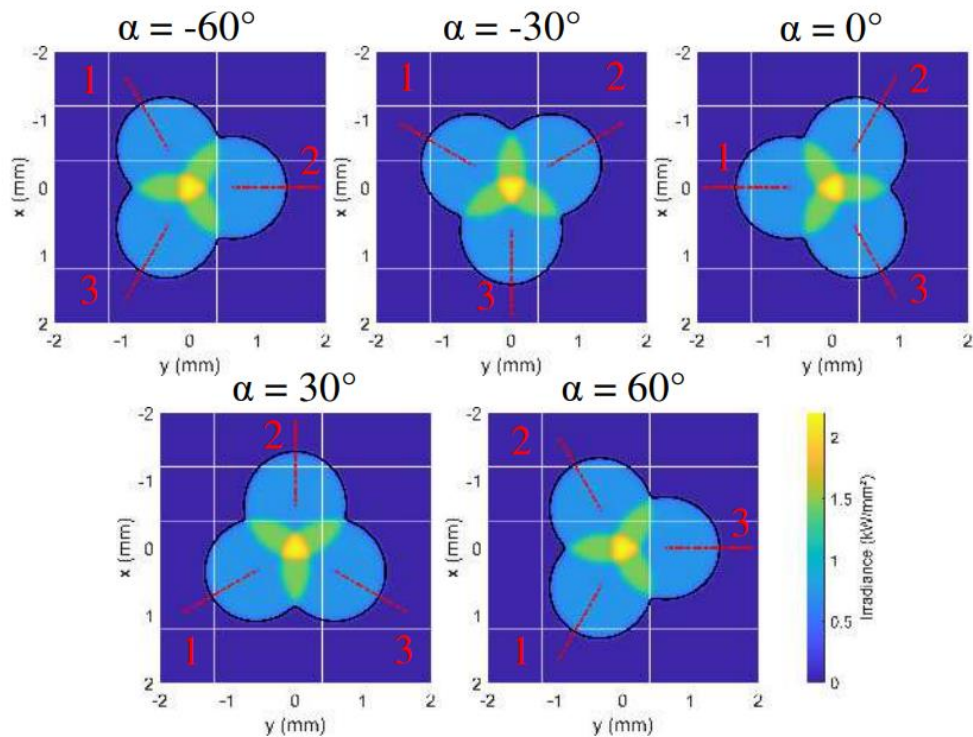


Figure 2-7 Power density and laser spot limit for different values of laser head rotation (Roch et al., 2023).

The results in Figure 2-8 show that a symmetrical laser beam arrangement along the deposition direction ($\alpha = \pm 30^\circ$) can create symmetrical beads, while the asymmetrical configuration with either two lasers on the left side or right side ($\alpha = \pm 60^\circ$, and $\alpha = 0^\circ$) results in a bead geometry displacing towards the higher laser irradiance area and a deeper penetration, which approved that the coaxial feeding with odd number of multi-beam configuration case still has a spatial-direction-dependent factor that will influent the deposition performance.

Also, in (Roch et al., 2023), the authors investigated the laser head orientation of three multi-beam configuration relative to the travel direction, and laser head tilted angle relative to the substrate factors on bead geometries, and got the conclusion that the deposition performance, the geometries and the asymmetry of the beads is also influenced by the laser head rotation and tilted extent, this shows that the coaxial wire-based laser DED is also a direction-dependent process which just removes the factor of the angle between laser beam and wire feed nozzle.

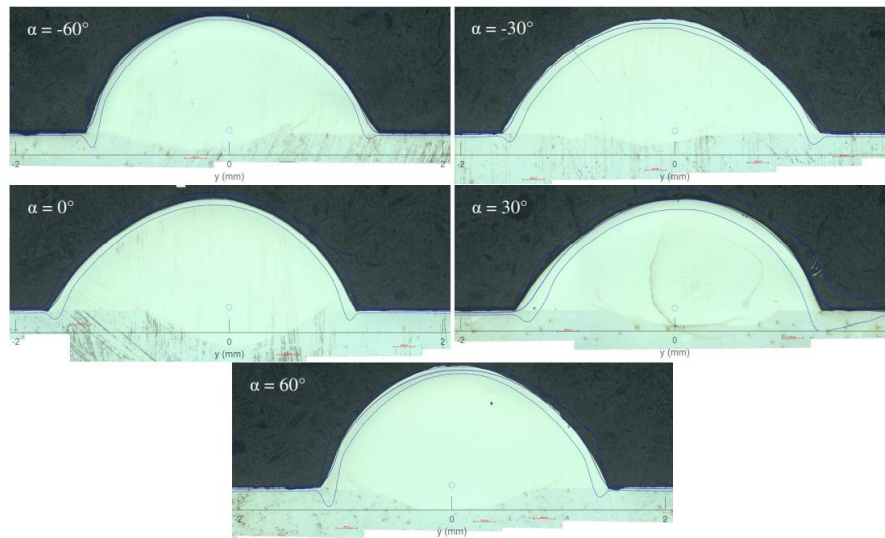


Figure 2-8 Variations of the bead dimensions with different head rotation angles (Roch et al., 2023).

(Schulz et al., 2019) argued that the off-axis wire feeding process is a bonus for local shielding over coaxial configuration because the size of the melt pool using coaxial configuration is usually bigger due to the integrated multi-beam configuration compared with a single laser beam.

Meanwhile, the ring-shaped case laser beam profile has a higher energy distribution than the single Gaussian-type laser beam case under the same displacement distance. (Explanation follows: take the ring-shaped profile as the displacement distance reference length (Figure 2-9 (a)), the energy distribution of the off-axis configuration case is lower under the same displacement length (Figure 2-9 (b)) (Chen et al., 2022), which results in a larger heat-affected zone forming in the coaxial configuration case, this increases the difficulty of protecting the interaction region when using local shielding with a coaxial configuration.)

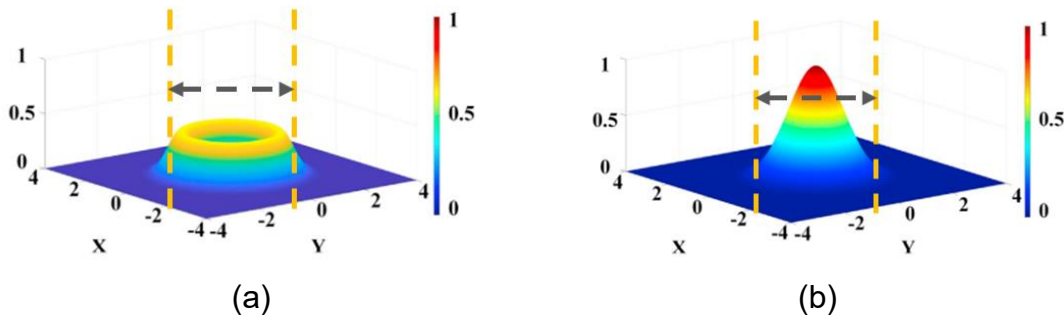


Figure 2-9 Comparison of the (a) ring-shaped case energy level and (b) Gaussian-type energy distribution (Chen et al., 2022) with the same length displacement.

In addition, coaxial deposition may still have some weaknesses in terms of the processing factors or the design of the configuration, which need to be investigated or solved in the future. For instance, the coaxial deposition is still sensitive to the process parameters which will interfere with the deposition stability, especially during the initial transient phase (Kotar et al., 2019), of which the phase requires a precise time synchronisation to establish a stable process. Moreover, the coaxial configuration makes it difficult to adjust the synchronisation time between the laser and the wire. On the contrary, off-axial configuration can adjust the wire feed nozzle position back or forth to delay or shorten the time of wire advancing into the melt pool, which makes it easy to achieve the synchronisation between wire and laser to promote to achieve the stable condition faster. Therefore, both coaxial and off-axial configurations have their own advantages in their working regimes. It is inadequate and superficial to conclude coaxial configuration is convenient and better than the off-axial configuration.

(Kotar et al., 2019) pointed out that even though coaxial wire feeding has many advantages over lateral feeding, it still has limitations. Figure 2-10 (a) shows that if there is a gap between the wire and the substrate, the melt pool can be created without laser beam shadowing and power attenuation caused by the wire interference. However, the laser beam irradiation and reflection after being projected on the substrate surface were redirected to the wire end or other unknown, non-specified directions, and the direction is uncontrollable. In this case, the wire end is very sensitive to the laser power variation, easy to form an uncontrollable pendant droplet and then cause the failure when the initial laser power applied on the wire surface is not in a proper range.

Thus, the authors proposed a new strategy by putting the wire end just above the substrate surface (Figure 2-10 (b)). The experimental results indicated that this method could speed up the transition into the stationary deposition process. A proper energy input and stable process can be achieved.

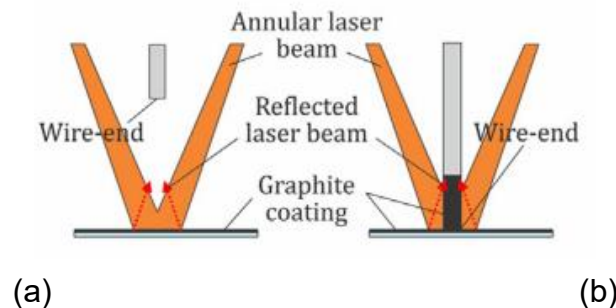


Figure 2-10 Initial wire-end position (a) suspending in the free space (unstable process) (b) just above substrate surface (stable process), and the corresponding workpiece laser irradiation (Kotar et al., 2019).

(Da Silva et al., 2020) proposed a new configuration design for the laser wire system, which is shown in Figure 2-11.

The laser head has a 50° tilted angle relative to the vertical position, and the wire was fed vertically. A 0.67 mm laser spot was pointed on a 1.60 mm thick wire with laser power ranging from 3.5 kW to 7.0 kW to only melt the wire to complete the deposition, which can save nearly 87% of the energy compared with the normal energy used in the regular configuration's laser metal wire deposition process.

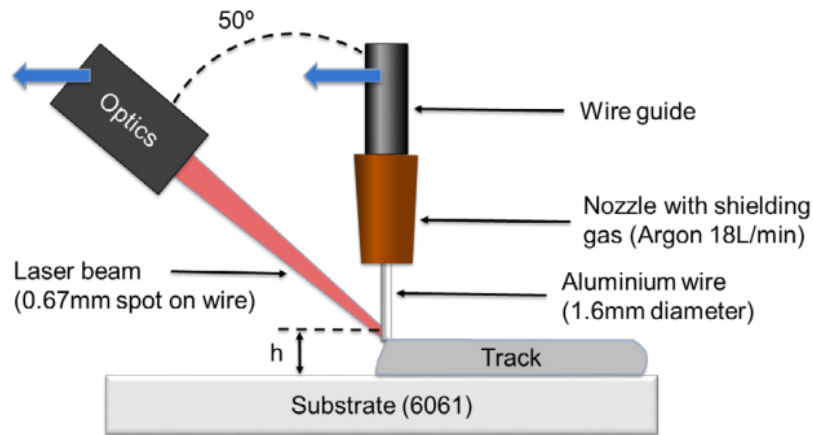
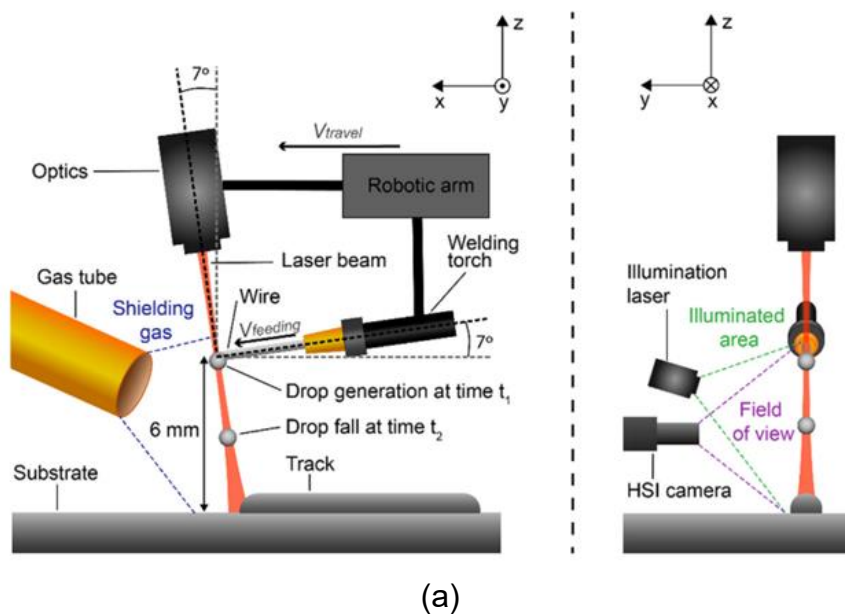


Figure 2-11 Image of the design of the vertical wire feeding configuration (Da Silva et al., 2020).

At the same time, many researchers are focusing on innovative wire-based laser DED experiments from other perspectives to achieve a stable process. (M. Liu et al., 2023) introduced the different oscillating paths in the experiments combined with dual wires feeding to reduce the temperature and temperature gradient of the melt pool, thus increasing the deposition stability. (Da Silva et al., 2021) investigated the novel technique of wire-based laser-assisted drop-by-drop additive manufacturing process, the setup and principle are shown in Figure 2-12 ((a), (b)) below.



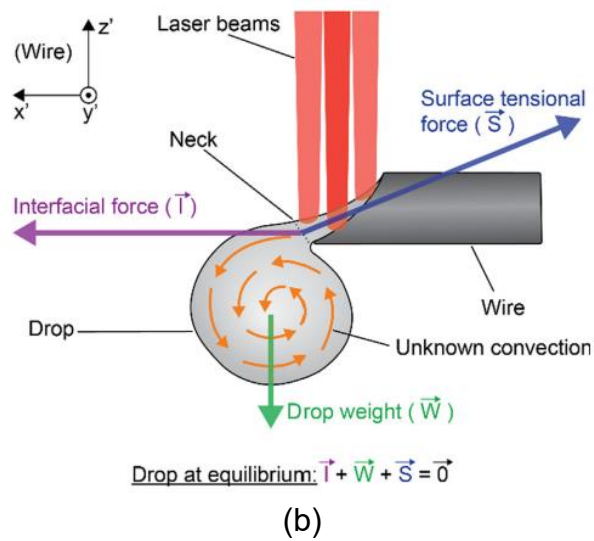
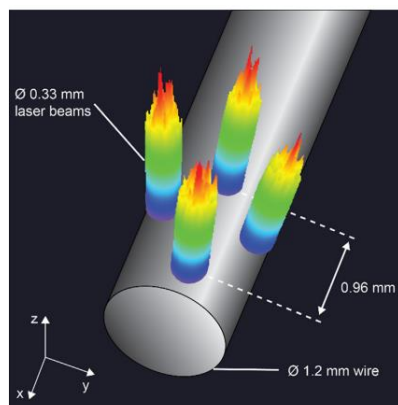


Figure 2-12 Images of (a) experimental setup for laser drop generation, and corresponding (b) mechanism of force balance in generating a droplet (Da Silva et al., 2021).

To achieve a stable process and stable guidance when the droplets are prone to fall, the system was equipped with four individual laser beams with 0.33 mm individual diameter (Figure 2-13 (a)) to avoid high laser beam intensities. The result showed that the process can successfully deposit a good track (Figure 2-13 (b)) with a relatively even distributed morphology (Figure 2-13 (c)). The mechanism of this process seems like a powder-based DED process, but if the powder is in a macro size.





(c)

Figure 2-13 Images of (a) layouts and working distance of four individual laser beams, (b) bead with good appearance, (c) longitudinal image with even distribution morphology (Da Silva et al., 2021).

Overall, much research was conducted considering the factors in the input, output, and post-output phases of the deposition, and some focused on assistant processes or affiliated facilities to improve the overall performance. However, using either off-axis feeding or coaxial feeding method, there is still the issue regarding the parameter transferability from one laser to another laser, from one system to another system, using different facilities or lasers always causes different parameters' study and process window investigation individually. In a keyhole welding study, (S. Williams & Suder, 2011) proposes the fundamental laser-material parameters (FLMIPs), i.e., average power density (PD), interaction time (IT), and specific point energy (Esp), which are independent of different laser systems (Suder et al., 2012) resulting in the parameters being transferable in keyhole regime welding.

PD, or intensity, is defined as the ratio of laser output power and laser beam area projected on the substrate, which is given by:

$$PD = \frac{LP}{A} \left(\frac{kW}{cm^2} \right) \quad (2-1)$$

IT defines one interacted period duration of a point exposed under the laser beam radiation while the laser beam or processing stage is moving at a constant speed, which is given by:

$$IT = \frac{BD}{TS} (s) \quad (2-2)$$

Esp defines the energy delivered to the laser spot at one interacted period duration, which is the integral of intensity (I) and IT over the diameter of the laser beam, for the top-hat beam with uniform intensity distribution or a rectangular

beam with constant IT across the whole laser spot region case, the formula also corresponds the product of laser output power and one interacted period duration, the formula is given by:

$$Esp = PD * IT * A = LP * IT (J) \quad (2-3)$$

If the intensity is not uniform, the original Esp formula given below should be used.

$$Esp = \iint I(x, y) * IT dx dy \quad (2-4)$$

(S. Williams & Suder, 2015) applied these FLMIPs to the conduction mode welding to study whether the geometries are controlled by the same parameters as keyhole mode cases (S. Williams & Suder, 2011), and finally reported conduction regime does not have a similar geometry response. In conduction mode, the weld width is controlled by the beam diameter and IT, the depth of penetration is controlled by the PD and IT (the product of PD and IT is surface energy density (ED)). Surface ED describes the spatial distribution of the energy applied to the unit material surface exposed to the laser beam (Ayoola, 2015), which is given by

$$Surface\ ED = PD * IT (J/mm^2) \quad (2-5)$$

Surface ED can directly reflect the impact of laser beam size, laser output power, and processing speed on geometry.

After identifying that the beam size and IT control the width of the weld in the conduction regime, the author extended the research to the PBF process (Ayoola, 2015) and got the same results of deposit width depending on the beam size and IT when using powder substance. However, for this PBF process, the authors pre-placed the powders in the pre-machined grooves; in this case, the process of melting the powders is similar to the welding process, which makes the conclusion of applying FLMIPs in this non-traditional PBF process feasible.

However, the wire size is significantly larger than that of powders (for instance, 600 µm of wire vs 60 µm of powders), and the round shape profile could cause

the energy distribution on the wire to be uneven, which increases the difficulty of using FLMIPs in the wire-based laser DED process. Nevertheless, from the other perspective, the Gaussian-type laser beam profile at larger laser beam conditions could match the wire profile to some extent, which may promote the possibility of applying FLMIPs on the wire-added process. Thus, it is interesting to see the feasibility of applying FLMIPs to the wire-based laser DED process.

Therefore, in this study, the deposition performance, geometrical variations, and the relevant factors' analysis and discussion will be partially based on FLMIPs.

2.2 State-of-the-art wire-based laser DED process for small features

Nowadays, the commonly used sizes of the commercial welding wire are above 0.6 mm, and normally, the wire needs to be fully covered by the laser beam size for the correct positioning of the heat source over the wire (Capello & Previtali, 2006), which resulting in a relatively larger melt pool that is up to several centimetres and a larger layer thickness which is normally beyond 0.5 mm (Z. Li et al., 2022), rare researchers paid attention to the wire-based laser DED process of high-resolution submillimetre scale features, few papers were found on manufacturing the millimetre and submillimetre scale features.

Nevertheless, the intrinsically precise merit of the laser as the heat source with the accurately controlled energy delivered to the process (Wei et al., 2021; Yang et al., 2016) has the prospective ability to fabricate the submillimetre features. In addition, the cleaner process (Z. Li et al., 2022), cheaper raw material (Mok et al., 2008), a nearly 100% wire utilisation (Kisielewicz et al., 2021), higher deposition efficiency and easier availability of the wire (Mbodj et al., 2021), and easier changing of the wire feedstock than powders make the wire-based laser DED become a potentially compatible process to fabricate submillimetre features using different materials or combining different materials together to achieve the multi-material submillimetre feature fabrication. Moreover, for space exploration, the wire-based process is safer and more efficient in satisfying the rapid prototyping (B. Li et al., 2021) of new tools, replacing damaged components or

repairing the damaged part in situ, which prompts the inspiration to investigate the wire-based laser DED process for submillimetre scale features further.

Compared with using wire-based laser DED for fabricating medium-sized to large-scale parts (Y. Ding et al., 2018), the naturally small dimension of the submillimetre-scale feature bead width requires precise control of the energy input and wire position to minimize the possibility of layer collapse when depositing each layer. Wire-based laser DED process generally produces lower accuracy parts than the PBF process (Shaikh et al., 2020). A high-energy heat source of the laser generally causes the deposition to easily have high residual stresses (Sun et al., 2020). Moreover, the small size of the wire can destabilise the process due to the mechanical stability of the wire flow (Kaljevic & Demir, 2022). Therefore, the technique for fabricating submillimetre-scale, net-shape profiles with stable performance is rigorous.

Several experimental parameters for investigating the small (and submillimetre) scale features are summarised and listed in Table 2-1.

Table 2-1 shows that, to date, the strategy for manufacturing small (and submillimetre) scale features is mainly focusing on using fine wire with a comparable laser beam size. (Demir & Biffi, 2019) successfully deposited the 4047 aluminium alloy millimetre to submillimetre (700 μm – 1100 μm) thin walls using a pulsed laser with 0.6 mm laser spot size and 0.4 mm in diameter wire, but reported the process window is narrow, the process is sensitive to the variation of the energy input which should be attributed to the low melting point and high reflectivity of the material. (Kaljevic & Demir, 2022) investigated the high reactive alloy of biodegradable Mg (Resoloy) alloy from the perspective of shielding gas flow with 0.9 mm of laser spot size, and 0.5 mm of the wire, and claimed that the small diameter of Resoloy alloy wire was easy to be bent and vibrated by the high gas flow rates due to the smaller elastic modulus compared with stainless steel. (Demir, 2018) used a pulsed laser with a 0.85 mm laser spot size and 0.5 mm AISI 301 stainless steel wire successfully deposited the submillimetre walls (700 μm – 800 μm) and features as shown below in Figure

2-14. And this process still exhibits the potential to reduce the width by using a thinner wire.

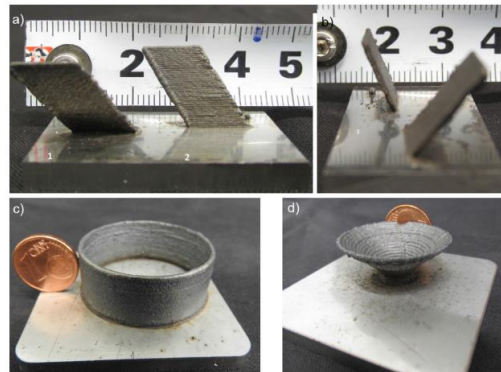


Figure 2-14 Image of thin-wall structures fabricated by the WLAM process (Demir, 2018).

(Shaikh et al., 2020) used a very fine 0.1 mm 304 stainless steel wire with 0.2 mm laser spot successfully fabricated the high-precision parts with enhanced resolution, dimensional accuracy, and better surface finishing. The wall width is between 500 μm - 800 μm . The surface roughness was comparable to the powder bed processes. (B. Li et al., 2021) used 50 W of laser power, 0.3 mm thick 316L stainless steel wire as well as resistance Joule heating to successfully achieve the fabrication of high-resolution, low roughness thin straight and inclined walls based on different wire feed to processing speed ratios (1.0, 1.2, 1.5) and claimed a well-matched energy input and wire feeding help produce parts with good quality, and the speed ratio is a key parameter for successful fabricate the part. (Du et al., 2019) successfully deposited the Ti-6Al-4V thin-walled components with 8 individual 50 W laser power sources which integrated into a 1.35 mm laser beam size, and reported that different height increments (0.24 mm to 0.30 mm) (i.e., laser head offset distance for the next layer deposition), heat inputs and cooling times affect the bead width, and all of these parameters have their own working ranges. The performance of the stability of the thin-walled component is better when the height increment increases from 0.24 mm to 0.28 mm because the layer width reaches the maximum stable condition. In addition, the authors reported that heat accumulation influences the process more than other conditions when the inter-layer cooling time is 1s. Beyond 5s of inter-layer cooling time, no obvious width variation is detected by the authors. Their research

team (X. Ding, Ma, et al., 2022) also claimed that they used a multi-laser beam (5 individual laser beams) with coaxial wire feeding successfully deposited the Ti-6Al-4V submillimetre walls.

(Sang et al., 2022) used 1.2 mm to 1.3 mm laser spot diameters combined with pulsed mode laser with 0.6 mm 304 stainless steel wire to investigate the different auxiliary heating strategy effects on the deposits, and claimed that auxiliary heating can reduce the porosities effectively. Preheating the wire and substrate together works better than the hot wire case; hot wire case works better than the substrate-only heating case in terms of deposition performance and defect removal due to the improvement of energy input and reduction of thermal gradient.

There is little wire-based laser DED process investigation for submillimetre features, and the research mainly focused on using small beam sizes (with the laser beam sizes just covering the size of the wire) to conduct the experiments. Generally, researchers assume that a wider laser beam results in a wider bead; in the conduction welding regime, the weld width is dependent on the width of the laser beam (Ayoola et al., 2017). As a result, not much research is focused on large-scale laser beams; hereby, the beam scales are defined as:

- 0 to 1.0 mm, small size
- 1.0 to 1.5 mm, relatively large size (medium size)
- above 1.5 mm, large beam size

And rare researchers consider the factor that a similar laser beam size, which is close but can just cover the fine wire size, can bring a positive or negative influence on deposition. Not many researchers reported the wire position sensitivity when using large size laser beams. And all the research is conducted at a relatively low speed, as seen in the summarised Table 2-1, which will not reach the high deposition rates target and the rapid manufacturing requirements.

Thus, this study would like to fill out the gap by investigating the use of large-sized laser beams to fabricate submillimetre-scale features and enhance the

deposition rate significantly while still maintaining good performance, and observe whether the wire positioning sensitivity is improved or deteriorated.

Table 2-1 Summarised experimental parameters for small (and submillimetre) scale features fabrication.

References	Laser mode (type)	Laser power (W)	Pulse energy E(J)	WFS (mm/s)	TS (mm/s)	Laser beam sizes (mm)	Wire material	Wire diameter (mm)	Substrate material	Beam-to-wire ratio	Wall width (μm)
(Demir & Biffi, 2019)	Ms-pulsed, flash-pumped Nd: YAG	/	12 – 13	1.43	1.17	0.60	AA 4047 Al alloy	0.40	AA 5754 Al alloy	1.50	700 – 1100
(Kaljevic & Demir, 2022)	μs to ms pulsed, flash-pumped Nd: YAG	/	2 – 5	3.67	1.00	0.90	Resoloy	0.50	AZ31 alloy	1.80	1565
(Demir, 2018)	μs to ms pulsed, flash-pumped Nd: YAG	/	9 12	3.83	1.50 – 3.00	0.85	AISI 301	0.50	AISI 316	1.70	750 – 850
(Shaikh et al., 2020)	Ms-pulsed, Nd: YAG	44 – 51	/	7.85	1.50 – 5.00	0.20	304 ss	0.10	316 L ss	2.00	500 – 800
(B. Li et al., 2021)	Ytterbium fibre laser	50	/	0.07 – 0.25	0.08 – 0.25	0.35	316 L ss	0.30	316 L ss	1.17	557 – 604
(Du et al., 2019)	Semiconductor laser	8 x 30 – 8 x 45	/	8.00 – 25.00	3.00 – 10.00	1.35	Ti-6Al-4V	0.40	Ti-6Al-4V	3.38	1503 – 1727
(X. Ding, Ma, et al., 2022)	Semiconductor laser	5 x 36	/	9.00	3.00	/	Ti-6Al-4V	0.40	Ti-6Al-4V	/	800 –1230
(Sang et al., 2022)	Ms-pulsed, Nd: YAG	300	/	4.00	0.42	1.20 – 1.30	304 ss	0.60	304 ss	2.00 – 2.17	496 –1138

2.3 Summary of the factors that influence the wire-based laser DED process

The motion system (robot or CNC), the laser source and the wire feedstock are the three main components that integrate the wire-based laser DED system. Generally, many factors coming from the laser system can influence, intervene or even deteriorate the wire-based laser DED process performance depending on whether the factors' operation regimes are reasonable or not.

Currently, many researchers are dedicated to investigating the process window of the relevant system parameters, using the parameters within the window/envelope can guide laser users to achieve stable deposition. Beyond the system parameters, there are also many other parameters coming from the laser itself, such as the optical system or laser physical characteristics (fibre, Nd-YAG, CO₂ types), which can also influence the deposition process; thus, the laser-based process is much more complex in terms of fully studying and comprehensively understanding the processing mechanism compared to arc-based processes. Below is a summary that lists the feasible factors that can influence the performance based on four-phase categories:

primary input parameters (parameters or a combination of several parameters directly related to the energy input)

secondary input parameters (parameters not directly related to the energy input but still exhibit a critical impact on the deposition performance)

output parameters (parameters based on visual inspection, measurement, and calculation)

and post-deposition parameters (parameters that are not related to the energy input but can contribute to the as-deposited deposit's final performance).

Primary input parameters:

Laser types (fibre, CO₂, etc). Laser power (LP). Laser beam diameter (BD) and the corresponding beam profile. Laser mode (continuous waveform mode or

pulsed mode, relevant variates for pulse variation). Laser processing plane before or after the focal point. The inner and outer circumference of the ring-shaped beam. The overlapping ratio of different individual beams, the quantity of beams (even or odd number) and the corresponding beam profile of the multi-laser beam configuration.

Material types of the wire include wire diameter. Wire feed speed (WFS). Travel speed (TS). Speed ratio (WFS/TS). Wire feeding angle. Wire feeding direction. Wire stick-out length and wire initial position. Laser-substrate-wire spatial interaction area for ring-shaped or multi-laser beam configuration. Spatial position of the coaxial head relative to the substrate and processing direction. Relative parameters related to the affiliated facilities (for instance, induction heating, resistance heating, laser scanning preheating equipment) for enhancing the output performance. Fundamental laser-material interaction parameters (FLMIPs) (PD, Esp, IT). Linear energy input (EI). Surface energy density (surface ED).

Secondary input parameters: Gas types. Shielding gas flow rate. Ambient pressure. Shielding methods. Substrate dimensions. Laser default manufacturing characteristics (for instance, fibre core diameter). Laser beam incident angle. Optical components' physical characteristics (for instance, optic's thickness, collimator length, depth of focus), etc.

Output parameters: Deposited material volume per unit length. Bead surface and interior quality, and defects. Bead dimensions. Aspect ratio (width/depth or depth/width). Contact angle. Dilution. Remelting ratio. Layer height. Material microstructures and characterisations. Mechanical properties, etc.

Post-deposition parameters: Heat treatment. Cold work. Machining, etc.

All three phases of the primary input phase, secondary input phase and post-deposition phase contribute individual effort to the outputs, which either directly or indirectly affect the deposition performance, process stability, and deposit quality, microstructure and properties. Currently, researchers are conducting experiments surrounding these factors at different phases, and based on the

output performance, modify the process, then carry out the modified process; thus, the closed loop is formed, and the component can be fabricated with high performance and good quality to prompt the prosperous development of the wire-based laser DED process.

2.4 Summary of the obstacles of the wire-based laser DED process and motivation for research topics

To date, much wire-based laser DED research has been conducted, and the evidence has proven the feasibility of building three-dimensional features using this technique. Nevertheless, much research was conducted under a different working range of LP, WFS, and TS, and it looks like each working envelope was working independently. This complicates the laser engineering processing investigation. Therefore, laser-based processing is difficult, intricate and requires more exploration to understand the principles and mechanisms. FLMIPs, which are regarded as the parameters that are independent of different laser systems and can make the interaction parameters transferable among other lasers and systems in the laser welding regime, especially the keyhole mode regime. However, (S. Williams & Suder, 2011) interpreted that formula (2-3) can only be fulfilled in the case of square or rectangular top-hat beams, which have a uniform intensity or a constant IT. This prevents the general Gaussian-type beam profile laser from applying FLMIPs to carry out the study.

Nevertheless, this PhD thesis, considering the small size of the wire and the relatively less steep PD distribution within a larger beam size, also, considering the round shape of the wire can match the PD distribution of a large laser beam case to some extent, formula (2-3) could be used in the Gaussian-type laser in this case. But from the author's opinion of this PhD thesis, the high peak power density (p-PD) (Stoll et al., 2024) within the laser beam should be added to the discussion when applying the formula (2-3) on the Gaussian-type laser profile. This is because the real profile of a Gaussian-type beam has an obvious p-PD with a steep PD reduction. The average PD value should be lower than the p-PD value. In this case, the real p-PD effect cannot be represented by the average PD effect. To enable the use of FLMIPs in large beam-sized Gaussian-type laser

beams means needing to assume that the Gaussian-type large size laser beam has a top-hat profile, in this case, addressing the p-PD value is critical because this can utilise the convenience of regarding the large size Gaussian-type laser profile as the top-hat profile, but also addresses the differences between the Gaussian and top-hat profiles, which could enable the feasibility of using FLMIPs in the Gaussian-type laser beams.

It is not easy or simple to conclude that the coaxial configuration is always more flexible and orientation-independent than the off-axis configuration. Off-axis and coaxial configurations have their own advantages and disadvantages in their own expertise regimes. Therefore, researchers should fully investigate and evaluate the coaxial configuration before concluding which configuration is better and more flexible.

Using the wire-based laser DED process to fabricate submillimetre scale parts, in the initial stage study, finding an appropriate wire diameter, and corresponding laser beam range is critical to succeeding in depositing the net-shape high-resolution parts, too thick wire is difficult to achieve the submillimetre scale part, a too thin wire is difficult to feed the wire forward smoothly and continuously due to the softness caused by the fine wire diameter and the friction between the wire and substrate. For beam size, a very small laser beam could cause the vaporisation of the material easily, even if this can deliver the energy accurately. A very large laser beam size can waste the applied energy on the substrate and cannot efficiently melt the feeding material. Thus, a reasonable wire and laser beam size correlation range should be studied, along with the proper laser power range.

A small laser beam size, with a small wire diameter, could cause the tolerance and threshold of the power density to be very sensitive and easy to reach the maximum, but it is good for accurately delivering the energy input. The relationship between the wire and the laser beam is very important. (M. Liu et al., 2023) proposed the oscillation deposition to increase the interaction area, which motivated and inspired the author to use large beam sizes to do the deposition and correlated the laser beam and wire size together to analyse the performance.

The relatively large beam size could potentially reduce the thermal gradient and increase the process stability, which is similar to the laser oscillation movement deposition mentioned in the paper.

To satisfy the requirement of rapid manufacturing in additive manufacturing, high deposition rate fabrication has been proposed, which should also be extended to submillimetre-scale features. In this case, a Gaussian-type laser beam profile with p-PD in the middle of the laser beam could be an advantage when using large beams to deposit the bead with widths significantly less than the laser beam size at a fast-processing speed. Off-axis wire feeding and coaxial wire feeding with multi-laser beam configuration possess this character, which prompts the author in this thesis to use a simple lateral wire feeding configuration to investigate the feasibility of high deposition rates' manufacturing of submillimetre scale features via wire-based laser DED process first.

Thus, in this thesis, the author would like to investigate using large laser beam sizes (≥ 1.5 mm) with 0.6 mm wire to deposit submillimetre-scale features and extend the study to high deposition rates at fast processing speed and higher-level laser powers using an off-axis wire feeding configuration. Meanwhile, correlates the beam and wire diameter to discuss the deposition performance, evaluate the influence of the laser beam to wire ratio on deposition stability and performance.

3 Experimental setup and methodology

In this section, the experimental methodology is explained in greater detail by introducing the experimental setup used in different phases of the experiments first and secondly, the methodology employed in each of the experimental sections of the work. A flow chart of the thesis structure is shown in Figure 3-1 below.

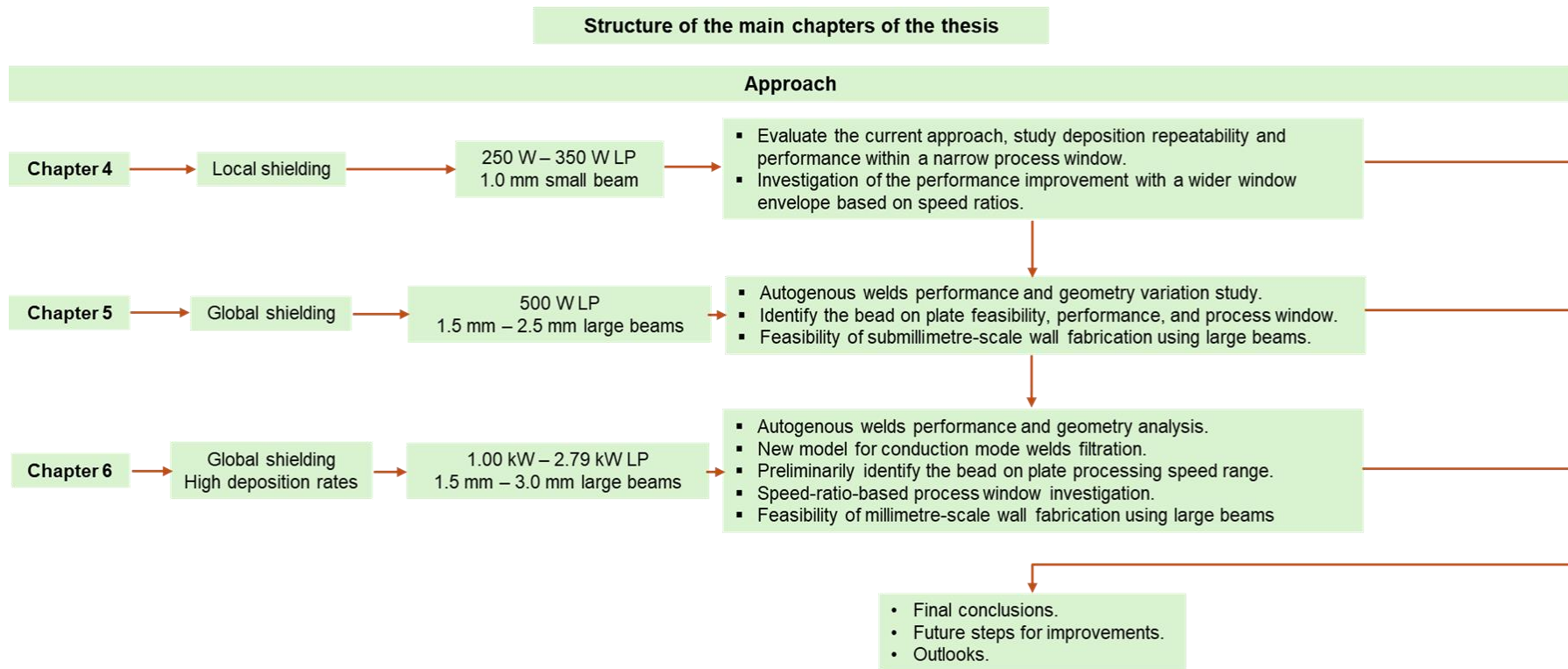


Figure 3-1 Flow chart of the thesis structure.

3.1 Equipment

3.1.1 500 W CW laser and wire setup with local shielding

The 500W continuous wave (CW) laser and wire system with local shielding is shown in Figure 3-2. This system is composed of three linear Owis axes and a rotational axis with a processing speed ranging from 0 mm/s to 7.5 mm/s. OwisSoft software was used to control the stage processing. FibreView software was used to control the laser power output.

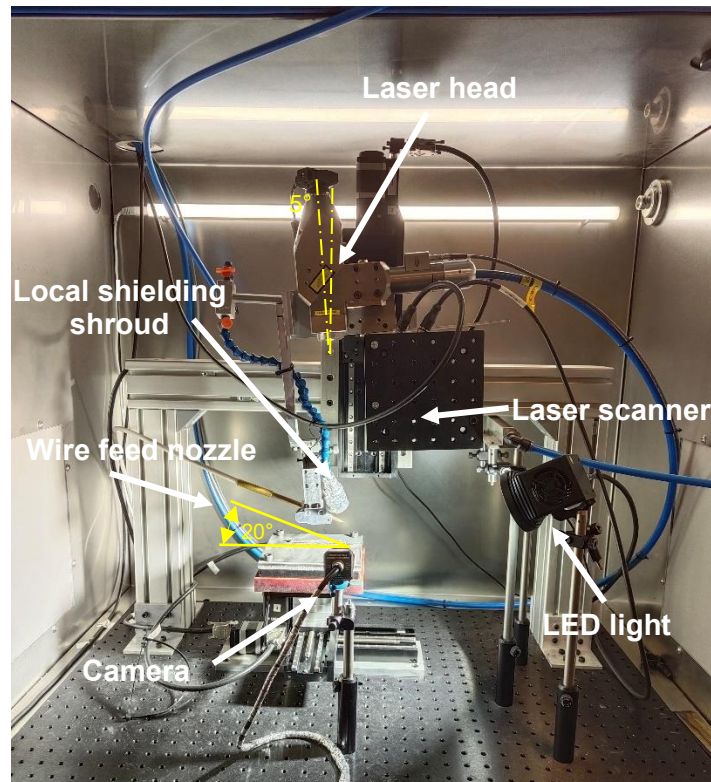


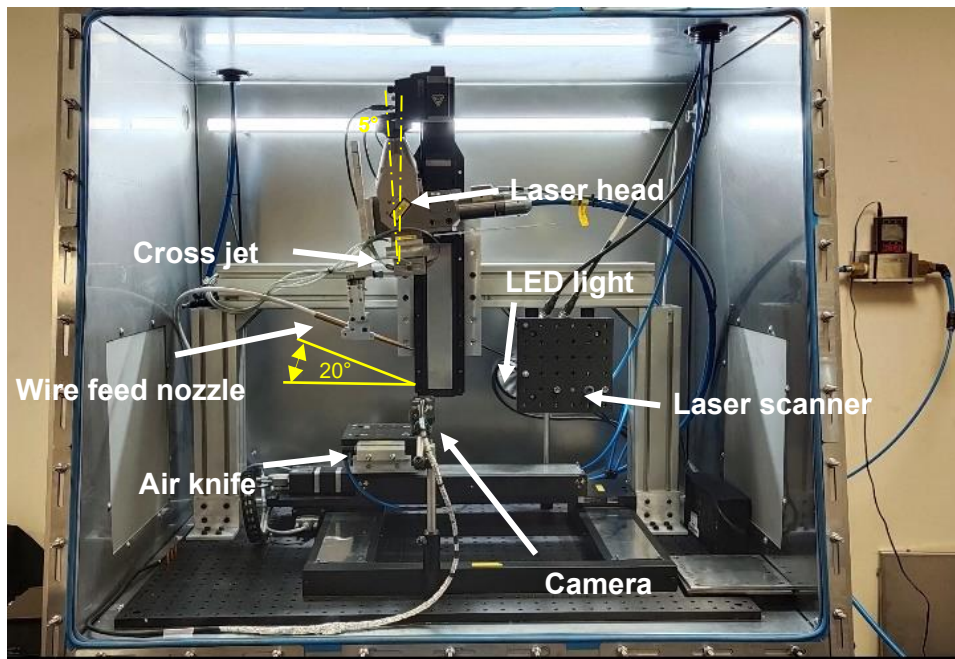
Figure 3-2 Experimental setup for 500 W laser wire local shielding deposition.

A single-mode fibre laser (GSI/ JK500 fibre laser) with 30 micrometres core diameter, and 1070 nanometres of wavelength was used. To monitor the process, a Redman camera (Redman controls MC500SW weld camera) was used with a strong LED light for illumination (Veritas, miniCONSTELLATION™ 120C28 5000K). A TIG shroud with a gas lens was used for local shielding, and the laser head was positioned with a 5-degree tilted angle (tilted into the deposition direction) along the vertical plane to avoid any laser back reflection. A wire feed nozzle with a 20-degree wire feeding angle along the horizontal direction was

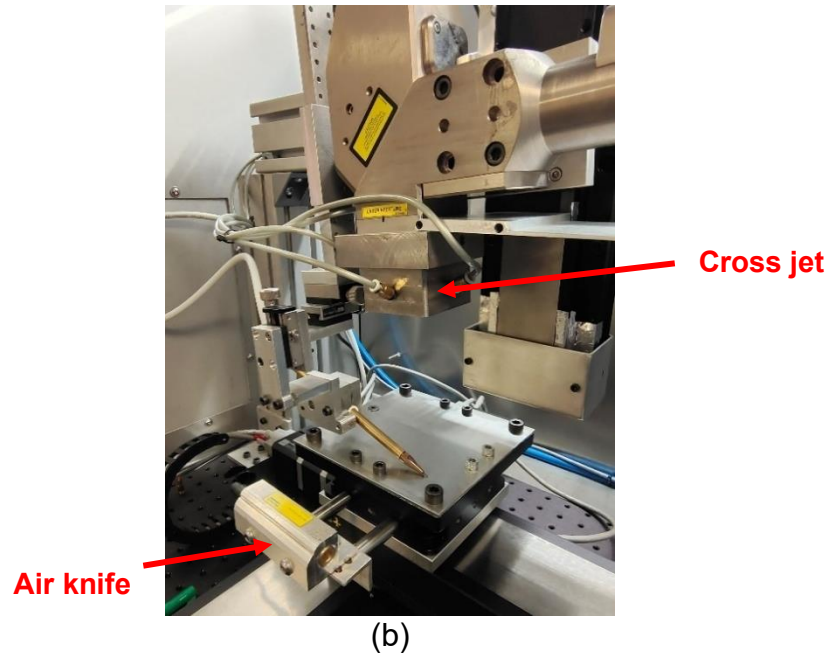
used. 316LSi wire 0.6 of wire diameter was fed using a customised wire feeder TIG FEED 40 from TecArc Ltd. This setup was used for all the local shielding trials mentioned in Chapter 4.

3.1.2 500 W CW laser and wire setup with global shielding

Due to the limitation of the travel speed from the previous setup (maximum 7.5 mm/s), two linear x-, and y-axes Zaber LRQ300 series CNC stages (maximum TS: 840 mm/s), one linear z-axis X-LRT250 series CNC stage, and one RSB120 series high-speed belt drive rotary stage were combined with the same laser CW 500 W system. The same glovebox was modified and fully closed to be used for global shielding. An air knife was fixed on the rotational stage to suppress any plume generated during deposition, and a cross jet was attached to the laser head to avoid the contamination of the protective window. The oxygen analyser (Rapidox 1100-z) was connected to the glovebox to analyse the oxygen content percentage, and the oxygen levels can be controlled to ppm levels. The rest of the setup was kept the same except for the local shielding device that was removed. Figure 3-3 (a) shows the overall setup layout. A closeup of the deposition unit with an air knife and a protective window cross jet is shown in Figure 3-3 (b). This setup was used for global shielding trials conducted under 500 W laser power conditions in Chapter 5.



(a)



(b)

Figure 3-3 Images of (a) overall setup layout, (b) closeup of deposition unit with air knife and cross jet attached to the 500 W laser wire system.

Zaber Console software was used to control the stage movement; Zaber stages were connected via the Zaber X-MCC4 series controller (Figure 3-4). FibreView software was used to control the laser power output.



Figure 3-4 Image of Zaber X-MCC4 controller.

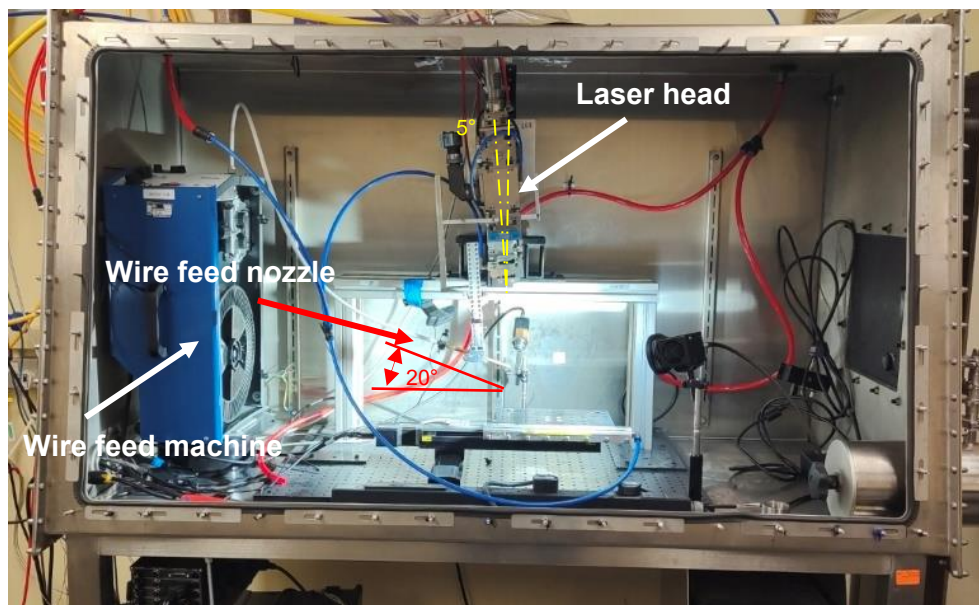
3.1.3 3 kW laser and wire setup with global shielding

A set of Zaber LSQ300 series CNC x-, y-, and z-axes stages (with a max speed of 840 mm/s), a fibre laser (GSI/ JK3000 fibre laser) with 50 micrometres core diameter, 1070 micrometres of wavelength, and a maximum 3 kW (nominal) LP

source were combined as the main system. The Precitec laser head (Precitec GJ21527) was used in this part of the experiments. To replicate the system in section 3.1.2, similarly, an air knife was fixed on the linear processing stage, a cross jet was attached below the laser head to blow away any contaminations that could attach to the laser optics, a Redman camera (Redman controls MC500SW weld camera) and a similar LED light (Veritas, miniCONSTELLATION™ 120C28 5000K) were used for illumination and deposition monitoring.

A wire feed nozzle with a 20-degree wire feeding angle along the horizontal direction was used in conjunction with the same TecArc Tig feed 40 wire feeder (maximum feeding speed can reach 100 mm/s). An oxygen analyser (GS) is connected to the chamber to monitor the oxygen level.

The overall setup layout is shown in Figure 3-5 (a). Figure 3-5 (b) shows the closeup of the wire-based laser DED system. This setup was used for all the trials conducted under high-level laser power, and global shielding conditions in Chapter 6.



(a)

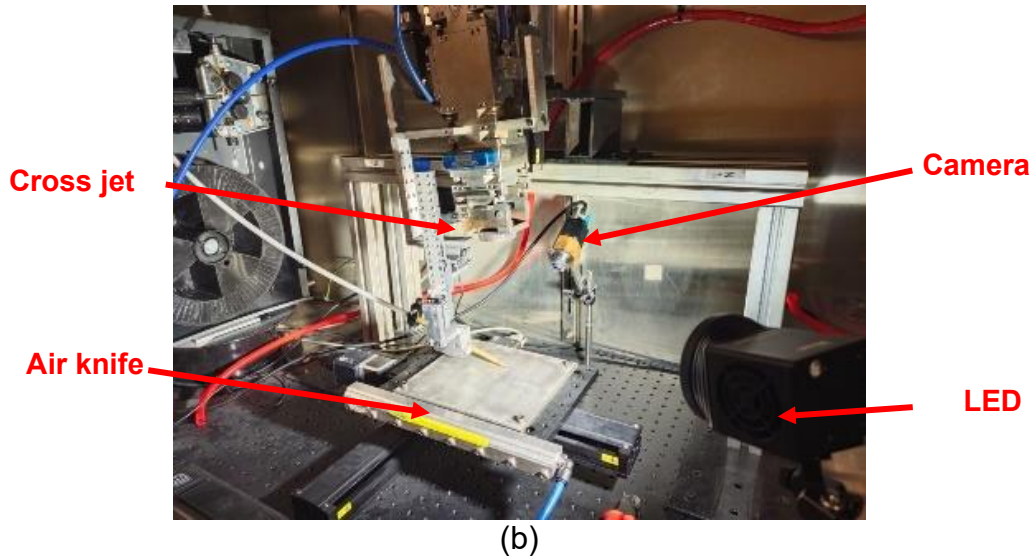


Figure 3-5 Images of (a) overall setup layout, (b) closeup of deposition unit with an air knife and a cross jet attached to the 3kW laser wire system.

Zaber Console software was used to control the stages' movement; the Zaber stages were connected together via the Zaber X-MCC4 series controller. FibreView software was used to control the laser power output.

3.2 Materials and consumables

3.2.1 Substrates and wire

Different dimensions of 316L stainless steel (SS) substrates were used along with a 0.6 mm in diameter 316LSi SS wire during the experiments as per the experimental design, and experimental requirements such as avoiding the substrate burning through and avoiding serious distortion when using the thin sheets. The dimensions of the wire, substrates used, and the corresponding experimental sections and the chemical compositions of the materials are listed in Table 3-1. Before the deposition, the substrate was ground with an angle grinder to make the surface rougher and to increase the laser absorption rate, then wiped with acetone to remove off all the oil, grease, and contamination. These substrate preparation procedures were applied to all the phases of the experiments. One point that needs to be mentioned is that before section 4.3.3, the substrates with 150 mm x 100 mm x 10 mm dimensions were ground and prepared by the technician (for the induction purpose) to enhance the laser

absorption rate. From section 4.3.3, the substrates were ground by the author. During the experiments, when observing the surface scores could affect the melt pool size stability due to laser reflection and absorption variations. After section 4.3.3, a more even surface finish condition was applied.

Table 3-1 Chemical composition of 316L SS substrates and 316L Si SS wire (weight%).

Dimensions	Materials	Chemical elements*									Section
		C	Cr	Mn	Mo	N	Ni	P	S	Si	
0.6 mm	316LSi ss wire	0.020	19	1.400	2.600	/	12.500	0.025 max	0.020 max	0.850	All deposition
150 mm x 100 mm x 10 mm	316L ss plate	0.03 max	16.50-18.50	2.00 max	2.00 - 2.50	/	10.00 - 13.00	0.05 max	0.02 max	1.00 max	4.3.1; 4.3.2
150 mm x 150 mm 10 mm	316L ss plate	0.03 max	16.50-18.50	2.00 max	2.00 - 2.50	/	10.00 - 13.00	0.05 max	0.02 max	1.00 max	4.3.3 - 4.3.5
150 mm x 150 mm x 2 mm	316L ss sheet	0.019	17.000	1.590	2.000	0.060	10.100	0.032	0.01	0.470	Chapter 5
180 mm x 190 mm x 6 mm	316L ss plate	0.018	17.100	1.270	2.030	0.039	10.100	0.030	0.001	0.450	Chapter 6

*: For the references of the chemical composition, please refer to the appendix.

3.2.2 Shielding and air knife gas

The gas used for shielding the process and protecting the optics was pure argon. A pressure regulator was attached to control the gas pressure. The specific pressures used in different phases of the experiments are listed in Table 3-2.

Table 3-2 Specific gas pressures and oxygen levels for different phases of the experimental configuration.

Configuration	Air knife gas pressure (Bar)	Shielding gas pressure (Bar)	Oxygen content level (PPM)
500 W LP with local shielding	/	2	/
500 W LP with global shielding	1	2	< 300
3 kW LP with global shielding	1	2	< 300

3.3 Laser measurement and calibration

3.3.1 Laser beam caustic profiling

Due to the high dependency and the emphasis on the importance and accuracy of the laser beam size used in these experiments, the laser beam was profiled and calibrated carefully to make sure the target laser beam sizes used for

experiments were accurate. Then, the linear model of laser beam size against defocused distance could be calculated precisely.

The laser head was vertically positioned along with the Z-axis processing stage, and a beam profiler was positioned with the focal point located in the middle of the measurement window (the height range of the measurement window is 35 mm, 10 planes measurements were applied) to get the minimum radius, of which will be regarded as the focal point. After this, move the laser head upward to have the smallest beam diameter of the laser beam in the top of the measurement window (top part of the window) to maximize the visibility of the defocused linear section of the beam caustic, and so being able to calculate bigger laser diameters.

A laser beam dump was positioned under the beam profiler to absorb the laser energy, the laser was set to 5% of maximum power to avoid beam profile saturation and the damage of the beam profiling system due to the high power densities achieved at the focal point. PRIMES Laser Diagnose Software was used to measure and yield the profile results.

A similar procedure was also applied to the 3 kW LP system experiments. Also, 5% of the 3 kW LP was used to avoid damage to the laser beam dump. The images of the setups for beam profiling of 30 μm and 50 μm core diameter fibre lasers are shown in Figure 3-6 (a), (b).

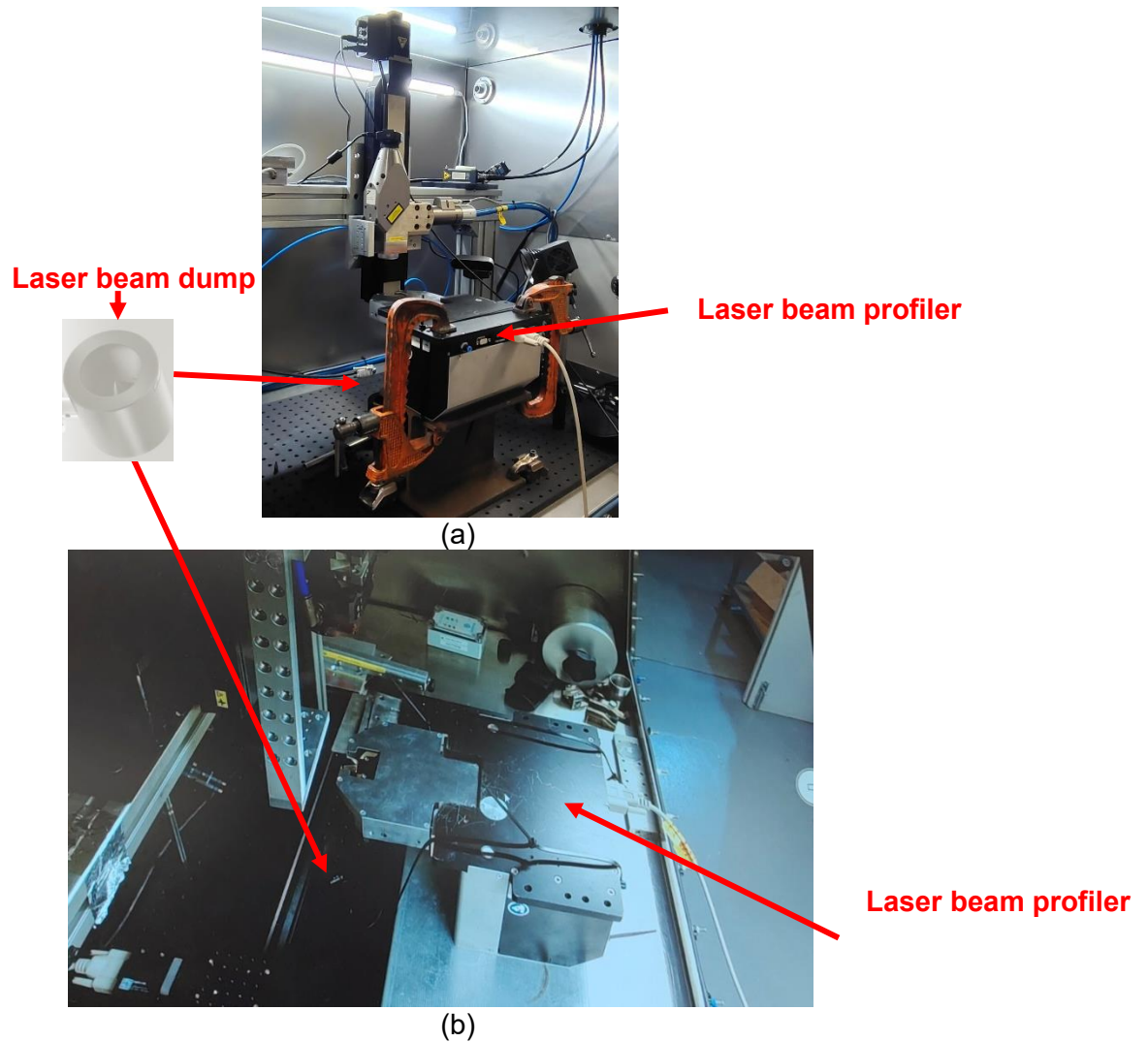


Figure 3-6 Images of the experimental setup for beam profiling of (a) 30 μm core diameter, (b) 50 μm core diameter fibre laser.

3.3.2 LP measurement

To make sure the applied LP is accurate and precise. LP measurement was conducted for the 500 W power source using a power meter (Laserpoint A-600-D60-SHC-USB) positioned under the laser.

The laser head was positioned with a 5-degree tilted angle on the Z-axis processing stage to conduct the LP measurement. When the stable condition of the LP was achieved (roughly 30 seconds) after the laser was fired, the accurate LP value shown on the Leonardo software was noted down to finish the LP calibration.

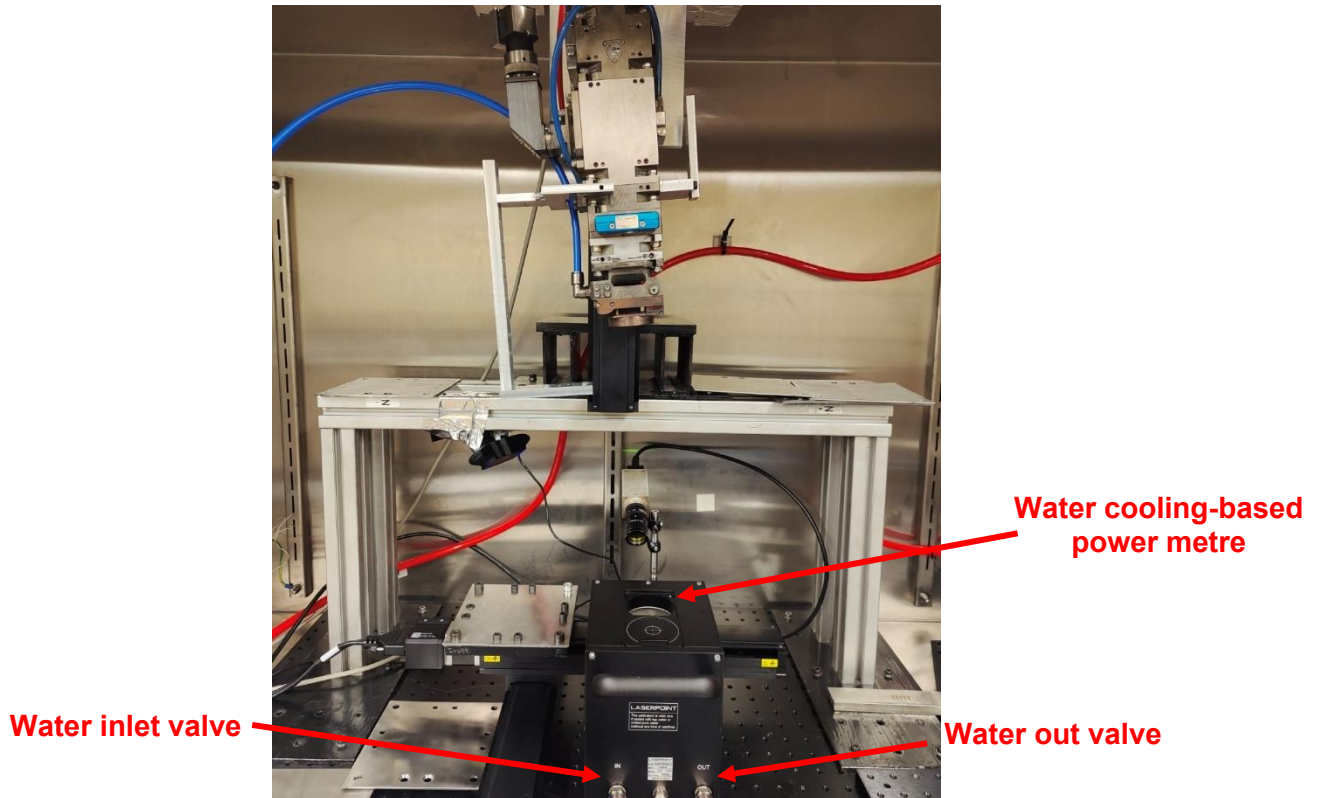


Figure 3-7 Image of the experimental setup for 3 kW laser power measurement.

These procedures were also applied to the later trials using a maximum (nominal) 3kW LP source; due to the higher LP used, a water-cooling-based power meter (W-12K-D55-SHC-USB) was used. The setup used for the 3 kW laser power measurement is shown in Figure 3-7.

3.4 Methodology of manufacturing submillimetre wall features using a small laser beam (1.0 mm) with local shielding

3.4.1 Laser spot and wire alignment

Before starting the trials, the position of the wire tip was carefully aligned with the spot of the guide laser. The wire tip was put in the middle position along the X-axis direction, but at the edge of the laser spot along the Y-axis direction, front feeding was adopted. The schematic of the top view of the wire and the guide laser beam relevant position is shown in Figure 3-8. In this case, the wire position relative to the substrate was not specified; the wire tip position was placed close to the substrate surface with a small gap or touch on the surface depending on the stick-out length (Figure 3-9).

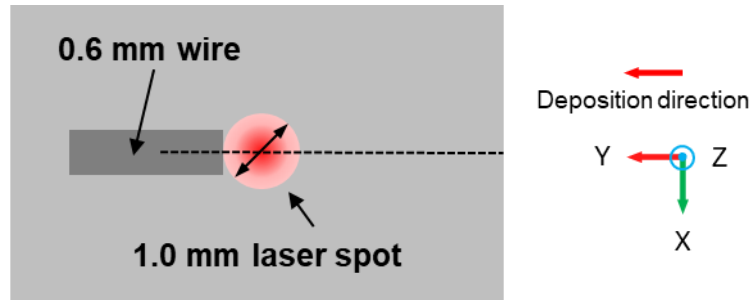


Figure 3-8 Schematic of the wire position relative to the 1.0 mm laser spot.

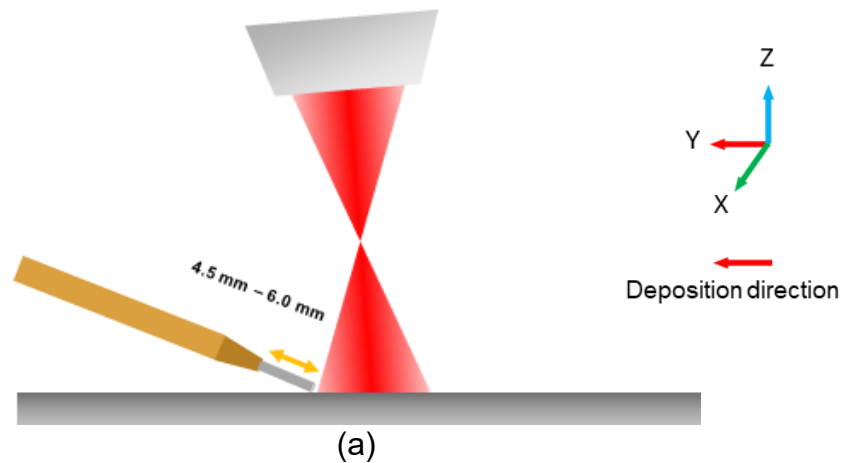
3.4.2 Assess the bead-on-plate deposition using a 1.0 mm beam (currently used approach)

In this section, the current approach of using a 1.0 mm laser beam was assessed first. The processing parameter ranges are listed in Table 3-3.

Table 3-3 Processing parameter range for assessing the current approach.

WFS (mm/s)	TS (mm/s)	LP (W)	BD (mm)
0.0, 8.5	5	200 – 350	1.0

The feasibility and repeatability of the bead on plate were studied, followed by the investigation of the wire feeding position relative to the substrate (wire suspended in the free space (Figure 3-9 (a)) (around 1.0 mm – 2.0 mm gap from the material surface), and gently touches the substrate surface (Figure 3-9 (b)).



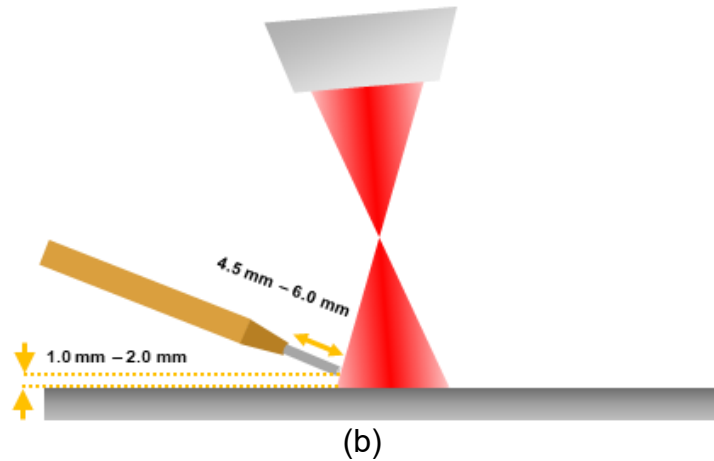


Figure 3-9 Schematics of the wire relative to the substrate position: (a) wire suspended in free space, (b) wire touching the substrate surface.

AISI 316LSi SS wire with 0.6 mm diameter and 316L SS with 150 mm x 100 mm x 10 mm substrate (L x W x H) were used to deposit the 30 mm length bead-on-plate deposits. The wire stick-out length was maintained within 4.5 mm to 6.0 mm.

After this, the autogenous laser welds and bead on plate deposition were conducted on a 150 mm x 150 mm x 10 mm 316 L SS substrate with a more uniform surface finish condition. After this phase of the experiments, the substrate surface finish condition was maintained at this more uniform level. To avoid the geometry instability during the initial acceleration and final deceleration phase of the stage movement, a 90 mm-long in length deposition was applied.

The design of the experiment layout is shown in Figure 3-10. A maximum of 10 trials on each plate with a 10 mm interval distance were made, and this layout was applied to all 90 mm-long length cases on 150 mm x 150 mm x 10 mm and 150 mm x 150 mm x 2 mm substrates.

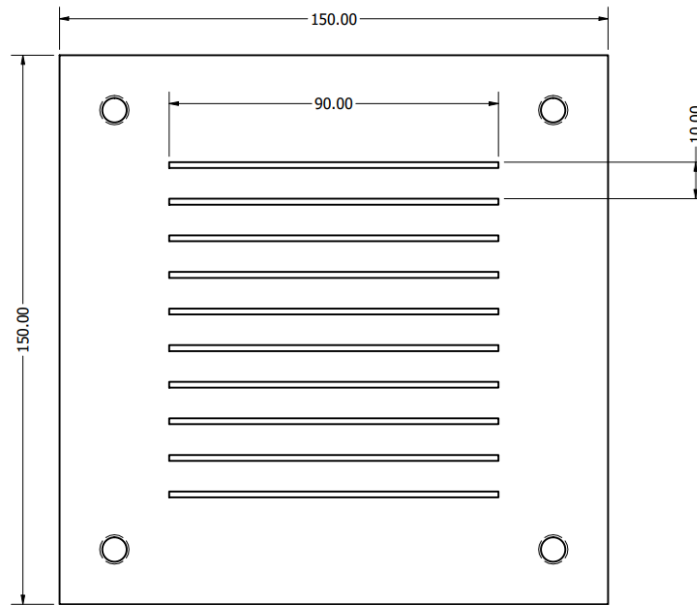


Figure 3-10 Schematic layout of the designed experimental trials (Unit: mm).

3.4.3 WFS to TS ratio-based process window investigation

In this section of experiments, the process window was studied with a wider range of WFS and TS based on the WFS/TS ratio. The ranges of the processing parameters are shown in Table 3-4. The WFS to TS ratios from 0.57 to 2.00 were investigated with starting from the value of 1.00.

Table 3-4 Processing parameters for WFS to TS ratio-based process window study.

WFS (mm/s)	TS (mm/s)	LP (W)	WFS/TS ratio
4 – 7	3 – 7	250 – 325	0.57 – 2.00

Before conducting the experiments, the wire was placed on the substrate by gently touching the surface of the substrate, and the wire stick-out length was maintained between 4.5 mm to 6.0 mm.

3.4.4 Wall fabrication using a 1.0 mm small laser beam

90 mm long, single-bead, ten-layer walls were deposited on 150 mm x 150 mm x 10 mm 316L SS substrate using a 1.0 mm laser spot followed by examining the wall deposition performance (for instance, plume formation, wall appearance and

wall surface condition). The specific parameters for the two walls shown in the thesis content are shown in Table 3-5.

Table 3-5 Specific processing parameters of two walls fabrication using a 1.0 mm laser beam.

ID	WFS (mm/s)	TS (mm/s)	LP (W)	Layers
Wall 1	4	4	300	10
Wall 2	5	5	300	10

3.4.5 Macroscopic samples preparation, image processing, and dimension measurement

After the experiments, the 90 mm long bead on plate were cut according to the positions shown in Figure 3-11. Two samples with the left face of sample 1 and the right face of sample 2 (the surface pointed by the two green arrows in Figure 3-11), where the positions closer to the middle stable section of the bead were chosen for sample preparation and image processing to get an average value for the individual bead.

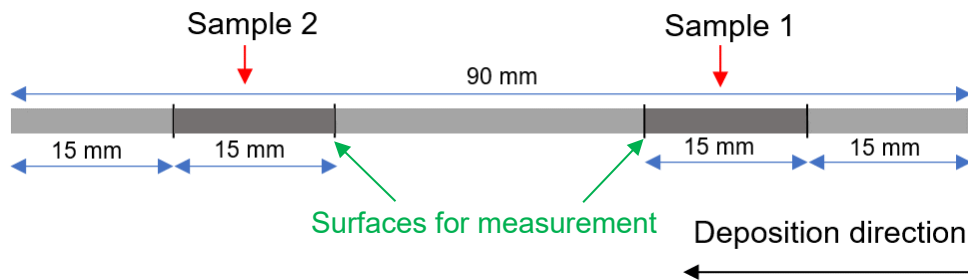


Figure 3-11 Schematic of sample preparation position of the deposit with a 90 mm length.

A systematic procedure of sample preparation and image processing are claimed as follows:

- Cold-mount (or hot-mount), ground and polish the samples.
- Electrolytically etching the samples using 10% Oxalic acid for 60 seconds.
- Optical macroscopy or microscopy imaging using the Leica, Zeiss optical macro-microscope, and Leica, Zeiss optical micro-microscopy

The dimensions of width, penetration depth, bead height, contact angles and cross-sectional area values were measured. The schematic of the contact angle measurement and the aspect ratio calculation is defined in Figure 3-12 below:

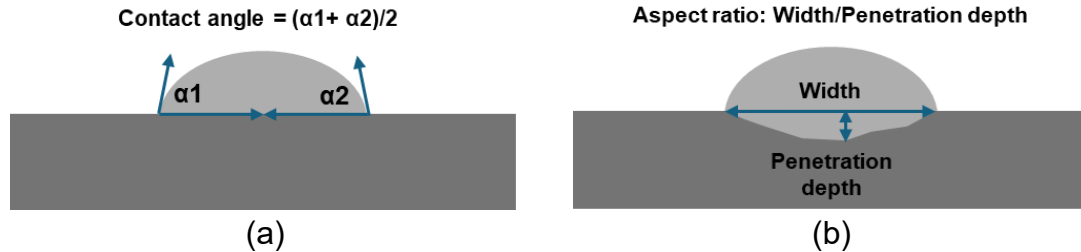


Figure 3-12 Schematics of (a) contact angle measurement; (b) aspect ratio calculation definition.

3.5 Methodology of manufacturing submillimetre wall features using large laser beams (1.5 mm to 2.5 mm) with global shielding

In this section, three general phases of the experiments (autogenous laser welds, bead on plate, and walls) were conducted on the 150 mm x 150 mm x 2 mm (L x W x H) 316L SS sheet using a 0.6 mm in diameter AISI 316LSi SS wire to study the possibility of using large laser beam sizes ranging from 1.5 mm to 2.5 mm to deposit the 90 mm long submillimetre-scale walls at low-level 500 W LP with global shielding. The setup mentioned in 3.1.2 was used for all experiments.

3.5.1 Autogenous laser welds and geometry analysis

The processing parameter ranges for autogenous laser welds are listed in Table 3-6. After the welding, the effects of IT (Esp), BD, and surface ED on weld geometry were analysed.

Table 3-6 Processing parameters for autogenous laser welds' performance study.

BD (mm)	TS (mm/s)	LP (W)
1.50	3 – 105	500
1.75	3 – 43	500
2.00	3 – 25	500
2.25	3 – 12	500
2.50	3 – 5	500

3.5.2 Bead on plate deposition and geometry analysis

In the second phase of the experiments, the wire was added to the process, followed by the process window investigation and deposition performance analysis (four defined categories will be discussed in the main content). Before the experiments, the wire was carefully aligned to the edge of the laser spot referred to the schematic shown in Figure 3-8 and gently touched the substrate surface to start the deposition. The processing parameter ranges are listed in Table 3-7.

Table 3-7 Processing parameter ranges for bead on plate deposition.

BD (mm)	WFS (mm/s)	TS (mm/s)	LP (W)
1.50	4 – 19	3 – 12	500
2.00	4 – 20	3 – 14	500
2.25	4 – 19	3 – 6	500

Thereafter, the effect of the D-ratio (defined as the ratio of laser beam size to wire size in diameter) on performance and process sensitivity will be discussed (1.0 mm laser beam case D-ratio will also be added as a discussion with comparison).

Then, the effects of IT, surface ED, and the corresponding BD, and WFS at different levels of IT, surface ED on the bead on plate geometry are studied.

3.5.3 Walls manufacturing – Strategy, performance, geometry analysis and deposition rate calculation.

In the third phase, one of the best sets of deposition parameters within the process window (5 mm/s for both the WFS and TS) was chosen to deposit the walls to study the feasibility of using a large-size laser beam (2.0 mm) to manufacture net-shape high-resolution submillimetre-scale walls with good performance and process stability. The processing parameters for wall fabrication and the strategies are listed in Table 3-8.

Table 3-8 Specific processing parameters and strategies for wall fabrication using a 2.0 mm laser beam.

Method	WFS (mm/s)	TS (mm/s)	LP (w)	Layers
Strategy 1	5	5	Constant 500 W	10
Strategy 2	5	5	500, 450, 400, 350, 300 W for the first five layers, 6-10 layers at constant 300 W	10
Strategy 3	5	5	500, 470, 450, 425, 400 W for the first five layers, 6-10 layers at constant 400 W	10

Initially, the reason for choosing this set of parameters is briefly interpreted. Then, the walls were deposited according to the different strategies. After the deposition, the deposition performance was evaluated, geometry was measured, and the effective width ratio and effective area ratio (deposition efficiency (Martina et al., 2012) were calculated, analysed and discussed. The schematic definitions of effective width ratio and effective area ratio (deposition efficiency) are explained and shown in Figure 3-13.

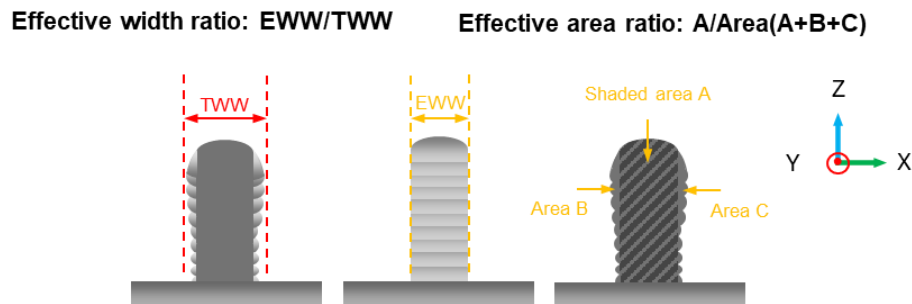


Figure 3-13 Schematic definitions of the effective width ratio and effective area ratio.

Finally, the deposition rate of the walls using a 2.0 mm large-size laser beam at 500 W of LP with global shielding is calculated, compared and discussed. The deposition rate calculation formula will be mentioned in the main content.

3.6 Methodology of investigation of high-power lasers to manufacture sub-millimetre to millimetre-scale wall features.

In this chapter, four general phases of the experiments (laser measurements and laser wire alignment, autogenous laser welds, bead on plate deposition, and walls fabrication) were conducted on 180 mm x 190 mm x 6 mm 316L SS substrates with the same spool 0.6 mm in diameter AISI 316LSi SS wire to investigate the feasibility of depositing millimetre to submillimetre features at high deposition rates. Setup mentioned in 3.1.3 was used for all following experiments.

3.6.1 Laser measurements and calibration

In the first phase, for accurately conducting the experiments, before carrying out the experiments, laser beam caustic profiling, LP measurement and calibration

were conducted. The relevant procedures are the same as using the 500 W LP cases as mentioned in section 3.3, therefore, the detailed methodology will not be repeated here.

3.6.2 Critical wire alignment

In this section of the first phase, the wire was carefully aligned with introducing the real laser spot marked by the laser with the marking spot size corresponding to the experimental requirements, i.e., 1.5 mm, 2.0 mm, and 3.0 mm instead of using the pointing laser because the experiments were processed at a high speed, in this case, the wire could be more sensitive to the laser spot position. A more critical wire alignment can increase the position accuracy and the possibility of success, in this case, 8%, 10%, and 23% of LP (shown on the software) (corresponding to 269 W, 323 W, and 677 W of the real LP output) with 1 – 2 seconds duration were used for the 1.5 mm to 3.0 mm laser spot marking. A ruler with a 0.5 mm scale was used to measure the diameters of the laser beams, and roughly 6 mm wire stick-out length was used for the wire.

3.6.3 Autogenous laser welds and geometry analysis

To identify the speed range that can achieve the autogenous laser weld width close to 1.0 mm, in the second phase, autogenous laser welds were conducted at four levels of LP between 1.00 kW to 2.79 kW with beam diameters ranging from 1.5 mm to 3.0 mm on 180 mm x 190 mm x 6 mm 316L SS substrate, the maximum processing speed is set as 200 mm/s. Considering the fast processing speed applied, the process can be sensitive to many factors such as energy, substrate surface unevenness, etc, which can cause the process stability or repeatability to be lower.

Therefore, a longer length of 160 mm track was applied, at the same time, for each set of parameters, two trials were conducted to obtain the average value, which enables the mitigation of the disturbances and errors which may be caused by the process instability. The experimental parameter ranges used are listed in Table 3-9.

Table 3-9 Processing parameter ranges for high-level LP autogenous laser welds.

BD (mm)	LP (kW)	TS (mm/s)
1.5	1.00	3 – 200
	1.50	10 – 200
	2.00	10 – 200
	2.79	15 – 200
2.0	1.00	3 – 200
	1.50	10 – 200
	2.00	10 – 200
	2.79	15 – 200
3.0	1.00	3 – 100
	1.50	10 – 200
	2.00	10 – 200
	2.79	15 – 200

After the experiments, 160 mm bead on plate were cut in the middle (Figure 3-14) where it should correspond to the relative process-stable section under the fast-processing speeds. The left surface of the sample was chosen for sample preparation and image processing (green arrows in Figure 3-14). Sample preparation and image processing were referred to the procedure shown in section 3.4.5.

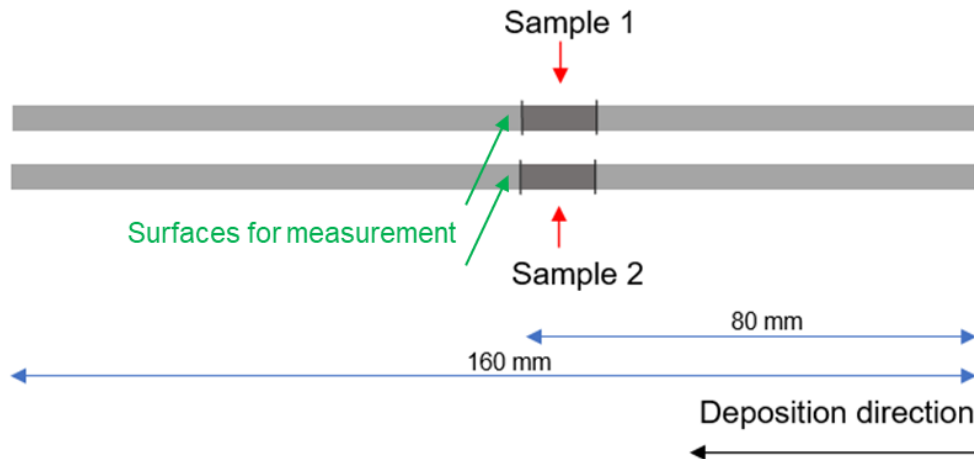


Figure 3-14 Schematic of the sample preparation position of the bead with 160 mm length.

Thereafter, the effects of EI, Esp, and surface ED, and the corresponding BD, and LP effects on width were analysed.

Then, the feasible autogenous laser welds with acceptable surface appearance and a close to 1.0 mm weld width were filtered out using a newly developed model formula (heat input index formula (formula 6-4 in the main context of 6.4.6)). The

selected parameters will be used for the investigation of the bead on plate deposition feasibility.

3.6.4 Bead on plate deposition

In the third phase of the experiments, the feasible processing speed range was first identified, followed by investigating the process window based on the speed ratios within the previous feasible processing speed ranges that have been selected.

3.6.4.1 Study of processing speed window range

When studying the processing speed range, two levels of TS, 50 mm/s and 100 mm/s, with two levels of laser beams, were chosen to test the feasibility of bead-on-plate deposition; the WFS to TS ratio was maintained at 1.0. The experimental parameter ranges are listed in Table 3-10. Three defined categories of deposition performance will be discussed in section 6.5.1.

Table 3-10 Parameter ranges for the processing speed range study.

BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Speed ratio
2.0	1.00 – 2.79	50, 100	50, 100	1.0
3.0	1.00 – 2.79	50, 100	50, 100	1.0

3.6.4.2 WFS to TS ratio-based process window investigation

When investigating the process window, two levels of laser beams with three levels of LP at three levels of WFS to TS ratios were used to investigate the process window. The parameter ranges are shown in Table 3-11. The bead on plate performance and process window variation were discussed and analysed in detail in Section 6.5.2.

Table 3-11 Processing parameter ranges for the WFS to TS ratio-based process window study.

BD	LP (kW)	WFS (mm/s)	TS (mm/s)	WFS/TS ratio
2.0	1.50 – 2.79	40.00 – 62.50	50	0.80 – 1.25
2.0	1.50 – 2.79	60.00 – 93.75	75	0.80 – 1.25
3.0	1.50 – 2.79	40.00 – 62.50	50	0.80 – 1.25
3.0	1.50 – 2.79	60.00 – 93.75	75	0.80 – 1.25

3.6.4.3 Study of the process repeatability

To assess the process repeatability, two groups of experiments were conducted. One group studied the repeatability on different substrates. The other group studied the repeatability based on the different levels of substrate initial experimental temperature. The specific parameters and experimental plan are listed in Table 3-12, and Table 3-13.

Table 3-12 Processing parameters and the corresponding substrate identification for the study of repeatability on different substrates.

BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Number of trials	Substrate ID
2.0	2.00	50	50	2	1
2.0	2.00	50	50	2	2
3.0	2.79	50	50	2	2
3.0	2.79	50	50	2	3

Table 3-13 Processing parameters, measures and the corresponding substrate identification for the study of initial substrate temperature.

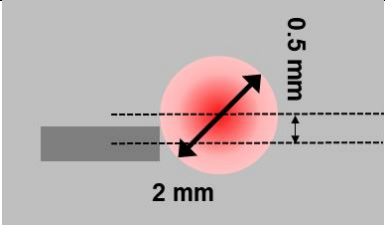
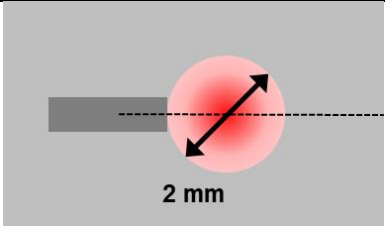
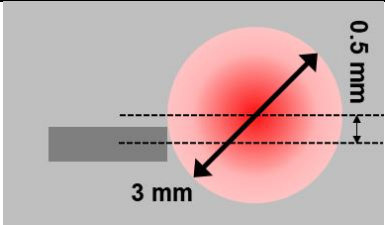
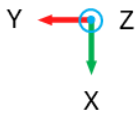
BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Number of trials	Measures	Substrate ID
3.0	2.79	50	50	2	Room temperature	2
3.0	2.79	75	75	2	Room temperature	2
3.0	2.79	50	50	2	Start experiments after 3 laser melting paths	3
3.0	2.79	75	75	2	Start experiments after 3 laser melting paths	3

3.6.4.4 Effect of BD on wire position sensitivity

In this section, the wire position sensitivity at high processing speed and under different sizes of the laser beams was examined using 2.0 mm and 3.0 mm laser beams. The wire was deviated by 0.5 mm on purpose to study the wire position sensitivity for the 2.0 mm and 3.0 mm laser beam cases.

The experimental parameters and the schematic of the wire position relative to the wire for these 2 laser beams are listed in Table 3-14.

Table 3-14 Processing parameters and the corresponding wire position for the study of beam size effect on wire position sensitivity.

BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Wire position
2.0	1.50	50	50	
2.0	1.50	50	50	
3.0	2.79	50	50	
				

3.6.5 High deposition rate wall manufacturing – Strategy, repeatability, feasibility, geometry, and deposition rate

In this section, the feasibility of manufacturing millimetre to submillimetre-scale walls was examined on a 180 mm x 190 mm x 6 mm 316L SS substrate with the same 0.6 mm in diameter AISI 316LSi SS wire. Similarly, a 160 mm long deposition length was applied.

To study the feasibility of depositing the millimetre to a submillimetre-scale wall at higher deposition rates, a single-bead, 10-layer wall was built using the parameters and strategy shown in Table 3-15 with varying LP as the deposited layer increases upward. Then the geometries were measured, and the cross-sectional area was inspected for defect detection.

Table 3-15 Processing parameters and strategy for the manufacturing of a 10-layer wall.

Wall ID	BD (mm)	WFS (mm/s)	TS (mm/s)	Number of layers	Strategy
Wall 1	3	50	50	10	Layer 1-5 2.79 kW Layer 6-10 2.75 kW

Afterwards, to examine the repeatability of the wall manufacturing, a single-bead, 20-layer wall was built using the parameters and strategy shown in Table 3-16, then the geometries were measured, and the cross-sectional area was examined for defect inspection.

Table 3-16 Processing parameters and strategy for manufacturing of a 20-layer wall.

Wall ID	BD (mm)	WFS (mm/s)	TS (mm/s)	Number of layers	Strategy
Wall 2	3	50	50	20	Layer 1-5 2.79 kW Layer 6-10 2.75 kW Layer 11-20 2.50 kW

Thereafter, the geometries of the walls were analysed, followed by the deposition rate calculation and discussion.

3.6.6 Melting efficiency of wire-based laser DED process (500 W LP cases added)

In this section, the melting efficiency for some representative autogenous welds and bead on plate of 500 W and high-level LP cases was calculated to analyse the effect of adding the wire to the welding process, and to investigate whether the melting efficiency can provide supporting evidence for the absorptivity increment when the wire is added to the process.

4 Manufacturing submillimetre wall features using a small beam (1.0 mm) with local shielding

In this chapter, the main aim and objectives of the experiments are illustrated briefly first. The feasibility of using a 1.0 mm small-size laser beam to manufacture the submillimetre-scale wall features is investigated. Contents are mainly divided into four academic sections: laser beam caustic measurement; LP measurement; evaluating the current traditional approach for submillimetre-scale bead on plate deposition and issues analysis; submillimetre-scale wall fabrication.

The main aim of this chapter is to successfully manufacture the near-net-shape profile, high resolution submillimetre wall features using 1.0 mm small beam under local shielding with a good deposition performance. Here, because there is no comparison or reference with other laser beam cases' performance yet, it is difficult to make a definition of 'good', in this case, a reasonable, stable performance with no obvious plume formation, and with a uniform surface appearance will be called good.

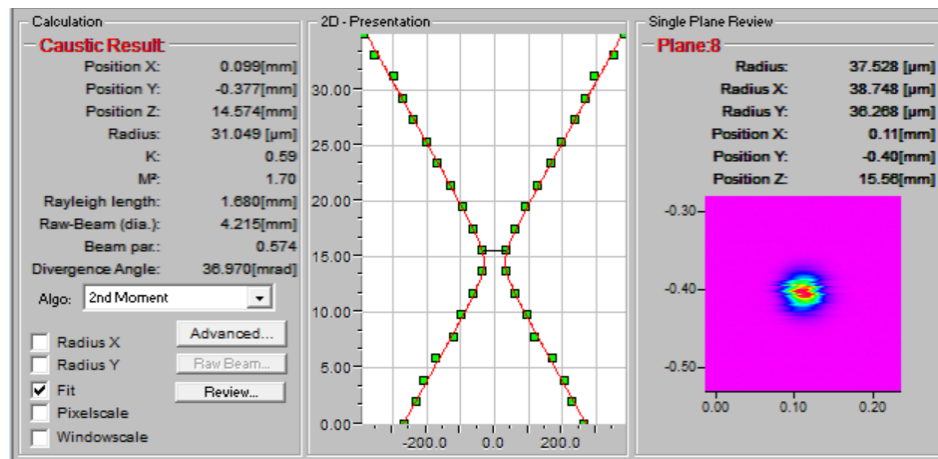
The objectives are:

- Examine the deposition performance of using a 1.0 mm beam to fabricate submillimetre wall features.
- Identify the frequently occurring issues and find a correlation between the processing conditions and the deposition performance.
- Achieve submillimetre wall features with reasonable process stability.

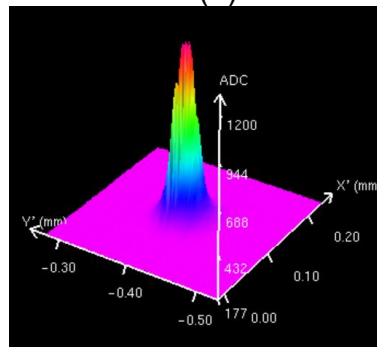
4.1 Laser beam caustic profiling

The measurement of the laser beam caustic was done as per the methodology procedure claimed in section 3.3.1. Figure 4-1 (a) shows the beam caustic of a single-mode 30 μm core diameter fibre laser measured around the focal point, the radius of 31 μm measured in this case was used as the minimum laser beam diameter at the focal point for the linear model of laser beam size against defocused distance calculation (nominal focal length of the optic is 114 mm), a

beam quality M^2 of 1.70 has been measured, which indicates a beam close to the perfect gaussian beam. The plane 8 in the right corner of Figure 4-1 (a) indicates the beam shape close to the laser beam waist position. The three-dimensional isometry profile of plane 8, of which the radius is very close to the minimum radius at the focal point (Figure 4-1 (b)) exhibits a typical Gaussian-type beam profile due to the characteristics of a single-mode, very fine core diameter fibre used. The extent of the PD reduction is very steep.



(a)



(b)

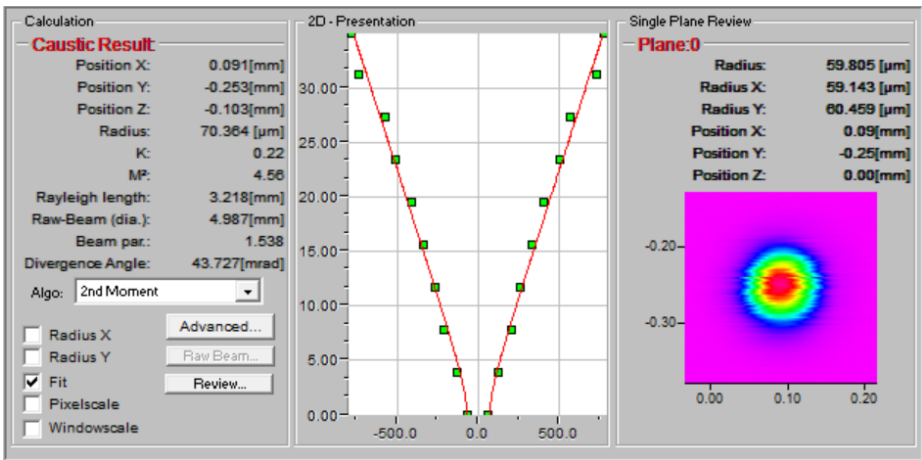
Figure 4-1 (a) Beam profile caustic and the beam shape close to the beam waist, (b) 3-dimensional Gaussian-type laser beam profile of 30 μm core diameter fibre laser optical properties with the focal point falling in the middle of the measurement window.

Figure 4-2 (a) shows the beam caustic at the region of defocused planes, 10 planes measurement was applied. The planes with a linear laser beam size increment trend were used to calculate and form the model of laser beam size versus defocused distance to get the target laser beam sizes.

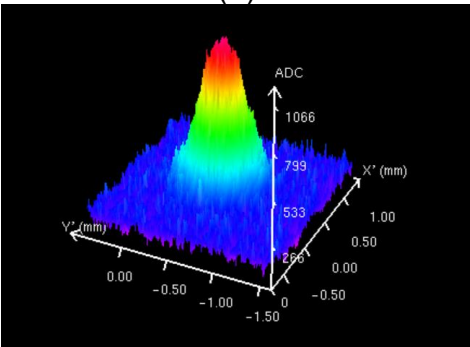
Three-dimensional PD isometry profile of plane 6, which corresponds to the 1.0 mm laser spot that will be used in the experiments is shown in Figure 4-2 (b). It can be seen that the profile is Gaussian-type with a steep PD reduction phenomenon from the middle of the laser towards the edge of the laser beam. (This steep PD transition phenomenon will be discussed combining with the deposition performance later)

Figure 4-2 (c) indicates that the p-PD at around 1.0 mm laser spot size is about 7.66 kW/cm² when using 25 W of LP (this value will be used later for the 300 W and 350 W LP case p-PD calculation and the deposition performance discussion).

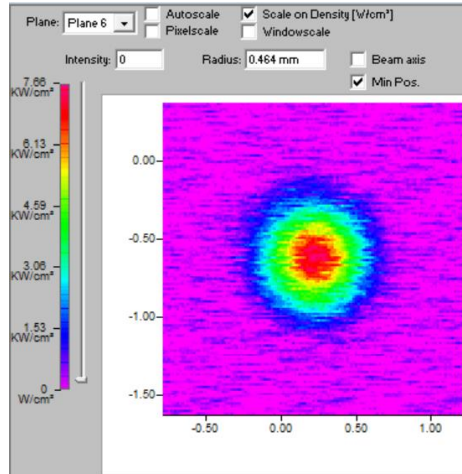
The model created based on the data in Figure 4-1 (a), and Figure 4-2 (a) is shown in Figure 4-3. Based on this model, when using a 1.0 mm laser beam, the defocused distance is 25.30 mm from the focal point. Considering the beam size tolerance and measurement error from the beam profiler, a ± 0.50 mm distance error will have the final beam diameter of 1.02 mm and 0.98 mm, respectively. The beam size variation is about 2%.



(a)



(b)



(c)

Figure 4-2 (a) Beam profile caustic (b) 3-dimensional Gaussian-type laser beam profile, and (c) 2-dimensional isometry PD profile of 30 μm core diameter fibre laser optical properties with distance defocusing to a 1.0 mm laser spot size.

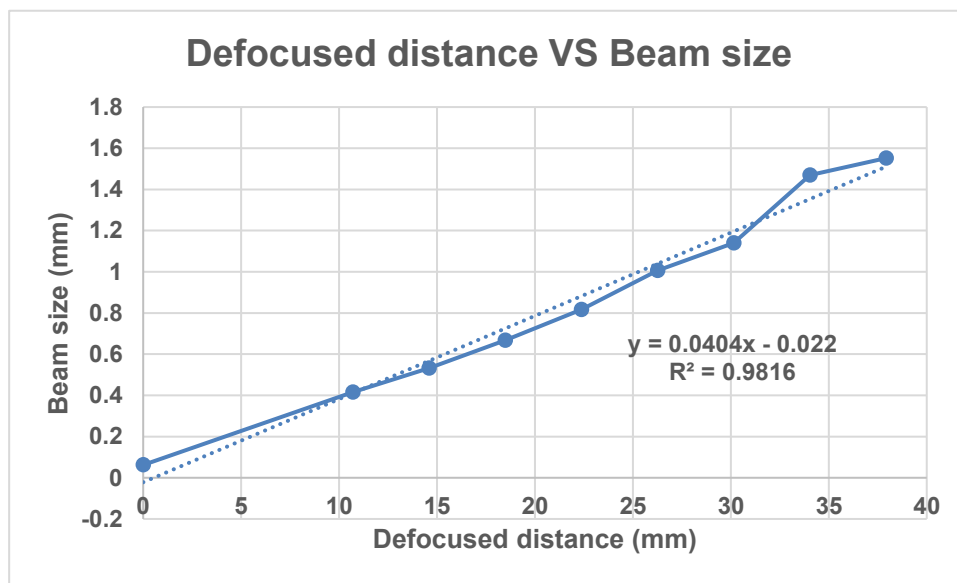


Figure 4-3 Linear regression model of defocused distance against the beam size for processing using the 30 μm core diameter fibre laser.

When using a 1.5 mm laser beam, a ± 0.50 mm distance deviation will have the final beam diameter of 1.52 mm and 1.48 mm. When using a 2.0 mm laser beam, a ± 0.50 mm distance deviation will have the final beam diameter of 2.02 mm and 1.98 mm. The beam size variation is around 1%. In this case, using a large beam size (1.50 mm to 2.00 mm) to fabricate the millimetre to submillimetre features can have more tolerance to the beam size variation.

4.2 LP measurement

To check the accuracy of the value shown on the panel of the laser software and ensure the applied LP is accurate for experiments, the LP measurement was conducted.

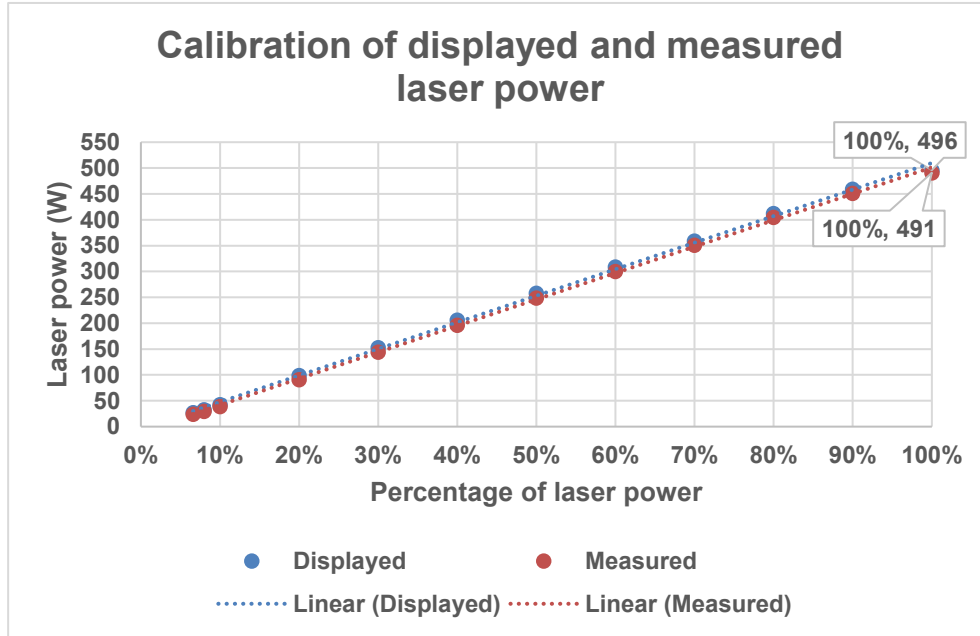


Figure 4-4 Diagram of 30 μm core diameter fibre LP measurement and calibration.

The results in Figure 4-4 show that the real LP and the values displayed on the screen of the software have only a small discrepancy of around 1% (displayed: 496 W; measured: 491 W). Therefore, the applied percentages of the LP on the software are relatively accurate and correct.

4.3 Assess the of bead-on-plate deposition using a 1.0 mm beam (currently used approach)

In this section, deposition at constant 8.5 mm/s of WFS and 5 mm/s of TS with varied LP ranging from 200 W to 350 W was tested first to examine the feasibility of the process and perceive the deposition performance extent at this set of parameters.

The repeatability of the deposition process was investigated to test if the process could be reproduced. A summarised table, Table 4-1 lists the bead on plate

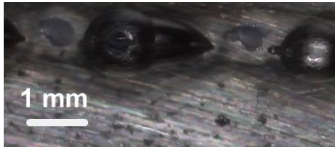
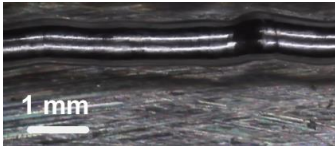
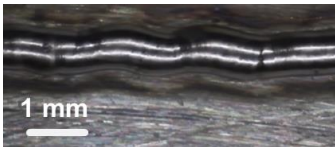
identification with system parameters and FLMIPs for a clear understanding of the study.

Table 4-1 Deposits identifications and the corresponding parameters.

Deposit ID	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
4-1	200	8.50	5	25.46	200	40
4-2	250	8.50	5	31.83	200	50
4-3	300	8.50	5	38.20	200	60
4-4	350	8.50	5	44.56	200	70

Before the experiments, aligning the wire with the laser spot was conducted as per the methodology in section 3.4.1. The top-view images of deposits 4-1 to 4-4 with the performance description are listed in Table 4-2. All the beads exhibit a poor performance; no straight bead was observed. Therefore, the reasons causing the poor performance should be investigated in depth further.

Table 4-2 Top-view of deposits and the corresponding performance.

Deposit ID	Top view	Performance
4-1		Poor, Non-continuous bead formed.
4-2		Poor, Waved bead formed.
4-3		Poor, Waved bead formed.
4-4		Poor, Waved bead formed.

During the deposition, a plume was observed in all of the deposited samples. The deposition performance of the individual bead of deposit 4-3 at different recording times is shown in Figure 4-5 (a) – (f), the plume was shown up within the individual bead deposition during the whole process, the volumetric size and shape of the plasma column (white arrow in Figure 4-5 (e)) varied instantaneously and non-

directionally, which resulted in extreme difficulty in controlling the stability and achieving a stable deposition performance during the whole deposition.

The trials with the same parameters have been repeated several times; the deposition process was always accompanied by the plume, and the plume column size and shape were always changed. Continuous bead on plate could be achieved; however, the deposition performance was not ideal and not stable, and the bead surface was not smooth, straight or uniform (Figure 4-5 (g)) resulting in the bead being difficult to reproduce.

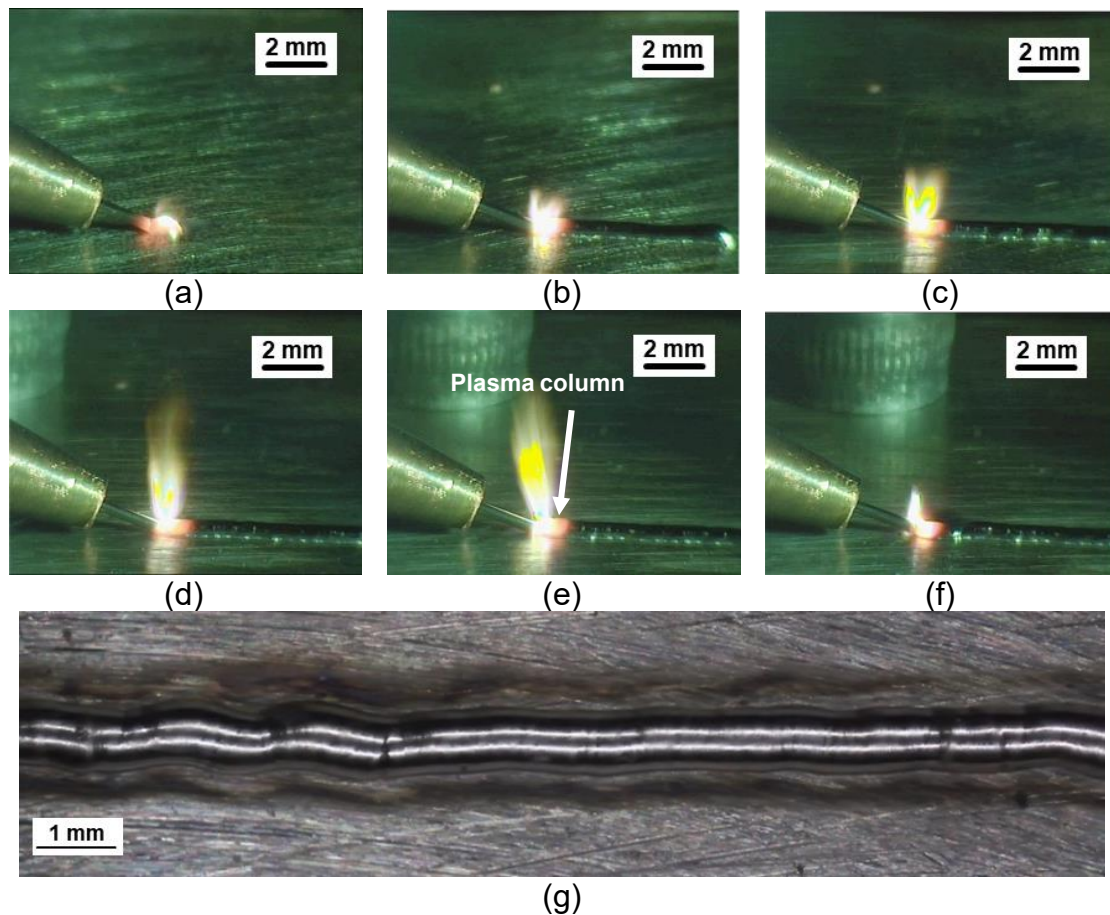


Figure 4-5 Different plume profiles at different recording times (a) – (f) during individual bead (deposit 4-3, LP: 300 W, WFS: 8.5 mm/s, TS 5 mm/s) deposition and the (g) corresponding bead top-view appearance.

When conducting the deposition using 200 W of LP (Deposit 4-1), the deposit didn't have a good bonding with the substrate; balling and wire dripping effect appeared (Figure 4-6 (a) and (b)). This is because, under 200 W of LP, firstly, the energy per unit of deposited material was low. Secondly, the energy per unit

deposited material was unstable due to the different cross-sectional area caused by the bead discontinuity. In this case, the process lacks sufficient energy to melt the wire and also create a melt pool in the substrate surface. A continuous melt pool with a stable melt pool size could not be maintained all the time, causing poor bonding with the substrate surface, resulting in the balling effect. In this case, the wire dripping phenomenon appeared. Therefore, no lower-level LP was investigated further, even though reducing the processing speed can increase the energy, but from the productivity perspective, it is not worth reducing the processing speed to observe the performance.

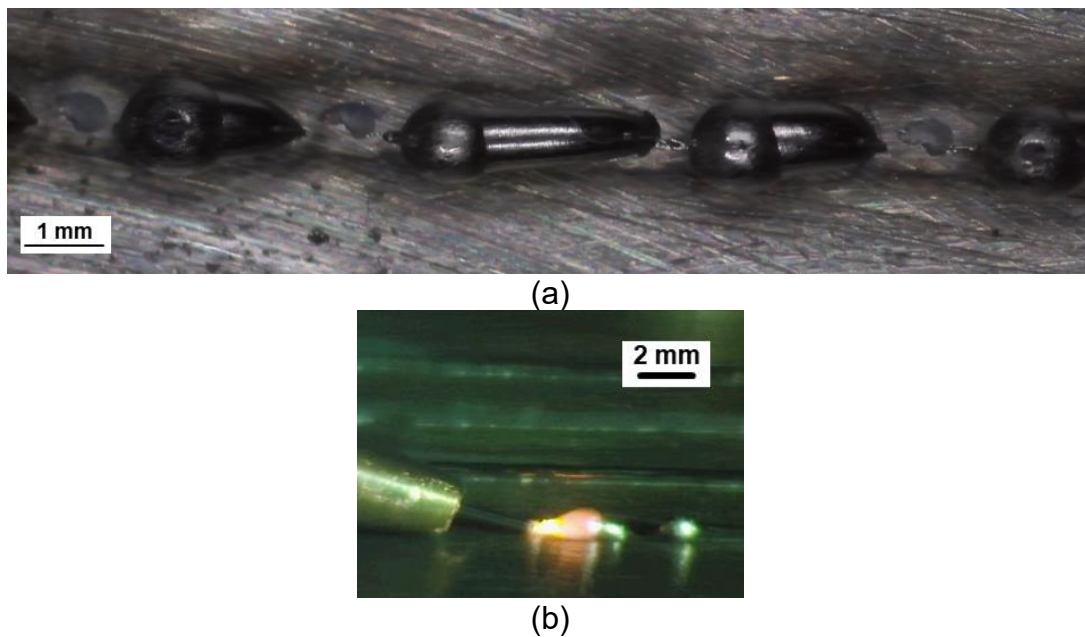


Figure 4-6 Phenomena of (a) balling effect and (b) wire dripping formation of deposit 4-1 (LP: 200 W, WFS: 8.5 mm/s, TS 5 mm/s).

When increasing the LP to 350 W (Deposit 4-4), the deposition performances at different recording time points are shown in Figure 4-7 (a) – (e) below, a more obvious plume and corresponding plasma column formed during the whole deposition phase, the plasma profile also varied nondirectionally as time elapsed, a good bonding and wetting behaviour could not be achieved. In addition, Figure 4-7 (f) shows that the bead is not straight with a winding zigzag profile formation, and the surface condition is not smooth. Therefore, the LP was not increased further for the tests because a stronger plume would deteriorate the process performance further.

These results indicate, within 200 W to 350 W of the LP under 8.5 mm/s of WFS and 5 mm/s of the TS, the trials with 300 W of LP (Deposit 4-3) exhibited a better performance with a continuous track formation than the 200 W case (Deposit 4-1), which had a failure formation. And exhibited a lesser extent of the plume than the 350 W case (Deposit 4-4). In this case, only a point with 300 W of LP was identified as good due to the less plume and a continuous bead formation; however, the continuous bead is not straight, therefore, no process window was identified.

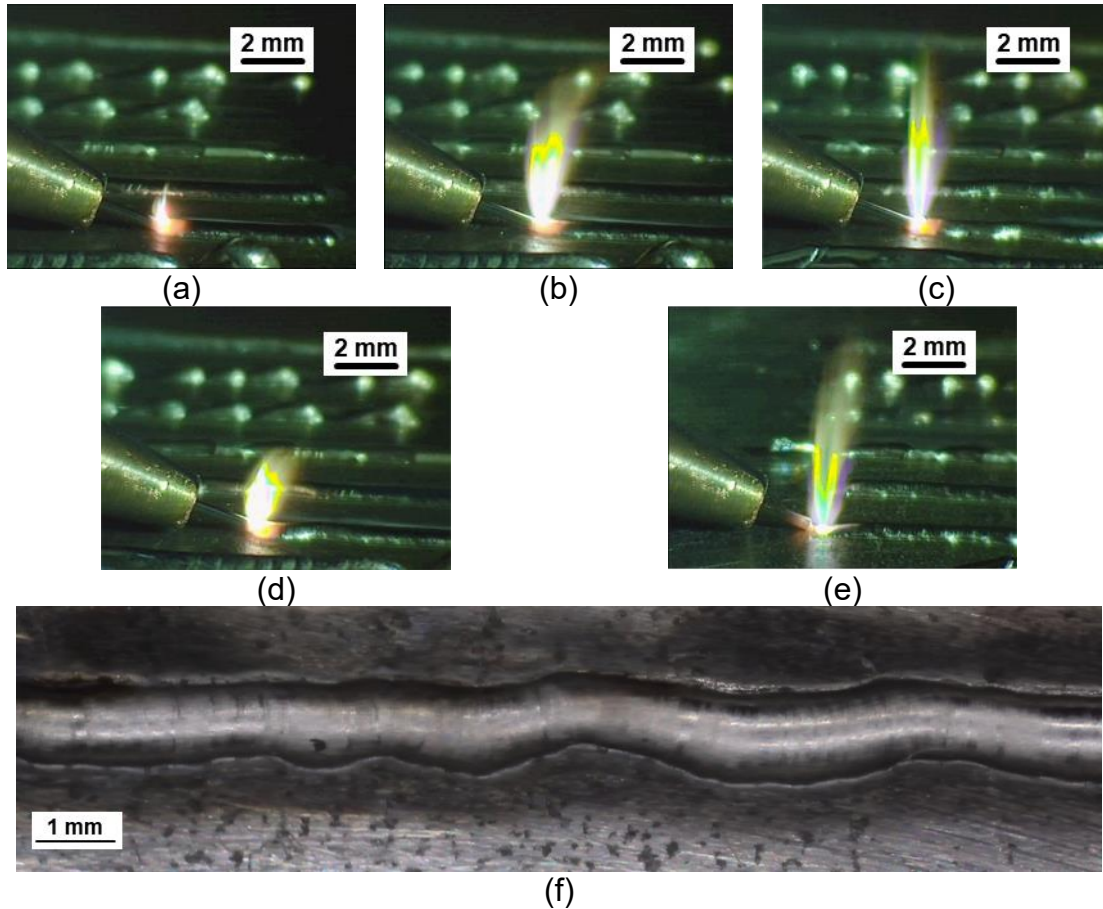


Figure 4-7 Different plume profiles at different recording times (a) – (e) during individual deposit 4-4 deposition and the (f) corresponding bead top-view appearance (LP: 350 W, WFS: 8.5 mm/s, TS 5 mm/s).

Figure 4-8 (a) and (b) show the appearance of lack-of-fusion defects at 300 W (Deposit 4-3) and 350 W of LP (Deposit 4-4), respectively (here, the definition of lack-of-fusion defect is different from the terminology in welding, this lack-of-fusion defect, especially refers to the first-layer bead, is caused by the lack of

enough energy at the edge of the bead to prompt a proper bonding with the substrate due to the steep laser beam profile reduction when using a 1.0 mm small laser beam). Both deposited beads suffered from lack-of-fusion defects; however, the defects look more obvious and serious at 350 W (Deposit 4-4), which indicates that the 350 W LP deteriorated the deposition performance further compared with the 300 W case (Deposit 4-3).

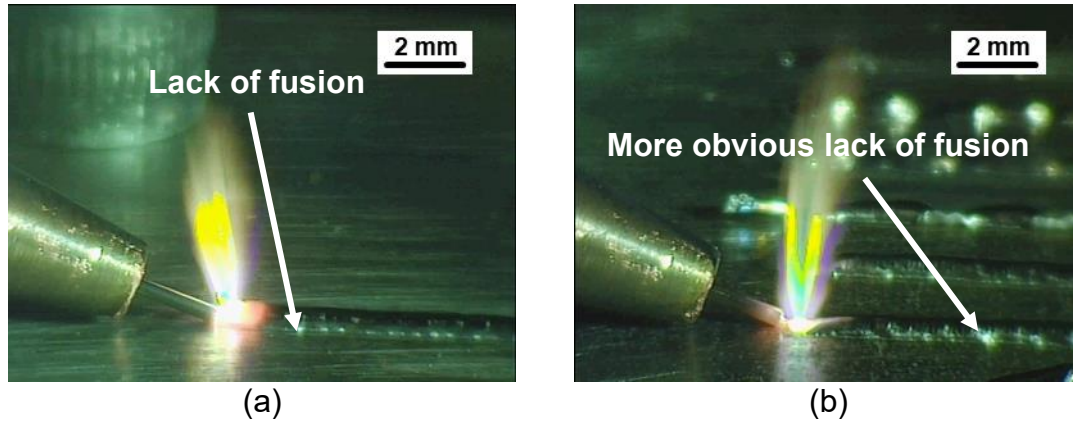


Figure 4-8 Lack of fusion defects appearing at (a) 300 W (Deposit 4-3), (b) 350 W (Deposit 4-4) of LP.

Overall, the deposition performance is poor and unstable using a 1.0 mm laser beam, with the plume being the primary issue observed in all trials, accompanied by other issues such as wire dripping and lack-of-fusion defects within the LP range of 200 W to 350 W. The bead is not straight, and the repeatability is low. High PD under a 1.0 mm laser beam induced the plume formation. Low energy transferred to the substrate either by the interference of the plume, which could block the propagation of laser radiation (J. Liu & Wen, 2022) or by the low level of energy in nature caused the defects to appear.

In detail, the reasons for the poor bead appearance with plume formation, defects appearing using a 1.0 mm laser beam, and identified as no process window are explained as follows:

First and foremost, for this single-mode fibre laser, the discrepancy of the intensity distributed on the wire is significantly different when using a 1.0 mm laser beam. And this discrepancy will be increased if the laser beam continuously decreases.

For the middle part of the wire, the laser intensity was high enough to vaporise the wire, but at the edge of the wire, the intensity was low; the instantaneous energy around the edge area of the wire was not enough, which mainly resulted in the lack-of-fusion defect. This is because the used laser fibre is a single-mode fibre, Gaussian-type profile is this fibre's typical and main beam profile (Figure 4-2 (b)), within the 1.0 mm laser beam profile, the intensity distribution varies a lot with a relatively high-level p-PD (Figure 4-2 (c)) followed by a steep and sharp transition along the horizontal X and Y axes positive direction (X and Y intensity contour line in Figure 4-9). This high-level p-PD value is only the case under 25 W of LP irradiation for the reasons of safe measurement and avoiding saturation, when using 300 W and 350 W of LP, the p-PD reached 91.92 kW/cm² and 107.24 kW/cm² theoretically, in this case, these p-PD should cause the plume formation on the small-size 0.60 mm in diameter wire.

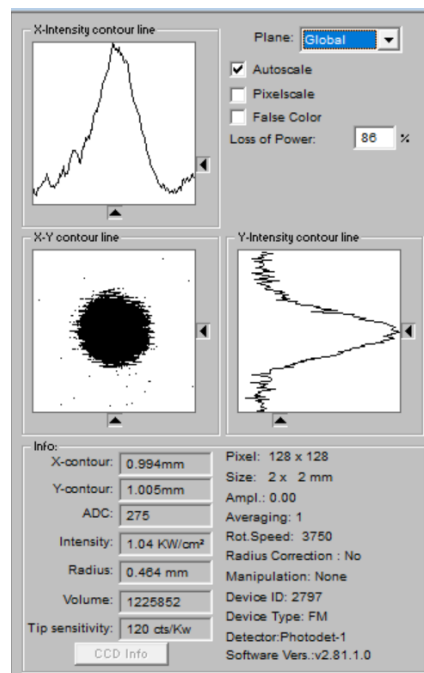


Figure 4-9 PD contour line of a 1.0 mm in diameter laser beam along the X-axis and Y-axis.

In (J. Liu & Wen, 2022; Steen, 2002), the authors mentioned the threshold of intensity for vaporisation is 10^6 MW/cm². However, this threshold is for welding, the size of the substrate is larger than that of the wire. Therefore, the threshold

for wire should be significantly lower, and the threshold should depend on the size of the wire.

Also, the high-PD (h-PD) region with PD ranging from 6.13 KW/cm² to 7.66 KW/cm² (Figure 4-10) (here, defined as the PD area within the 1-fifth (refers to the left side of Figure 4-10) of the PD scale bar regime) is smaller than the wire diameter (0.6 mm). The beam profile at the 1.0 mm laser spot indicates that the size of the h-PD region is just about 325 μ m (Figure 4-10) which is less than the wire diameter. This caused uneven energy distribution on the wire surface, especially the edge part of the wire, when assuming the wire was perfectly aligned with the laser spot.

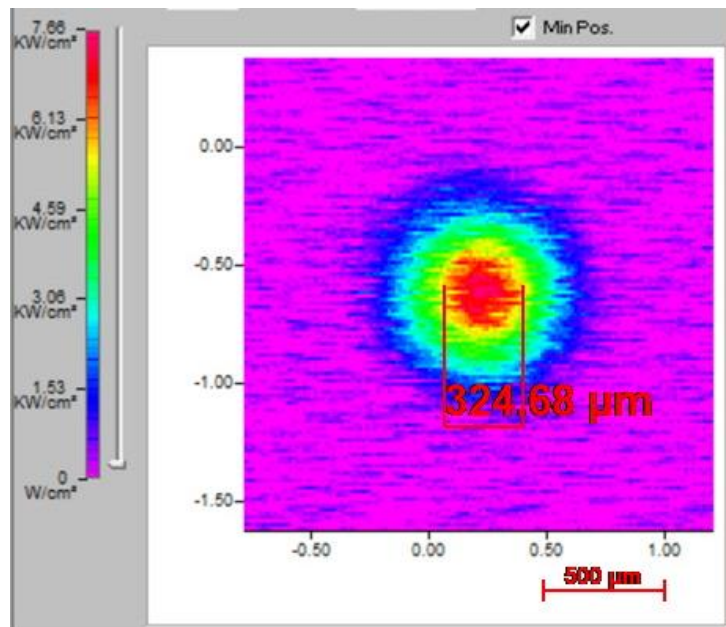


Figure 4-10 The dimension of the h-PD area of a 1.0 mm in diameter laser beam.

Secondly, the responses to the laser irradiation for wire and substrate were different; material vaporisation on the wire happened more easily than on the substrate when processing under the same laser conditions due to the different sizes and volumes of the wire and substrate materials. The wire with this small 0.6 mm diameter size and small mass could easily reach the boiling point and undergo material vaporisation compared with the substrate. This is because the substrate had enough extra volume to dissipate the heat towards the surrounding volumetric area three-dimensionally within the same medium, but the wire did not

have enough material to dissipate the heat, resulting in the wire absorbing most of the energy.

As a result, under the same laser irradiation, the small size wire was easier to vaporize and cause the plume, and then formed a plasma column above the melt pool. This plume caused by the material vaporization took away much of energy than the melt pool because, from the physical perspective, the latent heat of vaporization is more than ten times the latent heat of fusion (Verhaeghe et al., 2009). The plume also blocked the propagation of the laser radiation to the substrate and wire (J. Liu & Wen, 2022). Therefore, an inadequate amount of energy could reach the materials.

Meanwhile, the plasma column size increased as the LP increased. More heat can be taken away at higher LPs, which results in the wire not being fully melted. This can also help explain why at a higher LP of 350 W (Deposit 4-4), a serious lack-of-fusion defect appeared (Figure 4-8 (b)).

Thirdly, the applied Esp was potentially inadequate within the LP range of 200 W to 350 W, it was about 40 J to 70 J, this amount of energy could cause the frequent formation of lack-of-fusion defects.

Refer to the results shown in (Zapata et al., 2022), the authors used a 1.0 mm in diameter AISI 316L wire, a 2.6 mm outside diameter, 1.2 mm inside diameter ring-shaped laser spot (considering the real reaction beam region of the ring-shape profile, 1.4 mm was used as the effective beam diameter for IT calculation) to carry out the experiments. In this case, within the process window (Figure 4-11), the range of TS is between 0.4 m/min to 1.6 m/min (6.67 mm/s to 26.67 mm/s), the IT range corresponds to 0.21 s and 0.05 s, therefore, the Esp are between 63 J to 252 J. This indicates the 350 W LP case (deposit 4-4) having a higher Esp of 70 J than the minimum Esp boundary of 63 J that fell within the process window, but the performance showed this deposit (deposit 4-4) with the obvious plume appearing did not have the qualification to be classified as within the process window made by authors in (Zapata et al., 2022). This indicates that either low or high Esp is a judging point for good performance but is not the only absolute factor to determine the deposition performance; a higher Esp of 70 J

with a 1.0 mm laser beam can also induce poor performance with plume interference compared with Esp of 63 J with a 1.4 mm laser spot.

Therefore, some other factors need to be considered in parallel, such as beam size, the authors (Zapata et al., 2022) used a large ring-shaped beam profile as the processing plane at the defocused position with a relatively even distribution and medium intensity (Figure 4-12), this could be a positive point for having good deposition performance.

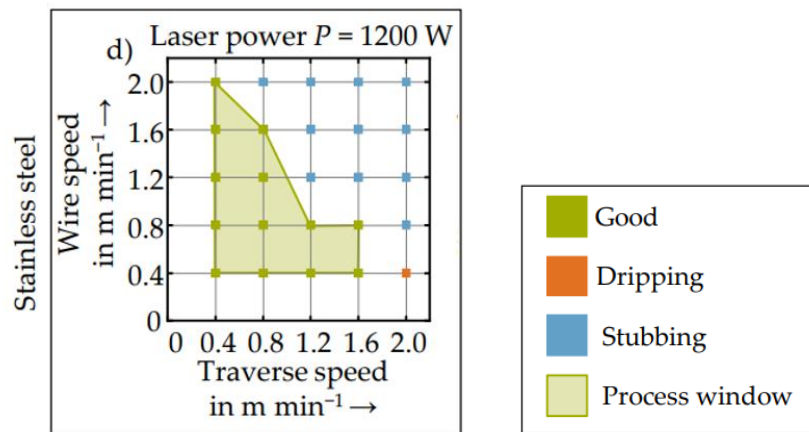


Figure 4-11 Process window envelope for 316L SS deposition in (Zapata et al., 2022).

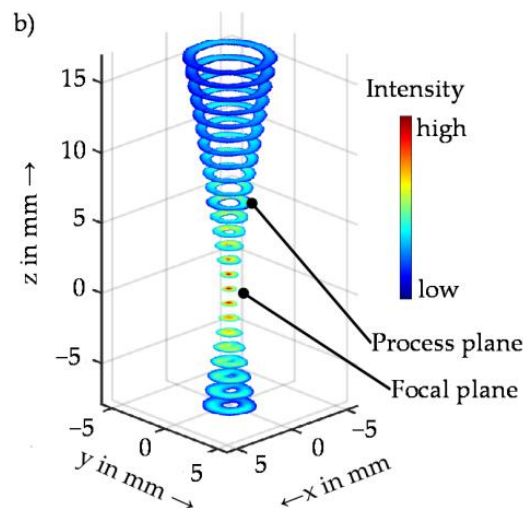


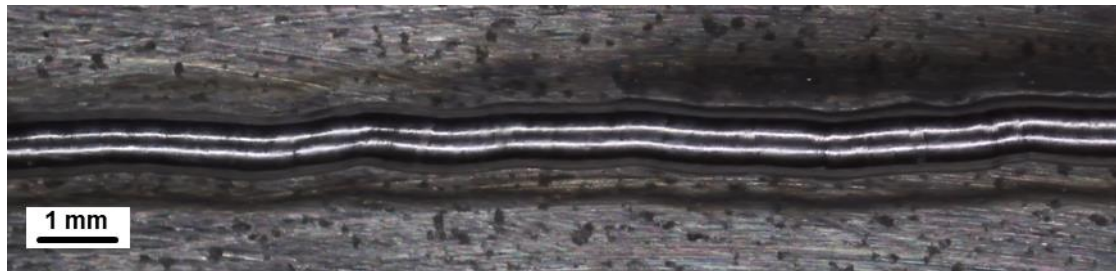
Figure 4-12 The beam profile of the laser and the processing plane used in (Zapata et al., 2022).

Afterwards, the repeatability of the deposition was tested on either the same substrate or on different substrates, several repeated beads were conducted. The results of two representative beads deposited on the same substrate with the same processing parameters (deposit identification and the corresponding parameters are listed in Table 4-3) are shown in Figure 4-13 (a) and (b). It can be seen that the repeatability is not acceptable due to the random waviness formation.

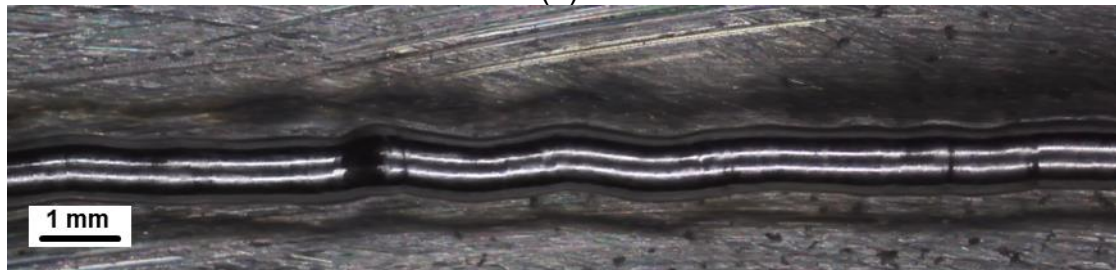
Table 4-3 Deposit identification and the corresponding parameters for the repeatability study.

Deposit ID	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
4-5	300	8.5	5	38.20	200	60
4-6	300	8.5	5	38.20	200	60

To understand this issue, knowing the autogenous laser weld consistency first was essential. Therefore, checking the consistency of the autogenous laser weld was proposed. Because checking the plume source (next section's content) also requires conducting the autogenous laser weld, in this case, the detailed discussion of this unacceptable repeatability of bead on plate will be spread in detail along with the next section (section 4.4) of identifying the plume source together.



(a)



(b)

Figure 4-13 Images of different bead appearances of (a) deposit 4-5, (b) deposit 4-6 under the same parameters (300 W of LP, 8.5 mm/s of WFS, 5 mm/s of TS).

During the experiments of study repeatability, the unstable performance and even the failure frequently happened under the same processing parameters. The main failure phenomenon of the deposition was the discontinuous bead formation, to figure out the reason for the issue, the wire feeding position was examined under the same processing parameters of 8.5 mm/s of WFS, 5 mm/s of TS, 350 W of LP but with different wire position relative to the substrate (Z direction), the deposit identification, corresponding parameters and wire position are listed in Table 4-4.

Table 4-4 Deposit identification, the corresponding parameters and wire position for wire feeding position study.

Deposit ID	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)	Wire position
4-7	350.00	8.50	5.00	44.56	200.00	70.00	Free space
4-8	350.00	8.50	5.00	44.56	200.00	70.00	On the substrate surface

Images (a) – (f) in Figure 4-14 show the deposition performance of deposit 4-7 with the wire slightly suspended in the free space; images (a) – (f) in Figure 4-15 show the deposition performance of the wire gently touching the substrate surface (Deposit 4-8). In Figure 4-14, under the same processing parameters, when the wire was suspended in the free space with a small gap (Figure 4-14 (a)). Once the laser was triggered, it was easy to have the balling effect (Figure 4-14 (b)) which caused the burning back of the wire tip (Figure 4-14 (c)) and then formed pendant droplets, finally detached from the wire tip and dropped down by the gravity force and surface tension force driven between the droplets and the substrate surface once the droplet was big enough and had contact with the substrate (Figure 4-14 (d)); the droplets attached to the substrate, and then the wire repeated the balling effect and burned back again (Figure 4-14 (e)).

Thus, on the substrate, the non-uniform, non-continuous bead formed (Figure 4-14 (f)). However, when the wire was gently pre-touched on the substrate (Figure 4-15 (a)), obvious contrasting results appeared, the balling effect of the wire tip and wire burning back phenomenon was avoided significantly, a continuous track was formed as shown in the details of Figure 4-15 (b) – (f). This

is because the surface tension force formed between the droplet and the substrate, making the metal transfer to the substrate smoothly, easily, and continuously.

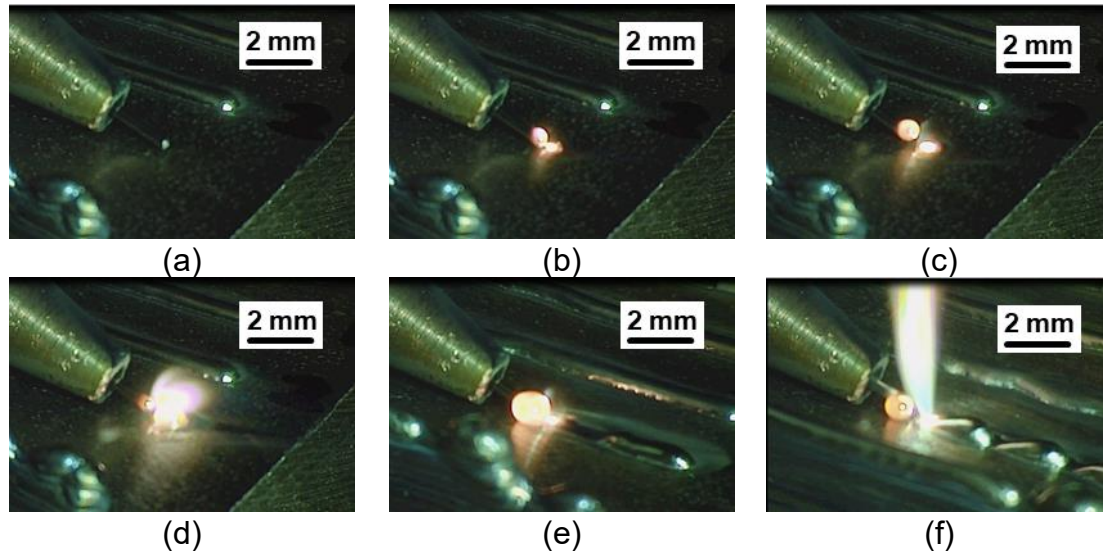


Figure 4-14 Deposition performance of different phases at different recording times (a) – (f) during individual bead (deposit 4-7) deposition with wire suspending in the free space.

Therefore, the wire is sensitive to the wire feed position relative to the substrate; touching the wire on the substrate surface (along the Z direction) was found to play a critical role in successfully depositing the continuous deposits using a 1.0 mm laser beam. A similar result of placing the wire on the surface of the substrate is the fastest way to achieve a stable stationary deposition process was reported by (Kotar et al., 2019), the authors claimed that placing the wire end on the substrate surface could achieve simultaneous heating of the substrate and the wire and achieve the most robust stable phase transition, if there is a small gap between the wire and the substrate, the balling effect will form, this phenomenon is frequently formed when the wire suspends in the free space, however, the authors (Da Silva et al., 2021) utilized this phenomenon as a bonus to achieve the droplet drop-by-drop deposition additive manufacturing. In reality, forming droplets is mainly because of the lack of an effective downward-driven force to drive the pendant droplets to detach from the wire tip when using a laser, of which the mechanism is different from the arc-based DED process, which has the arc pressure formation when doing the deposition (Wang et al., 2021).

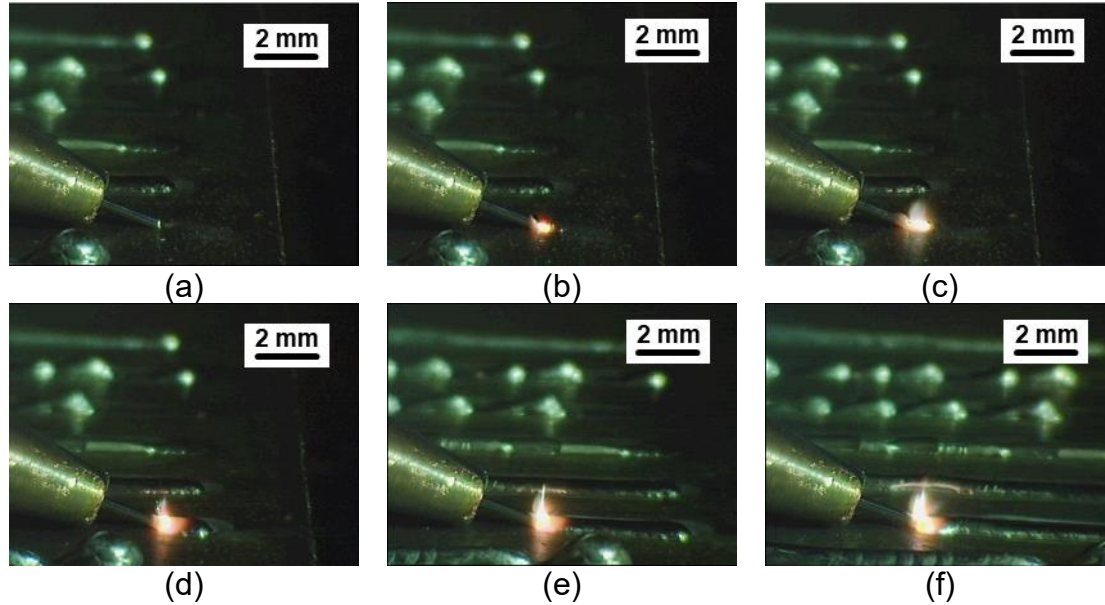


Figure 4-15 Deposition performance of different phases at different recording times (a) – (f) during individual bead deposition with wire gently touching the surface (deposit 4-8).

In addition, when the plume formed, the plume could absorb a percentage of the energy, thus, the lower temperature of the molten material resulted in a high viscosity of the droplet (Ebrahimi et al., 2022), which increased the difficulty of detachment. In the arc-based process, the arc pressure can prompt the droplets to detach from the wire tip instantly and at a constant rate. Once the wire is pre-positioned on the substrate surface, the surface tension forces can prompt the molten metal to have a good connection with the substrate, therefore transferring the droplet to the melt pool smoothly and more uniformly.

4.4 Identification of the plume source

After the wire feeding position was determined to be best at the substrate surface, bead on plate can be repeated to see the deposition repeatability with less interference. However, in most of the trials of the bead on plate, the plume was frequently observed, and it was also noted that it was interfering with the deposition quality.

To identify the major reason for the appearance of the plume and the main source of the plume, autogenous laser welds and bead on plate were studied under the same processing conditions for comparison.

In addition, as observed in 4.3, the deposition repeatability on the same substrate was not good, and wavy bead profiles were present (Figure 4-13) at the same processing parameters. To understand this, having a consistent autogenous laser weld width was essential.

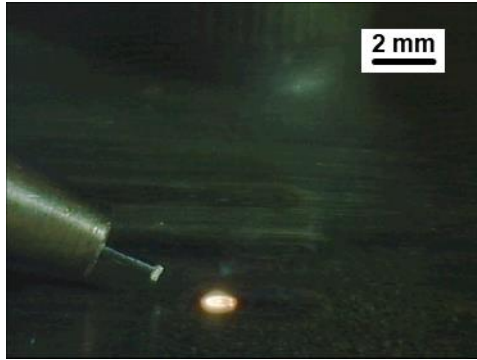
For the ease of observing if there is a significant difference in the plume extent between the autogenous laser welds and the bead on plate. And to mitigate the interference of the p-PD, which can cause serious plumes in both the welds and bead on plate at high-level LP, which will disturb the judgment. 250 W of the LP was chosen as the processing power; the specific experimental parameters and sample identification are listed below in Table 4-5 .

Table 4-5 Sample identification and the corresponding parameters for the plume source study.

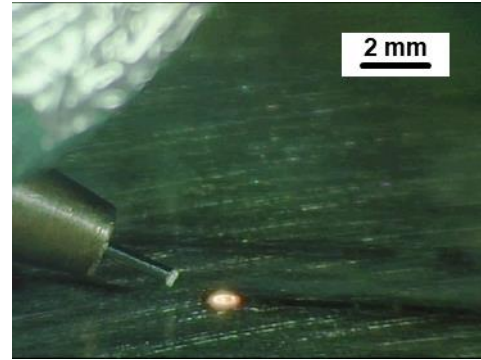
Sample ID	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
4-9	250	0.0	5	31.83	200	50
4-10	250	0.0	5	31.83	200	50
4-11	250	8.5	5	31.83	200	50
4-12	250	8.5	5	31.83	200	50

Figure 4-16 (a), (b) show two representative images of the autogenous laser welds (weld 4-9, 4-10) with nearly no obvious plume, but with a non-obvious plasma column formation.

Figure 4-17 (a), (b) shows the plume formation of the bead on plate processing at the same parameters. The extent of the plume of the bead on plate (deposit 4-11, 4-12) is stronger compared with that of autogenous laser welds (weld 4-9, 4-10).

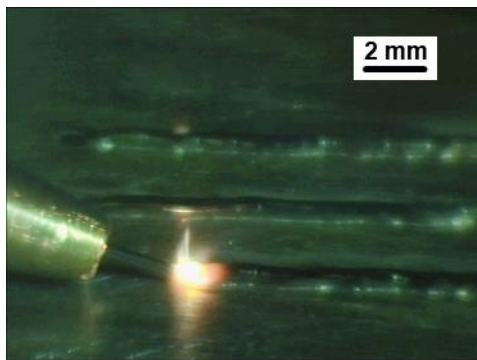


(a)

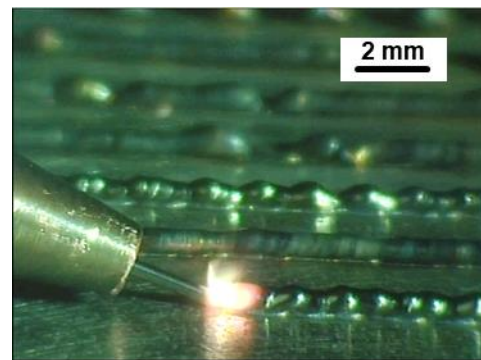


(b)

Figure 4-16 Images of no obvious plume formation for two autogenous laser welds (a) weld 4-9, and (b) weld 4-10.



(a)



(b)

Figure 4-17 Images of relatively more obvious plume formation than autogenous welds for two bead on plate (a) deposit 4-11, and (b) deposit 4-12.

In addition, an observation of inconsistent melt pool size within an individual track was found when conducting the autogenous laser welds. Take the weld 4-10 as an example, the size and the profile of the melt pool alternately changed as time elapsed. Figure 4-18 (a) shows a relatively large size melt pool. Figure 4-18 (b) shows a small melt pool within the same autogenous laser weld deposition. An overall top-view of the autogenous laser weld 4-10 with inconsistent width is shown in Figure 4-18 (c). The width consistency varied significantly.

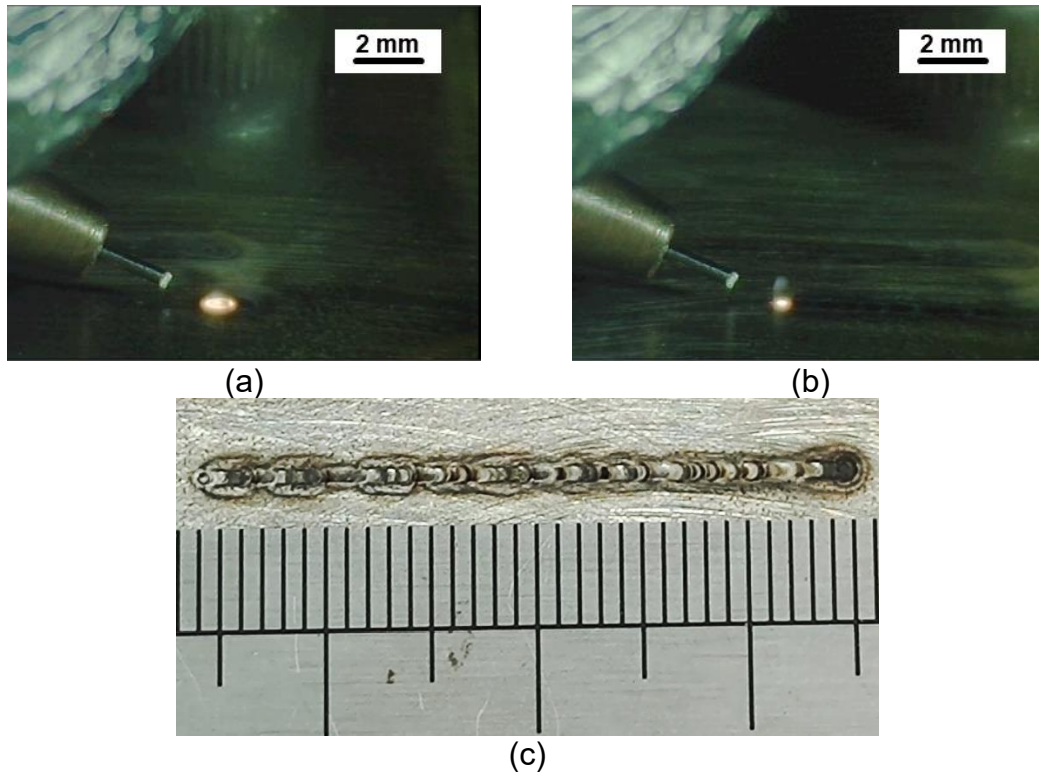


Figure 4-18 Images of inconsistent-size width melt pool (weld 4-10) with (a) large-size melt pool, (b) small-size melt pool, and the corresponding (c) overall top-view appearance.

In this case, the plume source could be identified as coming from the wire, however, this conclusion only applies to the 250 W case. Experiments at higher levels of LP are required to identify the overall plume source and to draw a comprehensive conclusion further.

Beyond that, the autogenous laser weld widths were found to be not consistent, and an obvious width size variation was observed, which can affect the deposit repeatability, uniformity, and straightness significantly. Through Figure 4-16 , and Figure 4-18 , it is easier to observe some surface scores in the substrate which can be regarded as the critical intervening factor for width consistency. To mitigate the factor, a more uniform surface finish of the substrate was used to carry out the experiments to finally identify the reasons for the poor repeatability, straightness and uniformity.

4.5 Investigation of the inconsistent width and verification of the main plume source

Due to the appearance of the inconsistent size of the melt pool when conducting the autogenous laser welds, substrate surface roughness was considered an important influential factor. To mitigate the interference of the scores significantly, the substrate was ground with fewer scores showing on the surface (a better and more uniform surface condition), and then, the autogenous laser weld (weld 4-13) was conducted using the same parameters, i.e., 5 mm/s of TS, 250 W of LP to see if a consistent width track can be achieved.

Thereafter, two higher levels of LP, 300 W (weld 4-14) and 350 W (weld 4-15) were applied to see if the appearance of plume exhibited a similar effect of intervening the width consistency of the autogenous laser weld as obvious scores case did at low-level 250 W of LP.

Then, the wire was added to the process using 250 W of LP (deposit 4-16) to see if the plume issue became obvious again compared to the autogenous laser weld to double verify the main source of the plume. The experimental parameters and sample identification are summarised and listed in Table 4-6 below.

Table 4-6 Sample identification and the corresponding parameters for the inconsistent width and verification of the main plume source study.

Sample ID	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
4-13	250	0.0	5	31.83	200	50
4-14	300	0.0	5	38.20	200	60
4-15	350	0.0	5	44.56	200	70
4-16	250	8.5	5	31.83	200	50

A consistent autogenous laser weld with an evenly distributed width along the deposition direction is the prerequisite of bead deposition success. Figure 4-19 (a), (b) show that a similar size melt pool within the individual weld track (weld 4-13) can be achieved without significant melt pool profile and size variation when the surface finish condition of the substrate was improved and more even with fewer scores.

Figure 4-19 (c) is the top view of the autogenous laser weld 4-13; the condition of the width of the autogenous laser weld is more even and consistent compared with the autogenous laser weld 4-10.

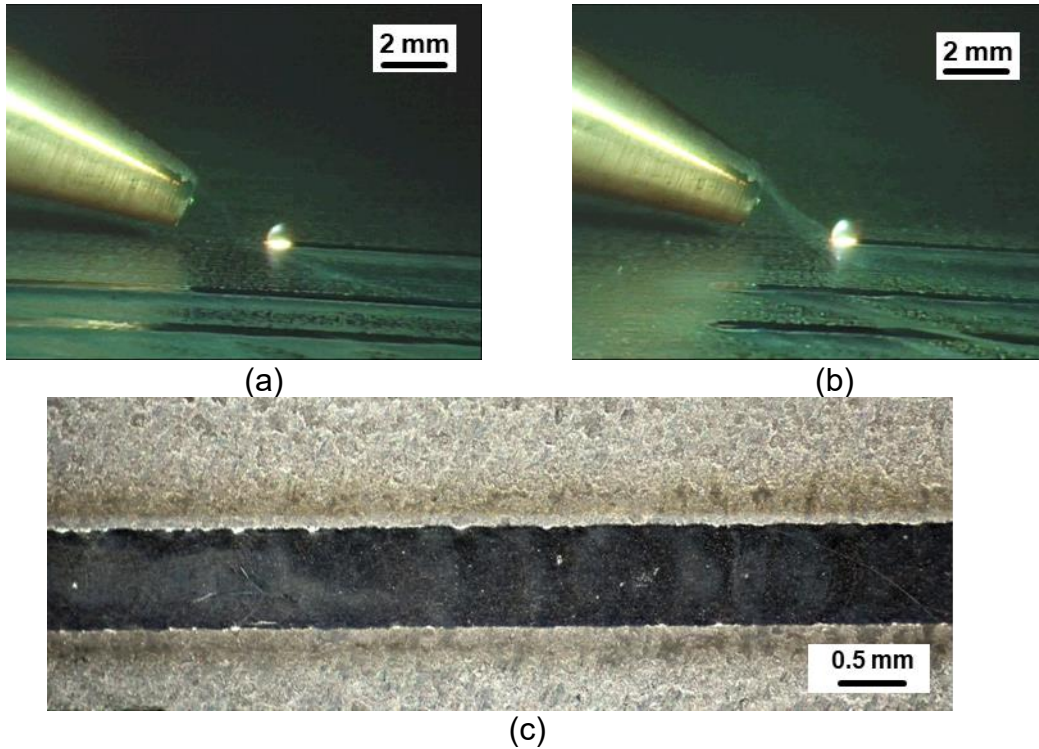


Figure 4-19 Images of consistent-size width melt pool at the (a) initial, (b) final phase of the weld 4-13 at 250 W of LP, and the corresponding top-view appearance.

When increasing the LP to 300 W and 350 W to see if the melt pool width was still constant, or whether the width had deteriorated due to the plume. The results shown in Figure 4-20 (c) reveals that the extent of the consistency looks still good at 300 W of LP (weld 4-14), but the extent of the plume is more obvious and unstable (Figure 4-20 (a), and (b)), a slight level of ripples appears (as an arrow pointed in Figure 4-20 (c)). The width consistency deteriorated by increasing the LP to 350 W (weld 4-15) with the unstable melt pool, uneven autogenous laser weld width, and obvious ripples formation. The plume became strong again when 350 W LP was applied on the substrate with a better and more uniform surface finish condition (Figure 4-21 (a)-(c)).

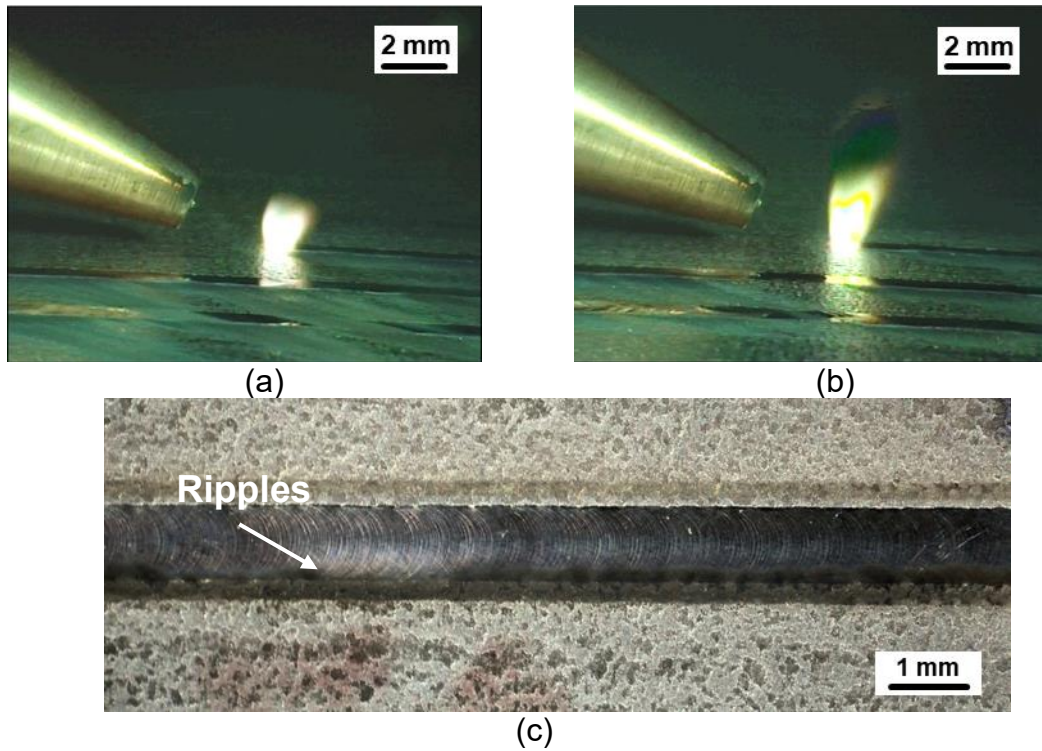


Figure 4-20 Images of consistent-size width melt pool at the (a) initial, (b) final phase of the weld 4-14 at 300 W of LP, and the corresponding top-view appearance.

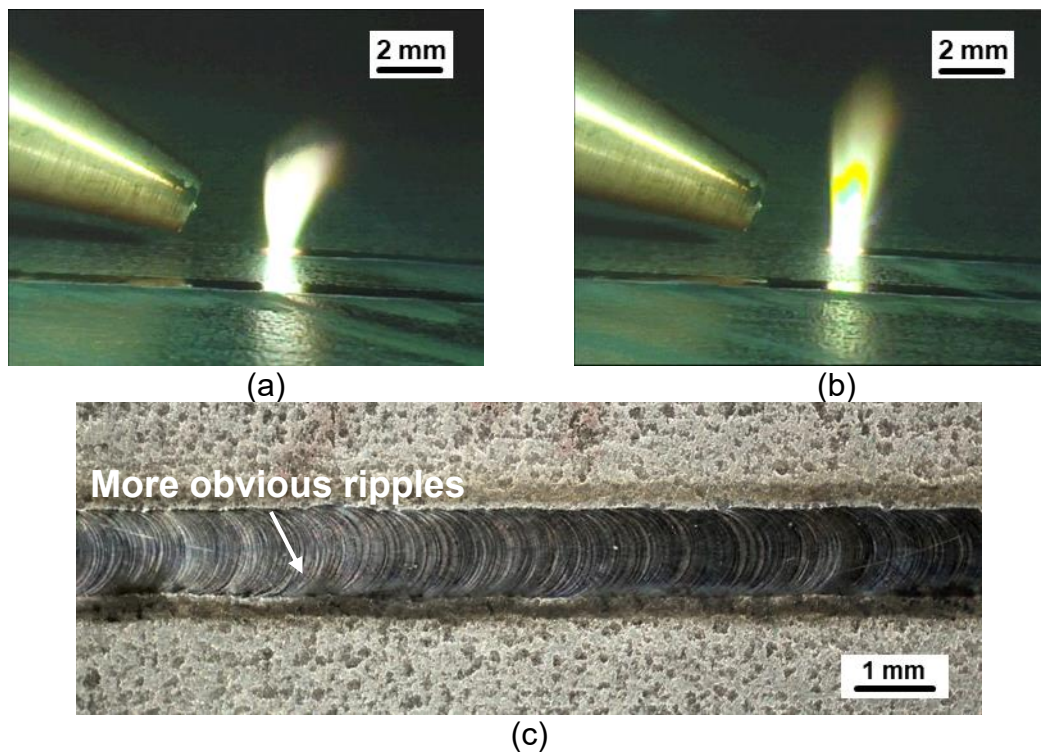


Figure 4-21 Images of consistent-size width melt pool at the (a) initial, (b) final phase of the weld 4-15 at 350 W of LP, and the corresponding top-view appearance.

When adding the wire in the process with 250 W of the LP (deposit 4-16), a similar result of a more obvious plume observation is shown in Figure 4-22 compared with the phenomenon of autogenous laser weld (weld 4-13) shown in Figure 4-19 (a)-(b). In this case, the main source of the plume can be determined.

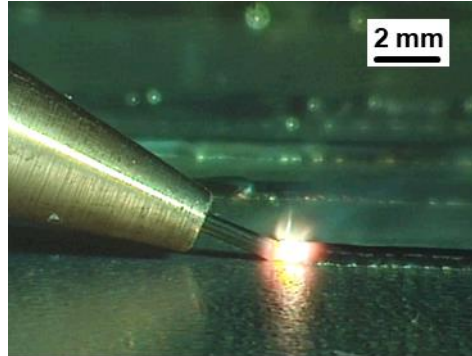


Figure 4-22 Image of plume formation for bead on plate at 250 W of LP (deposit 4-16).

When depositing the bead on plate, the main source of the plume should come from the wire, but here, the wire should be referred to as either one or two sections as per the level of LP used. At 250 W of LP, for the comparison experiments, no obvious plume appeared on the autogenous laser weld but on the bead on plate, which means that when the wire started receiving the energy from laser irradiation at 250 W of LP, the plume only came from the raw wire surface.

Based on the performance of the plume appears on the autogenous laser weld, as the LP increased to 300 W and 350 W, once the wire was added to the process with 300 W LP or above, the plume first came from the raw wire when the wire start experiencing the laser irradiation, then the plume came from the deposited bead where the bead was still experienced the laser irradiation.

Also, as shown in Figure 4-19, at 250 W of LP (weld 4-13), even though the width consistency of the autogenous laser welds can be improved, the appearance of the bead on plate (deposit 4-16) is still not straight, with the zigzag profile appearing (Figure 4-23). As a result, the reasons for the poor repeatability and zigzag appearance can be concluded comprehensively below:

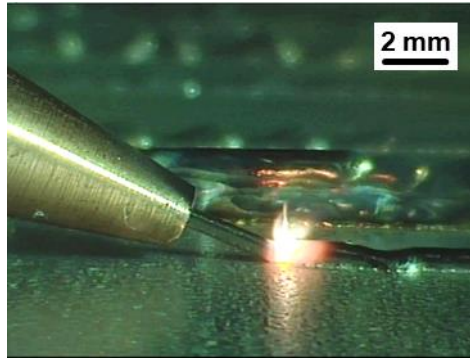


Figure 4-23 Image of poor straightness formation for bead on plate at 250 W of LP (deposit 4-16).

When the substrate surface condition is not uniform, a continuous autogenous laser weld with even width distribution along the deposition direction within one single weld was not achieved.

In this case, when adding the wire to the process, at a constant material feed rate, the uneven width of the autogenous laser weld would affect the bead on plate straightness and flatness, generating waviness and different heights in the deposited beads. Thus, the repeatability is low.

Moreover, when this bead with a irregular surface profile (poor flatness) experienced laser irradiation and continuously interacted with the laser, the plume rose in varied directions but was tangent to the irregular bead surface. In this case, even though the PD was high, the real energy that could be transferred to the wire and substrate was limited by the plume and plasma column formation, and this energy varied all the time, decreasing the repeatability of the deposited beads even further.

To avoid the effect of scores influencing the performance and to investigate if the consistent-width autogenous laser welds could be achieved using this 1.0 mm laser spot size, a substrate that has better, and more uniform surface finish condition was used to conduct the autogenous laser welds with 250 W of LP (deposit 4-13). Figure 4-19 (c) shows that the consistent-width track was achieved. However, when increasing the LP to 300 W and 350 W, the extent of the width consistency maintained at 300 W first (deposit 4-14) then deteriorated at 350 W (deposit 4-15) because of the serious plume appearance which

interfered with the laser irradiation and partially absorbed the energy that being transferred to the material. However, the overall consistency was better than the previous situation (Deposit 4-10) (Figure 4-18) with a relatively rougher surface finish. Therefore, rough surface conditions and higher LP can affect the width consistency for a 1.0 mm laser beam case.

When the wire was added to the process (deposit 4-16) with 250 W of LP, the autogenous laser weld exhibited a good, consistent width. The factors of poor surface condition and high levels of LP, which could affect the deposition stability, were mitigated significantly, but the zigzag bead profile still existed (Figure 4-23). This shows that even though the width of the autogenous laser weld is constant and the track is straight, a good deposited bead was still not achieved using a 1.0 mm laser spot. This could be attributed to two main reasons:

First is that at 250 W LP, as mentioned previously, the h-PD region is less than 0.6 mm, the edge and the bottom part of the wire at this level of LP cannot be evenly covered by the energy and be fully melted, this cannot ensure good bonding with the substrate, the non-melted wire can slip out of the middle of the melt pool and cause the wire deviation.

Secondly, the partially melted wire could absorb the energy from the melt pool, in this case, the melt pool size will reduce in volume, therefore, the constant width of the deposited bead cannot be guaranteed due to the melt pool size variation and unknown amount of energy being absorbed by the unmelted wire, in such a case, the non-fully melted part of wire will accumulate along the height or push the material sideways then cause the hump or waviness of the deposited bead.

Overall, a 1.0 mm laser beam cannot ensure a good, stable deposition, even though the consistent width of autogenous laser weld can be achieved at 250 W. When adding the wire to the process, and when the LP increased, the plume played a critical role in causing the bead waviness.

4.6 WFS to TS ratio-based process window investigation

In the first phase experiments, the result of studying the repeatability of the trials using 8.5 mm/s of WFS and 5 mm/s of TS with varied ranges of LP was not

successful with a very limited parameter range used, which could prevent the possibility of finding the matched set of parameters to yield relatively reasonable results. So, in the second phase, single-layer beads on plate within a wider speed range were conducted based on the WFS to TS ratio ranging from 0.57 to 2.00.

The summarised deposit identification and the specific parameters of the deposit for the following discussion are listed in Table 4-7 . Other trials have been done for performance investigation but not being discussed in detail due to the similar issues, such as obvious plume, surface waviness, and poor straightness, which frequently happened, are grouped and summarised in Table 4-8 .

The deposition performance, the extent of the plume and the extent of the lack-of-fusion defects of the bead on plate were compared with those of phase one to see whether there were some performance improvements by using the different combinations of WFS and TS to form different WFS to TS ratios to expand the parameter ranges. Then, the wire position sensitivity relative to the laser spot was judged through the trials. The possible process parameters that can be used for wall fabrication were identified.

Table 4-7 Deposit identification and the corresponding parameters for the WFS to TS ratio-based process window investigation.

Deposit ID	WFS/TS	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
4-17	1.00	300	5	5	38.20	200	60
4-18	1.00	250	5	5	31.83	200	50
4-19	1.00	325	5	5	41.38	200	65
4-20-A	1.25	275	5	4	35.01	250	69
4-20-B	1.25	275	5	4	35.01	250	69
4-21-A	1.25	300	5	4	38.20	250	75
4-21-B	1.25	300	5	4	38.20	250	75

Table 4-8 Deposit group identification and the corresponding parameter ranges.

Deposit Group ID	WFS/TS	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
G4-1	0.57-1.33	250 -325	4	3-7	31.83 - 41.38	143 - 333	35.75 -108.23
G4-2	0.71-1.67	250 -325	5	3-7*	31.83 - 41.38	143 - 333	35.75 -108.23
G4-3	0.86-2.00	250 -325	6	3-7	31.83 - 41.38	143 -333	35.75 -108.23
G4-4	1.00-1.75	250 -325	7	4-7	31.83 - 41.38	143 -250	35.75 - 81.25

*: Not including the cases with 5 mm/s of TS

Figure 4-24 shows the overall top-view of the bead on plate deposit 4-17 with a speed ratio of 1.0 (5 mm/s of the WFS, 5 mm/s of the TS) and with 300 W of the LP. The surface smoothness of the deposit was improved, and the deposit was straighter and flatter than the initial phase cases with 8.5 mm/s of WFS and 5 mm/s of TS (corresponding to a 1.70 of WFS to TS ratio) at 200 W to 350 W of LP.

The stability of the whole process was improved, but the deposition process still had a plume during the whole deposition progress. The plume was prone to ascending upward with a varied plume profile (Figure 4-25 (a)-(c)).



Figure 4-24 Overall top view of the bead on plate deposit 4-17.

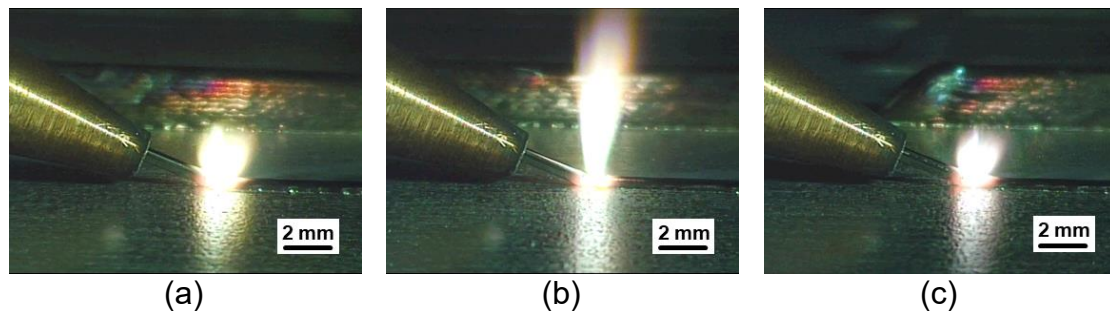


Figure 4-25 Images of plume appearance at different recording times (a) – (c) during individual bead deposition (deposit 4-17).

In addition, this deposition still showed the lack-of-fusion defects at the edge of the bead (Figure 4-26).

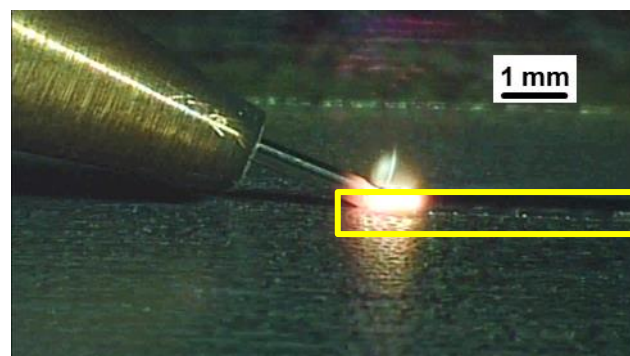


Figure 4-26 Image of lack-of-fusion defects still existing within the deposit 4-17.

The trials processed at 250 W and 325 W of LP with a WFS to TS ratio of 1.0 (5 mm/s of the WFS, 5 mm/s of the TS) were also tested. Figure 4-27 (a), and (b) show the deposit 4-18 processed at 250 W of LP, the process had a relatively stable plume column. Once the LP was increased to 325 W (deposit 4-19), a stronger and unstable plume column appeared (Figure 4-27 (c), (d)). All the plumes were ascending in an upward direction in both cases. The lack-of-fusion defects still existed adjacent to the bottom of the beads in both cases (Figure 4-28 (a) and (b)), the bonding condition did not improve significantly, and the lack-of-fusion defects with higher-level LP in deposit 4-19 looked even worse (Figure 4-28 (b)) than the low-level case of deposit 4-18 (Figure 4-28 (a)).

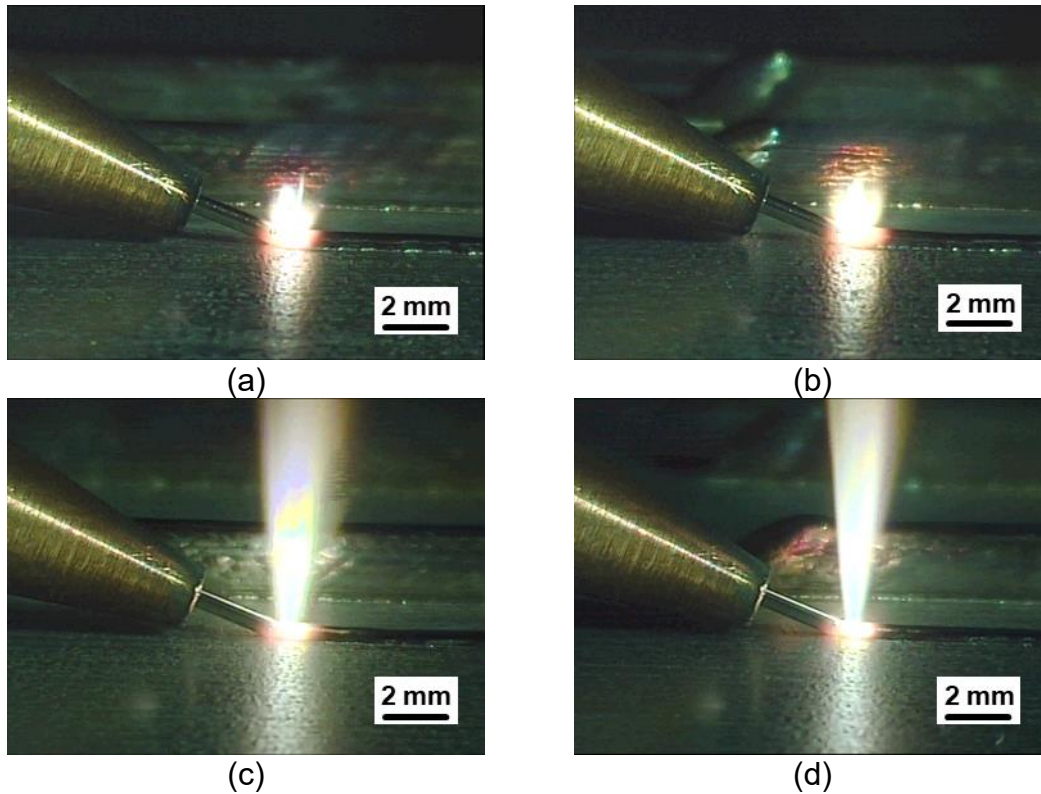


Figure 4-27 Images of different plume extents at 250 W (a) – (b) (deposit 4-18), and 325 W (c) – (d) (deposit 4-19) of LP.

These phenomena of plume and lack-of-fusion defects have commonly appeared in all other cases of bead on plate (G4-1 to G4-4) with different WFS to TS ratios (0.57 – 2.00) under the LP ranging from 250 W to 325 W. Therefore, no other beads on plate were tested anymore. And among all the WFS to TS values, only

the value of 1.00 with 5 mm/s of WFS and TS achieved continuous beads within the LP range of 250 W to 325 W without failure.

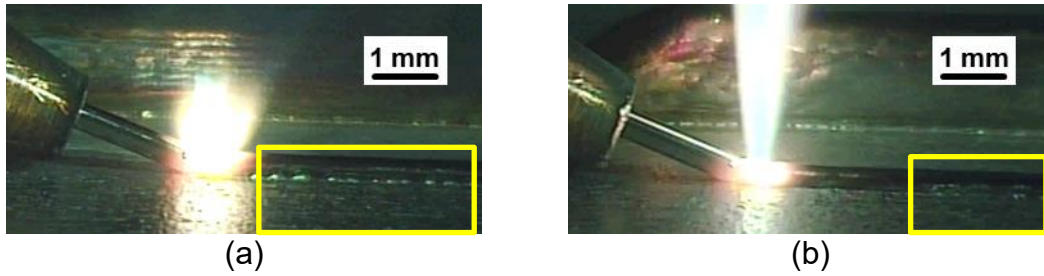


Figure 4-28 Images of different lack-of-fusion extents at (a) 250 W (deposit 4-18), and (b) 325 W (deposit 4-19) of LP.

These phenomena can be summarised, analysed and discussed as follows: after investigating other speed combinations to see the deposition performance, the results indicated that the deposition performance was not improved significantly, only when the trials with a speed ratio of 1.00 with 5 mm /s of WFS, and 5 mm/s of TS exhibited relatively good performance (Figure 4-24), and with all beads deposition successfully under LP ranging from 250 W to 325 W. However, Figure 4-25, and Figure 4-27 indicate that the plume still existed, the plume appeared in all cases of the deposition (LP range of 250 W to 325 W) due to the high value of PD (always above 31.83 kW/cm^2) applied on this 0.6 mm diameter thin wire, especially, the high value of p-PD, which will be much higher than the average PD value of 31.83 kW/cm^2 .

However, because the WFS to TS ratio was reduced due to the lower WFS, the surface smoothness of the deposits was better and flatter. In this case, even when the plume plasma column appeared, the plasma column size variation was prone to occur along the upward and vertical direction. Therefore, the deposition performance behaved slightly better and was more stable than that in phase one. Nevertheless, the plume plasma column size varied which still affected the substrate and wire's laser absorption rate, also affected the effective laser projected on the wire and substrate because the plume caused by the vaporised particles could be regarded as a barrier to prevent the laser from fully passing through (J. Liu & Wen, 2022) and projecting on the wire and substrate. In this case, the total amount of energy absorbed by the wire and the substrate was not

constant and was varied during the deposition process as the volume and profile of the plume column varied temporally and spatially.

In addition, the applied Esp to the process was not enough due to the short IT duration resulting from the small laser beam size (the perimeter of the laser beam had even less IT due to the characteristic of round shape laser beam) and the applied low-level LP; both together caused the applied energy on the wire not to be enough.

Overall, the imbalance of a too-high level PD, especially the p-PD level when using a 1.0 mm laser spot, combined with the inadequate energy caused mainly by the short IT as well as the low-level LP induces the difficulty of achieving good deposition. Therefore, there is no ideal process window for achieving good deposition when using a 1.0 mm laser spot size. A good balance and compensation between enough energy and proper PD are critical for prompting a good deposition with good performance. A 1.0 mm laser spot could not achieve this target.

Additionally, the sensitivity of the wire position relative to the laser spot size was observed during the experiments. It is hard to point out whether the wire was perfectly aligned in the middle of the laser beam because both sizes are too small and similar when using a 1.0 mm laser spot with a 0.6 mm wire. The results shown below in Figure 4-29 , and Figure 4-30 indicate that a slight deviation of the wire relative to the laser spot during the deposition can cause a failure (the wire position relative to the laser spot was maintained the same, the failure happened after a short length of bead that showed good performance). When conducting the set of experiments using 5 mm/s of WFS, and 4 mm/s of TS (WFS/TS ratio is 1.25) with varied LP ranging from 250W to 325W, the cases with 275W (deposit 4-20) and 300W of the LP (deposit 4-21) exhibited the issue of wire deviating from the original position amid the deposition progress, which caused the failure of the bead on plate deposition.

The failure is attributed to the 1.0 mm laser spot being so close to the 0.6 mm wire size (the ratio of laser spot to wire is 1.67) that the failure of the deposition is easy to happen because the tolerant space between the wire and the laser spot

is low resulting in the ability to accommodating the material being fed into the narrow size melt pool being small. Therefore, using 4 mm/s of TS and 5 mm/s of WFS, the speed ratio of which is 1.25, which was relatively high compared to the deposits with a speed ratio of 1.00 (5 mm/s of WFS, 5 mm/s of TS).



Figure 4-29 Images of the top-view appearance of the wire deviating from the original position of deposits 4-20-A and B.

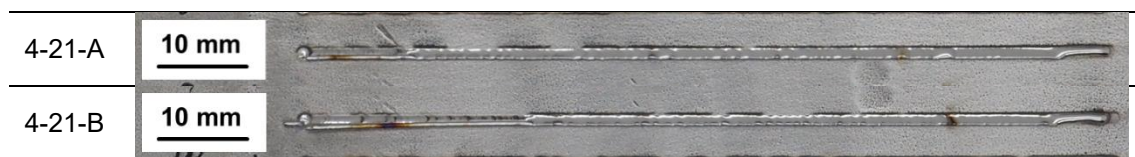


Figure 4-30 Images of the top-view appearance of the wire deviating from the original position of deposits 4-21-A and B.

This resulted in the partially melted wire sliding and deviating from the middle point, but still under enough laser irradiation, where it could melt the rest of the not fully melted wire. In this case, the continuous but not ideal bead was deposited. If the partially melted wire slid and deviated from the middle of the spot any further, the wire was not melted due to the lack of energy resulting in the wire stubbing or even not being melted. As a result, the intact, non-melted wire appeared on one side of the failed bead.

The images in Figure 4-31 show the evolution of a failed deposited trial (deposit 4-21-B) as the time elapses at 300 W of the LP with a speed ratio of 1.25. Initially, the wire is in the right position (Figure 4-31 (a)), but when the movement started, due to the lack of energy and high-speed ratio, the wire was not fully melted in the melt pool (Figure 4-31 (b)). Once continuous feeding the wire (Figure 4-31 (c)), The non-melted wire passed through the melt pool and slipped to the edge of the bead (Figure 4-31 (d)). This caused the wire to deviate from the original right middle position relative to the laser spot, thus the failure formed (Figure 4-31 (e)). At the end of this bead deposition, the non-melted wire even detached from the substrate, which is shown in Figure 4-31 (f). Thus, even a small wire position

movement can cause deposition failure when the tolerance between the wire and laser beam is low.

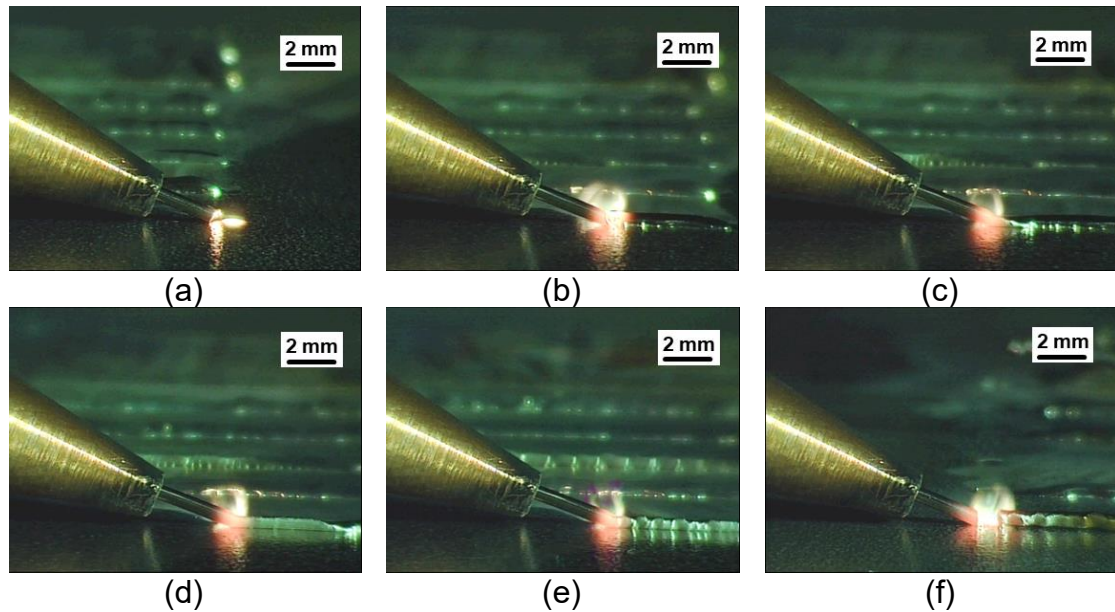


Figure 4-31 Images (a) – (f) of wire deviation evolution of deposit 4-21-B as time elapses.

In addition, a strong plume appeared (Figure 4-32) during the deposition at 325 W of the LP when using 5 mm/s for both the WFS and TS (deposit 4-19) (speed ratio of 1.00).

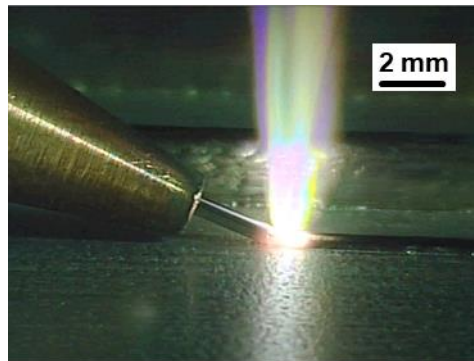


Figure 4-32 Image of a strong plume appearing in deposit 4-19.

To check whether the cross-sectional profile of the bead is suitable for wall fabrication (because the performance for all the trials in this section was not good, failure, defects were frequently appearing, not all the cross-sectional areas were checked), the representative cross-section of the bead with minimum WFS, i.e.,

4 mm/s, 3 mm/s of TS, and maximum 325 W of LP was examined (the deposit belonged to G4-1 group).

From the cross-section of the single-layer bead (Figure 4-33), the deposit exhibits a conduction mode profile, which indicates rest of the cases with less energy input than this case should be in conduction mode as well. These indicate that the conduction mode bead can still be achieved even if a serious plume appears.



Figure 4-33 Image of the conduction mode profile of the cross-section of the deposit within group G4-1 (WFS/TS: 1.33).

Therefore, the feasibility of wall fabrication can be examined even if there is no ideal process window.

4.7 Wall fabrication using a 1.0 mm small laser beam

In this section, several walls were fabricated within the parameters shown in Table 4-7 , and Table 4-8 . Three representative walls are shown in this thesis. The summarised parameters for these three walls are listed in Table 4-9 .

Table 4-9 Wall identification and the corresponding parameters for wall fabrication using 1.0 mm small laser beam.

Wall ID	Speed ratio	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)	Layer
4-1	1	300	4	4	38.20	250	75	10
4-2	1	300	5	5	38.20	200	60	10
4-3	1	325	5	5	41.38	200	65	10

Figure 4-34 shows the cross-sectional area of the wall 4-1 and wall 4-2 at the position of sample 1. Table 4-10 lists the linear dimensions of wall 4-1 and wall

4-2 at the position of sample 1. It can be seen that walls can be successfully built with an average layer height around 230 μm , the surface is not straight with obvious waviness appearing, therefore, the roughness is high.

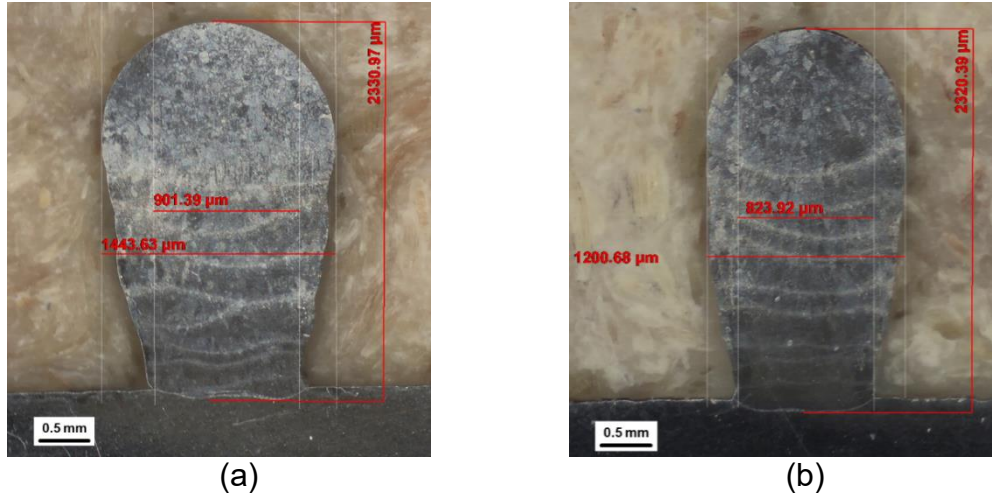


Figure 4-34 Images of the cross section of (a) wall 4-1, (b) wall 4-2, and the corresponding linear dimensions.

As the width data indicated in Table 4-10, it is possible to build walls with an effective wall width being less than 1.0 mm. However, a 1.0 mm wide effective width was not achieved with this 1.0 mm laser spot. This is mainly because the first layer of the deposition cannot reach 1.0 mm wide.

Table 4-10 Linear dimensions of wall 4-1 and wall 4-2 at the position of sample 1.

Linear dimensions	Wall 4-1	Wall 4-2
Effective width (μm)	901	824
Total width (μm)	1444	1201
Total height (μm)	2331	2320
Average layer height (μm)	233	232

Even if the walls could be built, the overall deposition performance was not acceptable, the process is unstable, and the performance is affected by the plume on every layer all the time (Figure 4-35).

In addition, the wall profile is not constant and uniform within an individual wall, Figure 4-36 (a), (b)) shows the two cross sections that were cut in the same wall at two different positions (positions of samples 1 and 2) as mentioned in the methodology section 3.4.5. A very obvious cross-sectional profile difference is

observed, which indicates that the wall profile stability and uniformity and surface evenness cannot be maintained when using a 1.0 mm laser beam.

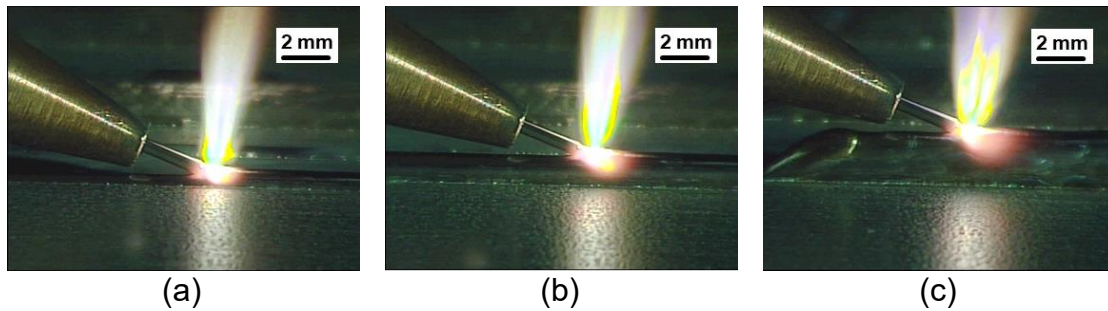


Figure 4-35 Images of strong plumes appearing at the (a) 2nd layer, (b) 5th layer, and (c) 10th layer during wall 4-3 fabrication.

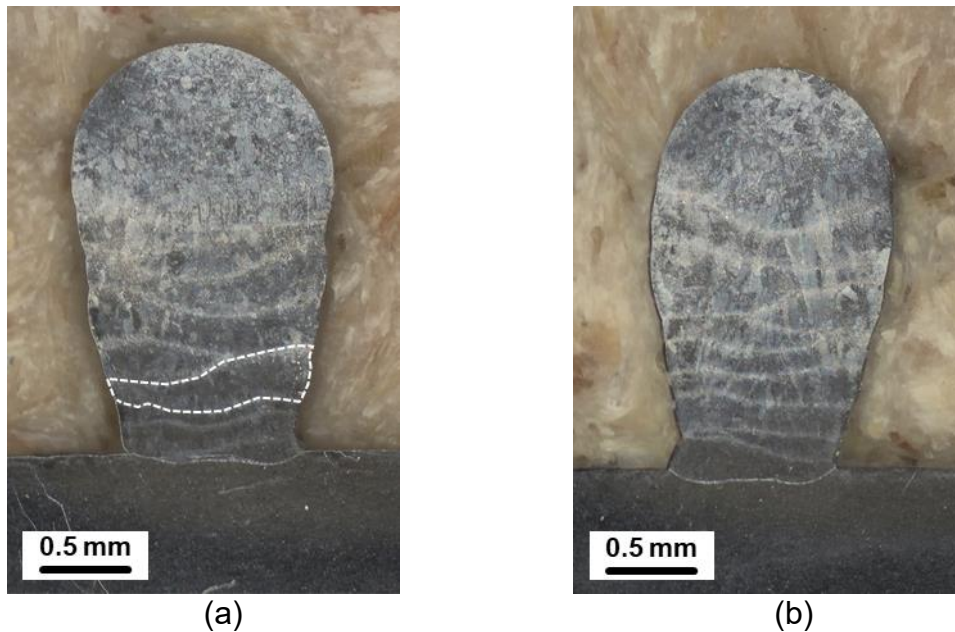


Figure 4-36 Comparison of wall 4-1 cross-section profiles at (a) sample 1, and (b) sample 2 position.

Also, the deposition position relative to the previous layer varies, which causes the deposited layer to accumulate more materials either at the right side (the fourth layer shown in Figure 4-36 (a)) with dashed line enclosure) or on the left side (the fifth layer above the dashed area), as a result, the layer height increment within each layer is not even through the observation of the remelting line. This indicates that the wire position or the position of the molten material that covered the previous layer varies towards different directions during the deposition;

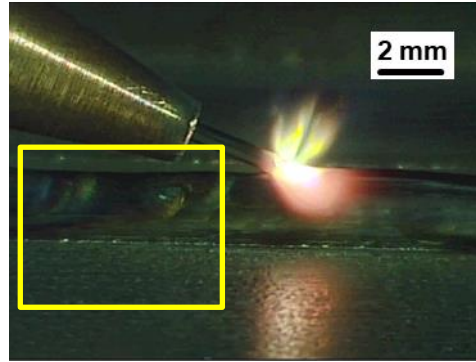
therefore, the deposition stability cannot be maintained when using a 1.0 mm laser beam.

Nevertheless, Table 4-11 shows the effective width, total width and total height for these two cross sections within the Wall 4-1. It can be seen that these values are not stable, but with an acceptable dimensional standard deviation even the cross-section areas in Figure 4-36 indicate that the wall did not exhibit a net-shape profile. This indicates that the target of manufacturing submillimetre-scale walls using a 1.0 mm laser beam can be achieved, but at the cost of machining off more materials from bottom to top, which mainly lies in the narrowest width of the second layer deposition (Du et al., 2019). Considering the cross-sectional profiles varied significantly within the same wall, even if the submillimetre-scale wall can be achieved, it can be concluded that using a 1.0 mm laser beam is not ideal for fabricating submillimetre-scale walls.

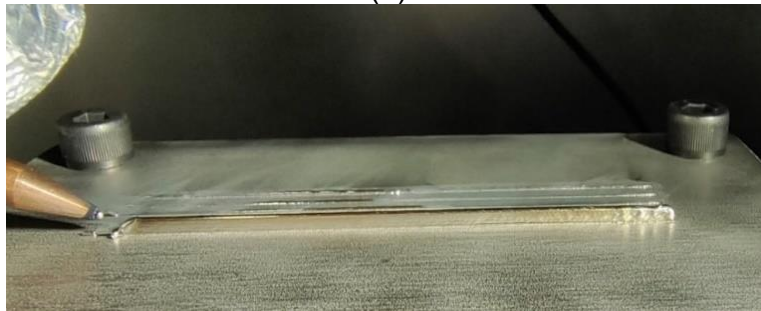
Table 4-11 Linear dimensions of wall 4-1 at the positions of samples 1 and 2.

Linear dimensions (μm)	Wall 4-1 sample 1	Wall 4-1 sample 2	Standard deviation (μm)
Effective width	901	838	45
Total width	1444	1334	78
Total height	2320	2225	67

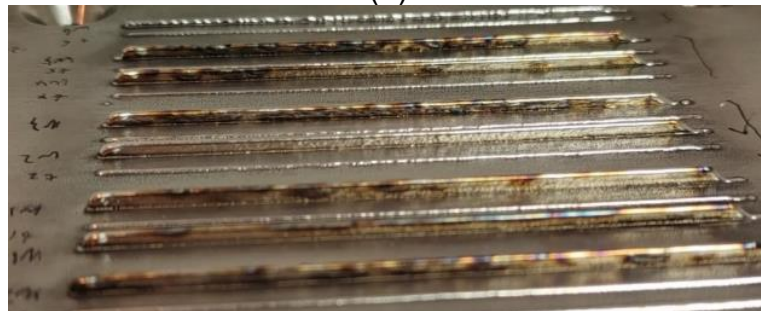
In addition, as seen in Figure 4-37, the oxidation behaviour occurred with rough wall surface conditions appearing (Figure 4-37 (a)) when using the local shielding. And the local shielding effect is not stable, sometimes it works (Figure 4-37 (b)), and sometimes the protection was poor (Figure 4-37 (c)). And poor performance happened more frequently. Therefore, this local shielding device was not efficient, and the protection performance could also be affected by many factors, such as the position of the shroud, the connection between the argon gas flow and the open environment air, etc.



(a)



(b)



(c)

Figure 4-37 Images of (a) oxidation and rough surfaces, (b) good surface protection efficiency of local shielding, and (c) poor and uneven surface protection of local shielding during the wall 4-3 fabrication.

Therefore, considering these poor overall performances, the study using a 1.0 mm laser spot with local shielding was terminated. Also, after fabricating the walls, it can be concluded that this kind of conduction mode bead with plume forming is not favourable for additive manufacturing deposition because the process is extremely unstable. Meanwhile, the vaporisation of the material causes the loss of material.

Thus, achieving the conduction mode deposition with a stable metal melting performance and without a plume appearing should be the ideal conduction regime. In that case, increasing the laser beam size is proposed in the next phase

of experiments, which will reduce the PD and the energy distribution discrepancy along the laser beam, at the same time, increasing the laser irradiation area and the interaction time between the laser beam and the substrate. This may prompt a better bonding between the molten metal and the substrate as well as having a conduction mode regime with no plume appearing.

At the same time, local shielding is not working very efficiently for surface oxidation protection, so changing to a global chamber will be considered.

4.8 Chapter summary

After these two phases of the experiments, the feasibility of using a 1.0 mm laser spot size to achieve submillimetre-scale walls was examined. The main summaries are listed below:

- The results indicated that it is difficult to achieve submillimetre walls with low surface roughness and good process stability.
- Special care needs to be taken to grind the surface of the substrates to avoid inconsistent surface roughness and melt pool width.
- Placing the wire on the substrate surface to conduct the deposition can promote the deposition to succeed by using the surface tension force.
- 1.0 mm laser spot is too small resulting in short IT and high PD, and an even higher p-PD; and a small ratio between the laser spot and the wire diameter (D-ratio, which represents the ratio of laser beam size to wire diameter (Miranda et al., 2008)). These factors cause the ease of plume formation, inadequate applied energy, low wire position tolerance, and high sensitivity to the wire feed rate. Larger beam sizes are required to test the performance.
- Local shielding device within the setup is not working efficiently to protect the wall from oxidation, and maybe the gas flow has an influence on the plume. Thus, global shielding is proposed. (A more reasonable and proper designed local shielding device should also be helpful for the protection, but will not be considered in this thesis)

5 Manufacturing submillimetre wall features using large beams (1.50 mm to 2.50 mm) with global shielding

In the previous chapter, experiments using large laser beam sizes were proposed. Therefore, the feasibility of using 1.5 mm to 2.5 mm large-size laser beams to fabricate submillimetre wall features will be studied and discussed in this chapter.

An updated laser wire deposition system with global shielding was put into use. In the previous chapter, when using a 1.0 mm laser spot size with 250 W of LP, the plume was not very obvious or serious; the PD is 31.83 kW/cm², which can be regarded as a good reference and starting value for this section. Thus, in this chapter, maintain the LP at 500 W for all the experiments (which is the maximum available LP on the current system). The starting laser beam size is from 1.5 mm of the laser spot which corresponds to 28.29 kW/cm² of the PD (close to 31.83 kW/cm² when using a 1.0 mm laser spot with 250 W LP), then gradually increases the beam size to 2.5 mm (corresponds to 10.19 kW/cm² of PD) to first, study if it is possible to eliminate the plume and then to achieve the conduction mode autogenous laser welds with consistent width. Then, study the different factors' influence on the weld width.

Thereafter, investigate the feasibility of bead on plate deposition and whether it is possible to obtain reasonable bonding between the wire and the substrate without defects and no plume interference. Also, explore the process window and analyse the wire positioning sensitivity, D-ratio (ratio of laser beam to wire) tolerance, and the geometrical variations.

Thirdly, to see the feasibility of depositing bead on plate deposits and walls with millimetre to submillimetre-scale width with stable deposition performance using laser beams bigger than 1.0 mm.

5.1 Autogenous laser welds and geometry analysis

Before adding the wire to the process, 90 mm length autogenous laser welds were conducted with 1.5 mm to 2.5 mm laser spots to identify the range of the

processing speed that can create the melt pool, which can give an available speed reference. Another point is to understand how the wire affects the geometry when the wire is added to the process compared with the autogenous laser welds. The experiments started using a 1.5 mm laser beam at 3 mm/s of TS to identify the performance (whether the plume is eliminated, the stability is improved or not) of the autogenous laser weld. Then, the processing speed was increased gradually from 3 mm/s until no melt pool was observed for each laser beam size case.

5.1.1 Identification of the welding performance improvement

In this section, the performance of the autogenous laser welds was examined at a relatively high energy input case to observe whether the issues suffered when using a 1.0 mm laser beam can be eliminated or mitigated when using large-sized laser beams.

A summarised table with weld identification and corresponding parameters is listed in Table 5-1.

Table 5-1 Specific weld identification and parameters of autogenous laser welds for the performance improvement study.

Sample ID	BD (mm)	LP (W)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
5-1	1.50	500	3	28.29	500	250
5-2	1.75	500	3	20.78	583	292
5-3	2.00	500	3	15.91	667	334
5-4	2.25	500	3	12.58	750	375
5-5	2.50	500	3	10.19	833	417

When processing the autogenous laser weld 5-1 at 3 mm/s, 500 W of LP with a 1.50 mm laser beam, as shown in Figure 5-1, the process of the autogenous laser weld was stable and smooth with a stable melt pool maintained during the whole progress (Figure 5-1 (a) – (c)), the width of the autogenous laser weld was consistent and even (Figure 5-1 (d)). Also, no plume and spatter was appearing, but a non-obvious plasma (plasma cloud) forming (unlike a plasma column formed in the previous chapter using a 1.0 mm laser beam, here, plasma cloud is defined as a plasma with a constant profile above the melt pool) on top of the

melt pool during the welding (pointed by the arrow in Figure 5-1(a)) which indicates that all the other tests with either higher processing speed (less energy input) or larger laser beam sizes (less PD) should not have spatters and plume, and the plasma column extent should be reduced because the energy input or the PD is reduced, the phenomenon level should be less than the case with minimum 3 mm/s of processing speed and 1.50 mm of laser beam size.

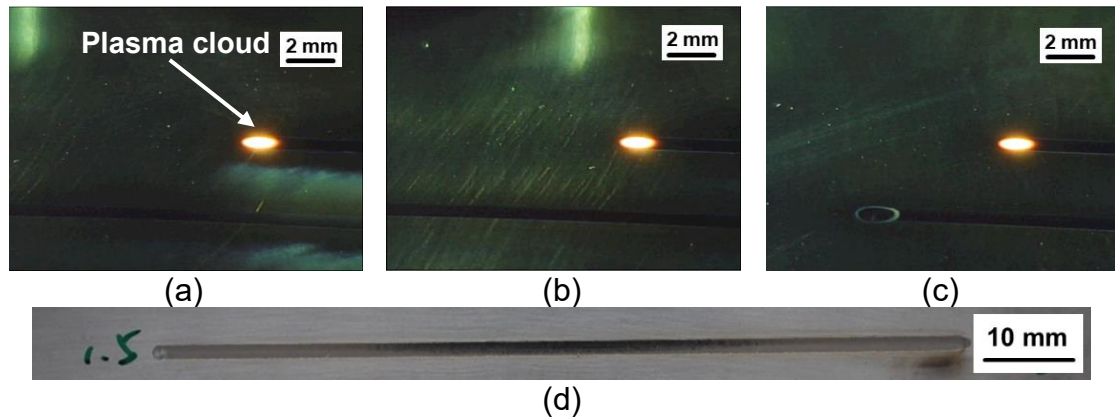
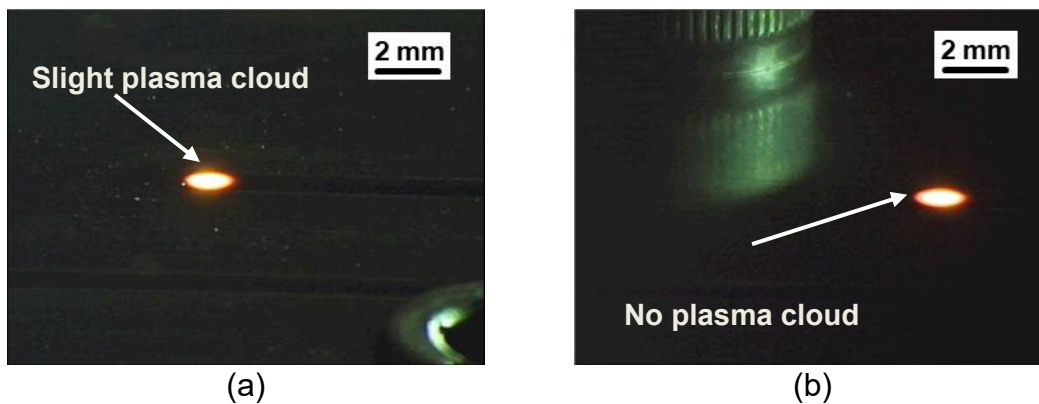


Figure 5-1 Images of plume appearance at the (a) initial, (b) middle, and (c) final welding phases during welding of weld 5-1. (d) Overall top-view appearance of the autogenous laser weld 5-1.

Figure 5-2 (a) and (b) show the melt pool performance of the autogenous laser welds using 1.75 mm and 2.00 mm laser beams with 20.78 kW/cm² (weld 5-2) and 15.91 kW/cm² of PD (weld 5-3). Figure 5-2 (c) and (d) show the melt pool performance of the autogenous laser welds using 2.25 mm and 2.50 mm laser beams with 12.58 kW/cm² (weld 5-4) and 10.19 kW/cm² of PD (weld 5-5), respectively.



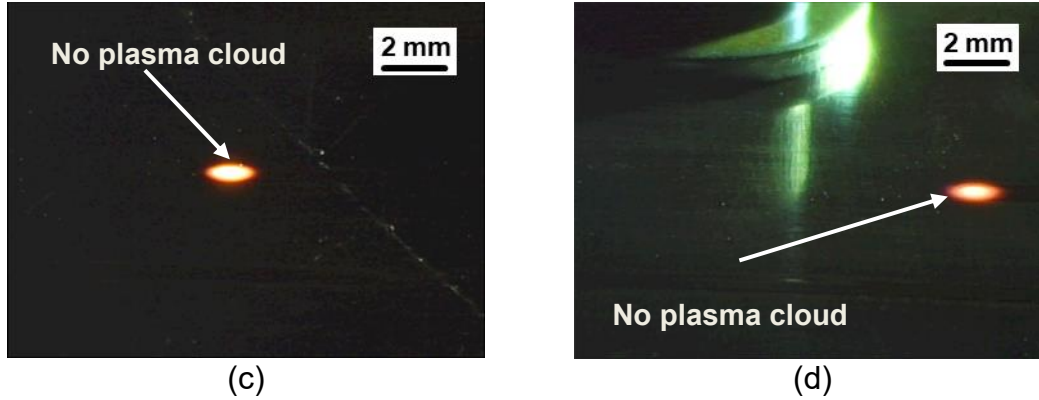


Figure 5-2 Melting pool performance of (a) weld 5-2; (b) weld 5-3; (c) weld 5-4; (d) weld 5-5

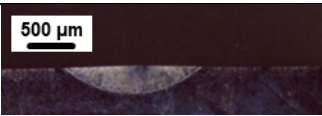
No plume or spatter appeared as well, and the melt pool was very stable. The plasma cloud disappeared as the PD decreased from 20.78 kW/cm^2 to 15.91 kW/cm^2 . Therefore, plume-free, consistent-width autogenous laser welds could be achieved, which shows the potential of achieving a stable deposition performance when introducing the wire to the process. In this case, the plasma cloud is mainly affected by the PD under the same processing speed. However, due to the different IT applied when considering from the same TS perspective. The geometry development trend is not clear, whether the width and depth of penetration are increased due to the longer interaction time and higher E_{sp} or are reduced due to the PD reduction when using larger beam sizes of 1.75 mm (PD: 20.78 kW/cm^2) to 2.50 mm laser beam (PD: 10.19 kW/cm^2) with the minimum 3 mm/s processing speed should be evaluated.

Therefore, the effect of PD and IT (E_{sp}) on geometry was evaluated. Table 5-2 shows the cross-sectional images of the autogenous laser welds at the sample 1 and sample 2 positions, along with their geometry dimensions and the corresponding beam size and FLMIPs. The average geometry of these five welds is also shown in Table 5-2. Figure 5-3 shows the geometry developing trend against the PD, when the PD changes from 28.29 kW/cm^2 to 20.78 kW/cm^2 and to 12.58 kW/cm^2 , the PD is reduced by two times, IT increases from 500 ms to 750 ms, the width does not change significantly through this progress. This is because of the longer IT causing a higher E_{sp} at a larger laser beam, which verifies the E_{sp} compensation effect on width. When the PD continues reducing

to 10.19 kW/cm², the width has an obvious drop trend, which is because the reduction of PD dominates over the IT increment significantly, even the IT increment still exhibits the impact.

In this case, from the width propagation perspective, the longer duration of IT and higher Esp have more effect than the PD reduction within the PD of 28.29 kW/cm² to 12.58 kW/cm² (1.50 mm to 2.25 mm of the laser beam) at 3 mm/s of TS. Starting from 2.50 mm of the laser beam, the PD reduction dominates more on the width propagation. This shows that the IT and PD could have a different regime that dominates the width propagation, respectively, which reveals a possibility of having a competition between PD and IT to achieve the final width.

Table 5-2 Cross-section images of the autogenous laser welds at the sample 1 and sample 2 positions with geometry dimensions and the corresponding beam size and FLMIPs.

	Weld 5-1	Weld 5-2	Weld 5-3	Weld 5-4	Weld 5-5
Position of Sample 1					
Width (μm)	1630	1636	1586	1475	1253
Depth of penetration (μm)	383	512	340	259	167
Position of Sample 2					
Width (μm)	1630	1611	1494	1531	1247
Depth of penetration (μm)	407	500	297	259	161
Average width (μm)	1630	1624	1540	1503	1250
Average depth of penetration (μm)	395	506	318	259	164
Aspect ratio	4.13	3.21	4.84	5.80	9.91
BD (mm)	1.50	1.75	2.00	2.25	2.50
PD (kW/cm ²)	28.29	20.79	15.92	12.58	10.19
IT (ms)	500	583	667	750	833
Esp (J)	250	292	334	375	417

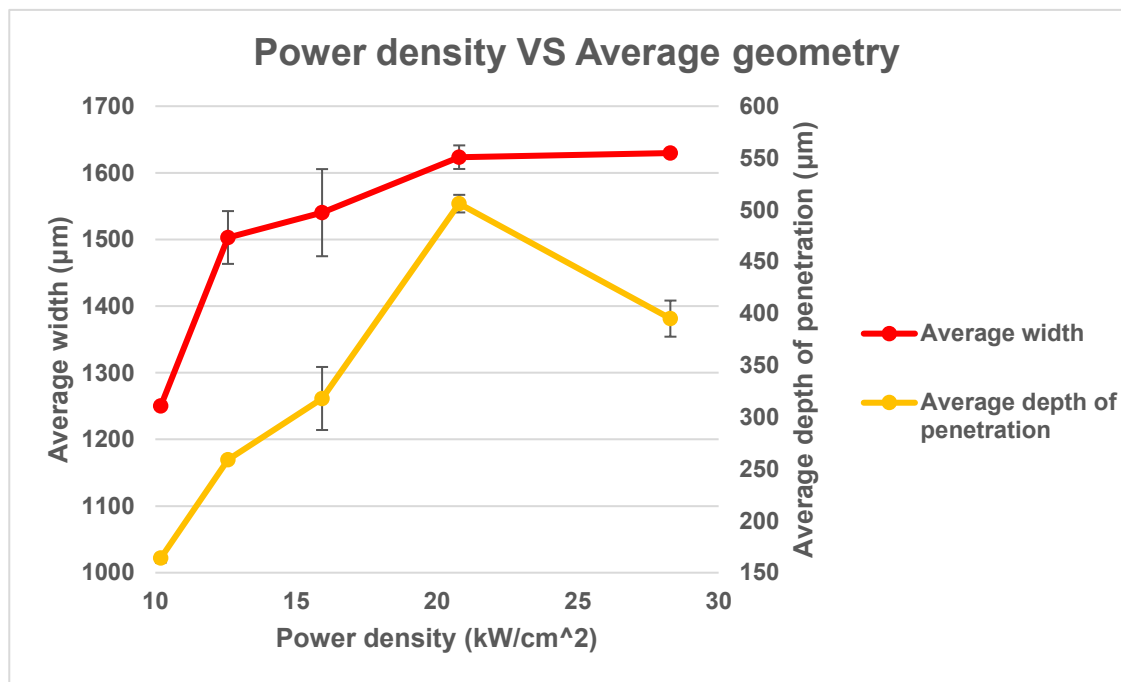


Figure 5-3 Image of PD versus average geometry development trend processed at 3 mm/s of TS.

Moreover, the penetration depth showed a trend of increasing first and then reducing when the PD is reduced accordingly, when using 20.78 kW/cm² of PD (1.75 mm laser beam, weld 5-2), the depth of penetration is deeper than that of using 28.29 kW/cm² of PD (1.50 mm laser beam, weld 5-1). The penetration depth showed a trend of increasing first and then reducing when the PD is reduced accordingly. This should be explained from two aspects. Firstly, when using 1.50 mm of the laser spot with 28.29 kW/cm² of PD, the material below the laser spot, especially the area below the p-PD region experienced the phase of absorbing energy to elevate the temperature from the melting point to the phase just exceeding the vaporizing point, this progress consumed a large portion of the energy, combining the relatively obvious plasma cloud formation (Figure 5-1 (a)) which can also both reflect and absorb part of the energy (Lampa, 1995), therefore the depth of penetration is lower. Secondly, the width of the autogenous laser weld using the 1.50 mm laser beam with 28.29 kW/cm² of PD is wider than the laser beam, on the contrary, when using the 1.75 mm laser beam with 20.78 kW/cm² of PD, the width of the autogenous laser weld is narrower than the laser beam. This caused the 1.50 mm laser beam with 28.29 kW/cm² of PD case to be

more prone to transferring the energy and dissipating the heat, i.e., heat flow, to the cooler adjacent area out of the melt pool region more than the downward region. However, in the 1.75 mm laser beam with 20.78 kW/cm² of PD case, the adjacent area out of the melt pool was still directly under the laser beam irradiation which caused the energy to be more prone to be transferred downward as well as the heat dissipate where has a lower temperature due to the heat transfer principle, this induced a higher energy utilisation rate for 1.75 mm laser beam with 20.78 kW/cm² of PD due to the energy being restricted within the laser beam, therefore, the penetration depth is deeper.

Also, the images and geometry shown in Table 5-2 indicate that the profiles of the autogenous laser welds are within the conduction mode as per the judgement claimed in (Assuncao et al., 2012) and (Abioye et al., 2013), and the surface of the autogenous laser welds was flat with no cracks, porosity or undercut. Thus, the working regime of these five cases could be identified as the conduction mode regime with no plume appearing, which is favourable for the next additive manufacturing deposition investigation. Unlike the case using a 1.00 mm laser spot, the conduction mode profile was still achieved; however, this conduction mode case was accompanied by material vaporisation, which induced plume formation, resulting in energy and material loss.

Overall, a longer IT causes a higher Esp, which can compensate for the PD reduction effect on geometries as the laser beam increases. A higher PD always induces a more obvious plasma cloud phenomenon. High PD with the plasma cloud appearing can absorb off or reflect away the energy, which will influence the energy being transferred downward. Therefore, affects the geometry propagation. In this case, from the author's point, for now, IT and PD, both factors, are critical for the geometrical variation. No individual FLMIPs can always dominate the geometries in the conduction mode working regime; there could be a competition between PD and IT resulting in the width dropping affected by the PD reduction over the IT increases due to the use of a larger laser beam. Therefore, integrating these two parameters is necessary for geometry analysis, this opinion complies with the conclusion that the conduction weld profile is

controlled by the energy density in (Ayoola, 2015), which is the product of PD and IT.

In terms of achieving a 1.00 mm bead-on-plate deposit of the final goal, the widths of these five autogenous laser welds (Table 5-2) are wider than 1.00 mm. In theory, when adding the wire in the process, the wire will absorb the energy from the melt pool. Thus, the width will reduce. Also, when increasing TS to reduce energy input further to investigate the process window boundary at which point could cause the failure, the width will reduce. In this case, these cases with widths wider than 1.0 mm can be regarded as good starting points for process window envelope investigation when the wire is added.

5.1.2 Effect of IT (Esp) on autogenous laser weld width

In this section, the autogenous laser welds were conducted within the laser beam of 1.50 mm to 2.50 mm; the experimental parameters are listed in Table 3-6. The samples of autogenous laser welds were prepared, and the images were processed for dimension measurement based on the procedure claimed in 3.4.5. The width development trend was analysed in detail from the perspective of IT (Esp) (Esp has the same trend due to the same LP used).

A full range of the results of the average laser autogenous weld width against the IT (Esp) at different laser beam sizes and the corresponding PD are shown in Figure 5-4, the logarithmic trendline was chosen to display the trend due to the highest R-squared value achieved.

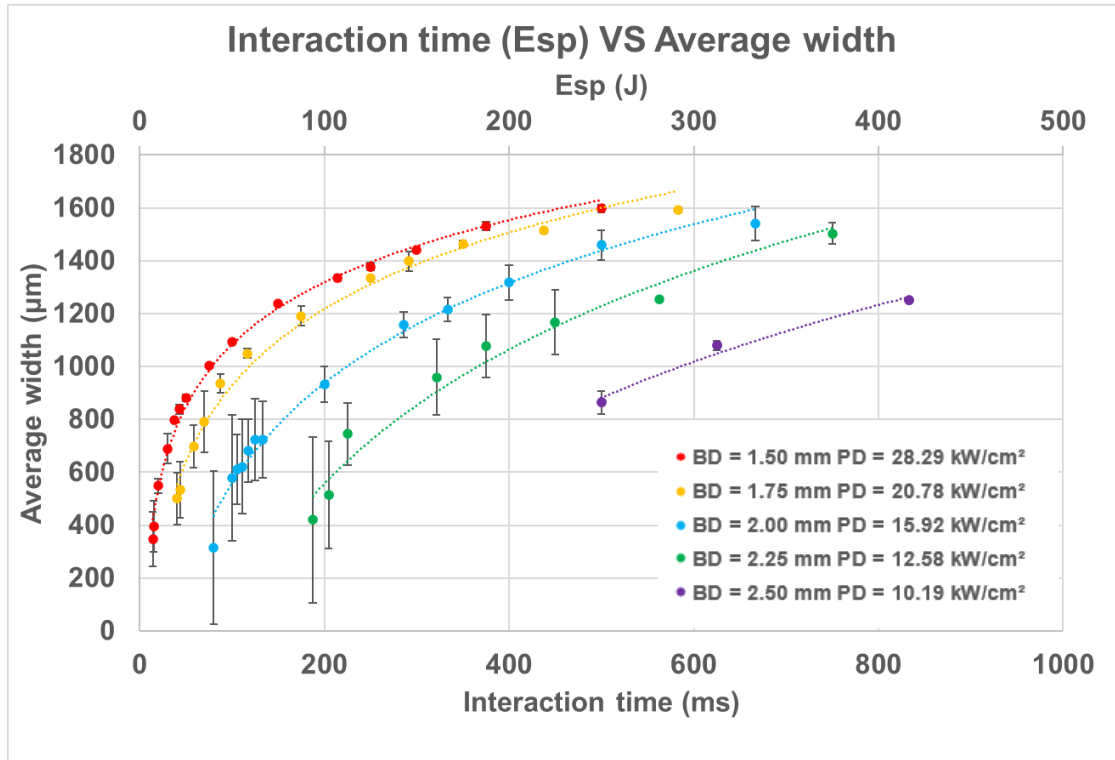


Figure 5-4 Results of IT (Esp) versus average width of the autogenous laser welds at different PD and laser beams.

The results show that the melt pool inception time is longer when increasing the laser beam size; when increasing the IT, the width increment rate is reduced with a converging trend for the beam size ranging from 1.50 mm to 2.25 mm cases. The available IT range of the 2.50 mm laser beam case becomes narrow compared with other laser beam cases. Nevertheless, all five laser beam sizes can achieve the 1.00 mm weld width. This can be explained as follows:

The available melt pool inception time is longer when increasing the laser beam sizes, this can be explained by analysing the converted version surface ED formula (5-1) of the original surface ED formula shown in the formula (2-5).

$$Surface\ ED = PD * (IT) = \frac{LP}{\pi * \left(\frac{BD}{2}\right)^2} * \left(\frac{BD}{TS}\right) = \frac{4LP}{\pi * (BD * TS)} \text{ (J/mm}^2\text{)} \quad (5-1)$$

Where LP represents laser power (W); BD represents beam diameter (mm); and TS represents travel speed (mm/s).

When increasing the laser beam size, the surface ED is reduced. to maintain the same level of surface ED, the processing speed will be lower to have the same amount of energy per unit surface area to interact with the material; thus, increasing the laser beam size, the available processing speed reduces. In this case, the interaction time will be longer for larger beam sizes to form the melt pool.

A steep slope of the width variation when using larger laser beams at the constant IT should be attributed to the flatter, wider, more even energy-distributed, convex Gaussian-type laser beam profile of a larger beam. This is because the width increment or reduction rate should be correlated to the laser beam profile (PD distribution). Once the material below the laser projected area is melted, a larger laser beam can melt and propagate to the adjacent outward material faster due to the flatter and less sharp and steep PD reduction transition profile with less energy discrepancy distribution from the centre of the beam towards outward, as a result, the width propagation will be faster.

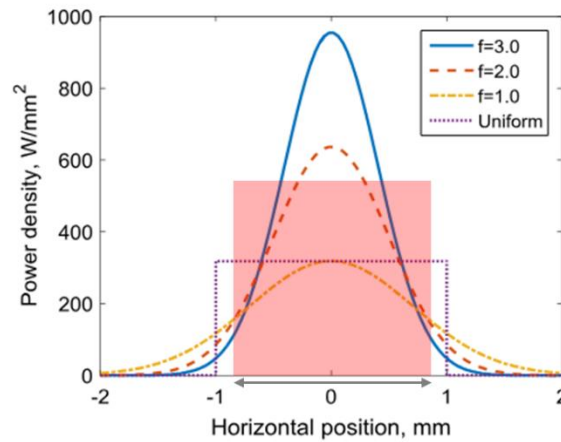


Figure 5-5 Schematic of PD profile at different BD for explaining the width propagation trend for larger BD (schematic is modified based on (DebRoy et al., 2018)).

This explanation can be found in Figure 5-5, for instance, for the blue and yellow beam profile cases, where the height of the red region represents the energy density level and the width represents the current melting width, if more energy is required to propagate the width along the arrow direction, the yellow beam with

a less steep profile can develop the width sideward faster due to the higher PD. This accounts for that the width propagation rate is determined by the laser beam profile.

Meanwhile, at the short IT phase (hereby defined as less than 200 ms), the heat flow is a two-dimensional case with a sideward direction dominating (Figure 5-6 (a)) due to the not enough time dissipating downward (Ayoola, 2015), when the IT continuously increases, the width size is limited by the laser beam size and the corresponding beam profile as well as the available energy to enable the sideward width propagation. In this case, the heat flow is two dimensions with a downward direction dominating (Figure 5-6 (b)) or can be assumed as a one-dimensional downward heat flow (Figure 5-6 (c)) if considering the width propagation has achieved the maximum value (this explanation should neglect the vaporisation and is applied to the conduction mode regime), this helps explain the width increment rate is reduced when increasing the IT under one constant laser beam size with a logarithmic trend.

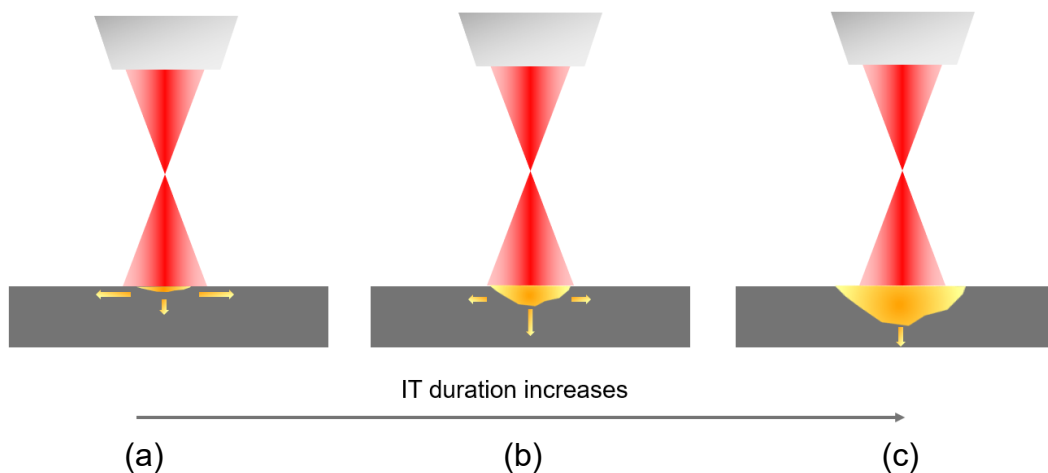


Figure 5-6 Schematic of heat flow dominated direction as the IT duration increases.

A similar 1.0 mm wide autogenous laser deposit width was achieved with the laser beam sizes ranging from 1.50 mm to 2.50 mm with varied IT (Figure 5-4), this reflects that the width is highly dependent on the IT especially when the laser beam size is increased. A larger laser beam size requires a longer IT to interact with the material to incept the melt pool. However, currently, under 500 W of LP, the effective IT range of using the 2.50 mm laser spot that can achieve the

autogenous laser deposit is too narrow due to the low PD even though the 1.00 mm weld width can still be achieved. To see if the width can be extended to a lower level at shorter IT with higher processing speed at 2.50 mm laser beam or larger beams, a higher LP is required.

Figure 5-4 also indicates that except for the 2.50 mm laser spot case, the rest of the four laser beams can achieve a nearly similar width with the width of four laser beam cases either exceeding or equal to the laser beam size of 1.50 mm, this should be related to the balance of the energy applied to the material and the energy dissipated to the surrounding environment. At such a long IT duration, the difference in the laser beam size, the extent of the heat dissipated, and the extent of energy applied on the surface area should be mitigated; therefore, a similar width could be achieved. Even the 2.50 mm laser beam case did not achieve a similar width compared with others; a longer IT will increase the width by compensating for the low-level PD through the increment of Esp.

Also, the width of autogenous laser weld using 1.50 mm is bigger than the laser beam size, this should also be because both the PD and the IT are high, and the energy has enough ability to conduct the heat to the area out of the laser beam size and melt this area, therefore, the final width is the combination of the laser beam size and the thermal conduction loss length (Ayoola et al., 2017), but this thermal loss length should be referred to as the efficient conduction loss that can melt the substrate, which has been excluded from the conduction loss for preheating, convective, radiative and reflected losses from the weld zone (Lampa, 1995), these parts of the thermal losses will not be applied to the width propagation.

5.1.3 Effect of beam size (PD) on width

Due to the same level LP used, the beam size and the corresponding PD effects have an inverse relationship on the width propagation. In this case, the beam size effect is mainly discussed. Figure 5-7 shows the relationship between beam sizes ranging from 1.50 mm to 2.50 mm (PD ranging from 28.29 kW/cm² to 10.19 kW/cm²) and average width at different IT (the average width values are extracted from the trendline shown in Figure 5-4). At the constant IT, a larger beam

diameter always causes a narrower width. The rate of the width variation depends on the IT and the beam size. A long IT causes a slow width reduction but as the laser beam size increases, the reduction rate of the width increases, resulting in a larger width discrepancy.

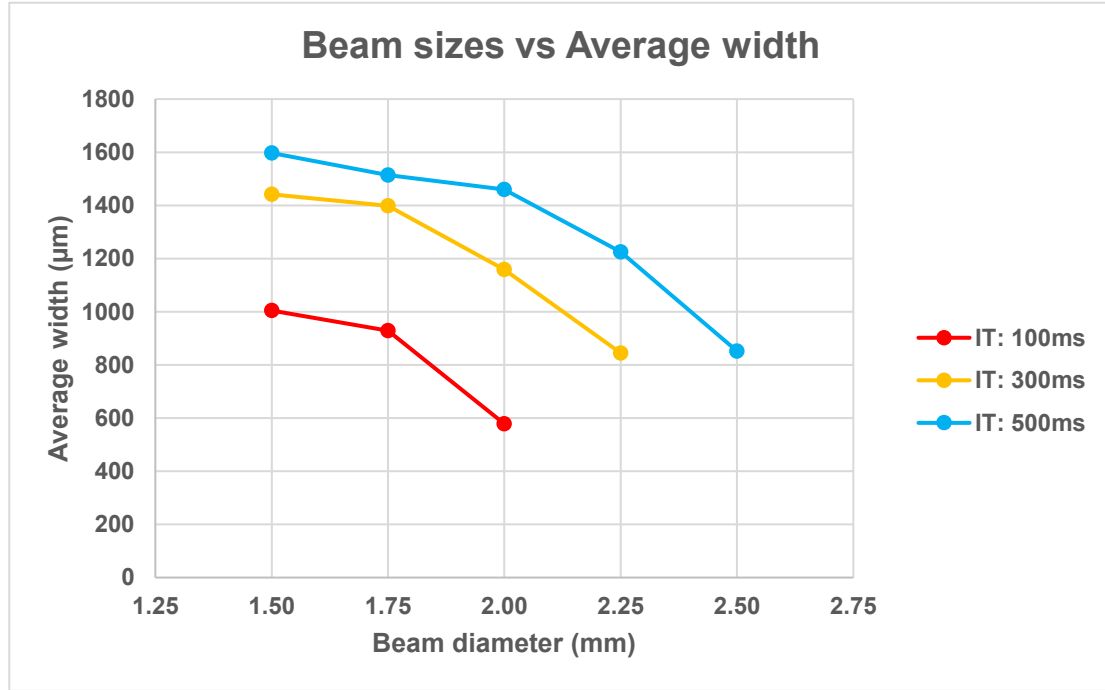


Figure 5-7 Image of BD versus average width at three levels of IT.

These can be explained as follows:

A larger laser beam has a narrower track width when at the constant IT can be explained through IT-based surface ED and PD based on the converted version formula (5-2) of the original surface ED formula (5-2) and PD formula (2-1):

$$IT - based Surface ED = \frac{4 * LP * IT}{\pi * BD^2} (J/mm^2) \quad (5-2)$$

Where IT represents interaction time (s); BD represents the diameter of the laser beam (mm).

As formula (5-2) shows, under the same IT and constant LP, using a larger laser beam size will have less surface ED, thus, having less energy per unit surface area to heat the material, to open the melt pool and melt the surface area compared with the smaller beam size cases. Also, as PD formula (2-1) indicates,

at constant LP, a smaller laser beam size will cause a higher PD, which means that using a smaller beam size, more power will be distributed within the unit area, in other words, completely melting one unit area of the material will take less time when using a smaller laser beam due to the higher amount of power. Therefore, under the same IT, which means that the particle material is irradiated by the laser for the same amount of time, a smaller laser beam size will form a larger melted area, this corresponds to a wider width because of the higher PD present on the particle.

Moreover, the laser beam profile of larger laser beams is flatter with lower p-PD (DebRoy et al., 2018). This resulted in a lower energy profile distribution within the h-PD regime of the laser beam (DebRoy et al., 2018; Stoll et al., 2024), in this case, having a lower amount of energy to enable the melt pool size propagation, thus, the width was narrower than that of the smaller laser beam case.

Figure 5-6 also indicates that the width reduction rate increases as the laser beam increases, and long IT duration can slow down the width reduction rate, this can also be explained by the IT-based surface ED (5-2), at constant IT, as the laser beam size increases, the surface ED presents a reduction by the square of the laser beam size increment. Therefore, the reduction rate increases as the laser beam size increases.

When increasing the IT, the surface ED reduction by the square of the laser beam size increment was mitigated and compensated by the increment of the IT, which caused the width reduction rate to be lower.

Because the extracted value cannot reflect the error bar range, Figure 5-4 is also used to discuss the beam size effect on width with the width variation (error bar range) included. It can be seen that as the beam size increases, generally, the width variation becomes obvious due to the PD reduction. At the short IT regime with the width less than 1.0 mm, it can be seen that the width variation is larger than the longer IT case, and as the beam size increases, the width variation (error bar range) is larger. However, each error bar falls within its own range without interfering or overlapping with other beam size cases when using 0.25 mm as the

beam size interval, which can guide the operator to choose a different laser beam properly, 0.25 mm interval should be good.

Considering the width variation (error bar range) is obvious at short IT regime with the width less than 1.0 mm, using these parameters for building the submillimetre-scale wall is not feasible and stable. Using the parameters that fall in longer IT is ideal. And adopting a varying LP or TS strategy to reduce the wall width size to achieve the submillimetre-scale target is a better choice.

5.1.4 Effect of surface ED and beam size on width

Linear energy density is a one-dimensional energy density formula. Applying this formula to the laser-based DED process cannot accurately reflect the beam size effect. In addition, in this chapter, a constant level of 500 W LP is used; therefore, the EI effect on autogenous laser welds naturally equals the inverse of the TS effect. In this case, the EI effect will not be discussed here. (An analysis based on EI will be spread in the next high-level LP cases chapter).

Surface ED shows the amount of energy radiated on the surface unit area with beam size effect included. The results of surface ED versus the average width at the different sizes of the laser beam are plotted and shown in Figure 5-8. It shows that at the low-level surface ED regime (here, defined as less than 30 J/mm²), a smaller beam causes a wider width under the same ED; when the surface ED is at high level (defined as higher than 70 J/mm²), it shows a trend of a larger laser beam causing a wider width under the same ED (discard the 2.5 mm laser beam case due to the relatively very low-level PD).

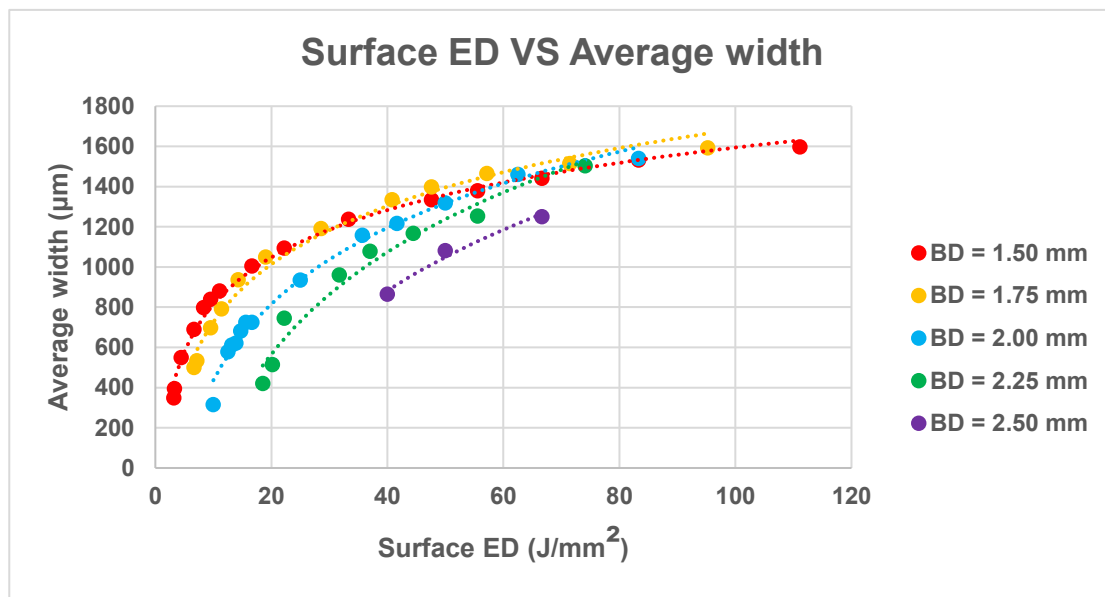


Figure 5-8 Images of surface ED versus average width at different levels of BD.

Figure 5-9 shows the relationship between laser beam size ranging from 1.50 mm to 2.25 mm and average width at different levels of surface ED, which can more clearly reflect that when the surface ED is around 67 J/mm², a very similar width which is around 1500 μm have been achieved under the laser beam sizes ranging from 1.50 mm to 2.25 mm. When the surface ED is less than 67 J/mm² with the width less than 1500 μm, a smaller laser beam has a wider width, but when the ED is more than 67 J/mm², a trend of larger laser beams dominating the width of the autogenous laser welds shows up.

At around 67 J/mm² of surface ED, using a 1.50 mm laser beam, the 1500 μm of the autogenous laser weld width is similar to the laser beam size, this indicates at this level of surface ED, the PD and IT (surface ED is the product of PD and IT) have an ideal thermal effect inducing the width of the autogenous laser weld is controlled by the laser beam size. Above this surface ED value for this 1.5 mm laser beam, the width will be dominated by the beam size and thermal loss length; below it, the width will be dominated by the thermal loss length.

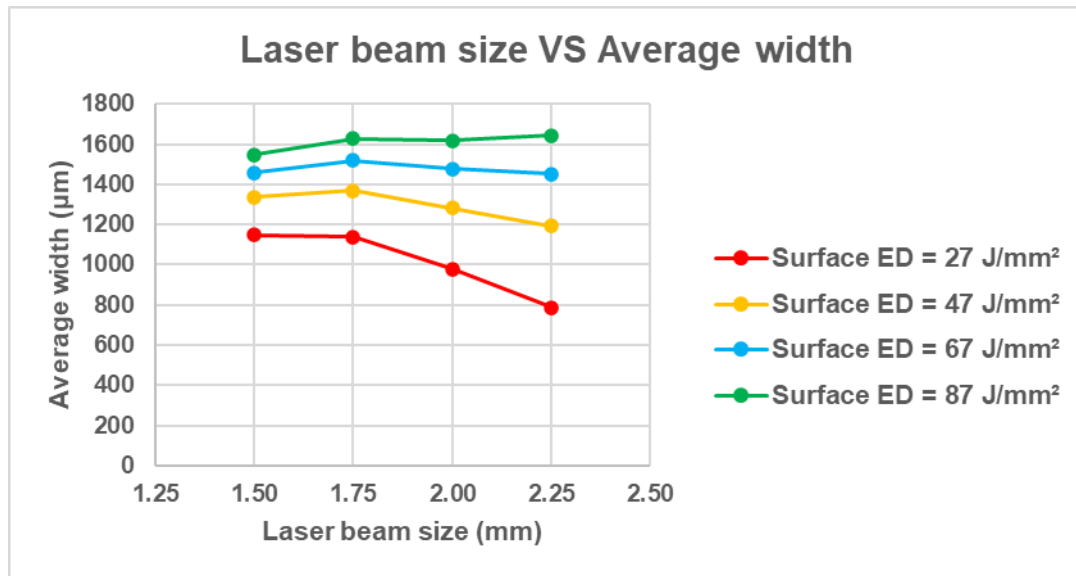


Figure 5-9 Image of BD versus average width at different levels of surface ED.

Therefore, surface ED has two different regimes with either a small size or a large size beam dominating the width for these cases' experiments using 500 W of LP, which can be explained as follows:

At the low surface ED regime, a smaller laser beam will have a larger width at the constant surface ED, this is because, the IT duration in this regime is very short, changing the laser beam size did not change the IT duration significantly, therefore IT can cause minor impact compared with the PD in the conduction regime resulting in PD controls the width more within this regime.

Moreover, actually, the real PD, mainly referred to the p-PD, which is higher than the average PD calculated by the formula, is the main factor that contributes to the PD effect in the short IT conduction mode regime. In this case, resulting in the width is mainly controlled by p-PD at the low surface ED regime. A smaller laser beam has a higher average PD with an even higher p-PD. When the smaller laser beam projects on the material, this p-PD profile can project more power on the unit material area; therefore, more material is melted.

When the surface ED falls in a high-level regime, due to the effect of the long duration of the IT, IT has a critical and dominant impact on the width, resulting in a large beam size causing a wider width. Section 5.1.1 has already claimed that

IT can compensate for the effect of PD reduction (as shown in Table 5-2), and in that case, a similar width has been achieved even though the beam sizes are different. Therefore, a longer IT should have more influence on the width, when the surface ED is high enough due to the longer IT applied, the larger laser beam will dominate the high-level surface ED regime resulting in the larger laser beam causing a wider width.

However, this conclusion can only be applied to 500 W LP with beams from 1.50 mm to 2.25 mm cases currently. Higher levels of LP and beam size should be examined as well, because once the initial surface ED is already high enough, the width control can be dominated by the large beam size, with jumping over the p-PD dominating the width regime already.

5.2 Bead on plate deposition and geometry analysis

In this section, the second phase of the experiments using large-sized laser beams was conducted. 1.50 mm – 2.25 mm of the laser beam sizes were planned to be used with 500 W of LP to investigate the feasibility and the performance of using large-sized laser beams to deposit beads on plate. Based on the experiments made in the previous chapter using the 1.0 mm laser beam, the speed ratio of 1.00 with 5 mm/s of WFS and TS and 1.0 mm of the laser spot size worked better than other cases with less plume appearing. And within the LP of 250 W to 325 W, all the beads and walls could be successfully deposited. Thus, the feasibility of the bead on plate deposition in this second phase of the experiments using large-size laser beams was started using these processing parameters (5 mm/s of the WFS and TS) for the 2.0 mm laser beam and varied slightly for other laser beams. In this case, the surface ED can also be maintained at the same value compared to the case with a 1.0 mm laser beam and 250 W of LP. A low TS also falls in the stable width variation regime, which is favourable for adding the wire.

Once the feasibility had been identified via the preliminary study, the process windows were investigated through the variation of processing parameters and were identified based on the defined performance category, and then the sensitivity of the wire position relative to the laser spot was analysed. Thereafter,

the effects of 1) D-ratio on deposition performance and sensitivity. 2) IT on width; 3) surface ED on the geometrical dimensions of the bead on plate at different levels of BD and WFS were analysed and discussed.

5.2.1 Study of deposition feasibility

The preliminary feasibility of bead on plate deposition has been studied with laser beams ranging from 1.50 mm to 2.25 mm. Table 5-3 lists the parameters and deposit identification.

Table 5-3 Specific deposit identification and parameters for the preliminary deposition feasibility study.

Deposit ID	BD (mm)	LP (W)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)	Surface ED (J/mm ²)
5-4	2.00	500	5	5	15.92	400	200	50
5-5	1.75	500	5	5	20.79	350	175	57
5-6	1.50	500	5	5	28.29	300	150	67
5-7	2.25	500	5	4	12.58	563	281	56
5-8	2.25	500	5	3	12.58	750	375	74

The deposition performance using a 2.0 mm laser spot with 5 mm/s of WFS and TS is shown in Figure 5-10. The initial, middle and final phases of the deposition of an individual bead on a 2.0 mm thick plate performed excellently with no plume and no spatter; the whole progress was smooth and stable.

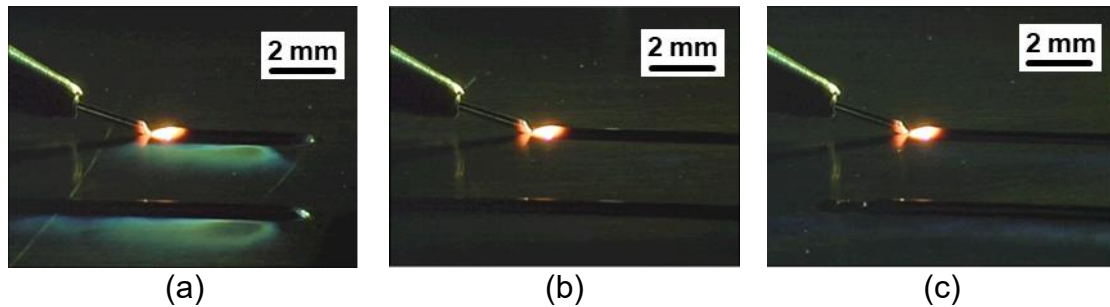


Figure 5-10 Images of the performance at (a) initial, (b) middle, (c) final deposition phases within the individual bead deposition of deposit 5-4.

Figure 5-11 shows the preliminary study results of the top view of the deposits with various processing parameters under different sizes of laser beam. Continuous beads with smooth, shiny surfaces were successfully deposited

within 1.50 mm – 2.00 mm of laser beam sizes. Therefore, further investigation of the process window envelope can be conducted.



Figure 5-11 Images of the overall top view of bead on plate at 1.50 mm to 2.00 mm BD, (a) deposit 5-4, (b) deposit 5-5, and (c) deposit 5-6. (WFS = 5; TS = 5). Unit: mm/s.

When the laser beam size increased to 2.25 mm, the processing speed was reduced from 5 mm/s to 3 mm/s – 4 mm/s to test the deposition feasibility due to the lower PD. The overall appearances of the beads are shown in Figure 5-12 (a), and (b), the deposition performance is not as good as the cases using 1.50 mm – 2.00 mm laser beam sizes, but the continuous track still can be achieved under 3 mm/s of the processing speed with some ripples on the surface.

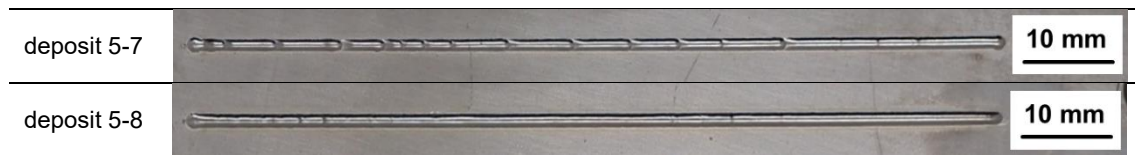


Figure 5-12 Images of the overall top view of bead on plate at 2.25 mm BD, (a) deposit 5-7 (WFS = 5; TS = 4), (b) deposit 5-8 (WFS = 5; TS = 3). Unit: mm/s.

In this case, it proves that bead-on-plate deposits with sound appearance and performance, no plume interference under conduction mode can be achieved using large-size laser beams. A summarised parameter table containing LP, BD, TS, IT, Esp, PD, and surface ED of the experiments that conducted at 1.0 mm laser beam with less plume appearing and large-size laser beams (1.50 mm to 2.25 mm) with no plume appearing cases, which can be used for parameters comparison, are listed in Table 5-4 (The list sequence is the same as the experimental sequence.)

Table 5-4 Summarised deposit identification and parameters for comparison.

Deposit identification	LP (W)	BD (mm)	TS (mm/s)	IT (ms)	Esp (J)	PD (kW/cm ²)	Surface ED (J/mm ²)
4-18	250	1.00	5	200	50	31.83	50
5-4	500	2.00	5	400	200	15.92	50
5-5	500	1.75	5	350	175	20.79	57
5-6	500	1.50	5	300	150	28.29	67
5-8	500	2.25	3	750	375	12.58	74

The plume was removed using 1.50 mm to 2.25 mm larger beam sizes under 500 W LP due to the lower PD applied, especially the lower p-PD. Using 1.50 mm to 2.25 mm laser beams, the PD range is within 28.29 kW/cm² to 12.58 kW/cm². In the previous chapter, the PD of using a 1.0 mm laser spot with 250 W (deposit 4-18) is 31.83 kW/cm², which is close but slightly higher than the 1.50 mm laser beam case of 28.29 kW/cm² of PD using 500 W (deposit 5-6), the PD does not have an obvious discrepancy, and both the Esp, surface ED are less than the 1.50 mm large laser beam case. But the plume in the 1.0 mm laser beam case is more obvious, which addresses the importance of the p-PD in causing the plume.

Also, the surface ED of using a 1.0 mm laser beam (deposit 4-18) is the same as the 2.0 mm laser beam case with 500 W of LP (deposit 5-4) as shown in Table 5-4, but the performance is different; using a 2.0 mm laser beam has better stability with no plume observed, which should be attributed to a longer IT, higher Esp, but less PD. This addresses the balance between a longer IT, higher Esp, and less unevenly distributed PD for prompting a stable deposition performance.

Therefore, through the comparison, either a similar PD (for deposit 4-18 and deposit 5-6) or the same surface ED (for deposit 4-18 and deposit 5-4) achieved, the results can exhibit an obvious deposition difference in plume formation, process stability, and deposition performance. And even if the PD and ED are similar (deposit 4-18 and deposit 5-6), if the IT and Esp are not enough, a good deposition will not be achieved, which addresses the importance of having enough IT and applied Esp.

Therefore, from the good results achieved using the 1.50 mm to 2.25 mm large-size laser beams at 500 W of LP, it can be verified that the reasons for the failure of using a 1.0 mm laser spot size explained in the previous chapter are correct.

And it can be concluded that it is difficult to use a small-sized 1.0 mm laser beam to achieve ideal and stable deposition.

On the contrary, using a larger beam size can reduce the discrepancy of the real PD distribution within the beam size with a lower peak intensity (Stoll et al., 2024), and thus, so as the energy distribution within the laser spot, this can reduce the possibility of vaporisation and increase the IT with the substrate to have more Esp for opening the stable melt pool as well as the increment of the IT with the wire for prompting a good melting and bonding by having more Esp.

5.2.2 Process window and performance investigation

Due to the feasibility of depositing bead on plate, an investigation of the process window envelope in more detail was conducted under laser beam sizes of 1.50 mm to 2.25 mm. 2.00 mm laser beam cases were fully investigated, then based on the knowledge and information of 2.0 mm laser beam case to reduce the number of experiments on the next beam sizes.

The experimental parameters are listed in Table 3-7. The wire position sensitivity of using a 1.50 mm laser beam was also examined through the repetition of the trials with parameters adjacent to the process window boundary. The diameter ratio factor, D-ratio, was introduced for discussion of the wire position sensitivity and deposition performance. Figure 5-14 to Figure 5-16 show the process window envelope using the laser beam size of 1.50 mm, 2.00 mm, and 2.25 mm, respectively, with some representative bead images attached and placed in the vicinity of the corresponding trial points. The categories of different deposition performances are defined as follows in Table 5-5:

The process windows with good performance were addressed by the green area in Figure 5-14 to Figure 5-16. For the 1.50 mm laser beam cases, for instance, WFS equals 13 mm/s, TS equals 3 mm/s case (as the light green circle shown in Figure 5-14) was classified as the continuous track but with imperfection due to the high amount of WFS resulting in a steep contact angle, which is close to 90° (image of cross section in Figure 5-14) and some lack-of-fusion defects appearing between the substrate and the melted material.

Table 5-5 Definitions of deposition performance categories for 500 W LP cases.

Symbol	Category	Descriptions	Image examples
●	Good	Stable and continuous tracks with smooth surfaces, no plume formation	
●	Fair	Continuous tracks but with imperfections	
●	Poor	Irregular tracks with bad surface texture	
✗	Failed	Discontinuous beads, wire dripping, wire stubbing	

For the 2.00 mm laser beam cases, there is a point where WFS equals 10 mm/s, and TS equals 9 mm/s (red circle shown in Figure 5-15). Many attempts of the deposition either on the same substrate or a different one were conducted, but it was hard to succeed; this should be attributed to the point falling adjacent to the boundary of failure.

For the 2.25 mm laser beam case, the case with 4 mm/s of WFS, and 3 mm/s of TS (light green circle shown in Figure 5-16) was classified as a continuous track but with imperfection because the discontinuity appeared on the bead surface (Figure 5-13) which should be attributed to the lack of enough PD and energy, therefore, a low temperature causes the viscosity to be higher (Ebrahimi et al., 2022) resulting in the difficulty of detaching from the wire tip.

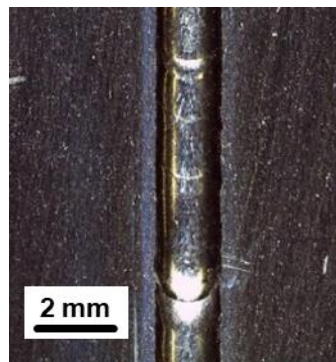


Figure 5-13 Discontinuity bead formation at 2.25 mm laser beam case.

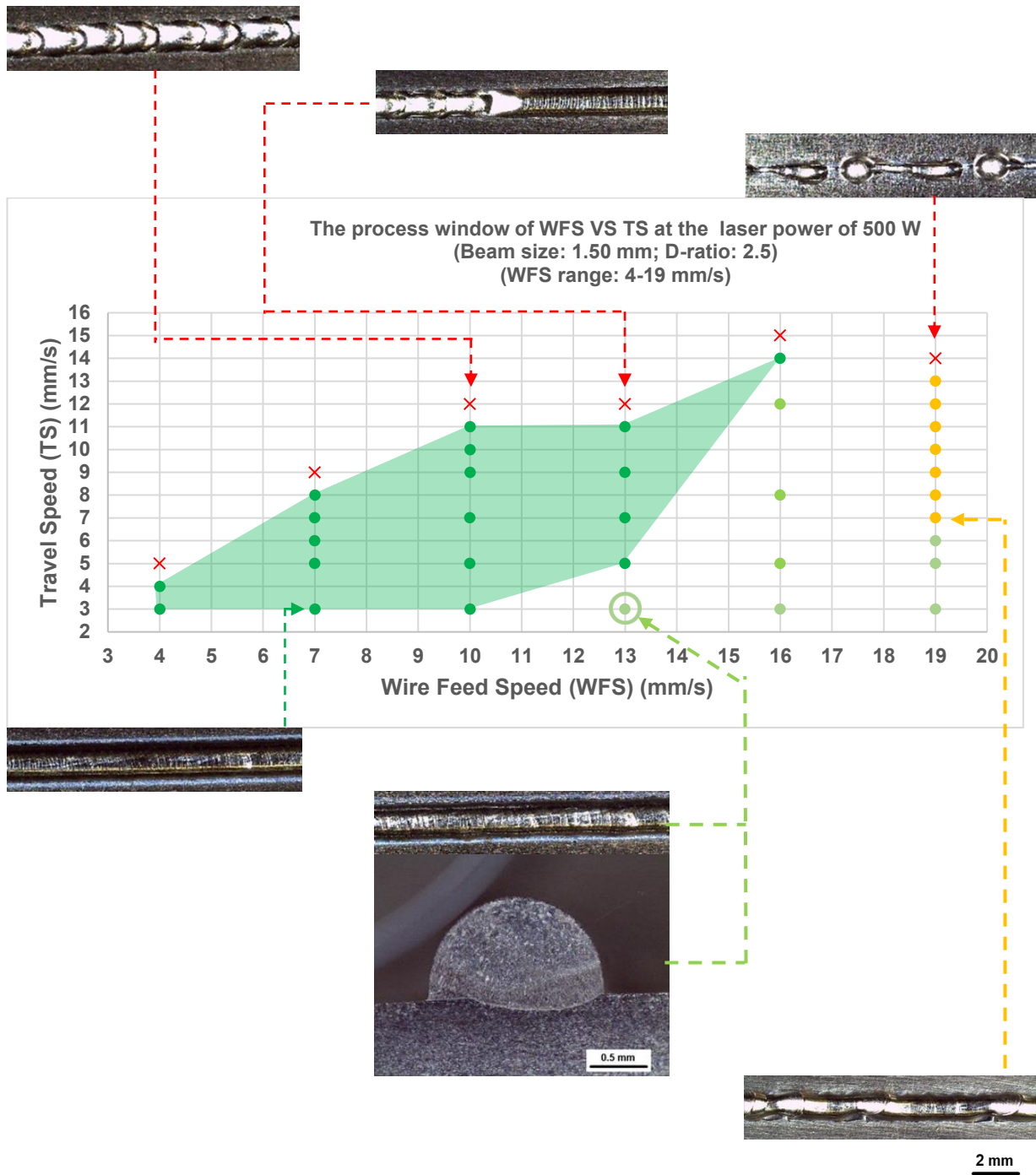


Figure 5-14 Process window of using a 1.50 mm BD.

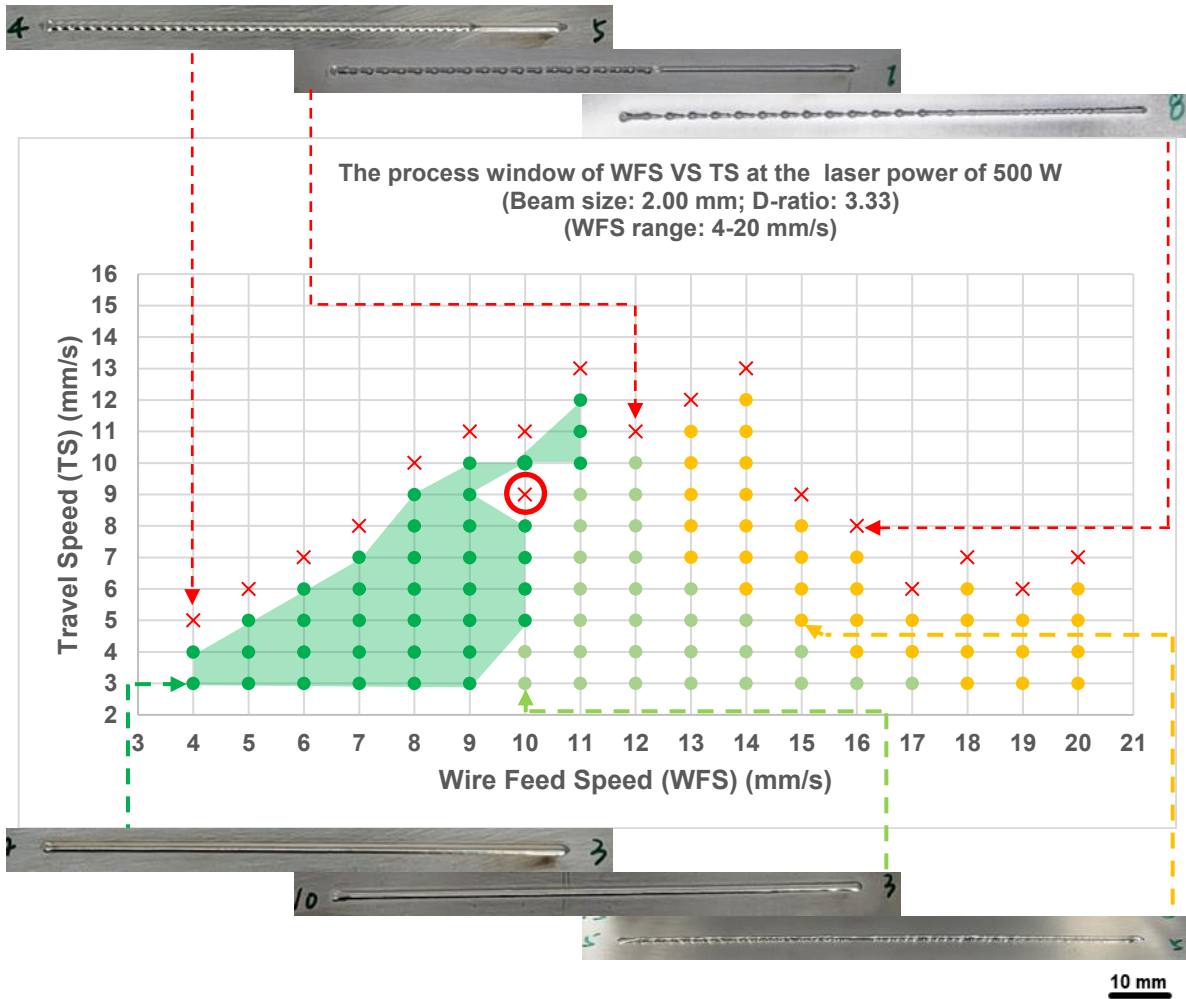


Figure 5-15 Process window of using a 2.00 mm BD.

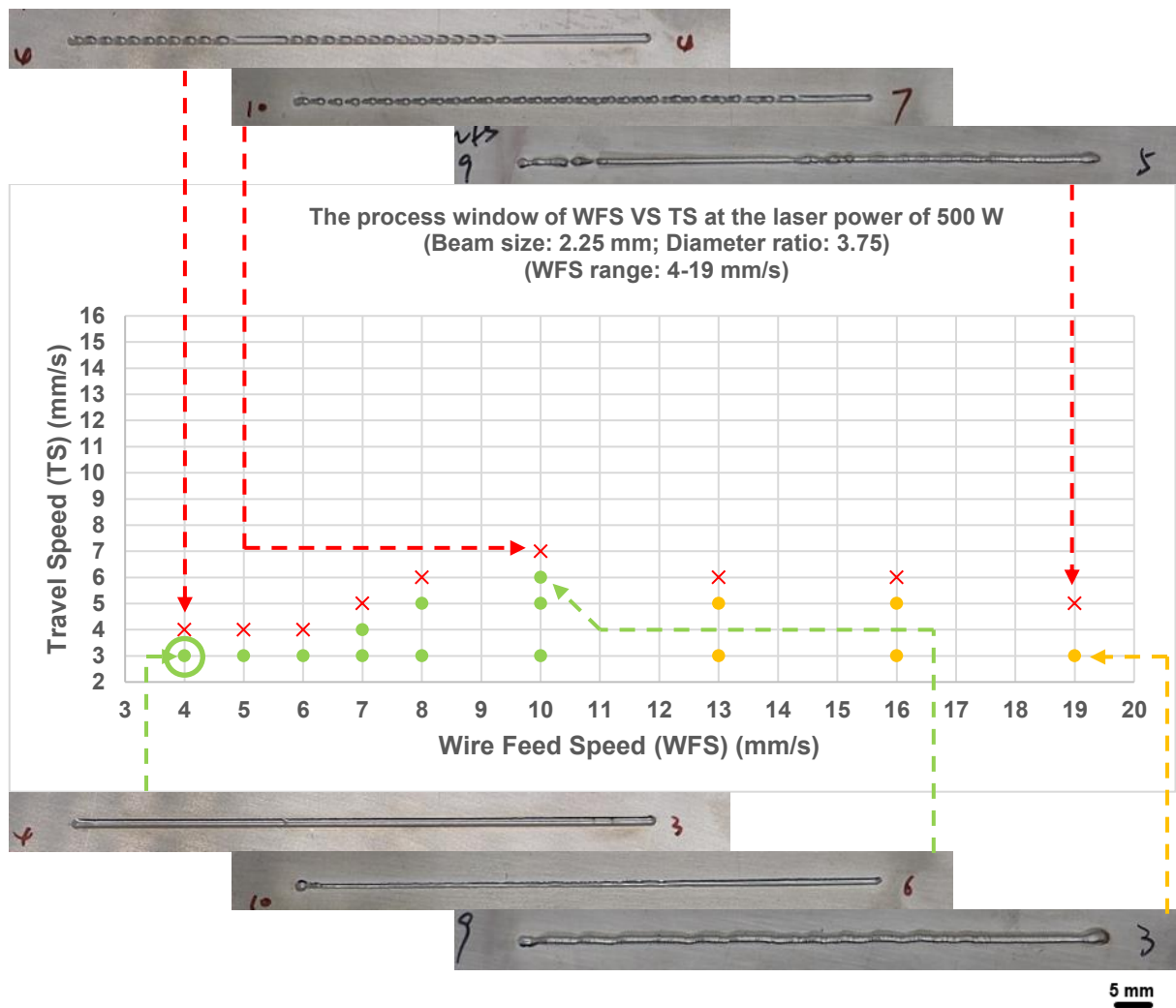


Figure 5-16 Process window of using a 2.25 mm BD.

The results of the process window map show that when the stable, smooth deposition process was achieved using a constant 500 W of LP, a smaller laser beam size could achieve a larger process window envelope, the main difference is that a smaller 1.50 mm laser spot can accommodate higher WFS; from the TS regards, there are not too many differences, 1.50 mm laser spot could have a slightly higher, generally just one figure higher feasible TS under the same WFS regime. When using the 2.00 mm of the laser beam, the WFS boundary with good deposition performance is around 10 mm/s – 11 mm/s (Figure 5-15). When using the 1.50 mm laser beam, good deposition performance was achieved with up to 16 mm/s of WFS (Figure 5-14).

A larger process window was achieved at the 1.50 mm laser beam size that is because a smaller laser beam can process faster to have the same level of surface ED applied on the wire and substrate. However, when the laser beam size increased to 2.25 mm (Figure 5-16), even though a continuous and fair performed bead can be achieved at a slow TS, due to the 2.25 mm laser spot cannot provide enough PD and surface ED at a faster TS to support good deposition performance. Therefore, the process window of the 2.25 mm laser spot case is narrowed down.

Figure 5-17 (a)-(d) show several macro images of the cross-section of the deposits and top view of the beads using a 2.00 mm laser spot around the process window boundary that possesses good deposition performance (WFS ranges from 4-9 mm/s).

The cross-section images indicate that there are no obvious defects, pores in the deposits, the surface of the beads is shiny and smooth with a good wetting behaviour, and no undercut is observed at the edge of the bead. The contact angles are around the range of 31° to 67°, which is within the acceptable range for additive manufacturing (Bailey et al., 2022). The dilution ranges from 9% to 45%. All these four cases' aspect ratios exhibit a conduction mode profile (Assuncao et al., 2012) and (Abioye et al., 2013).

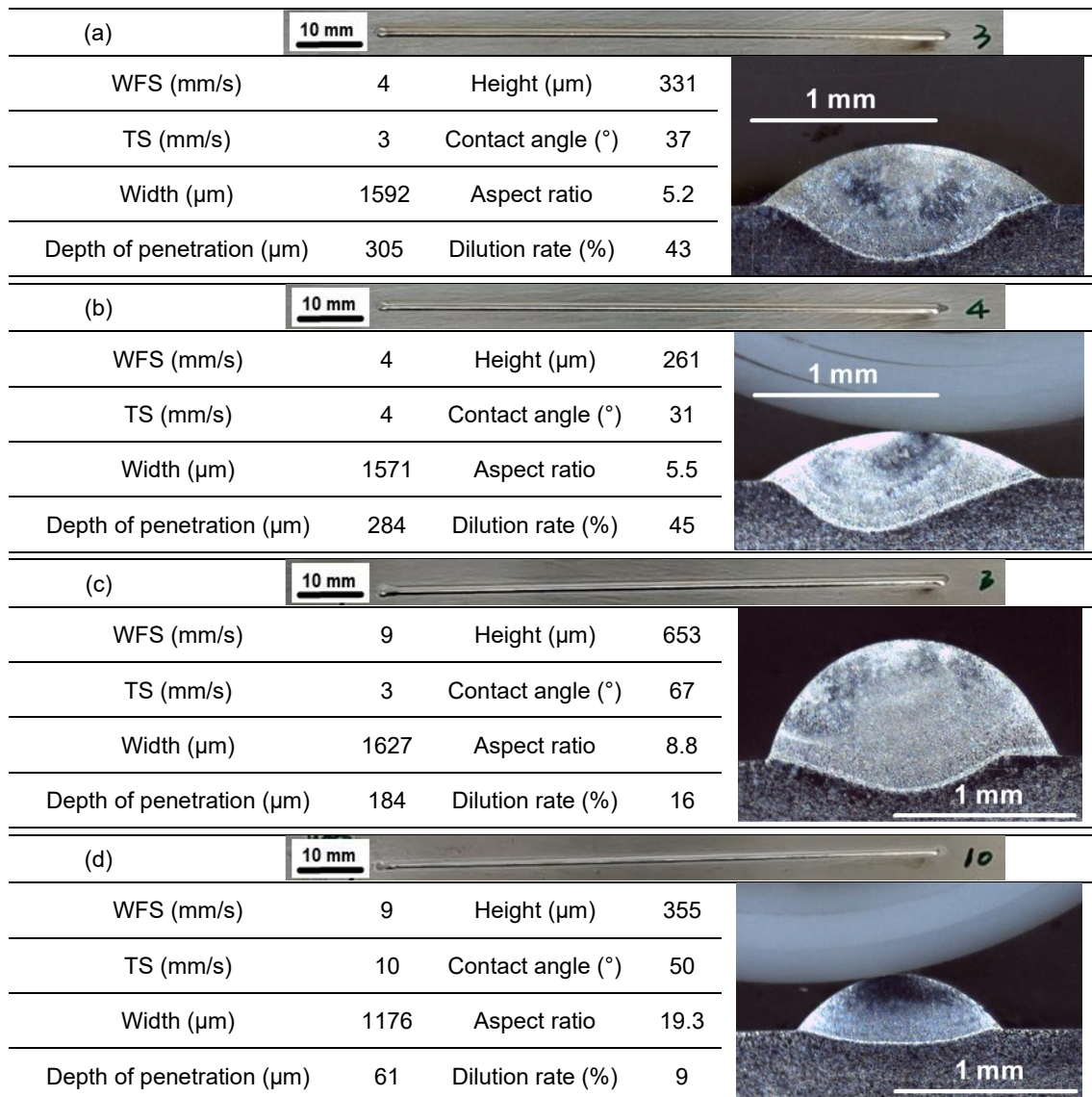


Figure 5-17 Geometries of bead on plate adjacent to the boundary within good performance at 2.00 mm of BD cases.

Figure 5-18 (a)-(f) show several macro images of the cross-section of the deposits and top view images using a 1.50 mm laser beam around the process window boundary that have good deposition performance (WFS ranges from 4-16 mm/s). As shown in all figures above, the deposits are straight with smooth, shiny surfaces, no obvious pores or other defects were detected. The contact angles are within the range of 31° to 74°. The dilution ranges from 5% to 45%. The aspect ratios of the deposits indicate that all the good trials are conducted within the conduction regime as well.

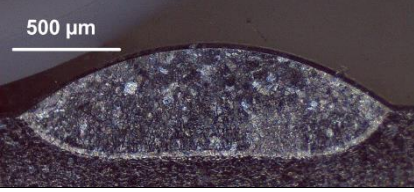
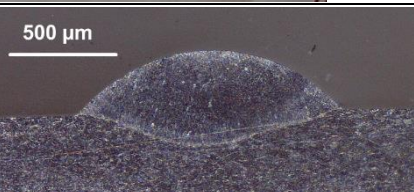
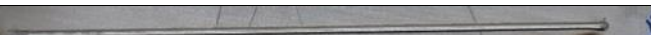
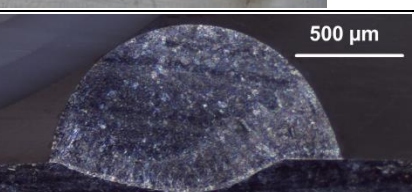
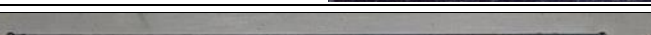
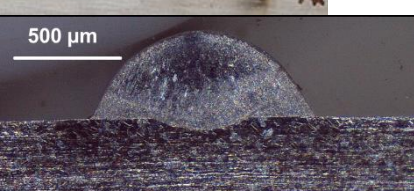
(a)			
WFS (mm/s)	4	Height (μm)	308
TS (mm/s)	3	Contact angle (°)	33
Width (μm)	1745	Aspect ratio	9.0
Depth of penetration (μm)	194	Dilution rate (%)	44
			
(b)			
WFS (mm/s)	7	Height (μm)	265
TS (mm/s)	8	Contact angle (°)	31
Width (μm)	1371	Aspect ratio	8.4
Depth of penetration (μm)	163	Dilution rate (%)	36
			
(c)			
WFS (mm/s)	10	Height (μm)	284
TS (mm/s)	11	Contact angle (°)	42
Width (μm)	1235	Aspect ratio	7.44
Depth of penetration (μm)	168	Dilution rate (%)	31
			
(d)			
WFS (mm/s)	13	Height (μm)	630
TS (mm/s)	5	Contact angle (°)	74
Width (μm)	1376	Aspect ratio	9.4
Depth of penetration (μm)	147	Dilution rate (%)	13
			
(e)			
WFS (mm/s)	13	Height (μm)	387
TS (mm/s)	11	Contact angle (°)	54
Width (μm)	1120	Aspect ratio	32.0
Depth of penetration (μm)	35	Dilution rate (%)	5
			
(f)			
WFS (mm/s)	16	Height (μm)	407
TS (mm/s)	14	Contact angle (°)	57
Width (μm)	1046	Aspect ratio	17.4
Depth of penetration (μm)	60	Dilution rate (%)	5
			

Figure 5-18 Geometries of bead on plate adjacent to the boundary within good performance at 1.50 mm of BD cases.

The results of the investigation of wire position sensitivity are shown in Figure 5-19 ((a)-(c)), the beads were conducted on either the same substrate or a

different substrate with the same parameters many times, it was difficult to successfully deposit the continuous bead with good performance which indicates the difficulty of using a 1.50 mm laser spot size to achieve a continuous track by one-stop; the bead with relatively good performance had to be repeated by several times, which indicates the wire position sensitivity relative to the laser spot position is higher when using 1.50 mm laser beam than the larger laser beam sizes. And the deposition performance using a 1.50 mm laser beam highly depends on the wire position relative to the laser beam. The performance of the bead is easier to swing between success and failure, even if there is a slight wire position deviation. Figure 5-19 ((a)-(c)) exhibit these phenomena when conducting the deposition with 16 mm/s of the WFS, and 12 mm/s of the TS, the case of which is located adjacent to the boundary of deposits with good and fair performance. Three trials were tested; however, three trials showed absolutely different deposition performances.

For the first trial, the trial failed with the molten metal deviating towards one side (Figure 5-19 (a)), the second trial was partially good, partially with some lack-of-fusion defect formation (Figure 5-19 (b)) which indicates that using a 1.50 mm laser beam to do the deposition, the process is also sensitive to the temporal deposition progress when the deposition process is adjacent to the process window boundary.

The third trial succeeded with a relatively good performance to some extent (Figure 5-19 (c)). The second and the third trials were conducted continuously on the same substrate; thus, the wire position relative to the laser spot is maintained in the same position theoretically, but one trial succeeded, and one trial failed; this phenomenon excluded the factor of laser beam and wire position misalignment caused in the preparation phase. Figure 5-19 (c) left image indicates the penetration was perfectly falling in the middle; therefore, the wire should accurately align in the middle position relative to the laser beam, however, the failed second trial showed the process was still sensitive and fragile to the failure. In this case, the failure reasons could be summarized as follows:

Firstly, the processing parameters naturally fell adjacent to the process window boundaries, which increased the possibility of process failure. A 1.50 mm laser beam had less tolerance space for the 0.6 mm in diameter wire deviation, which increased the possibility of process failure further.

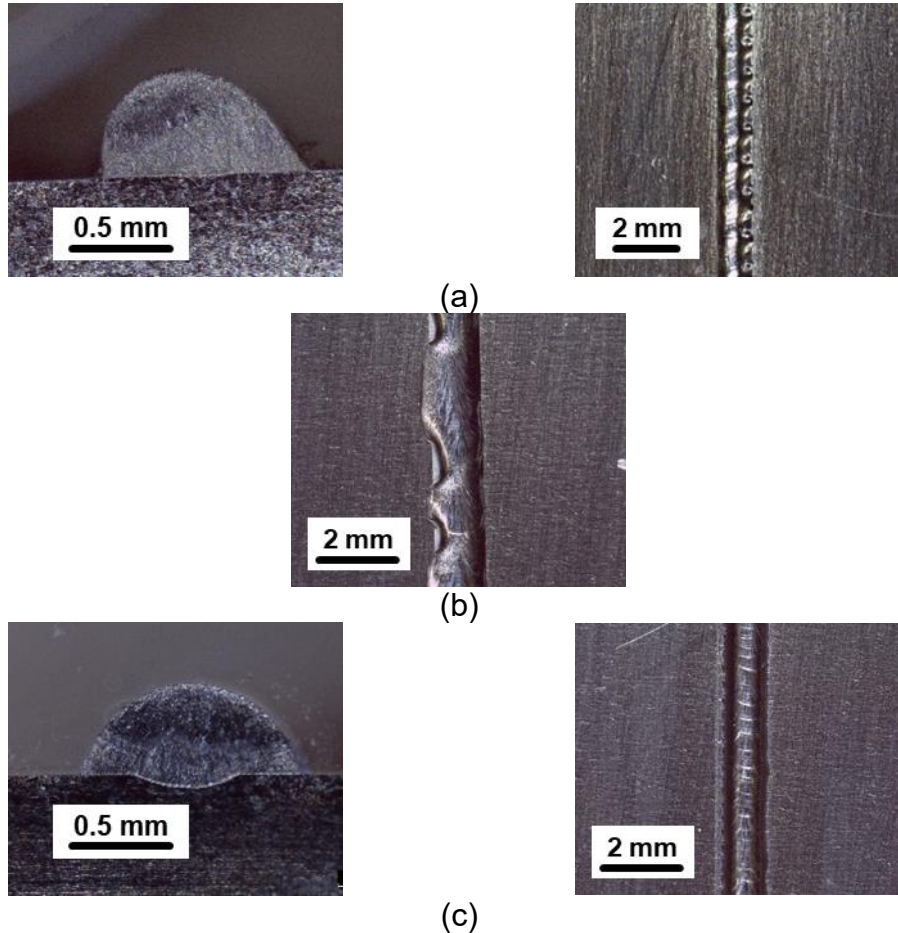


Figure 5-19 Images of bead on plate of 1.50 mm of BD cases for wire position sensitivity investigation, (a) first trial, (b) second trial, (c) third trial.

Secondly, the processing speed was relatively fast resulting in the applied energy being low, which increased the possibility of creating defects, forming not fully melted wire, and then poor bead appearance.

Thirdly, if the wire tip is slightly bent, which will cause the wire to deviate slightly from its original position, where it has already been aligned, this deviation could induce uneven wire melting, therefore, the possibility of partial melting is increased. When the WFS is high, the partially melted wire cannot break the

bridging; therefore, a continuous bead but with poor surface condition is formed, as the Figure 5-19 (a) case shows.

Since large-size laser beams ranging from 1.50 mm to 2.25 mm were used, the deposition performance was enhanced significantly, the plume was removed due to the PD reduction, IT and Esp increment and reasonably larger h-PD region of laser beam full coverage on the wire surface with less energy distribution discrepancy resulting from the flatter laser beam profile, bead on plate with good performance, smooth, shiny surfaces could be achieved. Using a 1.50 mm laser beam can achieve a larger process window envelope; however, the process, in this case, is more sensitive to the wire tip's initial position as well as deposition progress, especially at the process window boundary region. For bigger beams, the issue of having different results with the same parameters was not experienced. Therefore, the laser beam size plays an incredibly critical role in successfully depositing deposits with no plume formation under the conduction mode regime.

5.2.3 Effect of D-ratio on performance and sensitivity

To quantify the correlation between the laser beam size and the wire diameter, the D-ratio (i.e., laser beam diameter/wire diameter influence) is introduced and discussed in detail. The 1.00 mm small size case discussed in the previous chapter is also added as a comparison to get a comprehensive discussion.

When using 1.00 mm, 1.50 mm, and 2.00 mm of laser spot, the D-ratio corresponds to 1.67, 2.50, and 3.33, respectively. When the D-ratio equals 1.67, assuming the 0.60 mm wire is right in the middle of the 1.00 mm laser spot, there will be 0.20 mm space in theory on each side that can accommodate any lateral movement of the wire, this tolerant space is very narrow, a slight bend of the wire tip caused by the cutting of the wire can cause the wire to misalign with the right laser spot position which can disturb the initial even the whole phase of the deposition. If almost all portion of the laser beam is projected on the wire, there is not much energy being transferred to the substrate to create a melt pool, which will ease the wire deviations and cause the failure. These are the ideal situations. In reality, it is hard to perceive the wire deviation and difficult to align a 0.60 mm

wire right in the middle of a 1.00 mm laser spot perfectly, which will increase the chance of failure.

In addition, the laser beam profile under 1.00 mm has a Gaussian-type profile with a sharper reduction transition adjacent to the laser beam edge compared with larger laser beams, thus, a slight wire deviation can cause the wire to expose under an uneven laser beam profile distribution region which can easily cause the bad performance such as the lack-of-fusion defects or even failure deposition appearing, thus, the process is extremely sensitive to the wire position.

When the D-ratio equals 2.50 (1.50 mm of laser spot), 0.45 mm space on each side can be used to accommodate the wire movement, which is about 75% of the wire diameter size. In this case, as mentioned in the previous section, the process was still sensitive to the wire position and deposition progress especially when the processing parameters were adjacent to the boundary where the process was easy to form imperfections, but from the perspective of deposition performance and the wire position sensitivity, 2.50 of D-ratio performed better than 1.67 significantly.

Furthermore, when increases the D-ratio to 3.33 (2.00 mm of the laser spot), a wider space with theoretically 0.70 mm tolerance space on each side can be used to accommodate the wire deviation, meanwhile, it is easier to align the wire tip relative to the laser spot, and the wire position requirement is not as critical as the cases with smaller ratios of 2.50 and 1.67. The possibility of successfully depositing the smooth beads is higher than in the smaller D-ratio cases. Nevertheless, the process window is relatively smaller compared with the 2.50 of D-ratio case due to the relatively lower PD and surface ED resulting in not enough energy to melt the amount of the wire or substrate properly when using higher WFS or faster TS, but this could be improved by using a higher power laser to compensate the low level of surface ED by increasing the available energy.

Thus, based on the D-ratio performance under 500 W of the LP as well as the first phase experiments with varied LP from 250 W to 325 W, the value starting from 2.50 can be a reference point with the feasibility of good performance deposition, increasing to 3.33 can enhance the process stability, reduce the

process sensitivity and the possibility of deposition failure. Meanwhile, an estimation of 3.00 of the D-ratio (1.80 mm BD) can be a better choice for a more stable deposition regime, which is between the values of 2.50 and 3.33 and can be a compensation between the wire position sensitivity and the process window reduction. And a 0.60 mm tolerance space on each side, which equals the wire diameter, can be used to accommodate the wire deviation. Values below 2.50 should not be used due to difficulties in wire alignment and process sensitivity.

5.2.4 Effect of IT, BD, and WFS on geometry

In this section, the effect of IT on geometry at 1.50 mm and 2.00 mm laser beam diameter cases and at different levels of WFS is discussed; accordingly, the BD and WFS effects are also discussed.

Figure 5-20 shows the average width of bead on plate against the IT at different levels of the WFS using 1.50 mm and 2.00 mm laser beams. The available width range of bead on plate is reduced significantly when introducing the wire in the process, accordingly, the available IT window range is narrowed.

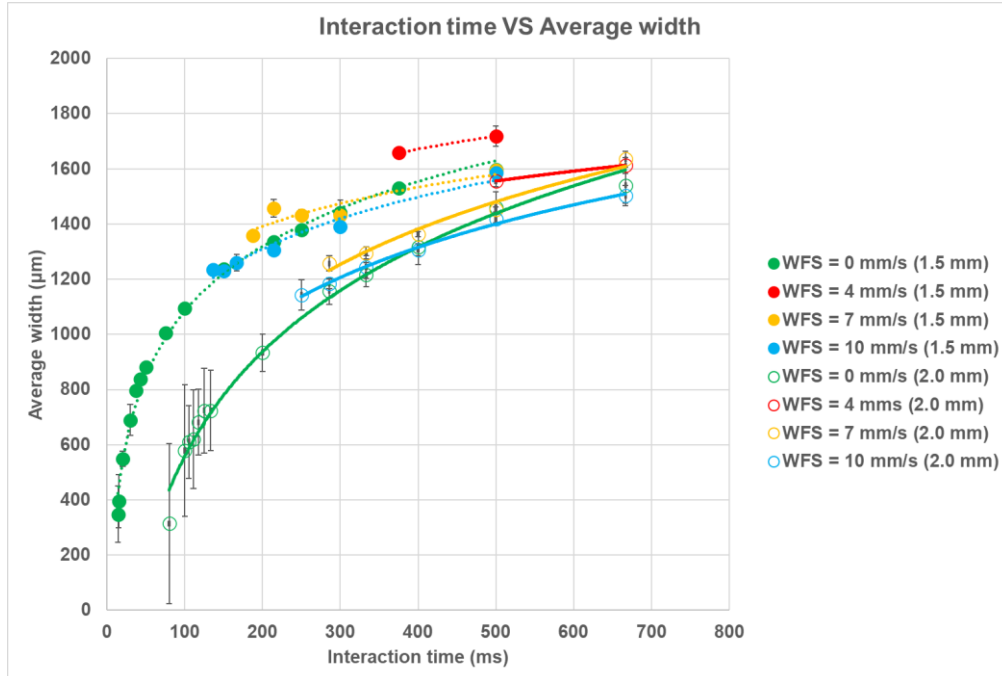


Figure 5-20 Image of IT versus average width at different levels of WFS with 1.50 mm to 2.00 mm BD.

However, the overall width development trend is similar to the autogenous laser welds as the IT increases, i.e., as the IT increases, the width increases, but the width increment rate is reduced, this should also be attributed to the different heat flow dominating directions at short and long IT due to the requirement of time for the heat to conduct from the laser interaction point to the material (Ayoola, 2015).

But adding the wire makes this heat flow more complicated because as seen in Figure 5-20, the width increment rate was reduced further after adding the wire, this should be because at long IT, the TS is low, and then the material input is relatively high resulting in the wire absorbing the energy from the melt pool, which mitigates the width propagation further.

Figure 5-21 indicates the effect of beam size versus width at 500 ms of IT for different WFS cases, the width values are extracted from trend lines shown in Figure 5-25, similar to the autogenous laser weld trend, a smaller laser beam has a wider width under the same IT and WFS, which is because of the higher PD of the smaller laser beam case.

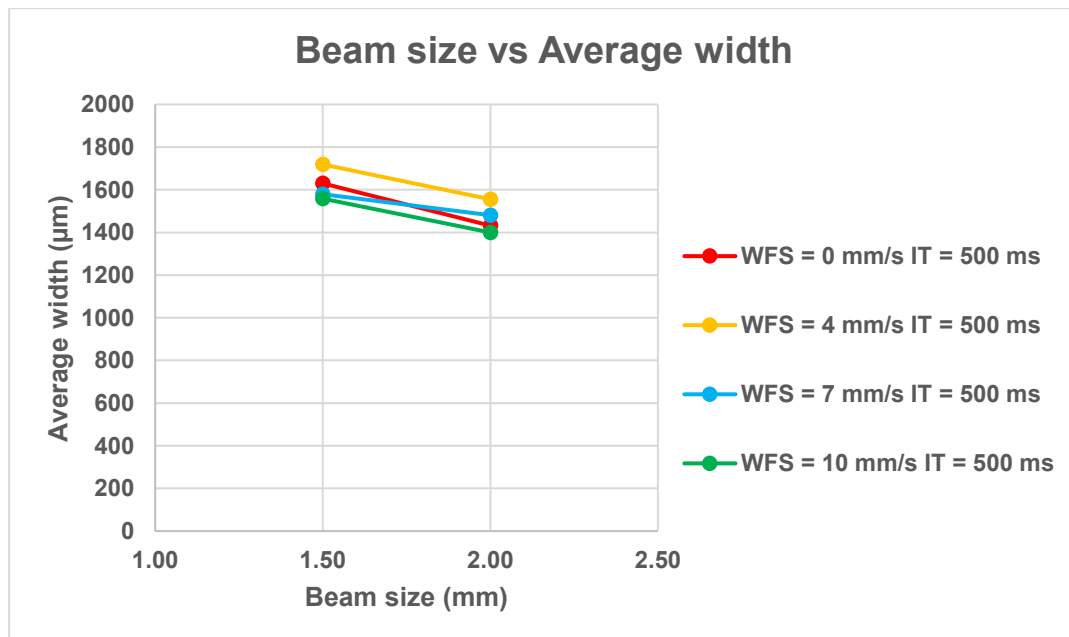


Figure 5-21 Image of BD versus average width at 500 ms of IT with different levels of WFS.

The WFS effect versus width at 1.50 mm and 2.00 mm laser beam cases with different IT is shown in Figure 5-22, the width values are extracted from the trend

lines shown in Figure 5-20 as well, when adding the wire with 4 mm/s of the WFS, the widths in all different IT cases are obviously wider than those of the autogenous laser welds. As the WFS continuously increases, the width reduces. When the WFS increases to 7 mm/s and 10 mm/s, there are still some points where the widths are wider than the autogenous laser welds under the same IT, for example, the 2.00 mm laser beam with 300 ms IT case. This should be attributed to the increase in laser absorption rate of the wire because the wire did not have enough medium to dissipate the heat. Therefore, the wire absorbed the energy from the laser significantly when the wire experienced the laser irradiation and transferred a portion of this amount of energy to the melt pool immediately due to the wire touching the surface of the substrate, resulting in the width propagation further. (A higher laser absorption rate of the wire will be discussed and verified via the melting efficiency in Chapter 6, integrated with the high laser power cases together).

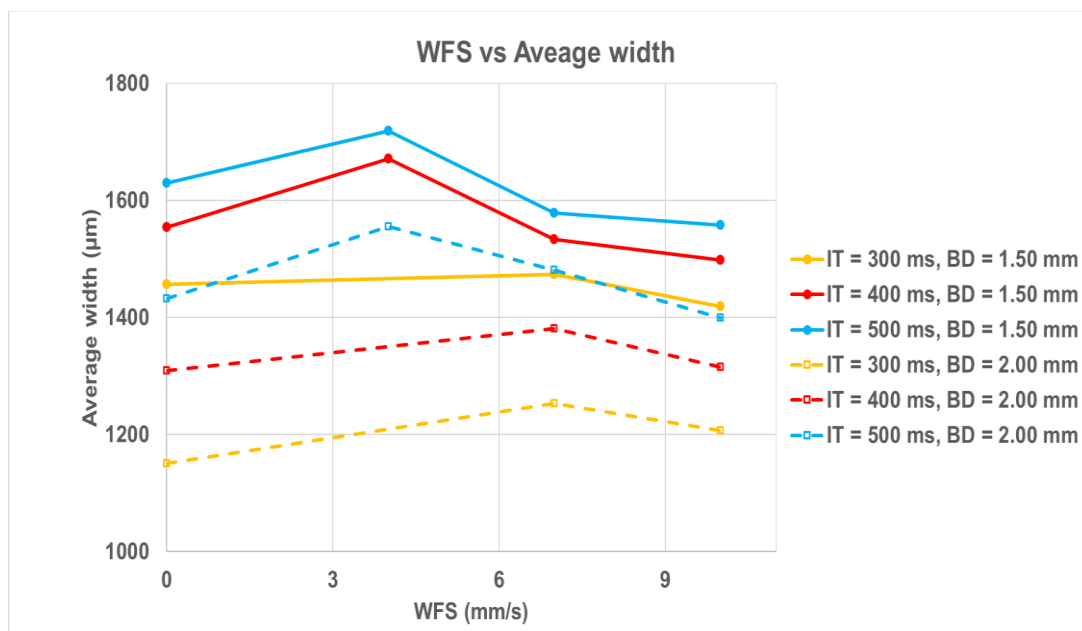


Figure 5-22 Image of WFS versus average width at different levels of IT with 1.50 mm to 2.00 mm BD.

Figure 5-23 shows the relationship of the height of the deposits against the IT at different levels of WFS and two different laser beams. The trends show that as the IT increases, the height increment rate reduces. (Considering the available IT range varies and is small for different WFS and different beam sizes, at some

IT ranges, the beam size effect on height cannot be reflected, for instance, at 200 ms of IT, 10 mm/s of WFS, 2.00 mm laser beam case has no data, therefore, the image of beam size effect on height cannot be plotted from the perspective of beam size effect versus height, only at 500 ms of IT, all points can be included, but this point cannot represent all other IT points, therefore, instead, the beam size effect on height will be discussed through the IT versus height image in Figure 5-23, this method also applies to other factors' study which are related to the beam size effect in the following content).

Regarding the beam size effect (Figure 5-23), under the same IT and WFS, a smaller laser beam has a higher height within the available IT range.

These phenomena can be explained by the formula (5-3) of IT-based material deposited per unit length, also named as the cross-section area of the bead, which is the conversion of the original formula in (Wang et al., 2021):

$$\begin{aligned}
 &IT - \text{based material deposited per unit length} \\
 &= \frac{WFS * IT}{BD} * \text{cross sectional area of the wire (mm}^2\text{)}
 \end{aligned}
 \tag{5-3}$$

Based on the formula (5-3), a smaller laser spot will have a larger cross-sectional area when processing at the same IT and WFS. The area increment should be a two-dimensional situation; therefore, the value of the width and the height should be larger than those of a larger laser spot under the same IT.

Also, when the IT increases at a constant laser beam and WFS case, the cross-sectional area increases, which should also be a two-dimensional increment; the area increment is shared by the width and the height increment simultaneously, thus, the height and width increment rates reduce. This two-dimensional increment as the IT increases can be verified through the observation of the width and height increment, simultaneously shown in Figure 5-20, and Figure 5-23.

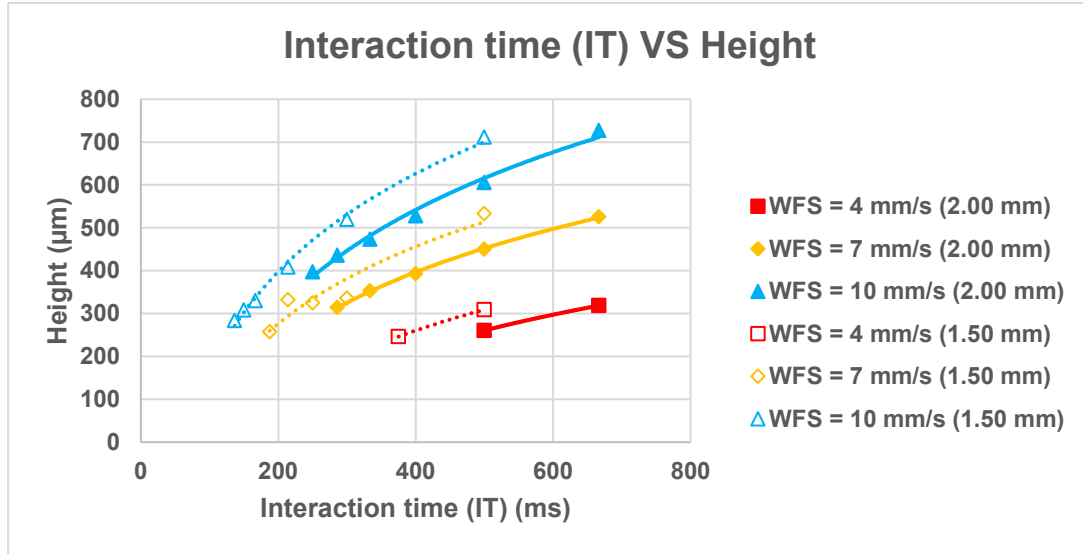


Figure 5-23 Image of IT versus height at different levels of WFS with 1.50 mm to 2.00 mm BD.

Figure 5-24 shows the relationship of IT against the contact angle of the bead. From the beam size perspective, a smaller laser beam has a higher contact angle increment rate, this could be because the energy of a smaller laser beam case is concentrated into a smaller area, which does not allow the material to flow, so the height increases faster than the width resulting in the angle become bigger.

In addition, in the case of the 2.00 mm laser beam with different levels of WFS, most of the trendlines are parallel which means increasing or decreasing the WFS does not influent the contact angle increment rate significantly. This indicates that a 2.00 mm laser beam can maintain a stable contact angle increment rate at different levels of WFS. Increasing WFS, the height of the bead increases; the bead width should increase accordingly to maintain a constant contact angle. This also proves that the area increment is a two-dimensional situation as mentioned in the previous paragraph in this section.

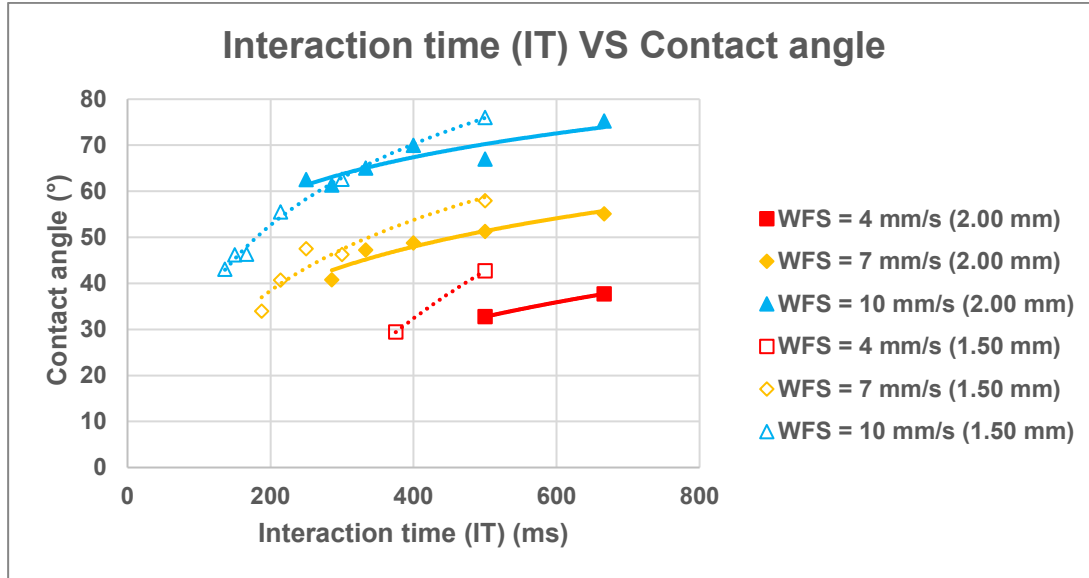


Figure 5-24 Image of IT versus contact angle at different levels of WFS with 1.50 mm to 2.00 mm BD.

Therefore, choosing a 2.00 mm laser beam regardless of the increment of WFS, a constant contact angle increment rate can ensure the bead profile is uniform. In this case, when building multi layers upward, the surface evenness will be better theoretically, which will increase the quality of wall straightness, and avoid deposited material collapse.

5.2.5 Effect of surface ED, BD, and WFS on geometry

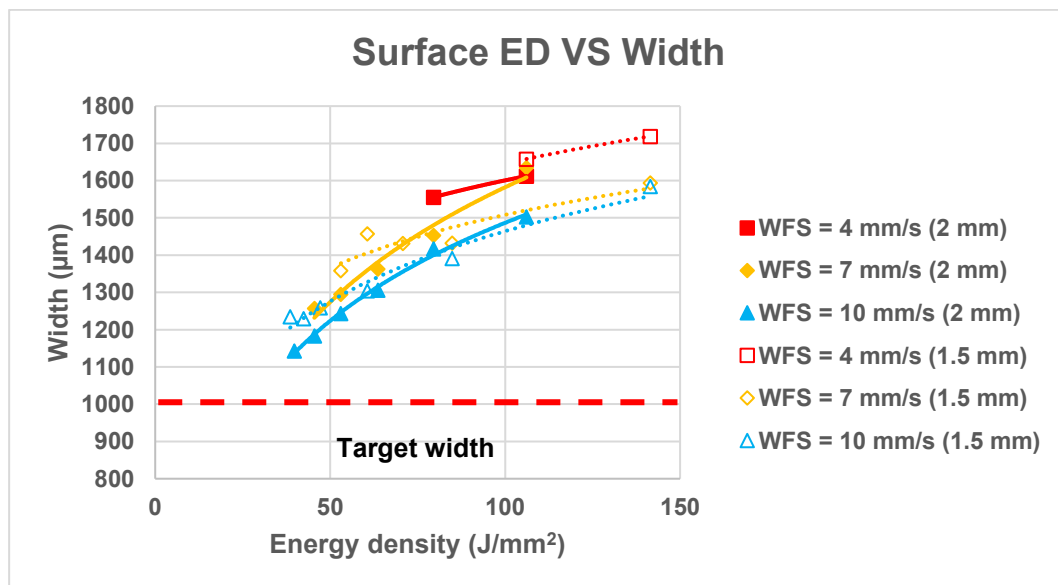
Before adding the wire to the process, surface ED exhibits a critical role in controlling the width, unlike the EI, which is linear energy that can reflect the energy applied on the material along the deposition direction but cannot accurately reflect the beam size effect even though the EI affects the width. Surface ED, however, can combine the linear energy and the laser beam size together to reflect the energy applied to the unit material surface beneath the laser spot, therefore can be more accurate to show the real effect on geometry. The effect of surface ED on geometry is discussed in this section in detail as well as BD and WFS effects.

Figure 5-25 (a), (b) shows the surface ED against the width and height of the bead on plate. Figure 5-25 (a) shows that based on the available width's process window, a 1.0 mm width cannot be achieved, but is very close. Increasing the BD

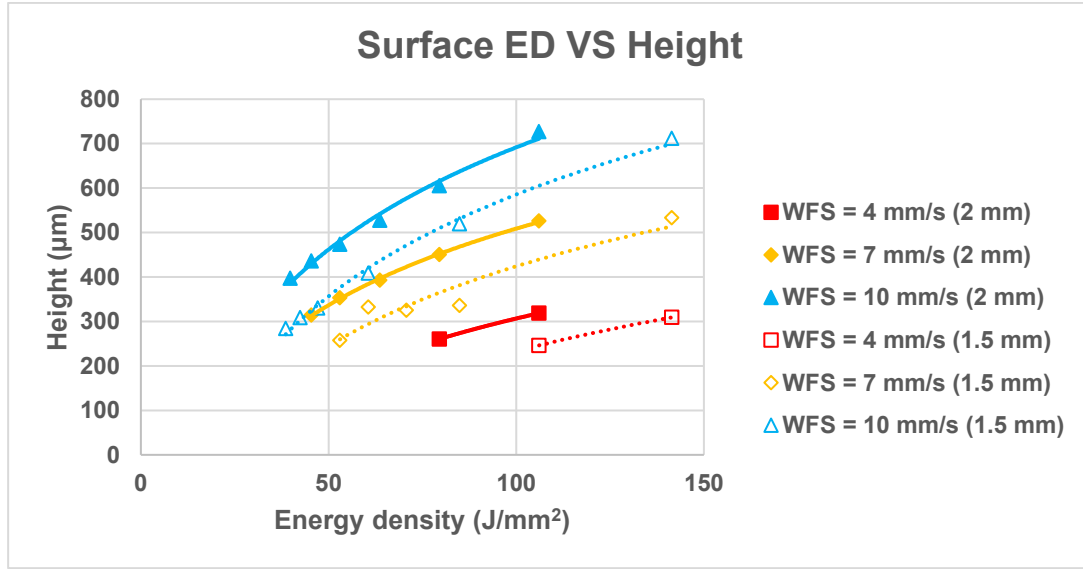
or WFS can allow the width to be close to 1.0 mm. However, from BD and WFS regards, different levels of WFS and BD do not have a critical impact on the width. Therefore, increasing BD or WFS may not be very efficient in achieving the 1.0 mm width. Before reaching the 1.0 mm width, the poor performance of bead on plate may have already appeared.

Compared to autogenous laser welds, there still exists a surface ED threshold (crossing point in Figure 5-25 (a)) for two laser beams to identify whether the width is dominated by the smaller laser beam (1.50 mm) or the larger laser beam (2.00 mm) under the same WFS, depending on the competition balance between the energy thermal losses and the energy inputs. However, after adding the wire, the threshold varies slightly for different levels of WFS, which could be because adding the wire to the process complicates the thermal cycle history. But generally, the width discrepancy is small.

One thing that needs to be mentioned is that this width measurement is based on the micrometre scale of the software scale bar used. If based on a millimetre scale, the width will exhibit a very similar trend, resulting in the width being controlled by the surface ED independent of the beam size within this process window range.



(a)



(b)

Figure 5-25 Image of surface ED versus (a) average width, (b) average height at different levels of WFS with 1.50 mm to 2.00 mm BD.

The relationship of height versus surface ED is shown in Figure 5-25 (b). From the beam size and WFS aspects, under the same surface ED and WFS, a larger laser beam has a higher height, and when processing at the same WFS, the height increment rate looks similar under the same range of surface ED for two levels of the laser beam. Increasing the WFS, the height increment rate is enhanced for both laser beam cases as the surface ED increases. Therefore, the height increment rate should rely more on WFS, beam size has no obvious effect on the height increment rate when the same surface ED is achieved. Therefore, the high deposition rate cannot get the benefit from the different beam sizes used.

5.3 Wall fabrication – Strategy, performance, geometry analysis and deposition rate calculation

In this section, the feasibility of wall fabrication is tested due to the good process window achievement of using 1.50 mm to 2.00 mm laser beams, 2.00 mm laser beam was chosen due to the higher D-ratio with less sensitivity to the wire position, relatively stable width and height propagations (more constant contact angle increment rate). Three 90 mm long, single-bead, 10-layer walls were deposited on the 150 mm x 150 mm x 2 mm substrate with three different

strategies. The sample identification, experimental parameters and corresponding three strategies are listed below in Table 5-6.

Table 5-6 Wall identification, parameters and strategies of using a 2.00 mm laser beam.

Sample ID	Method	WFS (mm/s)	TS (mm/s)	LP (w)	Layers
Wall 5-1	Strategy 1	5	5	Constant 500 W	10
Wall 5-2	Strategy 2	5	5	500, 450, 400, 350, 300 W for the first five layers, 6-10 layers at constant 300 W	10
Wall 5-3	Strategy 3	5	5	500, 475, 450, 425, 400 W for the first five layers, 6-10 layers at constant 400 W	10

Thereafter, the geometries were analysed, followed by the deposition efficiency and deposition rate calculation and analysis.

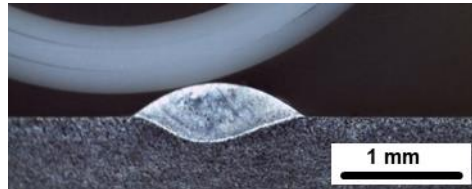


Figure 5-26 Cross-sectional profile of the bead on plate with the processing parameters that will be chosen for wall fabrications.

The image of the cross-sectional area of the bead on plate with a speed ratio of 1.0, 5 mm/s of the WFS and TS is shown in Figure 5-26; the corresponding geometrical information is shown in Table 5-7.

Table 5-7 Geometrical dimensions of bead on plate with the processing parameters that will be chosen for wall fabrications.

Width (μm)	Height (μm)	Penetration depth (μm)	Contact angle ($^{\circ}$)	Aspect ratio	Dilution ratio (%)
1443	276	209	35	5.2	38

Under these processing parameters, the bead possesses good wetting behaviour. The contact angle is not very steep (Wang et al., 2021), the top surface is relatively flat; a flatter bead can lead to a lower surface waviness of the wall (Wang et al., 2021). Also, a relatively flatter, convex-shaped surface should be a positive point to avoid the wire slipping or wire movements towards other directions apart from the wire position sensitivity reduction when using the larger

beams, thereby enhancing the possibility of success when depositing the next layer on top.

Thereafter, single-bead, 10-layer walls were built at the constant LP. The last layer (the 10th layer) deposition performance for strategy 1 (wall 5-1) is shown in Figure 5-27. The first, second and last layer's deposition performance of the wall 5-1 is put together in Figure 5-28 for comparison.

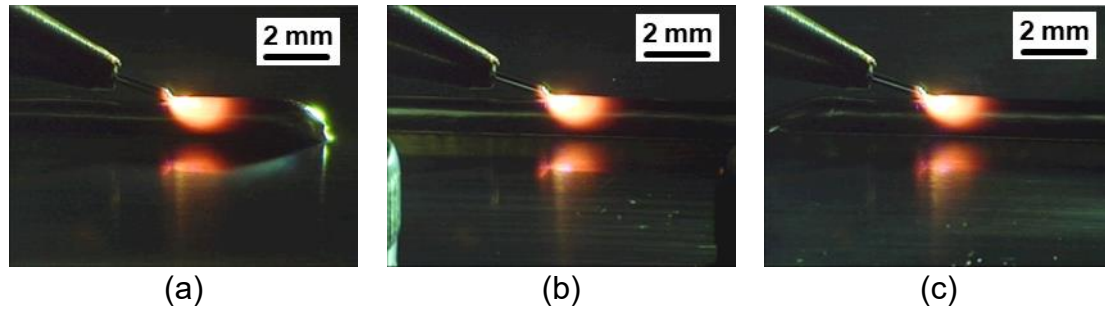
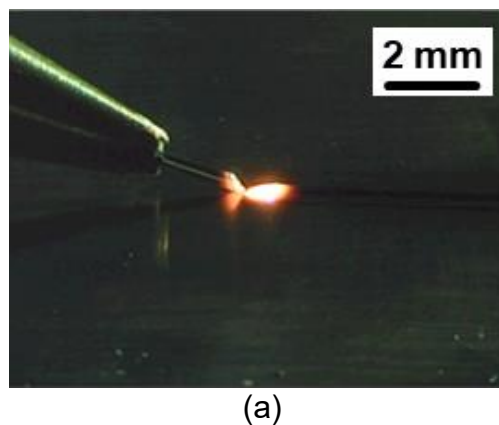


Figure 5-27 Deposition performance of strategy 1 at (a) initial, (b) middle, (c) and final phases of the 10th layer.

As seen in Figure 5-27, for the constant 500 W LP case, the deposition performs well, there is no plume, but the energy is a little bit high for the last layer deposition which caused the melt pool to affect several previous layers (by reheating or by remelting) and then form a large volume of hot material (Figure 5-28 (c)) compared with the first (Figure 5-28 (a)) and the second layer (Figure 5-28 (b)) of the deposition. This should be related to the high power being used, and the temperature buildup due to the poor thermal conductivity of stainless steel and the keep increased distance from the substrate surface to the continuously increased height of the wall as fabrication.



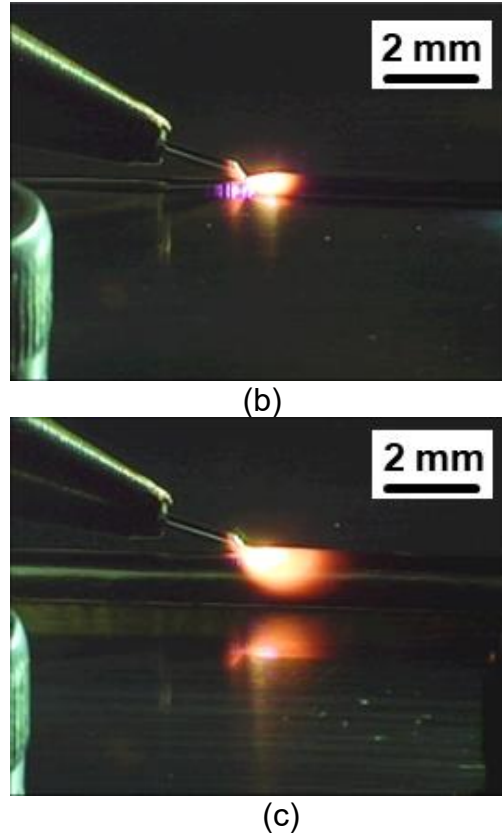


Figure 5-28 Comparison of the hot material volume of (a) 1st layer, (b) 2nd layer, (c) 10th layer of wall 5-1.

Thus, an energy reduction optimisation strategy was used in the next two walls to reduce the hot material volume size. This type of strategy is also used by (Zhou et al., 2021) to stabilise the bead dimensions, prevent damage or overheating to the previous layer and metal overflow when building thin walls. Normally, when building the walls upward, researchers will reduce the energy input either by applying energy reduction via increasing processing speed or lowering LP, or by feedstock rate variation (Du et al., 2019; B. Li et al., 2021). This is due to the reduction in thermal conduction from the 1st layer to the subsequent layers as the build progresses away from the substrate. Therefore, the following two walls adopted an energy reduction strategy with using strategy 2 (wall 5-2) and strategy 3 (wall 5-3), respectively, as the walls were built up.

Figure 5-29 exhibits the deposition performance with 10% LP reduction optimisation, the profile of each layer after deposition can be seen clearly, and

the melt pool can effectively melt the wire with a stable size melt pool (or hot material region) that can only remelt or reheat the previous layer.

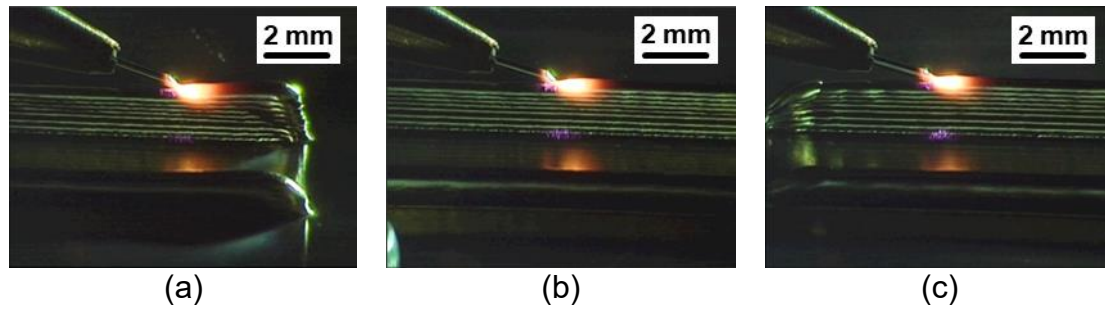


Figure 5-29 Deposition performance of wall 5-2 (strategy 2) at (a) initial, (b) middle, and (c) final phases.

Based on the first case of the LP optimization reduction strategy, the performance is excellent and acceptable. To see the deposition performance between the previous two strategies, a 5% LP reduction on each of the first five layers was applied in the third strategy, and the deposition performance of the last layer is shown in Figure 5-30.

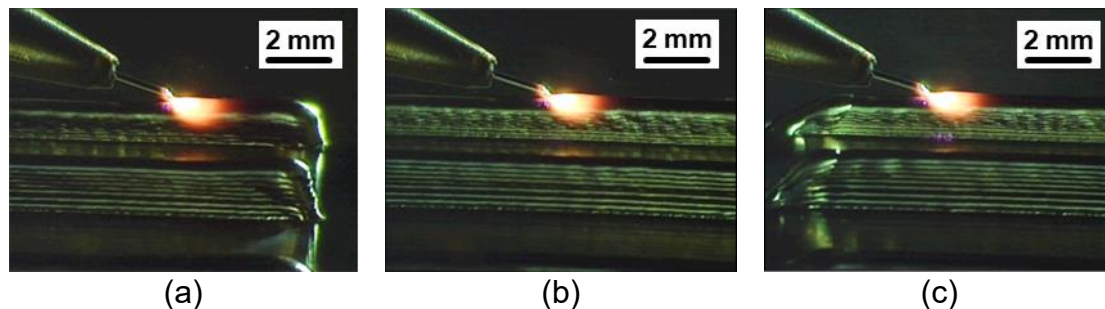


Figure 5-30 Deposition performance of wall 5-3 (strategy 3) at (a) initial, (b) middle, and (c) final phases.

From the images in Figure 5-30, the performance looks good as well during the whole deposition process progress, a stable process with no plume appearing, a reasonable size melt pool achieved and the melt pool cannot cover and remelt several previous layers; this reduced the risk of wall collapse which is mainly induced by the large size of the melt pool. However, the total height looks lower than the 10% reduction case, and the molten metal overlaps and covers the previous layer to some extent, a magnified image which shows the overlapping and covering of the previous layer is shown in Figure 5-31. In this case, it seems the surface roughness deteriorated to some extent.

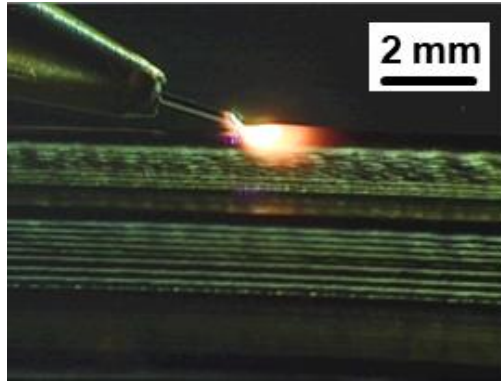


Figure 5-31 Image of the surface condition of strategy 3 showing the overlapping and covering of the previous layer.

The overall view of these three walls with three different strategies is shown in Figure 5-32. The feasibility of building the walls has been approved. All of these three walls have a smooth and shiny surface; the surface roughness depends on the surface condition and varies with the energy applied.



Figure 5-32 Overall view of three walls under three strategies.

The cross-section images of the three walls are shown below in Figure 5-33. The effective width, maximum width, the first layer width, effective and total area of the wall were measured. The effective width ratio, and effective area ratio (deposition efficiency) were calculated. Table 5-8 lists the geometrical dimensions of these three walls.

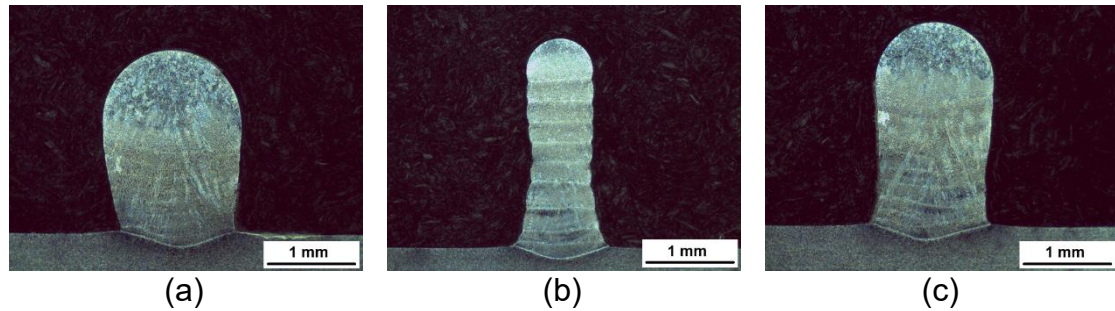


Figure 5-33 Cross-section images of the three walls under (a) strategy 1, (b) strategy 2, and (c) strategy 3.

It can be seen that an effective width either larger than 1.0 mm or less than 1.0 mm can be achieved. Wall 5-1 with strategy 1 achieved an effective width of 1271 μm , which is above the millimetre scale. Wall 5-2 with strategy 2 achieved the submillimetre-scale requirement with an effective width of 802 μm . Wall 5-3 with strategy 3 achieved an effective width of 1159 μm , which is very close to the millimetre scale. The average layer height varies between 204 μm to 297 μm with a uniform layer height distribution within each layer. Therefore, both the millimetre wall and the submillimetre wall can be deposited successfully; the difference lies in the heat accumulation of different levels of LP. A higher next-layer LP caused the material to reach the melting point more rapidly which promoted the fluidity of the molten metal (Du et al., 2019), therefore, the metal solidification progress became slow, so the layer width increased causing a wider wall.

Meanwhile, the widths of the first layer among these three strategies show a similar size, the deposition conditions of these three first layers are similar. And these values are also very similar to the width of the bead on plate (the width value is in Table 5-7) which means the process has a higher level of repeatability and reproducibility.

Therefore, using a 2.0 mm laser spot with 5 mm/s of the WFS and TS, a wall can be made with an effective wall width either slightly wider than 1.0 mm or less than 1.0 mm depending on the strategy used. No plume was observed, and the deposition process was stable and smooth.

Table 5-8 Geometrical dimensions of the walls manufactured with three different strategies.

	Strategy 1	Strategy 2	Strategy 3
1st layer width (μm)	1310	1384	1359
Effective wall width (μm)	1271	802	1159
Total wall width (μm)	1556	1384	1382
Waviness (μm)	143	291	112
Effective width ratio (%)	82%	58%	84%
Wall total height (μm)	2035	2968	2262
Average layer height (μm)	204	297	226
Effective area ratio	89%	85%	94%

The effective area ratio (deposition efficiency) in Table 5-8 reflects the deposited material utilisation rate. Strategy 3 has a very high deposited material utilisation rate of 94% with a nearly net shape outline profile, which is higher than that of 87% claimed in (Jhavar et al., 2014), of which the wall was fabricated by the AISI P-20 tool steel using the micro-plasma transferred arc process.

Also, strategies 2 and 3 still show the possibility of enhancing the deposited material utilisation rate performance based on the parameters optimisation, and strategy 2 shows a more potentially promising ability to reach a higher rate with excellent deposition performance, for instance, by maintaining the LP constant at an earlier layer (maintain the LP constant for 5th - 10th layer).

Therefore, using a constant 500W LP for the 10 layers deposition formed a large volumetric molten volume, which caused the melt pool to remelt a large volume of the previous layer. This case also caused the molten metal to cover the previous layer because of more heat accumulation, resulting in the reduction of the deposition efficiency, i.e., more material needs to be machined off to achieve the effective 1.0 mm wide wall width. Moreover, constant 500 W LP also induced more energy left in the previous layer when remelting it, therefore reducing the cooling rate of the previous layer, which could cause the large size of the microstructure, and affect the mechanical properties. Strategies with applied energy reduction are required to optimise the process.

Strategy 2 with a 10% reduction of the LP for the first five layers resulted in an effective width which is less than 1.0 mm. This wall has an effective area ratio of

85%, which is highly reliant on the minimum width of the fifth layer even though the effective width ratio is just 57.96%. The effective width and area ratio can be enhanced further when the narrowest part width is increased. For instance, if modifying the strategy such as keeping the LP constant at an earlier stage, such as at the third or fourth layer, the width will be wider, and the deposition efficiency should be higher with a higher effective width ratio.

Strategy 3 with a 5% reduction of the LP for the first five layers exhibits a better cross-sectional profile with a near-net shape. The deposition efficiency is about 94%. From the external overall appearance, its surface is not as good as the case of strategy 2, the deposited material covered the previous layer to some extent, but the overall profile in this strategy is better, the wall is straight and even. A good surface finishing with less roughness was achieved. Just 6% of the deposited material needs to be machined off, and the effective width is 1159 μm , which is very close to the target of 1.0 mm wide wall width, and still has the potential to increase the deposition efficiency.

Therefore, using a 2.0 mm laser beam, millimetre and submillimetre scale wall features, of which the size is less than the laser beam size can be excellently manufactured with good and stable deposition performance.

When it comes to the waviness, the waviness increases from wall 5-3 (strategy 3), wall 5-1 (strategy 1), to wall 5-2 (strategy 2), from 112 μm to 291 μm . In the wall 5-2 case, the stair-step effect is more significant, so the roughness is larger (DebRoy et al., 2018; B. Li et al., 2021). But the overall appearance of wall 5-2 looks similar to another laser wire process of Ti6Al4V wall (X. Ding, Ma, et al., 2022), the surface finish condition and the appearance of two thin-wall features manufactured by their team are shown in Figure 5-34. The calculated waviness for this Ti6Al4V wall is 251 μm (Figure 5-34 (b)). The high waviness of this Ti6Al4V wall is due to the narrow second layer (Du et al., 2019).



Figure 5-34 (a) Surface condition of Ti6Al4V thin-wall structures, and (b) cross-sectional profile and dimensions of Ti6Al4V thin wall (X. Ding, Ma, et al., 2022).

On top of this, the surface finish condition of the wire-based laser DED process in this thesis is better compared to the plasma-transferred arc additive manufacturing process for Ti6AL4V material (Figure 5-35, calculated waviness range: 400 μm – 1810 μm) (Wainwright et al., 2023).

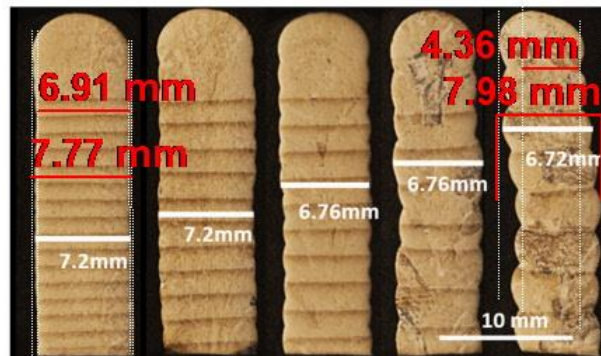


Figure 5-35 Geometrical dimensions of Ti6Al4V walls by plasma transferred arc process (Wainwright et al., 2023).

Also, the waviness level in this work is lower than the plasma laser hybrid additive manufacturing process (take Ti6Al4V walls in (Wang et al., 2021) as an example, Figure 5-36, calculated waviness range: 1625 μm – 1940 μm).

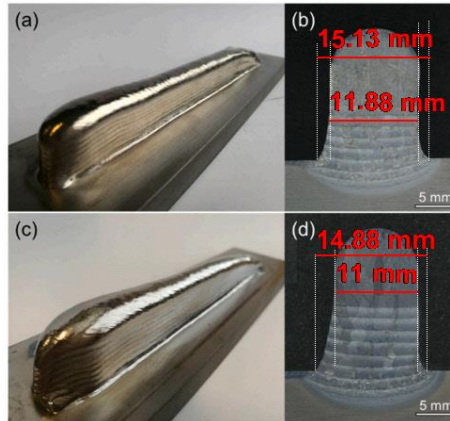


Figure 5-36 Geometrical dimensions of the cross-section of Ti6Al4V walls fabricated by plasma and laser hybrid process with good surface condition (Wang et al., 2021).

But it is comparable to the gas tungsten arc process for HASTELLOY X alloy (Figure 5-37, calculated waviness range: 200 μm – 305 μm , the surface oxidation condition could deteriorate the waviness condition) (Dinovitzer et al., 2019), and the micro-plasma transferred arc process for AISI P-20 walls (Jhavar et al., 2014) (Figure 5-38, calculated waviness 170 μm).

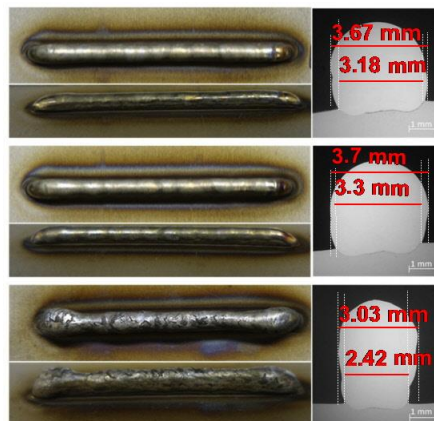


Figure 5-37 Geometrical dimensions measurement of the cross-section of HASTELLOY X alloy wall fabricated by gas tungsten arc process (Dinovitzer et al., 2019).

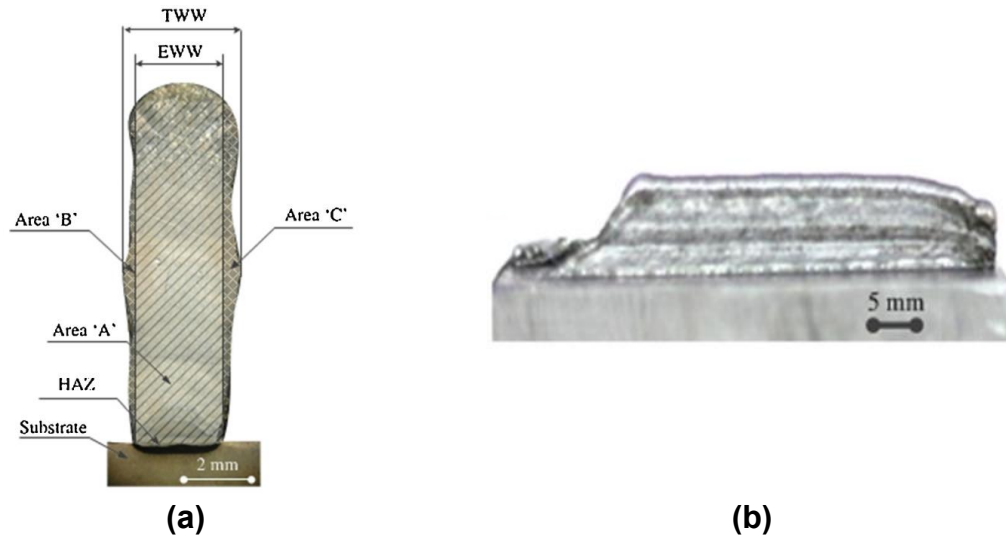


Figure 5-38 (a) Cross-section profile and (b) overall appearance of AISI P-20 tool steel wall fabricated by micro-plasma transferred arc wire deposition process (Jhavar et al., 2014).

And it is totally better than the gas metal arc additive manufacturing process for the AISI 316L SS wall (Figure 5-39) (Kumar et al., 2024) of which the process is normally used for large-scale parts, which is less critical for the surface conditions.



Figure 5-39 Surface roughness condition of AISI 316L SS fabricated by cold metal transfer WAAM process (Kumar et al., 2024).

So, the surface roughness of the walls 5-1 to 5-3 is acceptable and has a good surface condition compared with other wire-based processes. However, compared with the powder-based laser DED process ($15\ \mu\text{m} - 20\ \mu\text{m}$) using 316L SS powder (Figure 5-40 (Syed et al., 2006)). The roughness is still higher.

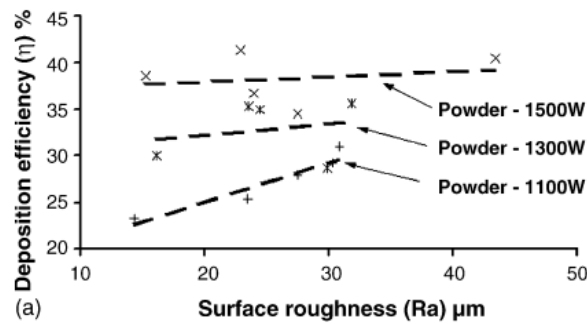


Figure 5-40 Surface roughness range of powder-based laser DED process using 316L SS powder (Syed et al., 2006).

However, judging or comparing the surface condition based on the process is not absolute, because the condition will change depending on what material is being used. For instance, in (Kaljevic & Demir, 2022), wire-based laser DED process was used, but the feedstock is Mg alloy (Resoloy), the as-deposited wall exhibited a cross-section profile with much waviness (Figure 5-41) and the surface roughness should be very high. But overall, the wire-based laser DED process for fabricating 316L SS submillimetre to millimetre scale wall features can create a relatively good wall surface finish condition.

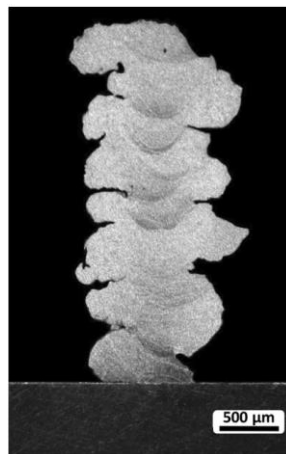


Figure 5-41 Cross-section profile of Resoloy alloy fabricated by WLAM process (Kaljevic & Demir, 2022).

Moreover, there is no porosity observed during the optical microscopy observation, which is an obvious advantage over the powder-based processes. The advantage of the laser wire process in this thesis can be attributed to the process not being operated at high PD; using wire as the feedstock makes it

difficult to entrap the gas compared with powder-based processes; and good bonding with the substrate (DebRoy et al., 2018) which utilises the surface tension force to a large extent with wire placing on the substrate surface, this enables the fastest and robust transition to the stable status (Kotar et al., 2019).

Thereafter, the deposition rate was calculated. Because the only variable for these three walls is LP, the deposition rate for these three walls is the same. The deposition rate of this process was calculated based on the formula (5-4):

$$Deposition\ rate = \frac{\pi * d^2 * v * \rho * 1000}{4} \ (g/h) \quad (5-4)$$

Where, d represents the wire diameter (m), v represents WFS (m/h), ρ represents material density (kg/m^3).

After the calculation, the result shows that the deposition rate is 40 g/h, which is higher than the regular deposition rate of 28.1 g/h using a micro-plasma transferred arc process for tool steel material fabrication, and it is comparable to the maximum deposition rate of 42 g/h for the same tool steel material fabrication in same article (Jhavar et al., 2014). (Mortello & Casalino, 2021) achieved 191 g/h using a 1.0 mm Titanium wire with a 1.00 mm beam size to fabricate less than 2.0 mm-thick 15-layer walls, which is around five times of this work in the thesis. This is mainly due to the thicker wire and three times the WFS the author used.

However, compared with powder-based processes, the wire-based process for the submillimetre feature deposition rate is relatively low. Powder-based DED processes can reach 0.6 kg to 2.0 kg/h (Z. Li et al., 2022). Considering the material utilization rate is very high for the wire process, increasing the material input is required if the target is to enhance the deposition rate, therefore, many ways can be applied such as increasing the energy inputs by increasing the LP with larger laser beams; increasing the material input by increasing WFS, applying multi-wire feeding nozzle to feed the wire simultaneously but still can fabricate small features; increasing the wire diameter to 0.8 to enhance the amount of material feeding in the process per unit of time and etc.

5.4 Chapter summary

In this chapter, using large laser beam sizes to manufacture submillimetre-scale wall features has been investigated at 500 W LP. Several critical points are drawn below:

- Using large beam sizes (1.50 mm – 2.00 mm) with a big D-ratio, good deposition performance and stability under conduction mode, without plume interference can be achieved. A larger laser beam size with a big D-ratio reduced the process and wire position sensitivity, suppressed the possibility of forming the plume, and enhanced the possibility of the success of deposition.
- D-ratio plays a critical role in the deposition performance. A large D-ratio of 3.33 can reduce the wire position sensitivity.
- Using a 2.00 mm large laser beam with 500 W LP can fabricate the near-net-shape millimetre to submillimetre-scale walls with a good performance and acceptable appearance waviness by optimising the parameters. And the process still exhibits the potential to be optimised from the deposition rate and deposition efficiency aspects.

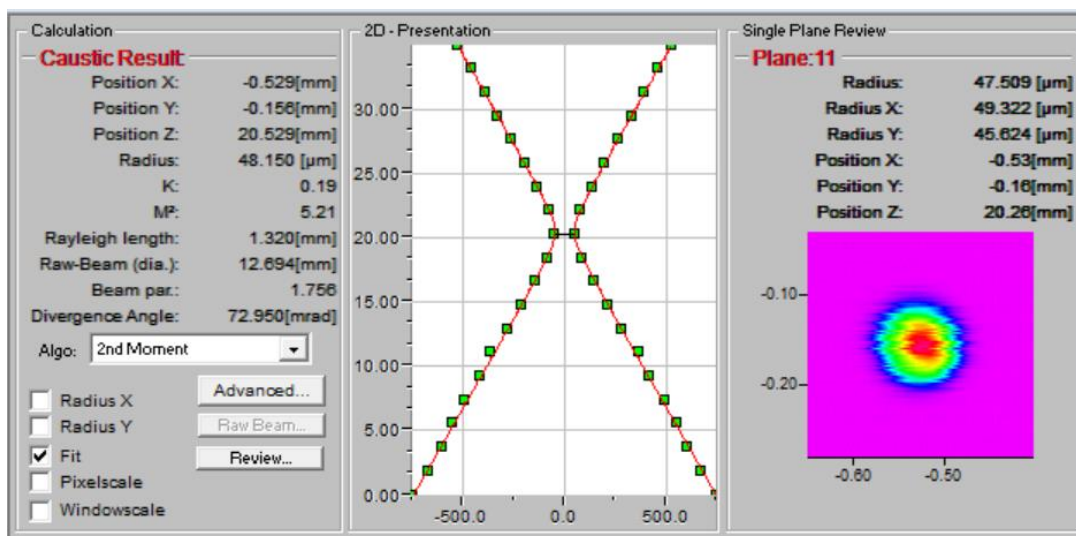
6 Investigation of high-power lasers to manufacture submillimetre to millimetre wall features

In Chapter 5, millimetre to submillimetre-scale wall features were successfully deposited using 500 W of LP. However, the deposition rate of 40 g/h is not competitive. To enhance the deposition rate, in this section, higher levels of LP combined with larger laser BDs are used to increase the surface energy with the goal of manufacturing millimetre to submillimetre wall features. Autogenous laser welds with higher LPs ranging from 1.00 kW to 2.79 kW combined with laser beams ranging from 1.5 mm to 3.0 mm were first conducted to identify the parameter ranges that can achieve the weld width which is close to 1.0 mm. Then, the feasible processing speed range of bead on plate was preliminarily identified. Thereafter, the feasibility of depositing bead on plate was examined based on different levels of speed ratio, followed by the investigation of the feasibility of fabricating walls using the feasible set of parameters. The deposition repeatability and wire position sensitivity were investigated in parallel during the bead on plate deposition. Finally, the deposition rate, and deposition efficiency were calculated, analysed and compared.

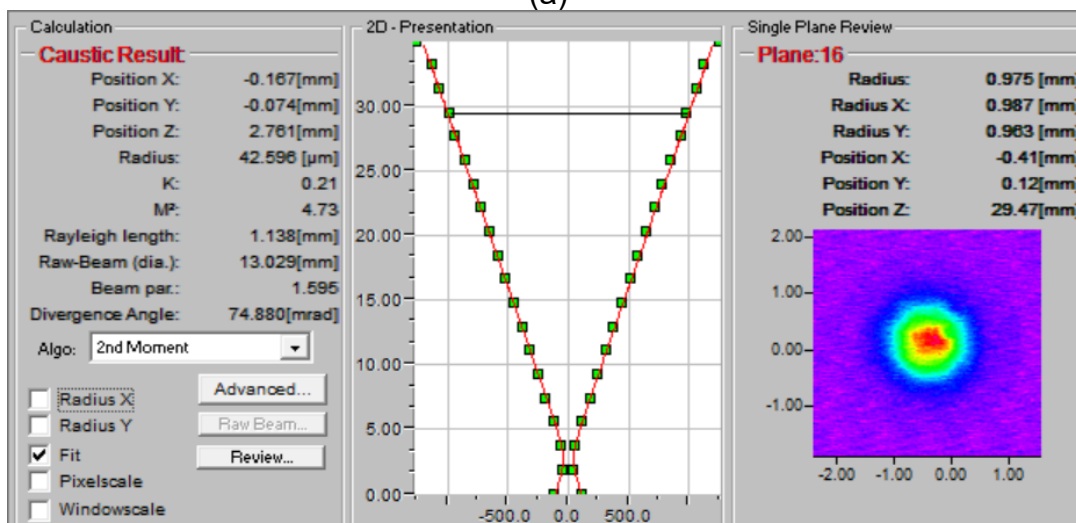
6.1 Laser beam caustic profiling

To get the accurate laser spot diameters for this chapter, beam profiling was conducted for the 50 μm core diameter fibre. Figure 6-1 (a) shows the results of the beam profile caustic of the 50 μm core diameter fibre. It indicates the minimum radius is about 48 μm , which will be used for the model calculation of beam diameter versus the defocused distance.

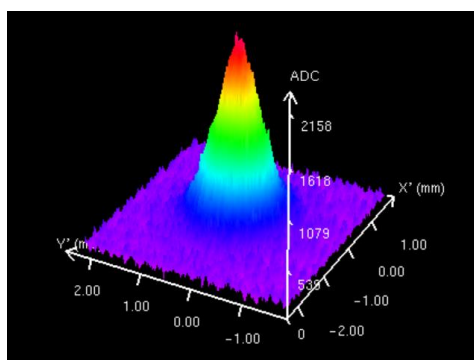
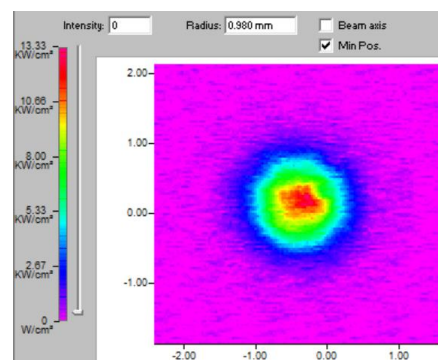
Figure 6-1 (b) indicates the beam profile under the defocused position with the focal point included, the linear trend sections were used for the beam size versus defocused distance model calculation.



(a)



(b)



(c)

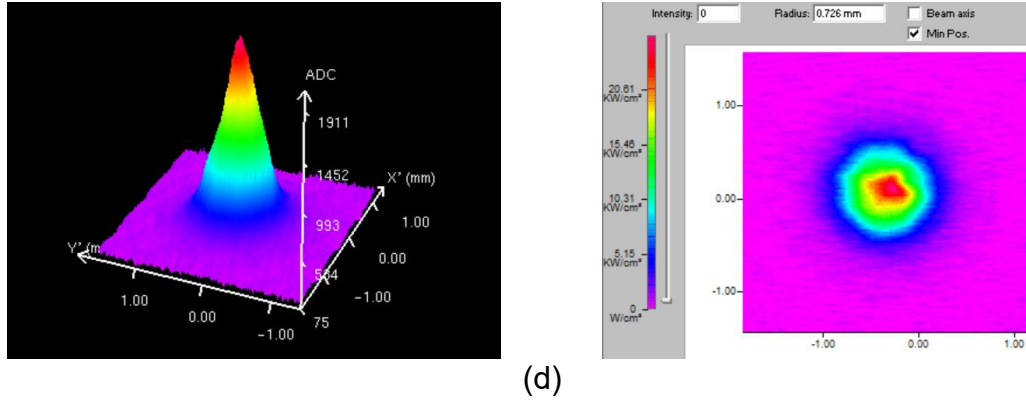


Figure 6-1 Images of (a) beam profile caustic at the focal position, (b) beam profile at the defocused position with the focal point included, (c) 2.0 mm BD laser beam profile, (d) 1.5 mm BD laser beam profile of the 50 μm core diameter fibre.

Figure 6-1 (c) indicates the 3D and 2D mode laser beam PD distribution profile of the 2.0 mm laser beam. Figure 6-1 (d) indicates the 3D and 2D beam profile of the 1.5 mm laser beam used in the experiments. For a 3.0 mm laser beam, the size of which exceeds the measurement range of this device when the focal point is maintained in the measurement region, thus, no beam profile result is exhibited for the 3.0 mm laser beam. Based on the data information in Figure 6-1 (a), (b), the linear regression relationship model of defocused distance versus laser BD can be calculated.

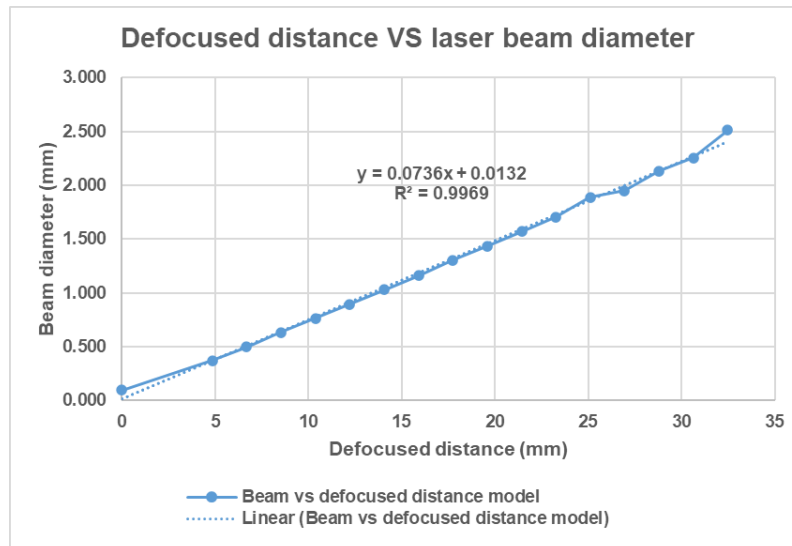


Figure 6-2 Linear regression model of defocused distance versus laser BD for processing using the 50 μm core diameter fibre laser.

Figure 6-2 shows this model with the linear regression formula. When using this model to determine the required beam size for processing, the distance errors with the corresponding final beam size are listed in Table 6-1.

Table 6-1 Distance error and the corresponding BD and BD variations compared with the nominal BD.

Nominal beam size (mm)	Distance error (mm)	Final beam size (mm)	Beam size variation
2.0	+0.5	2.04	2%
	-0.5	1.96	2%
3.0	+0.5	3.04	1%
	-0.5	2.96	1%

Therefore, when using 2.0 mm and 3.0 mm laser beams, the beam size variation is around 1% to 2% variation, which is acceptable.

6.2 LP measurement and calibration

For accurately conducting the experiments with accurate LP applied to the experiments, the LP value on the software panel was calibrated with the actual value measured by the power meter.

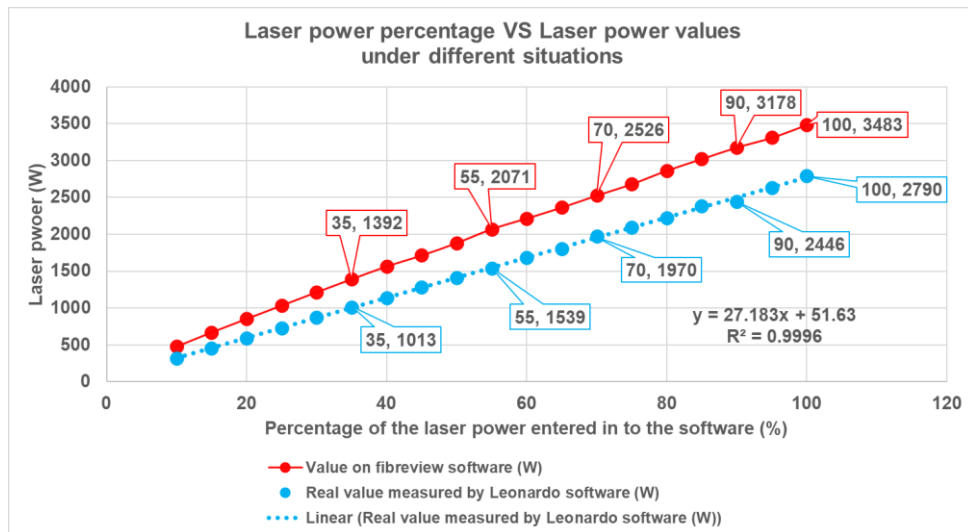


Figure 6-3 50 μ m core diameter fibre LP measurement and calibration.

The results in Figure 6-3 show a discrepancy between the power values shown on the software panel (red points) and the real value (blue points). The error discrepancy between the real values and the values shown on the software panel is within the range of 25% to 49%. The extent of error deviating from the real

value increases as the percentage of laser power increases. Considering the trend line of the real value (blue dotted line) is quite linear with a very high R^2 value obtained, the values on this trend line model should be quite accurate. Therefore, the data after calibration was used for experiments; the maximum real output is 2.79 kW.

6.3 Critical wire alignment

Considering high speed could increase the wire position sensitivity due to the wire and substrate having more opportunity to experience friction, and high-level LP could also reintroduce the plume during deposition, which can interfere with the energy absorbed by the wire and the substrate, the wire position could become more critical. To reduce these interference factors and to reduce their extents to the minimum level, a new wire positioning method with the real laser was used to align the wire with the laser spot. Figure 6-4 (a), (b) show this new procedure that consists of marking a 3.0 mm laser spot using the real laser and aligning the wire with this 3.0 mm real laser spot instead of using the guide laser to do the alignment as was done before. The laser marking point was created at 23% of the nominal total LP output (677 W in reality) for 2 seconds. In this case, the wire can be accurately aligned with the laser spot, which will be beneficial for the success of conducting experiments.

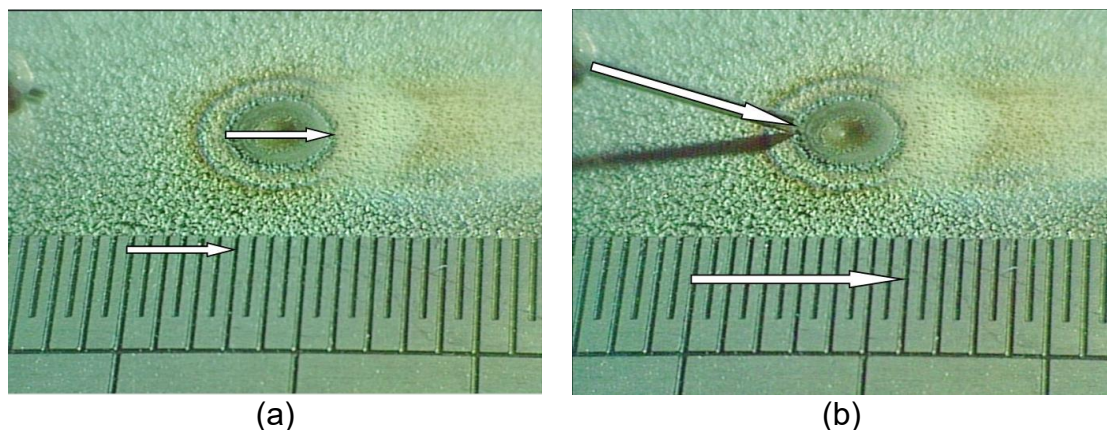


Figure 6-4 Image of the real 3.0 mm laser spot (a) marking and measurement, (b) critical wire positioning and wire stick-out length measurement.

This strategy was selected instead of using the guide laser to avoid any misalignment of the wire with the real melt pool, as the guide laser has a different

wavelength from the main laser (guide laser is visible). When using a large laser beam, the beam size accuracy of using the guide laser dimension as the real laser's beam size for alignment is uncertain. Therefore, by imprinting a small mark on the surface of the material, the alignment of the wire can be more accurate and ensure that the wire is placed at the edge of the real beam, where the melt pool will be created by the main laser when the laser is triggered for deposition.

6.4 Autogenous laser welds and geometry analysis

In this section, the performance of the autogenous laser welds was examined, followed by identifying the available processing speed range, and the corresponding width range as was done in the previous chapter. Afterwards, whether a similar 1.0 mm width track could be achieved under different laser beam sizes and different levels of LP was identified. Then identified the maximum processing speed at which level of the LP and BD can form an autogenous laser weld with a width adjacent to 1.0 mm. This can give an idea regarding the speed range chosen once the laser beam size and LP are determined for bead on plate deposition.

Due to the higher LP used in this chapter, the initial experimental TS was increased accordingly to avoid the possibility of burning through the 6 mm thick substrate, and serious distortion of the substrate. The maximum TS was set at 200 mm/s to observe the track consistency and welding performance. The experimental parameters are listed in Table 3-9. Due to the different levels of LP being used, either the summarised trends or issues will be more representative than the 500 W LP only cases. In this case, the effect of energy input (EI) on width will be introduced for discussion first to observe the width development trend. And the issue of using EI to conclude the beam size effect will be revealed.

Thereafter, Esp will be introduced (unlike the 500 W low-level LP cases, the IT has a similar effect as the Esp on width because the LP is constant. In these cases, different levels of LP were used; IT did not have a similar effect as Esp; therefore, Esp was mainly used for discussion, of which the formula also contains the IT factor). The BD and LP effects on width at different levels of Esp will be discussed. Thereafter, the effect of surface ED on width was analysed with 500

W laser power cases added as a comparison. Then, the feasible autogenous laser weld welded at the conduction mode will be filtered out from the transition and keyhole mode regimes, the cross-sectional area was examined to identify the width close to 1.0 mm and was filtered out, preparing for the bead on plate deposition.

6.4.1 Effect of EI, BD, and LP on geometry

EI, also called linear energy density, which defines the energy per unit length, the formula is expressed as below:

$$EI = \frac{LP}{TS} \text{ (J/mm)} \quad (6-1)$$

EI mainly reflects the energy density along the deposition direction through the variation of TS, which means it cannot reflect the beam size effect perpendicular to the deposition direction. In this case, the beam size effect is also added for discussion. The issue of using EI to evaluate the beam size effect will be explained in this section.

It is difficult to see the details at the low energy section with a width close to 1.0 mm for observing three levels of BD and four levels of LP's data together, to make the observation easier and the figure clearer, the images of EI versus width are separated to four levels LP cases for beam size discussion, and three levels of beam size for laser power effect discussions (See the Figure_Apx B-1 to Figure_Apx B-7 in the Appendix). To exhibit the weld profiles and working regime under different EI conditions more straightforwardly, three representative cross-sectional images (at the initial, middle and final phase of the EI) for each beam size at one specific level LP case as EI varies are shown in Table 6-2 to Table 6-5 to show the geometrical variations. All the initial EI phase cases exhibited in the Tables with a width close to 1.0 mm regardless of the working regimes.

Figure_Apx B-1 to Figure_Apx B-4 show the overall trends of EI against the average width at three levels of beam size for four levels of LP, respectively. (Logarithmic-type trend line was chosen because firstly, the highest R-square value was achieved. Secondly, the EI has the same effect as the IT does due to

the inverse relationship with TS. Therefore, the width development trend as the EI increases can refer to the IT effect on width shown in the previous chapter.) Around 1.0 mm wide autogenous laser welds can still be achieved in most cases when using larger laser beams and high levels of LP.

Table 6-2 Representative cross-sectional profiles with parameters and width at 1.00 kW of LP for BD ranging from 1.5 mm to 3.0 mm.

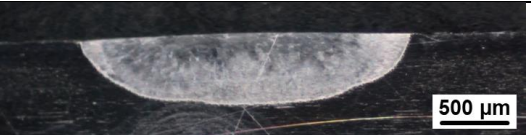
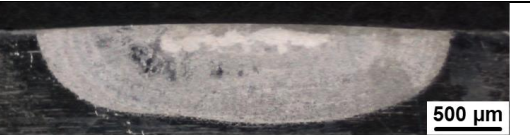
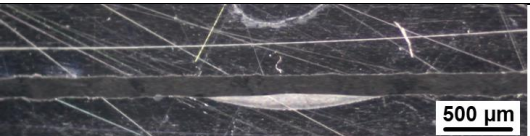
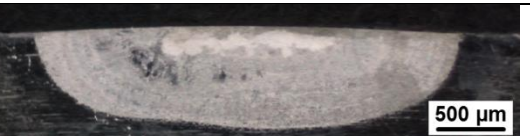
Beam size: 1.5 mm			
EI (J/mm)	20	100	333
TS (mm/s)	50	10	3
Average Width (μm)	1075	1951	2730
Beam size: 2.0 mm			
EI (J/mm)	13	100	333
TS (mm/s)	75	10	3
Average Width (μm)	1101	2057	2723
Beam size: 3.0 mm			
EI (J/mm)	20	100	333
TS (mm/s)	50	10	3
Average Width (μm)	1089	2149	2849
<u>500 μm</u>			

Table 6-3 Representative cross-sectional profiles with parameters and width at 1.50 kW of LP for BD ranging from 1.5 mm to 3.0 mm.

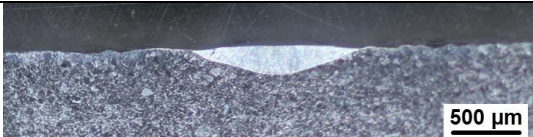
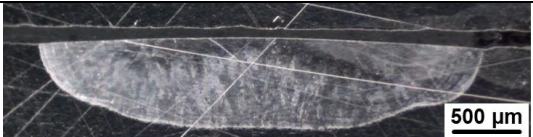
Beam size: 1.5 mm			
EI (J/mm)	15	50	150
TS (mm/s)	100	30	10
Average Width (μm)	1027	1747	2767
Beam size: 2.0 mm			
EI (J/mm)	12	50	150
TS (mm/s)	125	30	10
Average Width (μm)	1141	2002	2771
Beam size: 3.0 mm			
EI (J/mm)	15	50	150
TS (mm/s)	100	30	10
Average Width (μm)	1307	1937	2742
			

Table 6-4 Representative cross-sectional profiles with parameters and width at 2.00 kW of LP for BD ranging from 1.5 mm to 3.0 mm.

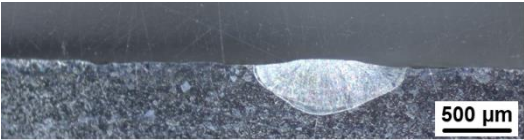
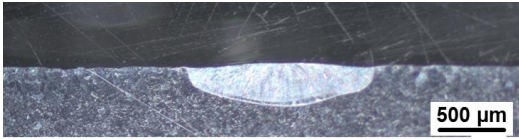
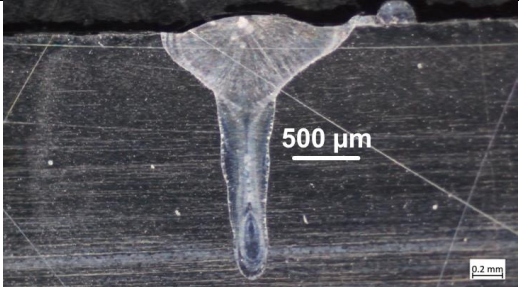
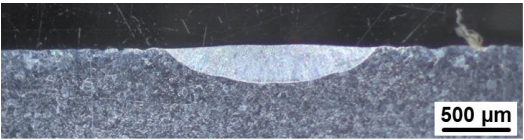
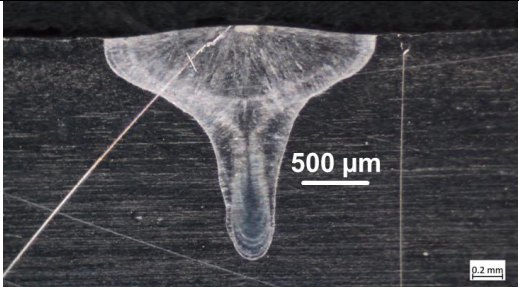
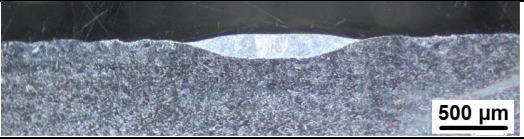
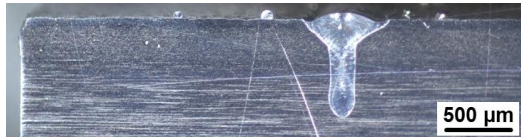
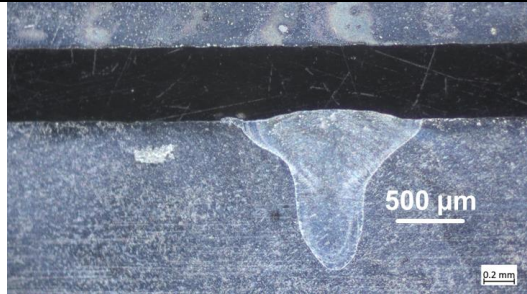
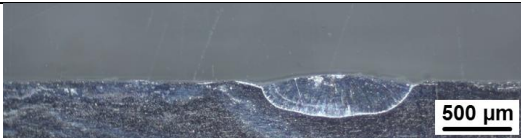
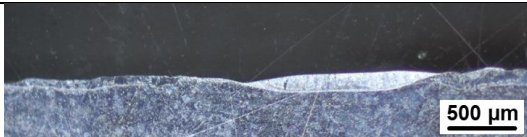
Beam size: 1.5 mm					
	EI (J/mm)	13	16	20	
	TS (mm/s)	150	125	100	
Average Width (μm)		1038	1233	1244	
Beam size: 2.0 mm					
	EI (J/mm)	16	20	40	
	TS (mm/s)	125	100	50	
Average Width (μm)		1773	1192	2771	
Beam size: 3.0 mm					
	EI (J/mm)	16	20	27	
	TS (mm/s)	125	100	75	
Average Width (μm)		1366	1192	1448	

Table 6-5 Representative cross-sectional profiles with parameters and width at 2.79 kW of LP for BD ranging from 1.5 mm to 3.0 mm.

Beam size: 1.5 mm			
El (J/mm)	14	16	
TS (mm/s)	200	175	
Average Width (μm)	1205	1174	
Beam size: 2.0 mm			
El (J/mm)	14	16	
TS (mm/s)	200	175	
Average Width (μm)	1037	1086	
Beam size: 3.0 mm			
El (J/mm)	14	16	
TS (mm/s)	200	175	
Average Width (μm)	1353	1321	

In detail, at 1.00 kW to 2.00 kW of LP, a 1.0 mm wide autogenous laser weld can be achieved at the low energy input phase for all the laser beam cases (Figure_Apx B-1 to Figure_Apx B-3). This is attributed to the fast processing speed, in this case, the IT is short, the weld width is mainly affected by the p-PD within the beam profile and determined by the combination of p-PD with the short IT duration to form the energy which is mainly for creating the thermal conduction loss length dominated narrow width, of which the width should represent the boundary of the melting.

At 2.79 kW of LP (Figure_Apx B-4), a 1.00 mm wide autogenous laser weld cannot be reached at the current experimental parameters. A lower EI is required, which means the processing speed should be faster to extend the width to a lower-level range.

Table 6-2 to Table 6-5 show the cross-sectional profiles of the autogenous laser welds at some representative regimes with BD ranging from 1.5 mm to 3.0 mm.

At 1.00 kW of LP (Table 6-2), all the cases within the energy input range exhibited the conduction mode profile as per the aspect ratio judgment in (Assuncao et al., 2012). At 1.50 kW of LP (Table 6-3), 1.5 mm cases started exhibiting the transition mode due to the high-level PD, 2.0 mm and 3.0 mm laser beam cases were all within the conduction mode. When the LP increased to 2.00 kW (Table 6-4), for 1.5 mm cases, as the energy input reduced from 20 J/mm to 16 J/mm, the profile changed from keyhole to conduction mode, then as the energy input reduced further, the transition mode reappeared, but the extent was not obvious, which reflects the parameters for the process at these range of energy input was adjacent to the boundary of conduction mode and transition mode, therefore, the weld profile was sensitive to the energy input variation. For 2.0 mm cases, as the energy input reduced from 20 J/mm to 16 J/mm, the profile changed from transition mode to conduction mode. Keyhole mode was observed in 1.5 mm and 2.0 mm laser beam cases. When the LP was increased to 2.79 kW further (Table 6-5), keyhole mode appeared in all the cases when using the 1.5 mm laser beam. For 2.0 mm BD cases, the conduction mode profile reappeared when the energy

input reached the minimum, and the width was close to 1.0 mm in this case. All the cases using a 3.0 mm laser spot were still under the conduction regime.

From Figure_Apx B-1 to Figure_Apx B-7, it can be seen that regardless of different levels of BD or LP, at a low level of EI, a similar width could be achieved. To investigate this phenomenon further, the effects of BD and LP on the width at different levels of EI are discussed. (For the LP effect on width at three levels of BD, the values were obtained from the trendlines. Therefore, no error bars can be exhibited).

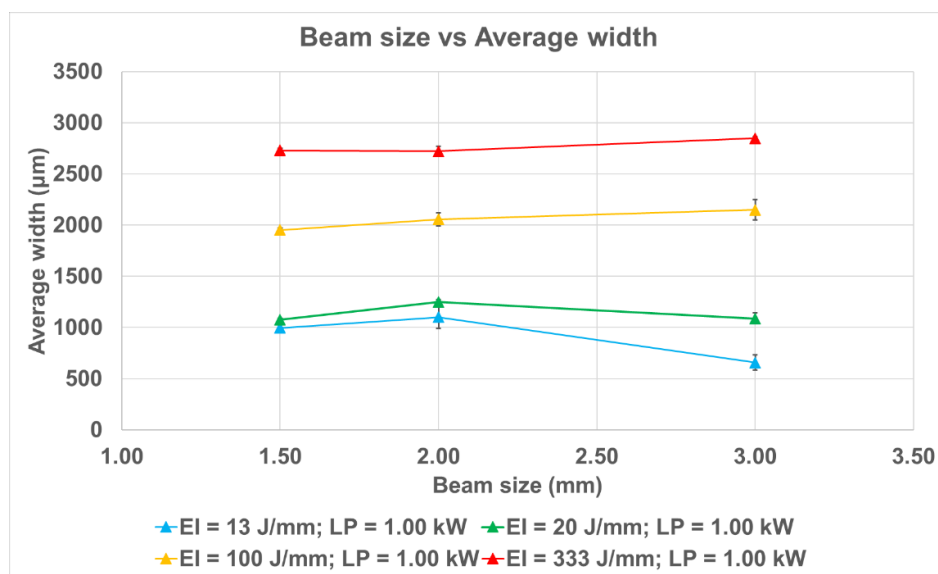


Figure 6-5 Beam size versus average width with different levels of EI at 1.00 kW of LP.

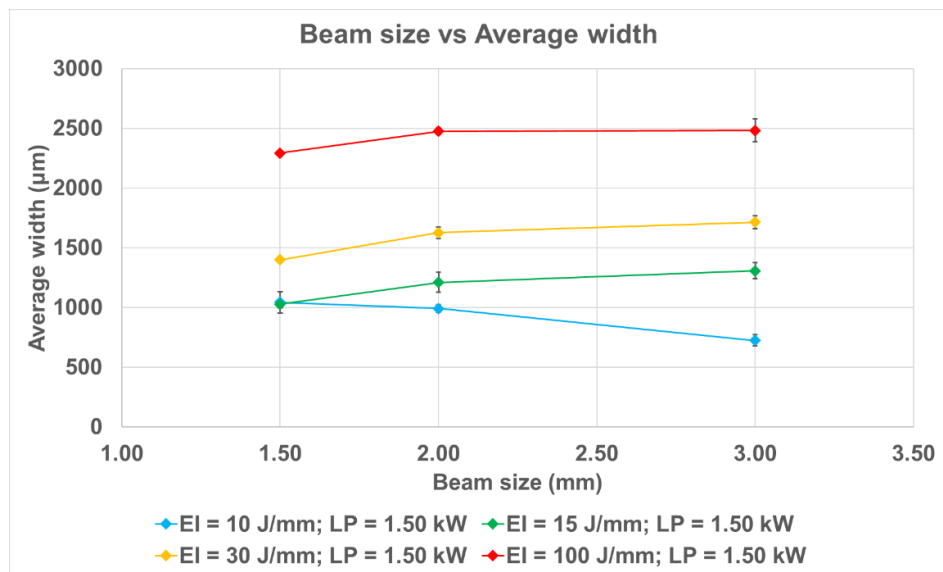


Figure 6-6 Beam size versus average width with different levels of EI at 1.50 kW of LP.

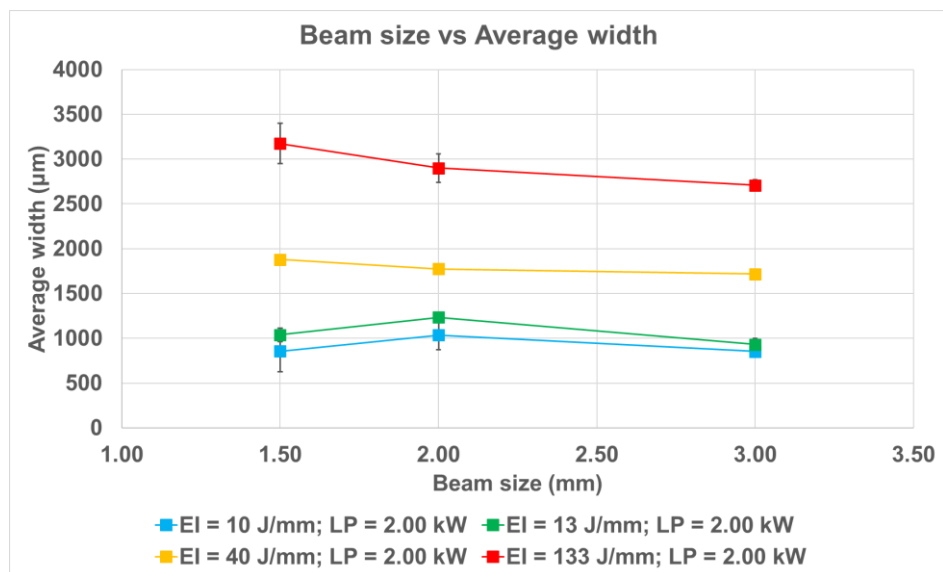


Figure 6-7 Beam size versus average width with different levels of EI at 2.00 kW of LP.

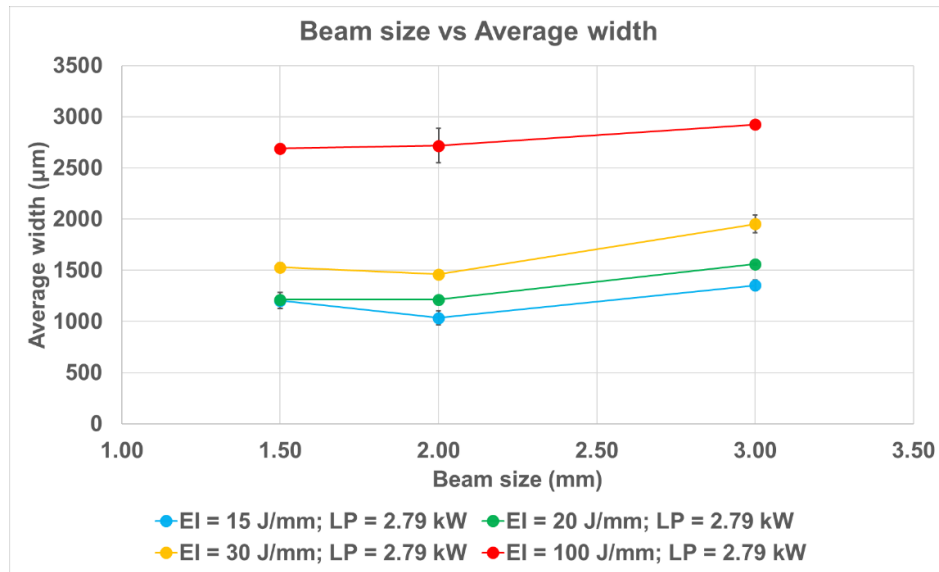


Figure 6-8 Beam size versus average width with different levels of EI at 2.79 kW of LP

From Figure 6-5 to Figure 6-8, the results show that the beam size does not affect the width significantly, and the overall trend does not show an obvious development trend. Sometimes, as the BD increases, the width increases, but sometimes the opposite trend is observed. And sometimes, a similar width can be achieved independent of the beam size variation, for instance, 333 J/mm, 100 J/mm of EI for the 1.00 kW LP case, 40 J/mm of EI for the 2.00 kW LP case. This can cause the researcher to have an inaccurate width development trend conclusion if the researcher chooses the processing parameter that just falls into one type of width development trend regime by chance, for instance, the width increment regime as the BD increases, or the width independent of BD variation regime. Therefore, the reason for this irregular width variation as BD varies when using EI as the energy factor should be figured out.

The following content will give explanations from three perspectives. Firstly, from the EI perspective, based on the converted FLMIPs-based EI formula (6-2) from formula (6-1), which is expressed below:

$$EI = \frac{LP * IT}{BD} \text{ (J/mm)} \quad (6-2)$$

Under the same EI, at a constant LP, a larger BD causes a longer IT; accordingly, a larger laser beam always induces a lower PD at a constant LP; a longer IT can always compensate for the weakened effect of PD reduction.

The second reason is related to the surface ED, of which is the product of IT and PD. There is a balance and finally a dominant factor between the IT increment and PD reduction when increasing the BD. If the IT increment weighs more, the width will be mainly controlled by IT and will be affected by the BD. If the PD reduction has more effect, as the BD increases, the width will be reduced. This balance is related to the LP levels, laser beam sizes, processing speed, and the ability to melt the material (beam profile); these four factors form the third reason, i.e., working regimes (modes).

Conduction mode, transition mode, and keyhole mode have different responses to the thermal effect and laser absorption rate (Ebrahimi et al., 2022). Figure 6-6 shows that for the EI above 15 J/mm, the 1.5 mm cases' widths usually have a narrower width than the 2.0 mm and 3.0 mm cases. This should be because the transition mode appeared when processing at 1.50 kW of LP using a 1.5 mm laser beam (Table 6-3). In the transition mode phase, part of the energy was used to elevate the molten material temperature from the melting point to the boiling point, which mitigates the width propagation (Assuncao et al., 2012).

Figure 6-8 shows the 1.5 mm case has a similar width as the 2.0 mm laser beam case but less than the 3.0 mm case, this could be because when the keyhole formed, much of the energy is absorbed within the keyhole, and this amount of energy is used to propagate the depth of penetration without much ability to propagate the width due to the multi-reflection within the keyhole (Mayi et al., 2023).

These reasons explain that the width development trend is casual without a specific trend from the perspective of BD effect using EI as the energy factor.

In addition, in Figure 6-9, at low levels of EI (green and blue colour cases), when the BD was increased to 3.0 mm, the width discrepancy was enlarged for different levels of LP, this should be related to the PD reduction dominating over the IT

increment. For the 1.5 mm and 2.0 mm cases, a balance of the energy between the PD and IT variations prompted the process to be insensitive to the LP changing at the low levels of EI.

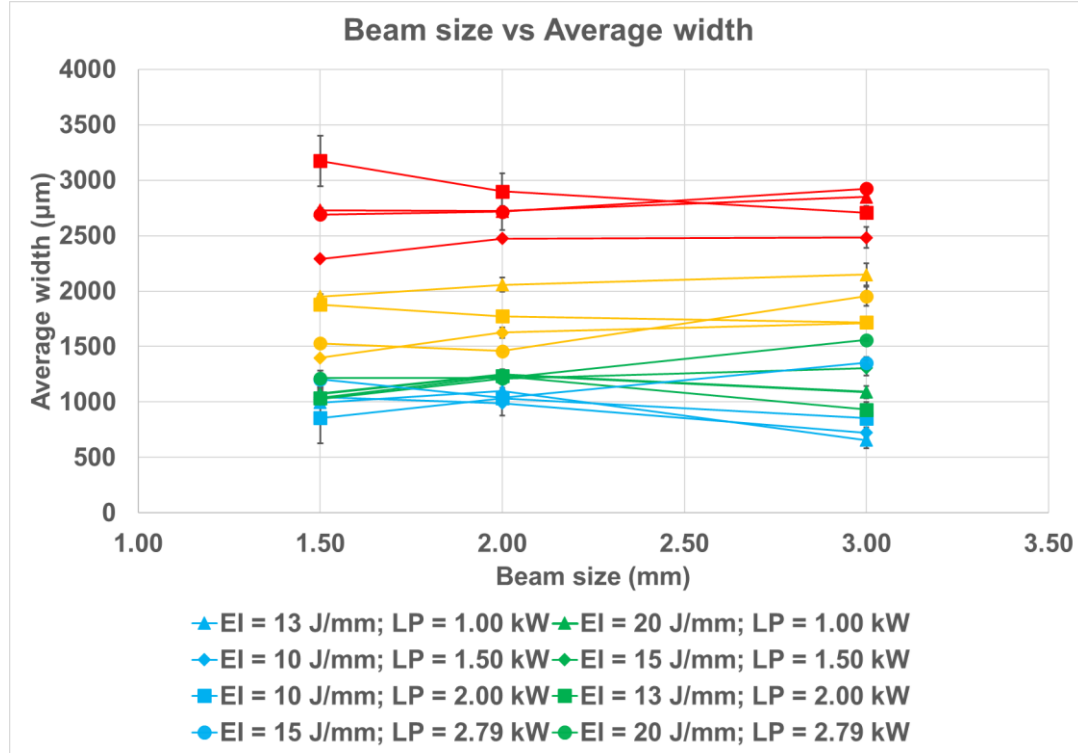


Figure 6-9 Image of BD versus average width at different levels of EI and LP.

In this case, the LP effect was investigated. Figure 6-10 to Figure 6-12 show the LP effect on width at four different levels of EI for three laser beams, respectively. It can be seen that at the 25 J/mm of the low-level EI, the LP did not obviously affect the width compared with the LP variation extent itself.

When the EI, and the BD are the same, based on the EI-based surface ED formula, which is the converted formula from the original surface ED formula (2-5), and EI formula (6-1), the surface ED will be the same.

$$EI - based \text{ Surface } ED = \frac{4EI}{\pi * BD} (J/mm) \quad (6-3)$$

In this case, the reason for similar width at the 25 J/mm of the low-level EI should be attributed to the faster TS compensating for the higher level of LP effect resulting in the same EI with a similar level of thermal cycle and thermal effect. In

this case, a similar width was achieved, of which the length was dominated by the thermal loss.

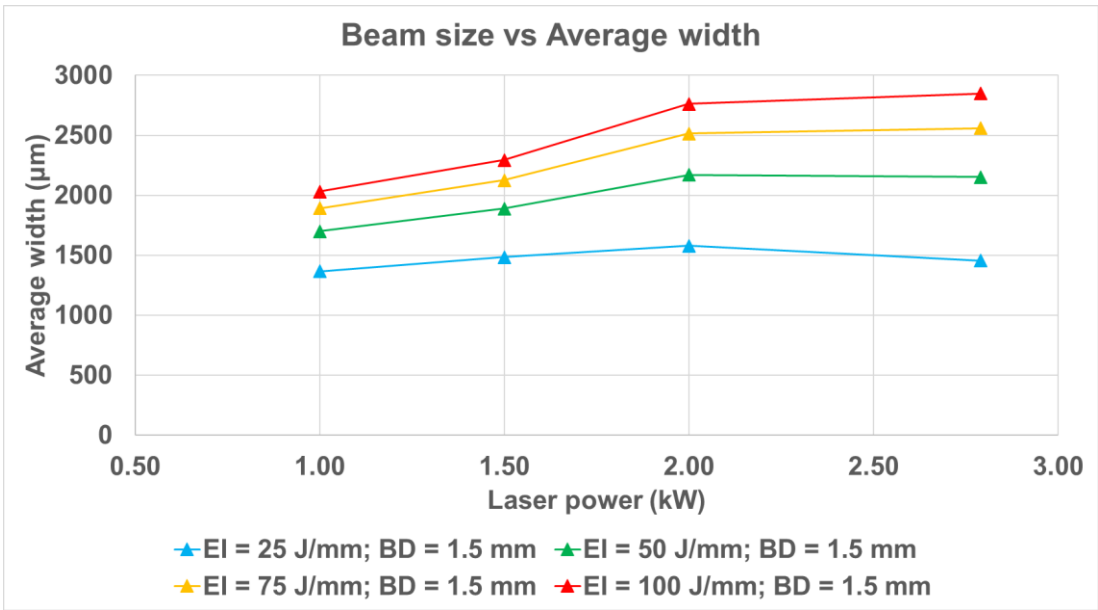


Figure 6-10 Image of LP versus average width at different levels of EI using a 1.5 mm BD.

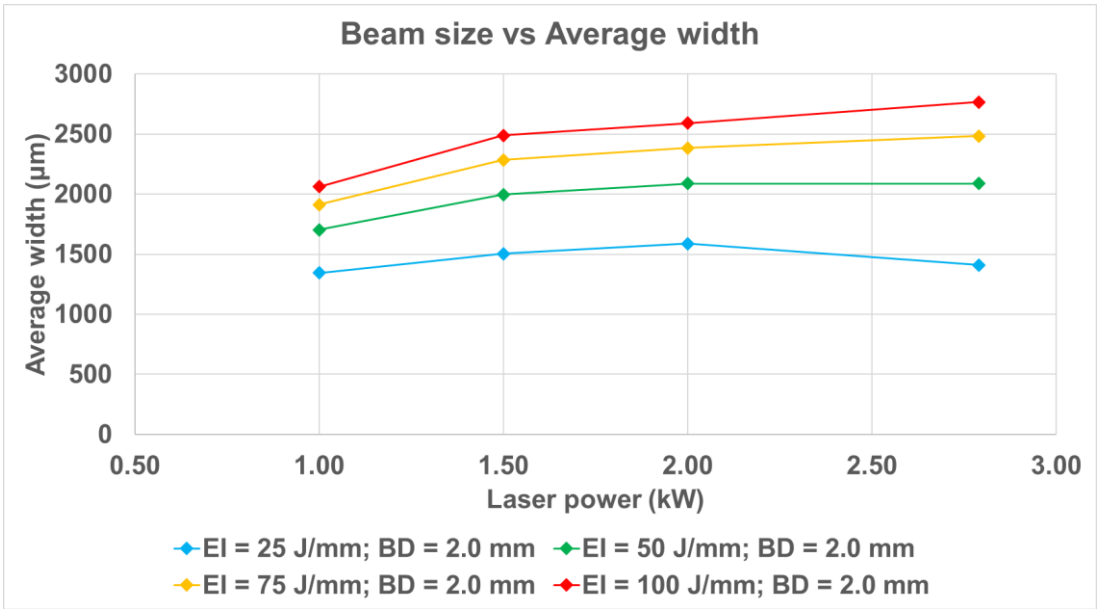


Figure 6-11 Image of LP versus average width at different levels of EI using a 2.0 mm BD.

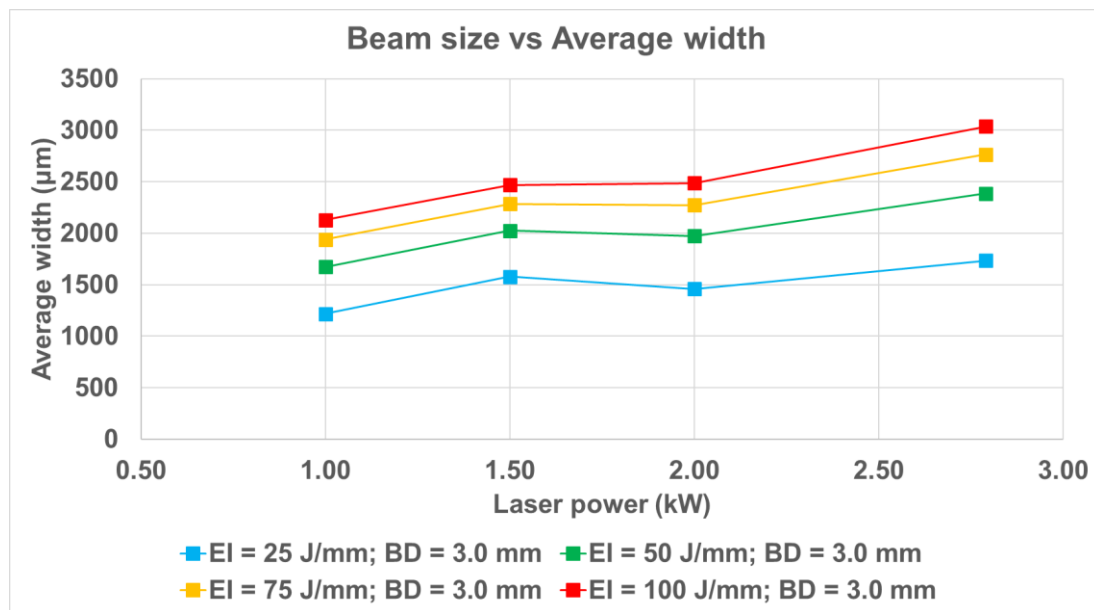


Figure 6-12 Image of LP versus average width at different levels of EI using a 3.0 mm BD.

As a result, for the target width above but close to 1.0 mm at a specific BD ranging from 1.5 mm to 3.0 mm, the weld width is independent of the LP. Based on the same level of EI within the LP ranging from 1.00 kW to 2.79 kW, the required TS can be calculated based on the EI formula (6-1) to achieve the target weld width control independent of the LP.

Therefore, EI is suitable for evaluating the LP effect, but it interferes with the final analysis of the BD effect due to the IT at a larger BD compensation of the PD reduction effect. A similar width that is independent of BD can appear in some specific regimes, but this is not a general trend. The width trend is a competition between the PD and IT, therefore, using EI to judge the BD effect on width performance could make the researcher get a conclusion that at low-level of EI, width is independent of the BD due to the experimental parameters falling into a specific-type width development performance region by chance, this will lead the wrong data analysis and misunderstand the laser BD effect on width from the EI perspective.

Therefore, the BD effect should be discussed at the same IT level base to ensure the true beam size effect under the same laser-material interaction time for a particle material can be reflected.

Due to the different levels of LP used, IT cannot reflect the LP effect. Esp, however, can reflect the LP effect, and the formula contains the IT factor. In this case, the Esp-based LP and BD effect on width will be discussed in the next section.

6.4.2 Effect of Esp, BD, and LP on width

Figure 6-13 shows the overall effect of Esp on width at different levels of LP and BD. Similarly, because the Esp has an inverse relationship with the TS, the width development trend should also exhibit a logarithmic trend referring to the IT trend. Figure_Apx B-8 to Figure_Apx B-14 show the effect of Esp on width at four levels of LP and three levels of BD. (The main purpose is to get the trendline formula; therefore, these figures are placed in the Appendix.)

Esp provides the energy for width propagation, Figure 6-13 indicates that at the low level of Esp (here defined as less than 50 J), as Esp reduces, all the trendlines exhibit a converged trend. At a constant Esp, a higher LP will cause a faster TS to reduce the applied energy via a shorter IT within the laser spot; this will cause the width to be more converged at the low-level Esp cases compared with the IT effect.

Therefore, to investigate the BD and LP influence at the low-level Esp, two levels of low-level Esp (less than 50 J) will be analysed, combined with two higher levels of 100 J and 200 J of Esp to see the width developing trend.

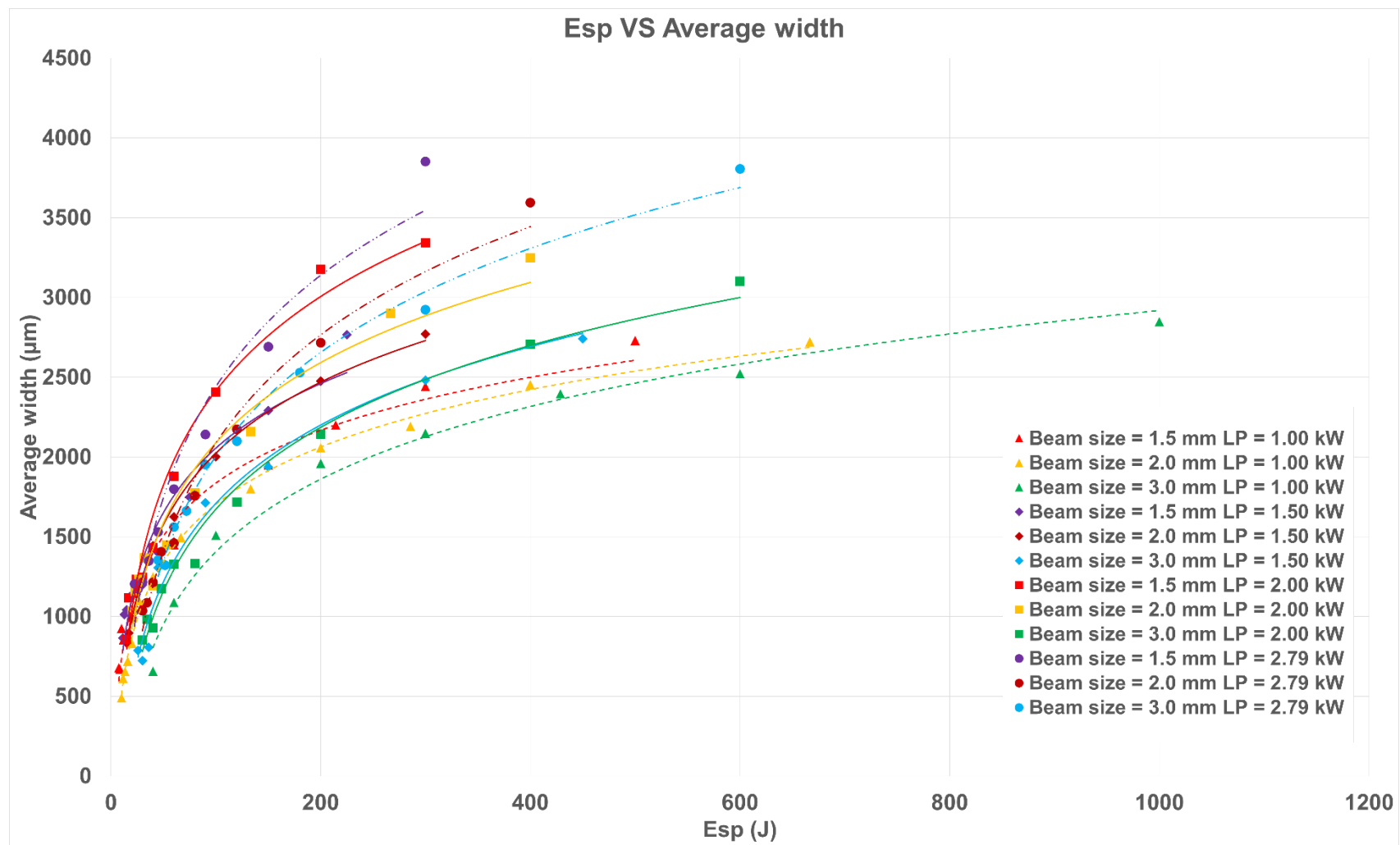


Figure 6-13 Image of Esp versus average width with 1.00 kW to 2.79 kW of LP at 1.5 mm to 3.0 mm BD.

6.4.3 Effect of BD on width at different levels of Esp and LP

In this section, the BD effect versus the average width at different levels of Esp and LP is discussed. Due to the FLMIPs applied, as the BD varies, for a specific level of Esp at a specific level of LP, the IT will always be the same based on the formula (2-3), this ensures the laser-material interaction time for a specific particle within the laser beam is constant and not affected by the longer IT compensation effect as using the EI case exhibited when a larger beam is used. In this case, it can be seen that when increasing the laser beam, the width has a general reduction trend for all cases (Figure 6-14). This is normal because the beam size increases, and the PD reduces accordingly.

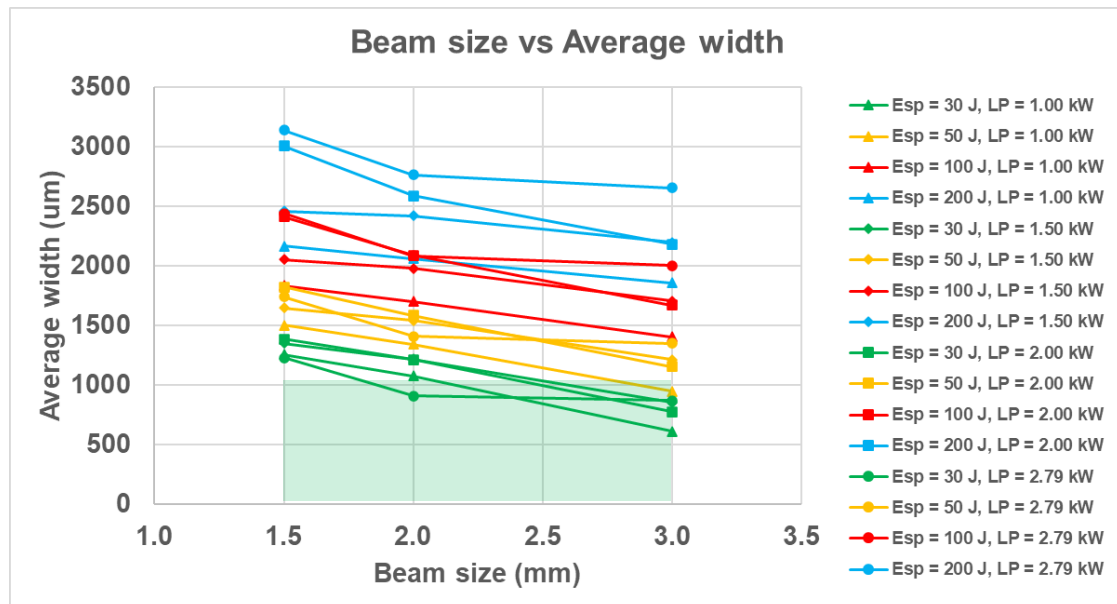


Figure 6-14 Image of BD versus average width with 1.00 kW to 2.79 kW of LP at 30 J to 200 J of Esp.

Also, in Figure 6-14, it can be seen that the millimetre and submillimetre-scale weld widths (green area) were mainly achieved by the Esp falls into the low-level of 30 J for the 1.5 mm to 3.0 mm BD cases. However, for other levels of Esp cases, as the overall width reduction trend shows when the laser beam size increases, either increasing the BD or reducing the Esp to a relatively lower level can prompt the millimetre and submillimetre weld widths achieved for the LP ranging from 1.00 kW to 2.79 kW. However, for the cases with a higher level of

Esp, maybe through the increment of BD to reduce the width cannot work due to the lower-level PD. In this case, the weld width melting could have already been terminated before reaching the millimetre to submillimetre-scale length due to the energy used for melting the width induced by the thermal loss falling below the energy level that cannot enable the material under the laser irradiation to exceed the material's melting point. In this case, a slight increment of LP is essential. Therefore, in the next section, the LP effect on width will be discussed.

6.4.4 Effect of LP on width at different levels of Esp and BD

Figure 6-15 shows the effect of LP versus width at different levels of Esp and BD. Different from the BD effect on width under the same level of Esp, of which the trend is always reduced as the BD increases, this is because of the PD and surface ED reduction. However, the LP effect on width under the same level of Esp is a competition between PD and IT to form the final surface ED, this is because, based on formula (2-1), and (2-3), under the same Esp and laser beam size, increasing the LP reduces the IT, and the PD increases accordingly, which is an inverse relationship for PD and IT. Therefore, the width development trend depends on the dominant factor of either PD or IT.

Figure 6-15 also shows that under different levels of Esp, LP has different effects on the width propagation. At the low-level Esp of 30 J and 50 J, LP did not influence the width obviously compared with the LP variation itself, in this case, the width variation can be concluded as independent of the LP effect when the Esp is below 50 J. This should be because, at low-level Esp, the processing speed is fast, as a result, the IT is short. As the LP increases, the processing speed will increase accordingly; therefore, the effect of increasing LP will be mitigated by the shorter IT further. Moreover, under the same Esp and laser beam size, the surface ED will be the same. At the low level of Esp, even the PD and IT vary and have a competition on PD increment and IT reduction as the LP increases, the integrated same surface ED promoted a similar level of thermal cycle and thermal history effects applied on the surface of the material, therefore, resulting in a similar width performance.

This phenomenon is also observed in the LP effect on width at different levels of EI. Actually, the LP's effect on width considered either from the EI or the Esp perspective is the same, this is because when discussing about the LP effect and maintaining the beam size constant, when looking into the EI formula (formula 6-1) and Esp formula (a combination of formula 2-2 and formula 2-3), the only difference is the Esp has the BD factor in the formula to limit the particle interaction with the laser within the beam size length. If the beam size is constant, EI and Esp will have the same impact in terms of the LP influence on width.

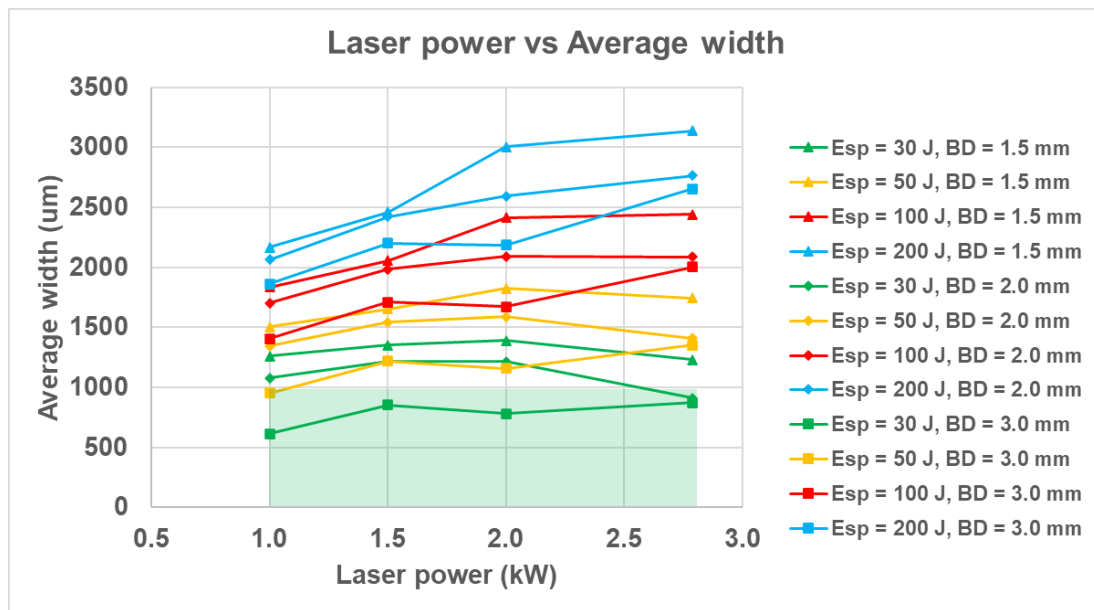


Figure 6-15 LP versus average width with 1.5 mm to 3.0 mm of BD at 30 J to 200 J of Esp.

The difference lies in that, for the EI-based width development trend analysis, when analysing the BD effect, IT is used to explain the issue; when analysing the LP effect, the surface ED is also mentioned in the context to help explain the reason for similar widths achieved under different BD, surface ED comes from the combination of PD and IT, these two parameters belong to the FLMIPs. In this case, the advantage of using Esp-based energy factor over EI-based energy factor to analyse the BD and LP width development trend on width stands out: i.e., using the Esp-based energy factor can utilise the factors belonging to FLMIPs to help analyse the reason directly. However, using the EI-based energy factor to analyse the LP and BD effect, the IT, surface ED (PD x IT) coming from FLMIPs

has to be used to assist in analysing the reasons, even if the LP effect on width are the same from either the EI or Esp-based energy factor perspective consideration.

Moreover, when using the Esp-based energy factor to analyse the BD effect on width, the interference of longer IT when using a larger beam can be avoided, the same IT for different BD cases can be maintained. Overall, FLMIPs are more useful than the EI itself to analyse the BD and LP effects on width evolution trends, especially for the BD effect, using FLMIPs can maintain the same IT for comparison.

On top of that, when it comes to the comparison of LP and BD effect on width, it can be seen that BD has more influence than the LP on the width variation when the Esp is less than 50 J. This reveals that when processing at fast speeds to achieve the same low-level Esp, for instance, less than 50J, the change of laser beam profile by varying the BD has a greater effect on width variation than the LP variation effect with a constant beam profile. This is because: increasing PD has two ways, one is reducing the BD (beam profile changes also), and the other one is increasing the LP (beam profile does not change), at the short Esp phase, the laser-material interacted duration is short and this duration is reduced further accordingly as the LP increases to maintain the same level of Esp, this will weaken the LP increment influence significantly, but the beam profile does not change. In this case, LP variation has less effect compared with the BD variation effect on the width variation under the same but relatively low-level Esp due to the BD variation also causing the beam profile to change.

Overall, from FLMIPs perspective, when using the Esp-based energy factor, for analysing the BD effect only, IT are maintained constant to remove the interference of compensation PD reduction effect caused by a longer IT of using a larger beam. For analysing the LP effect only, IT will accordingly adjust to ensure the energy within the laser spot is constant. Similarly, to maintain the same EI at different levels of LP from the system parameter perspective, TS will also adjust accordingly to ensure the energy along the deposition direction is constant. Therefore, for studying the BD effect only, Esp should be used. For

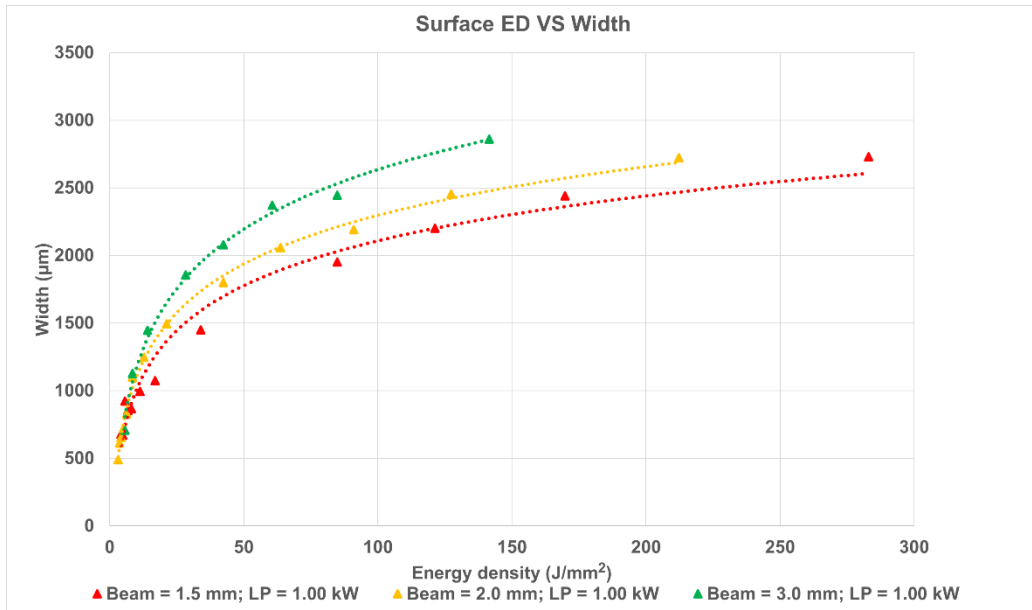
studying the LP effect only, either using EI or Esp as the energy is making sense, the only difference is the Esp has a BD factor in the formula, however, when study the LP effect only, the BD factor needs to be kept constant. Thus, there is no difference between using EI and Esp. But using Esp as the energy is a more reasonable way to express the energy within the laser spot,

However, if changing the LP and BD simultaneously to investigate, for instance, the same PD effect on width. Esp-based energy factor should be used for discussion because the IT will be adjusted according to both the LP and BD variation to achieve the final but same Esp.

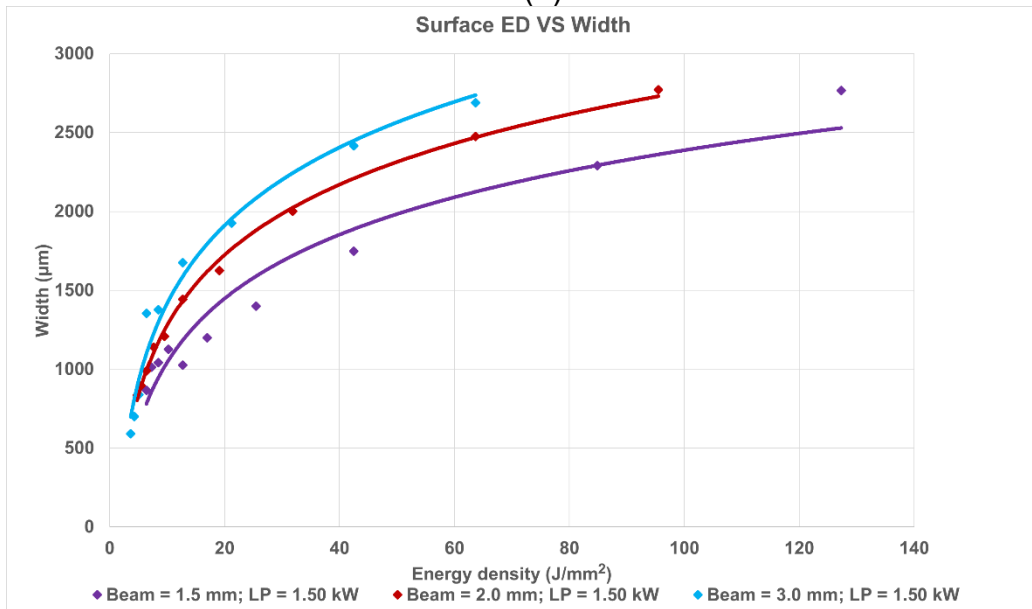
As for the LP effect, FLMIPs enable the weld width development phenomenon analysis through the IT and PD effect, of which the product is surface ED. This indicates the importance of using FLMIPs in analysing the weld width development trend processed at low-level energy (conduction mode welds). Also, emphasises the importance of using the surface ED factor on weld width development analysis at different levels of LP. Therefore, the surface ED will be mainly discussed in the next section.

6.4.5 Effect of surface ED, BD, and LP on the width

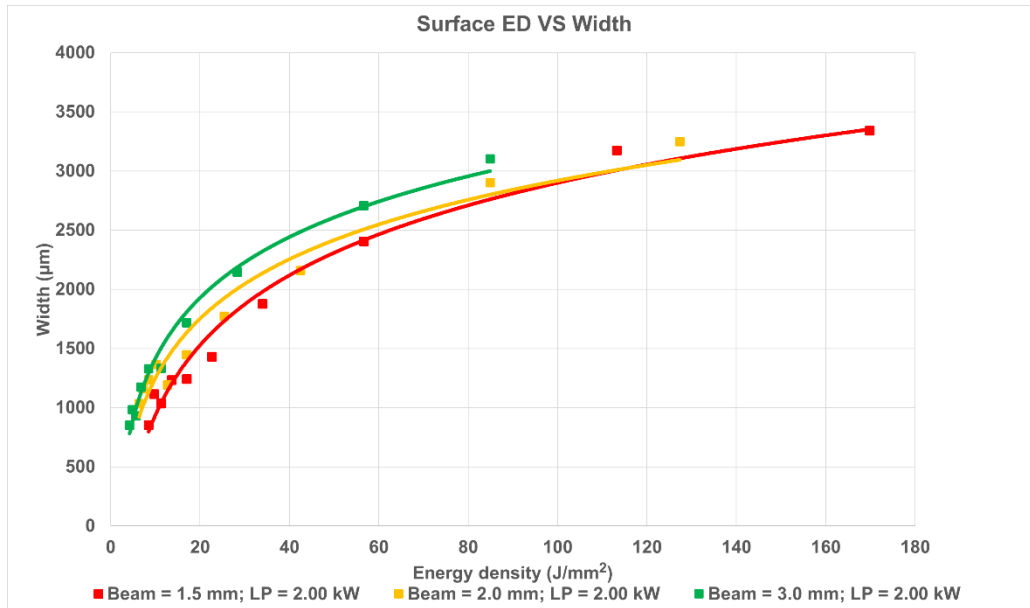
EI reflects the linear energy density; it is a one-dimensional factor mainly focusing on the deposition direction's influence. Therefore, the laser beam size effect cannot be truly reflected. On the contrary, surface ED with laser beam size included in the formula, which is a 2-dimensional factor. Therefore, the beam size effect can be reflected through investigating the surface ED on the geometry dimensions. Figure 6-16 (a) – (d) indicates the surface ED versus the width at four levels of LP for three levels of BD, unlike the cases using 500 W of LP, the crossing point that inverses the beam size's effect on width (Figure 5-8) is not observed at the width close to 1.0 mm as the surface ED increases in these cases which indicates that the surface ED only has one regime to control the width due to the high energy applied within the LP ranging from 1.00 kW to 2.79 kW. I.e., a large beam size always has a wider width. But the trendlines show a converging trend at a narrower width as the surface ED reduces, which indicates that a crossing point could happen at a lower surface ED.



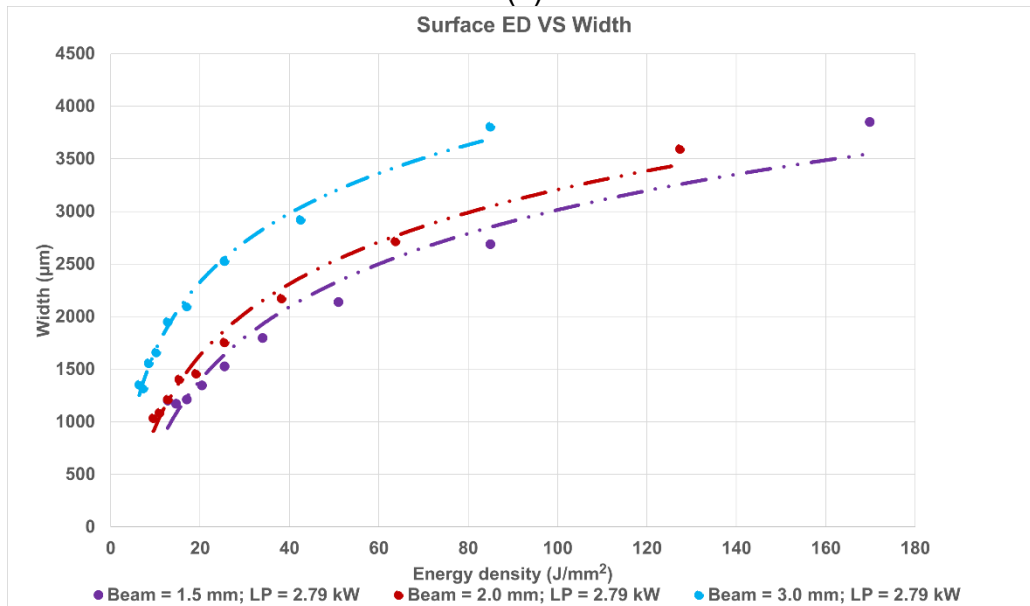
(a)



(b)



(c)



(d)

Figure 6-16 Surface ED versus average width at (a) 1.00 kW, (b) 1.50 kW, (c) 2.00 kW, and (d) 2.79 kW of LP under 1.5 mm to 3.0 mm of BD.

When adding the 500 W of LP, 1.5 mm and 2.0 mm laser beam cases conducted in the previous chapter as comparison. The results in Figure 6-17 indicate that under the same surface ED for the same laser beam case, a higher level of LP always has a wider width. And to achieve a 1.0 mm width, a higher LP is used, a lower surface ED is required, but as the LP increases, the discrepancy of the required surface ED becomes small.

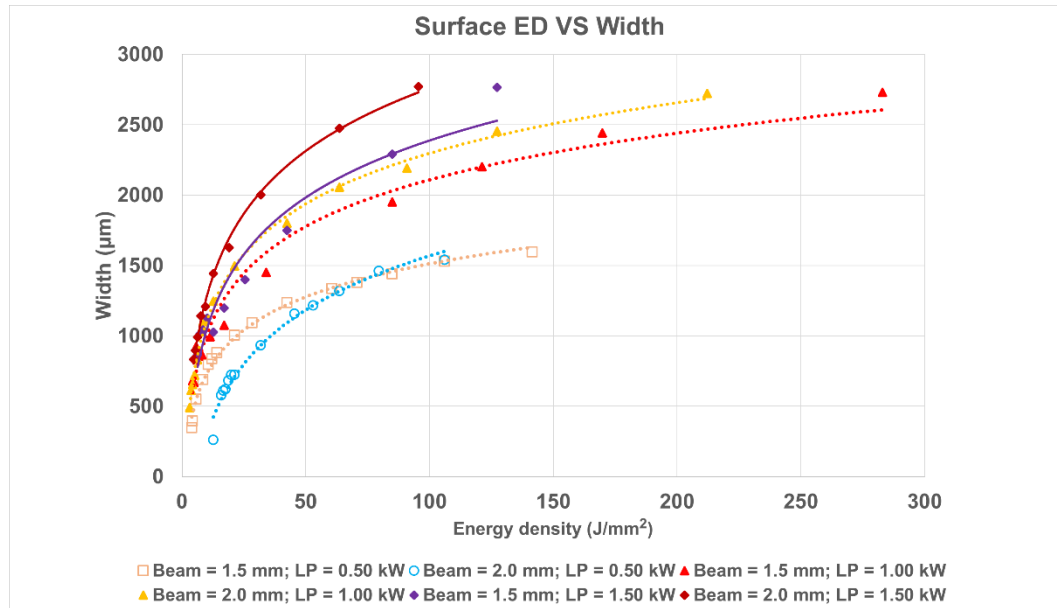


Figure 6-17 Surface ED versus average width with 0.50 kW to 1.50 kW of LP at 1.5 mm to 2.0 mm of BD.

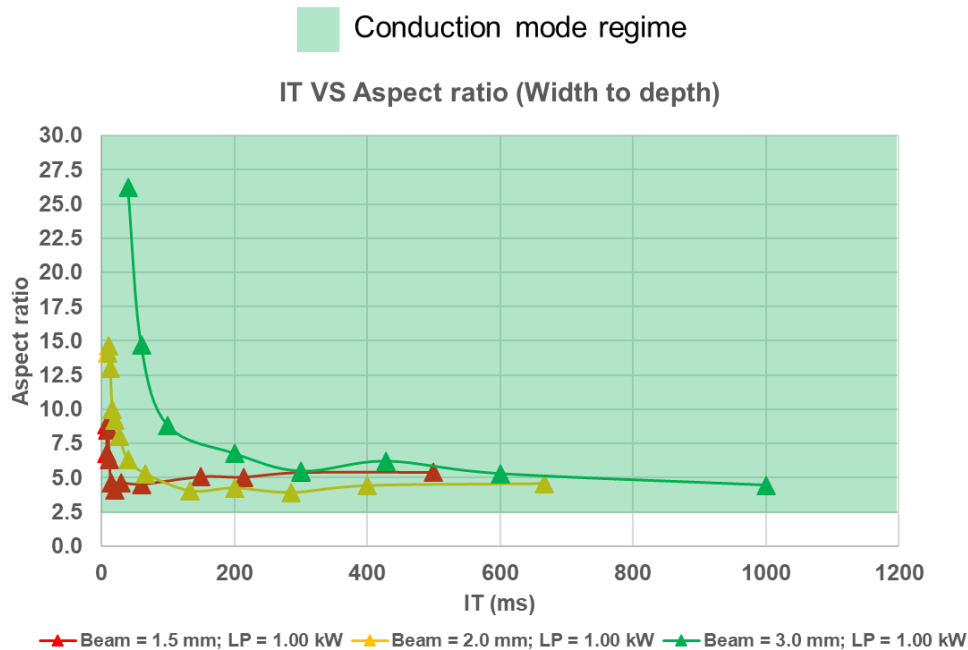
Based on the surface ED density formula (5-2), at a constant beam diameter, increasing LP, the IT will reduce accordingly to have the same surface ED. A higher LP with a shorter IT to achieve the same surface ED, but caused a wider width, this should be attributed to the higher PD. A shorter IT means a faster processing speed, therefore, accurately, the phenomenon of wider width at a higher level of LP but the same surface ED should be because of the higher p-PD, which shows a more obvious and real influence when processing at a fast speed.

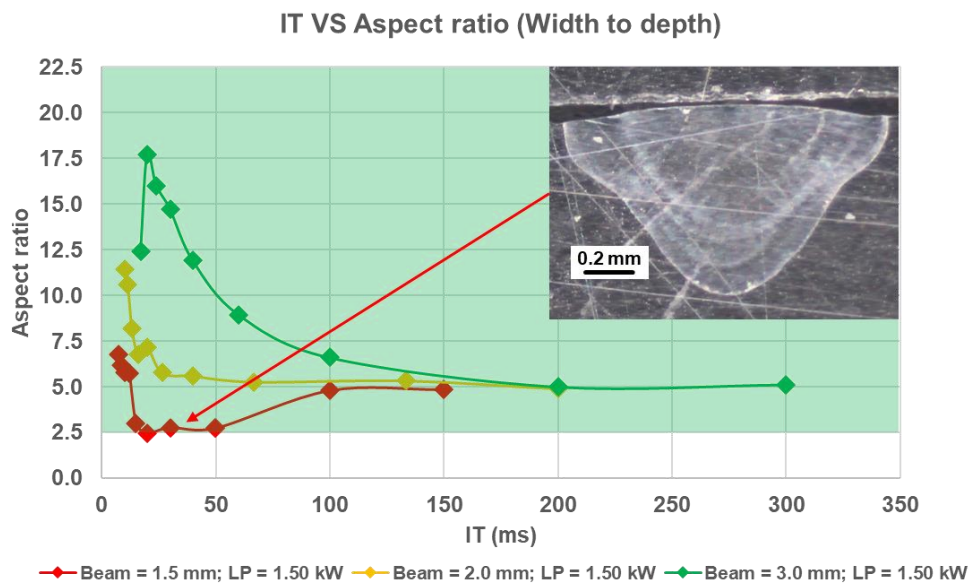
This reflects the importance of the real energy distribution effect applied on the substrate, which integrates the real laser beam intensity profile with different processing IT durations on the width propagation when the surface ED is the same. A higher LP will cause a higher energy distribution along the laser beam profile, even the speed is higher at high-level LP case, and even the surface ED, Esp are the same, the instantaneous energy caused by the high peak power density combined with the corresponding IT that can project on the material surface is higher resulting in a wider width. In this case, the calculated surface ED is the same, but the real instantaneous surface ED is different, which is independent of the formula calculation and mainly affected by the high peak

power density. This explains why achieving a 1.0 mm weld width, a lower LP requires more surface ED rather than a similar surface ED. And also explains why as the LP reduces, the discrepancy of required surface ED compared with that of a higher-level LP becomes larger.

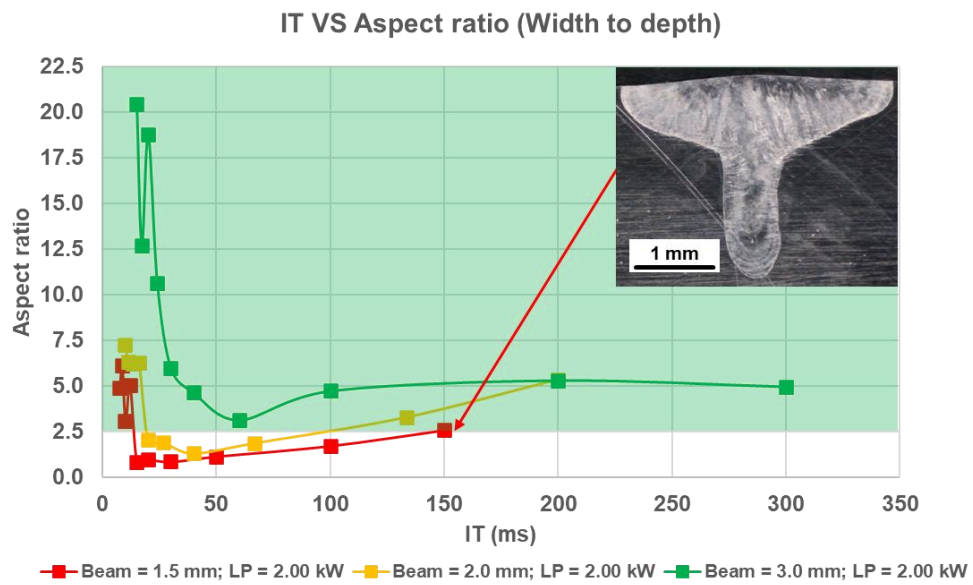
6.4.6 Determination of the bead profile regime and parameters filtering

Conduction mode deposition is favourable for additive manufacturing. To prompt the successful deposition (here, due to the high-level LP used, the successful deposition is defined as a stable process with continuous bead formation without the plume interference), welds with conduction mode profiles should be filtered out accurately to obtain the processing parameters information. Figure 6-18 (a) – (d) indicates the IT against the aspect ratio of width over depth of penetration at different levels of LP, based on the judgement criteria, the value over 2.5 should correspond to conduction mode (Assuncao et al., 2012) and (Abioye et al., 2013)





(b)



(c)

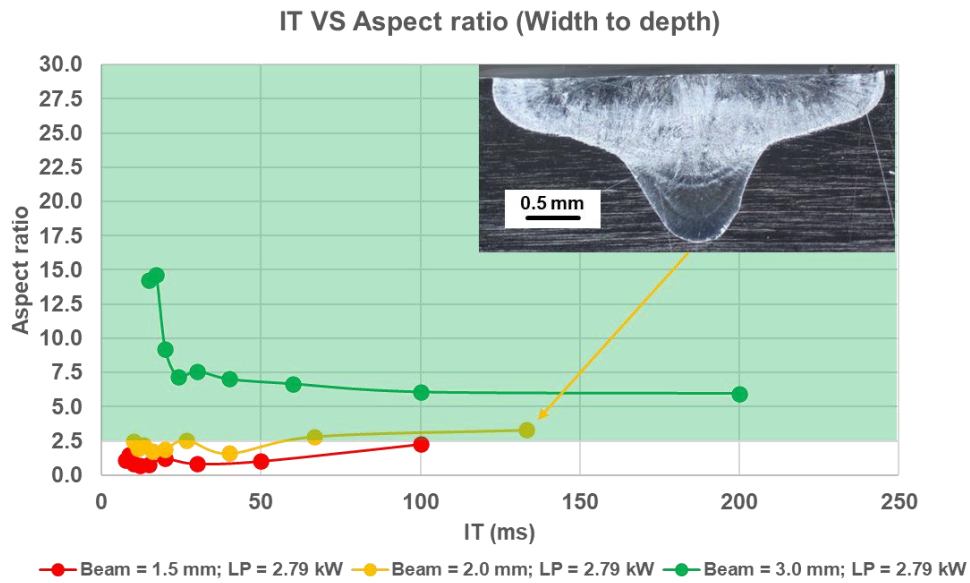


Figure 6-18 Images of IT versus aspect ratio at (a) 1.00 kW, (b) 1.50 kW, (c) 2.00 kW, and (d) 2.79 kW of LP and the corresponding conduction regime region.

However, due to the large BD and high LP used, the commonly used criterion to identify the regime of the deposits is not accurate, large width will interfere with the aspect ratio significantly.

For instance, using a 1.50 kW of LP and a 1.5 mm laser beam, the cross-sectional image shown in Figure 6-18 (b) exhibits a transition mode profile but is classified as a conduction mode profile based on the width-to-depth aspect ratio. Similarly, the cross-sectional profiles shown in Figure 6-18 (c) and Figure 6-18 (d) also have this misjudgment issue.

Therefore, using the width-to-depth aspect ratio method cannot filter the work mode out accurately. This indicated that each case with a different level of LP and laser beam size has a unique judging criterion.

A modified formula of heat input index based on the experimental width and depth of penetration originally from (Chowdhury et al., 2020) was proposed to use the experimental volumetric energy density applied on the enthalpy needed to melt the unit volume of the autogenous laser weld from room temperature to melting temperature to get the heat input index to filter the conduction mode out accurately. The heat input index formula is given below:

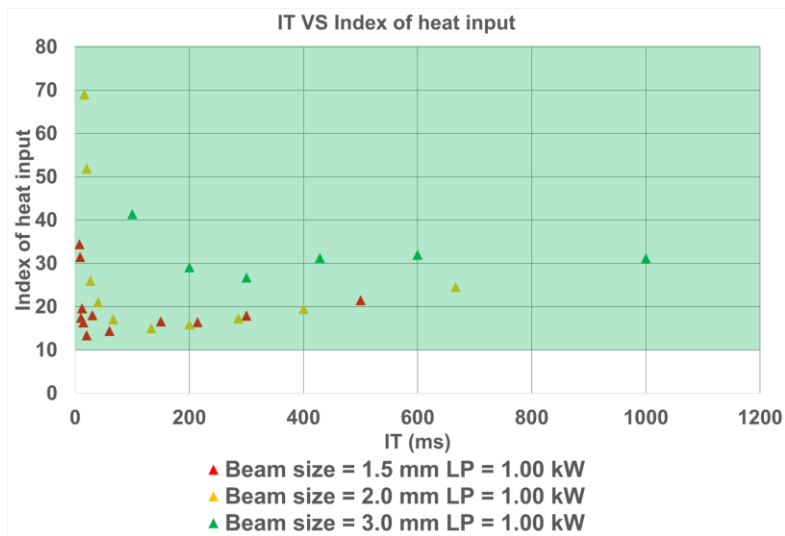
$$\text{Heat input index} = \frac{4 * E_{sp} / (\pi * w^2 * d)}{\rho [C_p (T_m - T_0) + L]} \quad (6-4)$$

Where w represents the experimental width of the autogenous laser weld, d represents the experimental depth of penetration, ρ represents the material density (kg/m^3), C_p represents the heat capacity ($\text{J}/(\text{kg} \cdot \text{K})$), T_m represents the liquidus temperature (K), T_0 represents the room temperature (K), L represents the latent heat of fusion (J/kg).

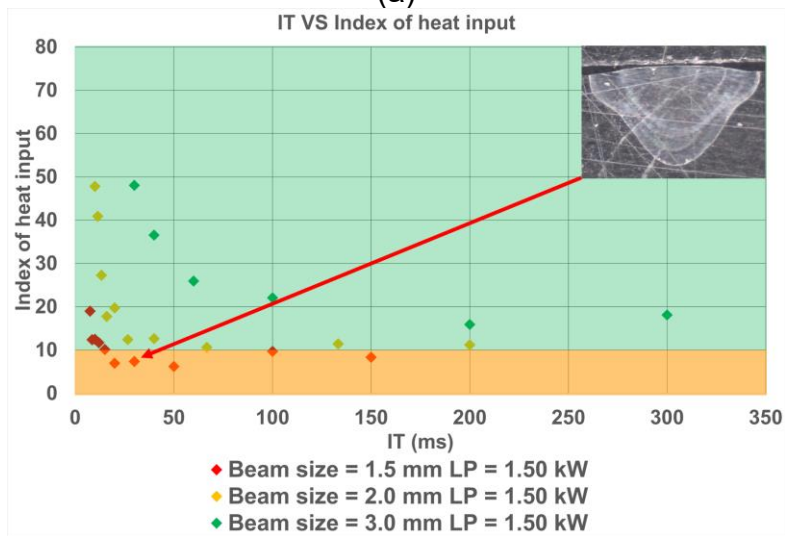
The heat input index indicates the required heat input index level to achieve the specific type(s) of autogenous laser weld profile(s). The index is used to distinguish the conduction mode from the transition and keyhole mode weld profiles. A high index value above 10 refers to the process that requires a high level of volumetric energy density to melt the material from the solid state to the melt state, resulting in difficulty in reaching the transition mode or keyhole mode. As the index reduces, the required volumetric energy density reduces, which means under this case, it is easy to open the melt pool. This results in a large size of the melt pool formation, therefore easy to form the transition mode and the keyhole mode profile. In this case, the transition mode and keyhole mode profiles can be constricted within a relatively low heat input index value and are easy to filter out due to the wide width and deep penetration achieved.

Figure 6-19 (a)-(d) shows the results of the heat input index against the IT. The cases that fall above a value of roughly 10 of the heat input index can be judged as the conduction mode. In this situation, the keyhole mode and transition mode cases can be constricted below 10. The misjudgements mentioned in the width-depth aspect ratio can be sorted out in this case. Therefore, the accurate conduction mode cases can be filtered out by one standard criterion without varying the reference value.

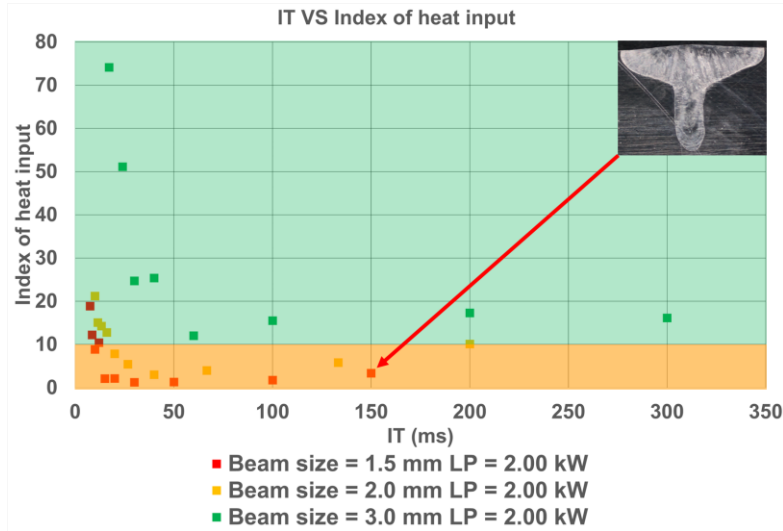
Conduction regime
 Transition and keyhole regime



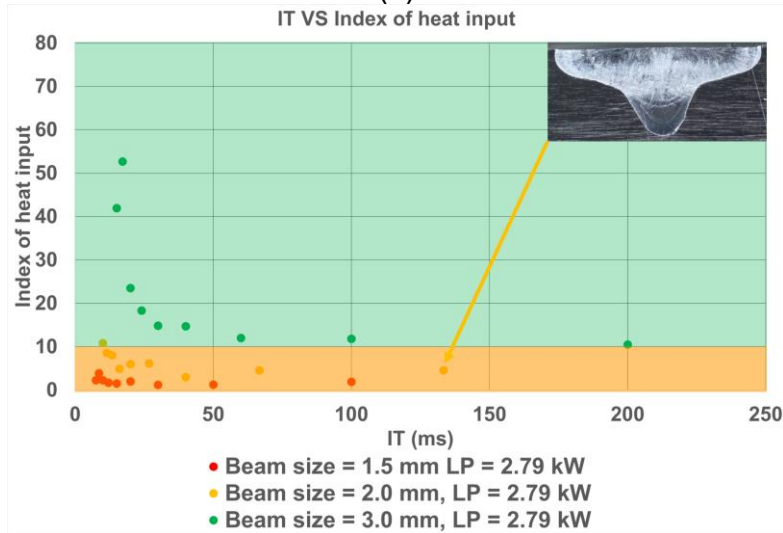
(a)



(b)



(c)



(d)

Figure 6-19 Images of IT versus heat input index at (a) 1.00 kW, (b) 1.50 kW, (c) 2.00 kW, and (d) 2.79 kW of LP and the corresponding conduction, transition and keyhole regime region.

Thereafter, the width close to 1.0 mm, conduction mode autogenous laser welds with good appearance and surface condition within the BD ranging from 1.5 mm to 3.0 mm were filtered out. The parameters are summarised below in Table 6-6 to Table 6-9.

Table 6-6 to Table 6-9 also exhibit the top-view of the autogenous laser welds that performed relatively good, the widths are close but larger than 1.0 mm, the surface condition is good with a consistent width achieved. The welds are straight

and continuous, of which the parameters can be used for future added wire process studies.

Table 6-6 Filtered autogenous laser welds and the corresponding parameters and width at 1.00 kW of LP.

Beam size (mm)	IT (ms)	TS range (mm/s)	Average width (μm)
1.5	30	50	1075
			
2.0	27	50	1248
			
2.0	40	75	1101
			
3.0	60	50	1089
			

Table 6-7 Filtered autogenous laser welds and the corresponding parameters and width at 1.50 kW of LP.

Beam size (mm)	IT (ms)	TS range (mm/s)	Average width (μm)
1.5	12	125	1125
			
1.5	10	150	1042
			
1.5	9	175	1013
			
2.0	40	50	1626
			
2.0	27	75	1443
			
2.0	20	100	1209
			
2.0	16	125	1141
			
3.0	60	50	1714

			
3.0	40	75	1468
			
3.0	30	100	1307
			

Table 6-8 Filtered autogenous laser welds and the corresponding parameters and width at 2.00 kW of LP.

Beam size (mm)	IT (ms)	TS range (mm/s)	Average width (μm)
1.5	9	175	1116
 			
2.0	16	125	1366
 			
2.0	13	150	1234
 			
2.0	11	175	1158
 			
2.0	10	200	1039
 			
3.0	40	75	1332
 			
3.0	30	100	1329
 			
3.0	24	125	1173
 			

Table 6-9 Filtered autogenous laser welds and the corresponding parameters and width at 2.79 kW of LP.

Beam size (mm)	IT (ms)	TS range (mm/s)	Average width (μm)
3.0	15	200	1353
			

Overall, the autogenous laser welds of the 2.0 mm and 3.0 mm cases performed better than the 1.5 mm BD cases. 1.00 kW to 2.00 kW of LP performed better

than 2.79 kW. The surface conditions of the beads produced with larger beams are better, with fewer ripples appearing, and with a wider processing window to produce welds in conduction mode. Therefore, 2.0 mm and 3.0 mm laser beams will be used for the bead on plate deposition. The speed range was initially identified as a wide range of between 50 mm/s to 200 mm/s because when adding the wire to the process, a three-dimensional energy distribution can complicate the deposition process; therefore, a wide speed range for deposition feasibility investigation is ideal.

6.5 Bead on plate deposition

The feasible speed range within 1.5 mm to 3.0 mm of laser BD under 1.00 kW to 2.79 kW levels of LP has been identified as between 50 mm/s to 200 mm/s in the previous autogenous laser welds section. In this section, the feasible speed range after adding the wire is identified followed by investigating the process window based on WFS to TS ratios within the available speed range on the 180 mm x 190 mm x 6 mm 316L SS substrate. A 0.6 mm in diameter wire was used. Thereafter, the process window performance is discussed. The process repeatability of the bead-on-plate with good performance was examined on either the same substrate or a different substrate. The effect of BD on wire position sensitivity was studied by deviating the wire from the aligned position.

6.5.1 Study of processing speed window

The feasible parameters that can form a weld width close to 1.0 mm have been identified. 2.0 mm and 3.0 mm laser beams were chosen for the bead on plate deposition. In these preliminary experiments for the processing speed range study, 50 mm/s and 100 mm/s of the TS were mainly used, which can set a baseline and reference point for the available processing speed range of the wire added process, thereafter, a determination of whether is necessary to increase the TS to 200 mm/s finally can be judged. Accordingly, use 50 mm/s and 100 mm/s of the WFS with a WFS to TS ratio of 1 to test the feasibility of bead on plate deposition, this is because, firstly, based on 500 W cases, the WFS to TS ratio equals 1 is always the boundary for the successful deposition, this enables the future investigation on the increment of the WFS. Secondly, using this level

of WFS with the WFS to TS ratio of 1 can allow more energy to be transferred to the substrate compared with higher-level WFS cases, which can ensure the substrate receives a higher amount of energy. Meanwhile, this can give a reference for whether feasible or necessary to reduce the WFS further to achieve the continuous bead by allowing more energy to be transferred to the substrate.

The feasible LP range has been identified for the specific laser beams as between 1.00 kW to 2.00 kW; the 2.79 kW LP case has just one feasible parameter set with the use of a 3.0 mm laser beam. However, considering the wire can also absorb the energy from the laser heat source, which reduces the amount of energy being transferred to the substrate resulting in mitigating or even blocking the keyhole mode and transition mode formation. In this case, full levels of LP ranging from 1.00 kW to 2.79 kW were investigated to observe the deposition phenomenon. The sample identification and the corresponding parameters using 2.0 mm and 3.0 mm are listed in Table 6-10, Table 6-11.

Table 6-10 Sample identifications and parameters of the 2.0 mm laser BD cases.

Deposit ID	BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
6-1	2.0	1.00	50	50	31.83	40	40
6-2	2.0	1.50	50	50	47.74	40	60
6-3	2.0	2.00	50	50	63.66	40	80
6-4	2.0	2.79	50	50	88.81	40	112
6-5	2.0	1.00	100	100	31.83	20	20
6-6	2.0	1.50	100	100	47.74	20	30
6-7	2.0	2.00	100	100	63.66	20	40
6-8	2.0	2.79	100	100	88.81	20	56

Table 6-11 Sample identifications and parameters of the 3.0 mm laser BD cases.

Deposit ID	BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	PD (kW/cm ²)	IT (ms)	Esp (J)
6-9	3.0	1.00	50	50	14.14	60	60
6-10	3.0	1.50	50	50	21.22	60	90
6-11	3.0	2.00	50	50	28.29	60	120
6-12	3.0	2.79	50	50	39.47	60	167
6-13	3.0	1.00	100	100	14.14	30	20
6-14	3.0	1.50	100	100	21.22	30	45
6-15	3.0	2.00	100	100	28.29	30	60
6-16	3.0	2.79	100	100	39.47	30	84

The bead on plate deposition performance evaluation criterion is listed in Table 6-12.

Table 6-12 Deposition performance evaluation criterion of bead on plate processed at high-level LP.

Symbol	Category	Descriptions
	Good	Stable performed, and continuous tracks with smooth surfaces without the plume interference
	Poor	Irregular tracks with bad surface texture
	Failed	Discontinuous beads, wire dripping, wire stubbing

The preliminary process windows are shown in Figure 6-20 and Figure 6-21. The corresponding bead performance of the overall top view for 2.0 mm and 3.0 mm BD cases is listed in Table 6-13 and Table 6-14, respectively. Compared with these results, it can be seen that the 50 mm/s of the TS case performed better than the 100 mm/s case for both laser beam cases. The 2.0 mm laser beam cases at 50 mm/s of TS performed better than the 3.0 mm laser beam cases processed at 50 mm/s of TS. The bad performance of the 100 mm/s cases for the two laser beams cases should be due to the lack of enough energy owing to the processing speed being too fast. Therefore, 200 mm/s of TS maximumly identified which can achieve the autogenous weld width close to 1.0 mm previously will not be considered. A lower processing speed of less than 100 mm/s is necessary; thus, for the process window study, the maximum TS was set at 75 mm/s, which can increase the energy and also compensate for the PD reduction effect when using a 3.0 mm laser beam.

Figure 6-20 Preliminary process window of 2.0 mm BD case at 50 mm/s to 100 mm/s of TS.

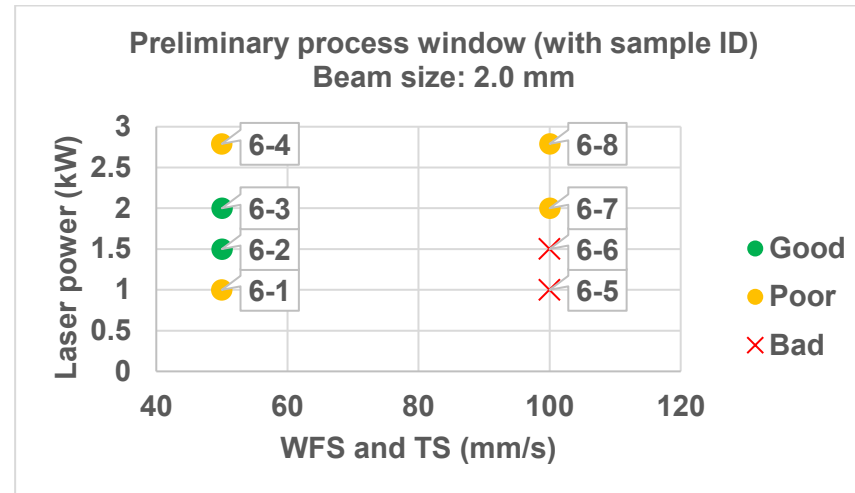


Table 6-13 The top-view appearance of the bead on plate and the corresponding sample ID.

ID	Top-view appearance	ID	Top-view appearance
6-4		6-8	
6-3		6-7	
6-2		6-6	
6-1		6-5	

Figure 6-21 Preliminary process window of 3.0 mm BD case at 50 mm/s to 100 mm/s of TS.

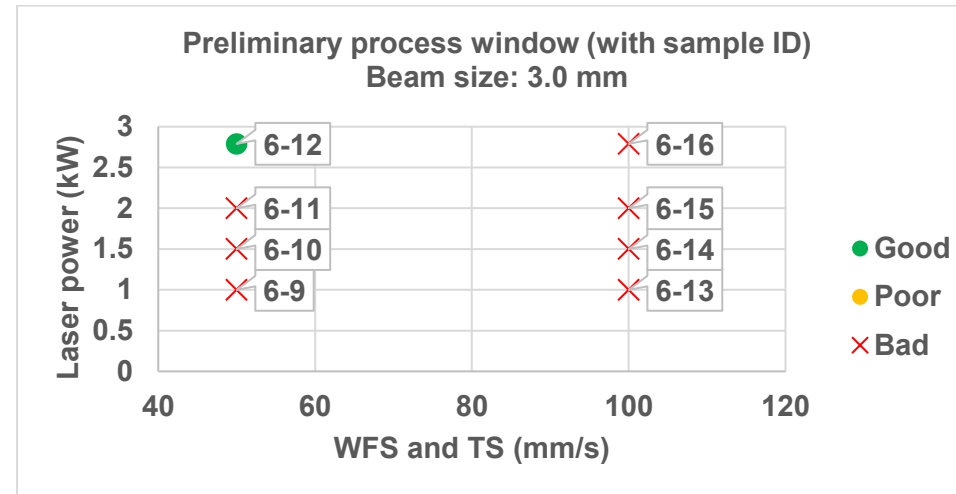


Table 6-14 The top-view appearance of the bead-on-plate and corresponding sample ID.

ID	Top-view appearance	ID	Top-view appearance
6-12		6-16	
6-11		6-15	
6-10		6-14	
6-9		6-13	

6.5.2 WFS to TS ratio-based process window investigation

In this section, 50 mm/s and 75 mm/s of the TS were adopted with different WFS combinations for achieving the target WFS to TS ratios of 0.80, 1.00 and 1.25, respectively, to study the feasibility of bead on plate deposition and to identify the process window. 1.00 kW of LP was excluded due to the poor performance shown in the preliminary study. Table 6-15 lists the sample ID and the corresponding processing parameters for 2.0 mm and 3.0 mm BD cases processing at 50 mm/s and 75 mm/s of TS.

Table 6-15 Sample identification and the corresponding parameters at 2.0 mm and 3.0 mm BD, 50 mm/s, and 75 mm/s of TS.

Deposit ID	WFS/ TS	WFS (mm/s)	TS (mm/s)	BD (mm)	LP (kW)	PD (kW/cm ²)	IT (ms)	Esp (J)	Surface ED (J/mm ²)
6s-2-1	0.80	40.00	50	2	1.50	47.75	40.00	60	15.00
6s-2-2	0.80	40.00	50	2	2.00	63.66	40.00	80	20.00
6s-2-3	0.80	40.00	50	2	2.79	88.81	40.00	112	27.90
6s-2-4	1.00	50.00	50	2	1.50	47.75	40.00	60	15.00
6s-2-5	1.00	50.00	50	2	2.00	63.66	40.00	80	20.00
6s-2-6	1.00	50.00	50	2	2.79	88.81	40.00	112	27.90
6s-2-7	1.25	62.50	50	2	1.50	47.75	40.00	60	15.00
6s-2-8	1.25	62.50	50	2	2.00	63.66	40.00	80	20.00
6s-2-9	1.25	62.50	50	2	2.79	88.81	40.00	112	27.90
6s-2-10	0.80	60.00	75	2	1.50	47.75	26.67	40	10.00
6s-2-11	0.80	60.00	75	2	2.00	63.66	26.67	53	13.33
6s-2-12	0.80	60.00	75	2	2.79	88.81	26.67	74	18.60
6s-2-13	1.00	75.00	75	2	1.50	47.75	26.67	40	10.00
6s-2-14	1.00	75.00	75	2	2.00	63.66	26.67	53	13.33
6s-2-15	1.00	75.00	75	2	2.79	88.81	26.67	74	18.60
6s-2-16	1.25	93.75	75	2	1.50	47.75	26.67	40	10.00
6s-2-17	1.25	93.75	75	2	2.00	63.66	26.67	53	13.33
6s-2-18	1.25	93.75	75	2	2.79	88.81	26.67	74	18.60
6s-3-1	0.80	40.00	50	3	1.50	21.22	60.00	90	10.00
6s-3-2	0.80	40.00	50	3	2.00	28.29	60.00	120	13.33
6s-3-3	0.80	40.00	50	3	2.79	39.47	60.00	167	18.60
6s-3-4	1.00	50.00	50	3	1.50	21.22	60.00	90	10.00
6s-3-5	1.00	50.00	50	3	2.00	28.29	60.00	120	13.33
6s-3-6	1.00	50.00	50	3	2.79	39.47	60.00	167	18.60
6s-3-7	1.25	62.50	50	3	1.50	21.22	60.00	90	10.00
6s-3-8	1.25	62.50	50	3	2.00	28.29	60.00	120	13.33
6s-3-9	1.25	62.50	50	3	2.79	39.47	60.00	167	18.60
6s-3-10	0.80	60.00	75	3	1.50	21.22	40.00	60	6.67
6s-3-11	0.80	60.00	75	3	2.00	28.29	40.00	80	8.89
6s-3-12	0.80	60.00	75	3	2.79	39.47	40.00	112	12.40

6s-3-13	1.00	75.00	75	3	1.50	21.22	40.00	60	6.67
6s-3-14	1.00	75.00	75	3	2.00	28.29	40.00	80	8.89
6s-3-15	1.00	75.00	75	3	2.79	39.47	40.00	112	12.40
6s-3-16	1.25	93.75	75	3	1.50	21.22	40.00	60	6.67
6s-3-17	1.25	93.75	75	3	2.00	28.29	40.00	80	8.89
6s-3-18	1.25	93.75	75	3	2.79	39.47	40.00	112	12.40

Figure 6-22 – Figure 6-23 show the process window using a 2.0 mm laser beam size with 50 mm/s and 75 mm/s of TS, respectively. Table 6-16 and Table 6-17 list all these cases' top-view appearance for a better observation of different categories of the performance.

When using a 2.0 mm laser beam size with 50 mm/s of TS, only the cases with a WFS to TS ratio of 1, LP ranging from 1.50 kW to 2.00 kW (6s-2-4, 6s-2-5) were stable and judged as good performance. This is because of the enough applied energy on the substrate to open a stable size melt pool, and enough energy applied on the reasonable amount of material input of the wire to properly melt the wire, in this case, the melt pool could accommodate this volumetric amount of melted wire properly resulting in a smooth, continuous bead formation.

As for the WFS to TS ratio of 0.80 cases with 50 mm/s of TS, due to not enough WFS, the continuity of the bridging was sometimes partially but not fully broken between the molten wire and the melt pool, this disturbed the melt pool stability. Also, the plume showed up in all the cases (sample 6s-2-1 to 6s-2-9), when the bead surface was not smooth and flat, the plume column direction was changed, this varied the amount of energy being transferred to the wire and material, therefore, disturbed the process stability.

When the WFS to TS ratio equals 1.25, the material input was higher, this prevented a huge amount of energy from being transferred to the substrate. Also, the plume played as the role of a barrier (J. Liu & Wen, 2022) interfered with the instant energy being transferred to the substrate and surface resulting in the energy for melting the wire material not being enough.

When the TS increases to 75 mm/s, all cases exhibit an unstable situation with poor surfaces; therefore, they were judged as poor cases.

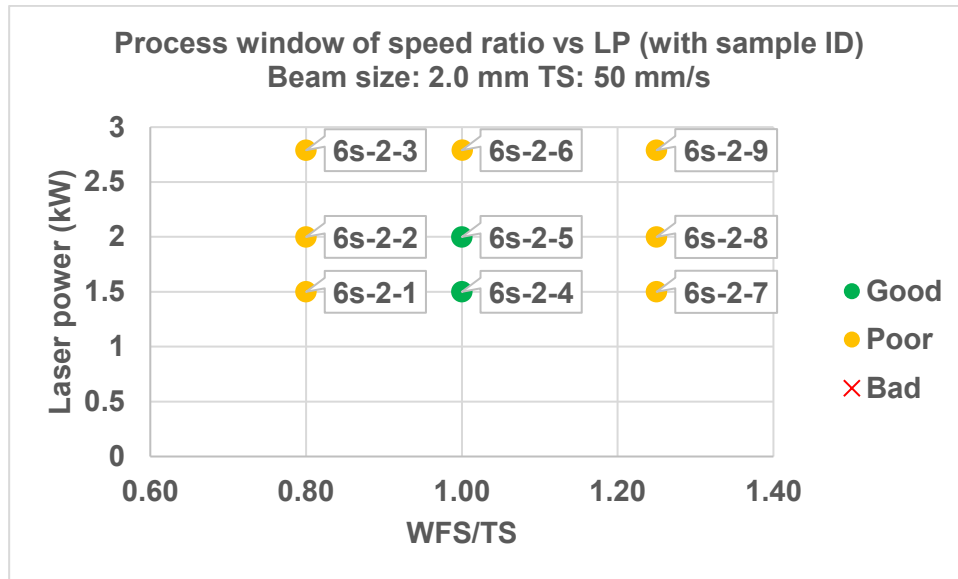


Figure 6-22 Process window of WFS to TS ratio versus LP using a 2.0 mm beam at 50 mm/s of TS.

Table 6-16 The top-view appearance of the bead on plate and the corresponding sample ID processed at 50 mm/s of TS using a 2.0 mm beam.

ID	Top-view appearance (ID sequence corresponds to the process window case)
6s-2-3	
6s-2-2	
6s-2-1	
6s-2-6	
6s-2-5	
6s-2-4	
6s-2-9	
6s-2-8	
6s-2-7	

10 mm

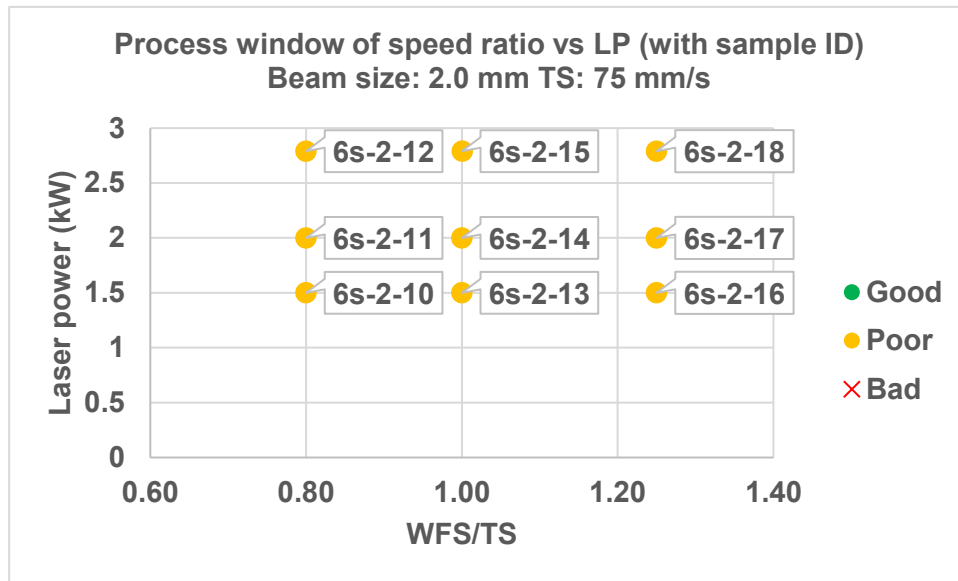


Figure 6-23 Process window of WFS to TS ratio versus LP using a 2.0 mm beam at 75 mm/s of TS.

Table 6-17 The top-view appearance of the bead on plate and the corresponding sample ID processed at 75 mm/s of TS using a 2.0 mm beam.

ID	Top-view appearance (ID sequence corresponds to the process window case)	
6s-2-12		
6s-2-11		
6s-2-10		
6s-2-15		
6s-2-14		
6s-2-13		
6s-2-18		
6s-2-17		
6s-2-16		

10 mm

As a result, these deposition performances prove the complexity of the wire-based laser DED process. An energy balance is always required. Excessive energy for the wire can cause the wire to burn back and balling effect formation

to form the wire dripping phenomenon. When the energy for the wire is reasonable and the wire got fully melted, but if the substrate cannot have a stable melt pool due to the low PD, the droplet cannot fully use the surface tension force to attach to the substrate, at the same time, the non-detached droplet will continue accept the laser irradiation resulting the final absorbed energy exceeded the reasonable range, wire dripping appeared again. Therefore, two regimes of wire dripping should exist in the wire-based laser DED process. Furthermore, when the wire cannot be fully melted, the wire stubbing phenomenon should start appearing. The stubbing level should depend on the viscosity of the wire tip's material, which is a temperature-dependent physical factor (Ebrahimi et al., 2022); therefore, the expressions of wire stubbing phenomena should be volatile.

The requirement of enough and reasonable energy both for the wire and the substrate proves the complexity of this process when the wire is added to the process compared to the autogenous laser weld. Other than that, the wire-based laser DED process also requires a balance of energy similar to the welding process, but the energy distribution is more complex. Based on the welding regime input power distribution (Lampa, 1995), a modified input energy distribution in wire-based laser DED is listed below: the total energy output E applied to the process based on the total laser power is divided into the useful and lost parts during the laser-material interaction:

$$E = E_{\text{wire}} + E_{\text{substrate}} + E_1$$

Where:

E_{wire} = energy used to melt the wire (useful)

$E_{\text{substrate}}$ = energy used to melt the substrate (useful)

E_1 = energy dissipated from the interaction zone by conduction, convection, vaporisation, etc. (lost)

The factor $E_{\text{substrate}}$ can be expanded further to clarify the distribution of the input energy:

$$E_{\text{substrate}} = E_{\text{depth}} + E_{\text{width}}$$

E_{depth} = the proportion of the substrate energy for propagating the depth of the penetration of the weld

E_{width} = the proportion of the substrate energy for propagating the lateral melting of the width of the substrate

The factor E_1 can be subdivided into six parts:

$$E_1 = E_u + E_v + E_w + E_x + E_y + E_z$$

Where:

E_u = conducted losses from the melt zone

E_v = energy used in boiling the material and in ionising the corresponding vapour

E_w = energy prevented from interaction with the material as a result of absorption by, or reflection off from the plasma cloud

E_x = convective thermal losses from the melt pool

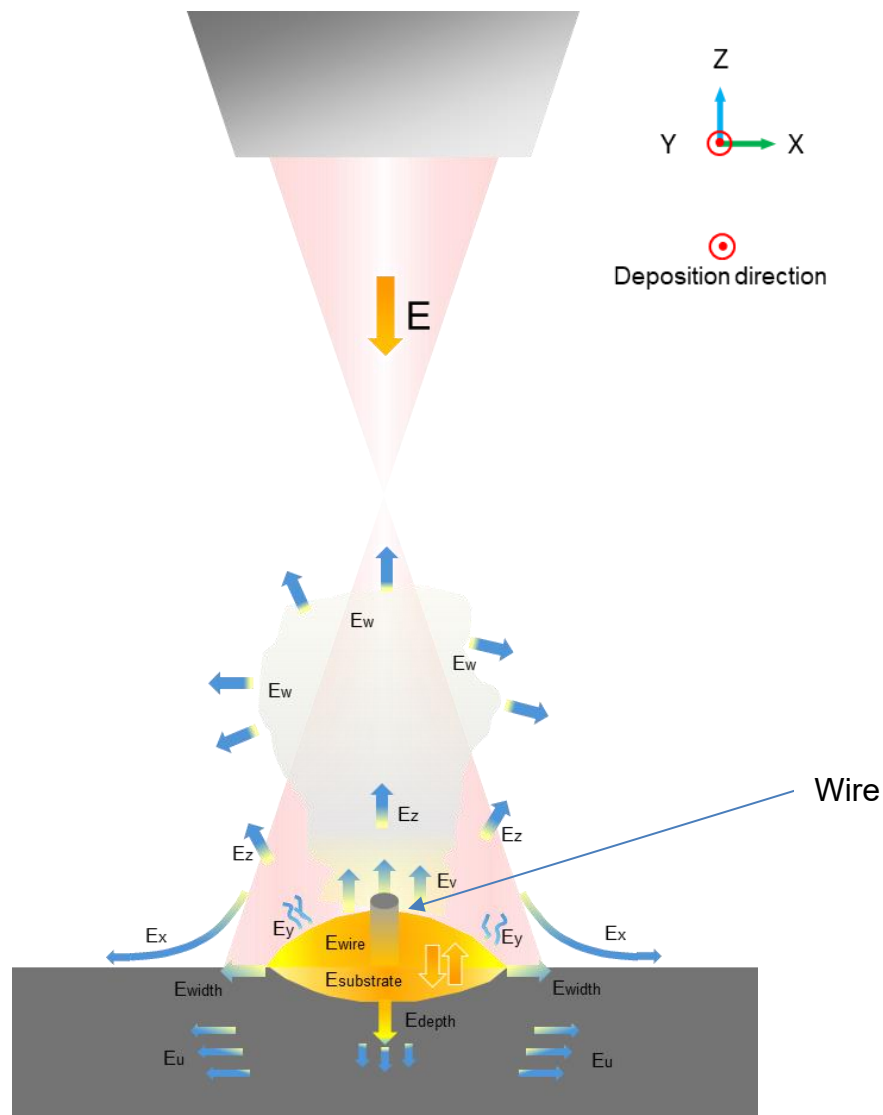
E_y = radiative thermal losses from the melt pool

E_z = reflected losses from the melt pool

In this case, the total applied energy is based on the balance of E_{wire} , $E_{\text{substrate}}$ and E_1 . (Lampa, 1995) pointed out that the power used to melt the workpiece and used for dissipation are interrelated variables. This should also apply to the energy; therefore, the energy used to melt the material (E_{wire} and $E_{\text{substrate}}$) and the energy used for lost (E_1) are complex interrelated variables. In this case, assuming the E_{wire} and $E_{\text{substrate}}$ as an integrity, a thermal balance should happen between the E_{wire} and $E_{\text{substrate}}$ before the solidification. Therefore, an energy transfer should also happen between the E_{wire} and $E_{\text{substrate}}$ based on the heat flow direction caused by the thermal gradient (as the yellow arrows with white brims indicate). This can help explain that in some cases that the bead width is wider than the width of the autogenous laser weld.

A schematic visual representation of the total and the subdivided different parts of the energy is shown in Figure 6-24 for a more straightforward observation. In

this case, it can be seen that wire-based laser DED process integrates the energy for wire, energy for substrate, and energy for losses allaying with a heat transfer between the melt wire and melt pool to form the final bead.



E = total applied energy

E_u = conducted losses from the melt zone

E_v = energy used in boiling the material and in ionising the corresponding vapour

E_w = energy prevented from interaction with the material as a result of absorption by, or reflection off the plasma cloud

E_x = convective thermal losses from the melt pool

E_y = radiative thermal losses from the melt pool

E_z = reflected losses from the melt pool

E_{wire} = energy used to melt the wire

$E_{substrate}$ = energy used to melt the substrate

E_{depth} = the proportion of the $E_{substrate}$ for propagating the depth of the penetration of the weld

E_{width} = the proportion of the $E_{substrate}$ for propagating the lateral melting of the width of the substrate

Figure 6-24 Schematic visual representation of the total and the subdivided different parts of the energy of the wire-based laser DED process.

The dimensions and the cross-sectional profile of the bead on plate with good performance (6s-2-4, 6s-2-5) at the 2.0 mm laser beam, 50 mm/s of TS, and the dimensions of the corresponding autogenous laser weld under the same processing parameters are summarised in Figure 6-25, and Figure 6-26.

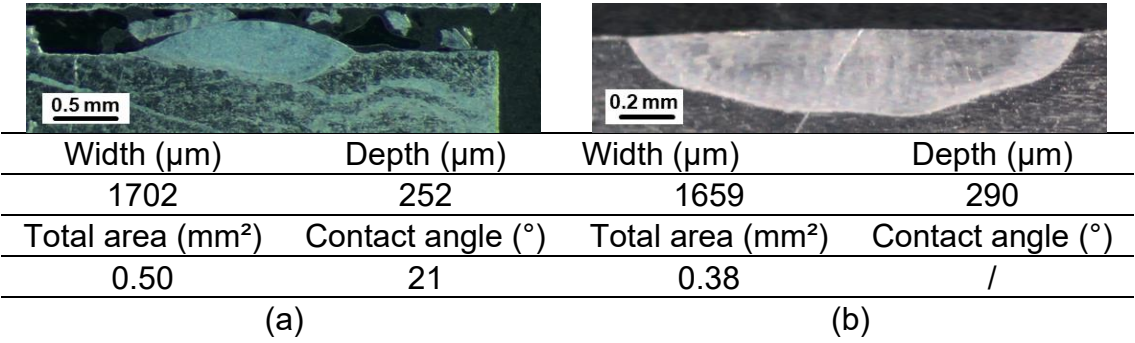


Figure 6-25 Images of (a) the cross-sectional area of the bead, (b) the cross-sectional area of the autogenous laser weld conducted at 50 mm/s of TS using a 2.0 mm beam at 1.50 kW of LP (6s-2-4).

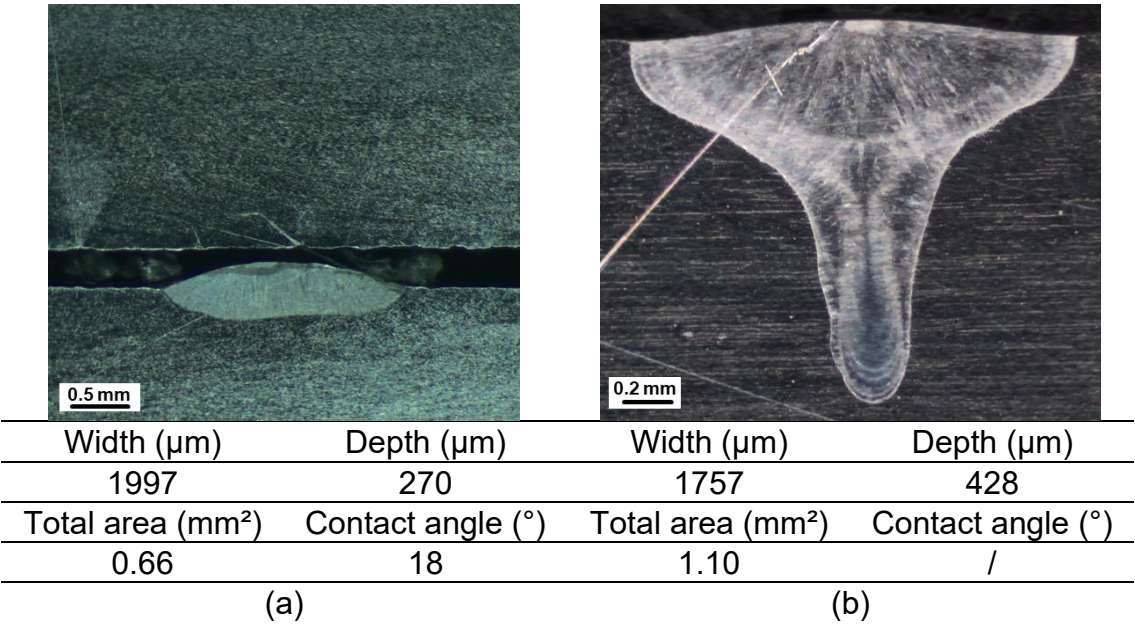


Figure 6-26 Images of (a) the cross-sectional area of the bead, (b) the cross-sectional area of the autogenous laser weld conducted at 50 mm/s of TS using a 2.0 mm beam, at 2.00 kW of LP (6s-2-5).

After adding the wire, in these two cases, the widths of the beads are wider than those of the autogenous laser welds processed under the same LP and TS; this also happened to the 500 W LP cases. This phenomenon should be related to the laser absorptivity increment of the small size of the wire for additive

manufacturing compared with the absorptivity of the substrate for autogenous laser welding. When a reasonable amount of wire experienced the laser irradiation, due to the small size of the wire, unlike the size of the substrate, the wire had no space to dissipate the heat within the wire itself, in this case, the temperature of the wire was higher compared with the temperature of the autogenous laser weld melt pool processed under the same parameters. Generally, a higher temperature has a higher laser absorptivity (Ebrahimi et al., 2022). Therefore, when adding a reasonable amount of wire to the process, the wire can absorb more energy from the laser compared with the substrate.

And because the wire was touching the substrate surface. In this case, the melted material transferred a portion of absorbed energy to the melt pool immediately resulting in the width propagation further under this set of parameters.

However, the situation where the width of the bead on plate was wider than that of the autogenous laser weld did not happen in all the cases. In the previous preliminary study of the processing speed range section (section 6.5.1), the cases with 1.00 kW of LP, 2.0 mm of BD, and 50 mm/s for both the WFS and TS (deposit 6-1) indicate a width and penetration reduction (Figure 6-27 (a), and (b)) when adding the wire in the process compared with the width of the autogenous laser weld (Figure 6-27 (c), and (d)) (to verify the width reduction when adding the wire did not happen by chance, two cross-section profiles of two trials are used to compare). This width reduction after adding the wire is because the applied energy on wire and substrate using 1.00 kW LP is essentially low, plus the wire absorbs a significant portion of the energy, the plume can also take away the energy, therefore, the leftover energy that can be transferred downward to the substrate is low. The wire is not hot enough to widen the melt pool. Even if bonding can be achieved, the lack-of-fusion defects can be observed at the bottom of the bead as shown in Figure 6-27 (e), (f). And this type of lack-of-fusion defect should be caused by the melted material overflowing sideways because the width of the penetration area on the substrate is smaller than the width of the bead, there is no melt pool forming underneath some part of the bead; in this

case, the wire material overflowed sideways forming the lack-of-fusion defects, and the poor bonding with the substrate formed.

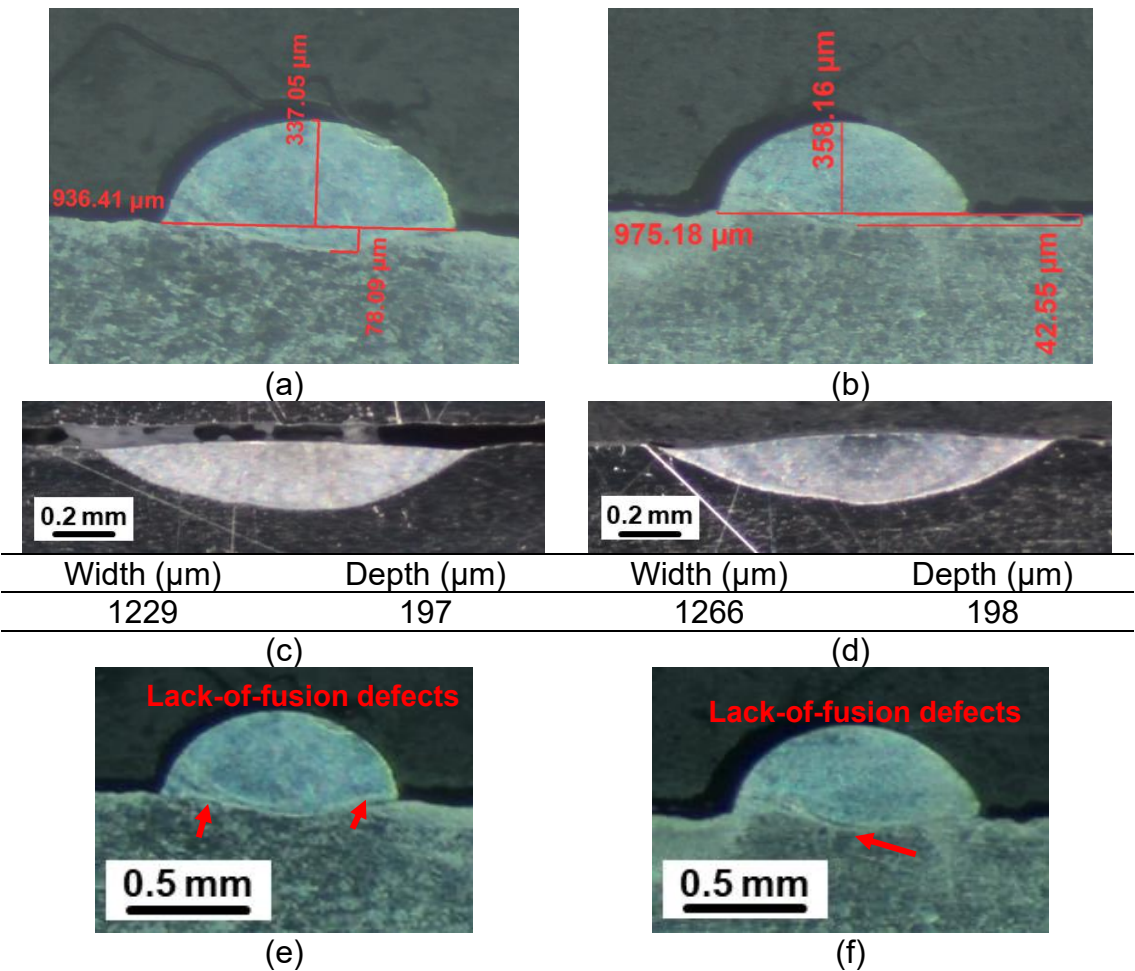


Figure 6-27 Images of (a), (b) geometries of bead on plate, (c), (d) geometries of autogenous laser welds, (e), (f) observation of lack-of-fusion defects on the sample (a), (b) (1.00 kW of LP, 2.0 mm BD, 50 mm/s WFS and TS).

Figure 6-25 (a) and Figure 6-26 (a) show the contact angles of the bead-on-plate for two cases ((6s-2-4, and 6s-2-5) are between 18° to 21° . This contact angle is relatively flat, which should be a positive point for the wall deposition at high speed, which can increase the possibility of maintaining the wire in the middle region of the previous bead, not slipping sideways, therefore, increasing the chance of success. Also, a lower contact angle means better wetting behaviour, which can lead to a lower surface waviness (Wang et al., 2021).

In addition, compared with the 2.00 kW LP bead on plate case (6s-2-5), the autogenous laser weld exhibits a keyhole mode profile, the keyhole profile did not

appear in that of bead on plate case should be, firstly, because the wire absorbed a large portion of the energy. Secondly, due to the plume formation, the plume took away a portion of energy resulting in the energy being transferred to the substrate being lower.

Figure 6-28 – Figure 6-29 show the process window using a 3.0 mm laser beam with 50 mm/s and 75 mm/s of TS, respectively.

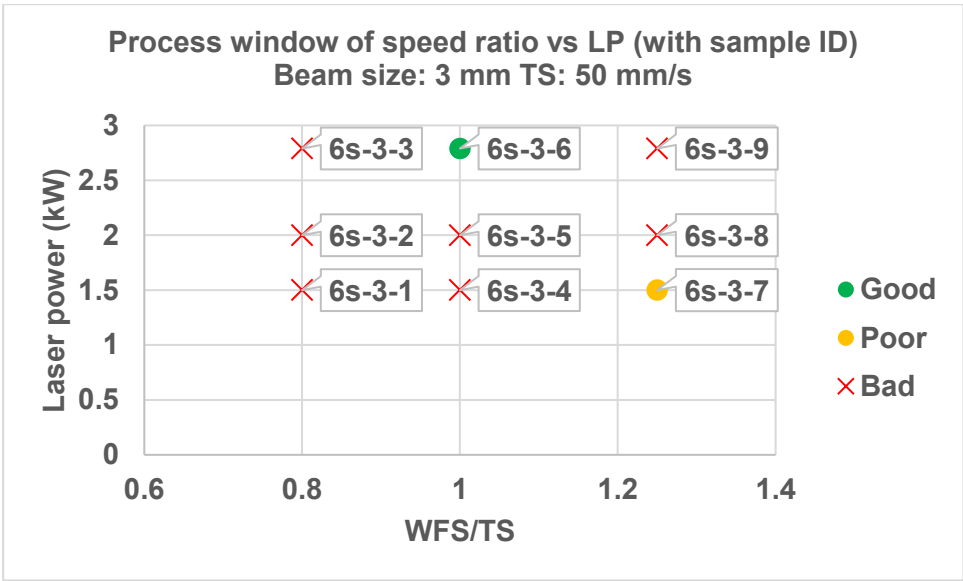


Figure 6-28 Process window of WFS to TS ratio versus LP using a 3.0 mm beam at 50 mm/s of TS.

Table 6-18 The top-view appearance of the bead on plate and the corresponding sample ID processed at 50 mm/s of TS using a 3.0 mm beam.

ID	Top-view appearance (ID sequence corresponds to the process window case)	
6s-3-3		
6s-3-2		
6s-3-1		
6s-3-6		
6s-3-9		
6s-3-8		
6s-3-7		

10 mm

Table 6-18 and Table 6-19 show all the corresponding top-view appearances of the bead on plate, the list of the sample sequence is the same as the sequence shown in the process window.

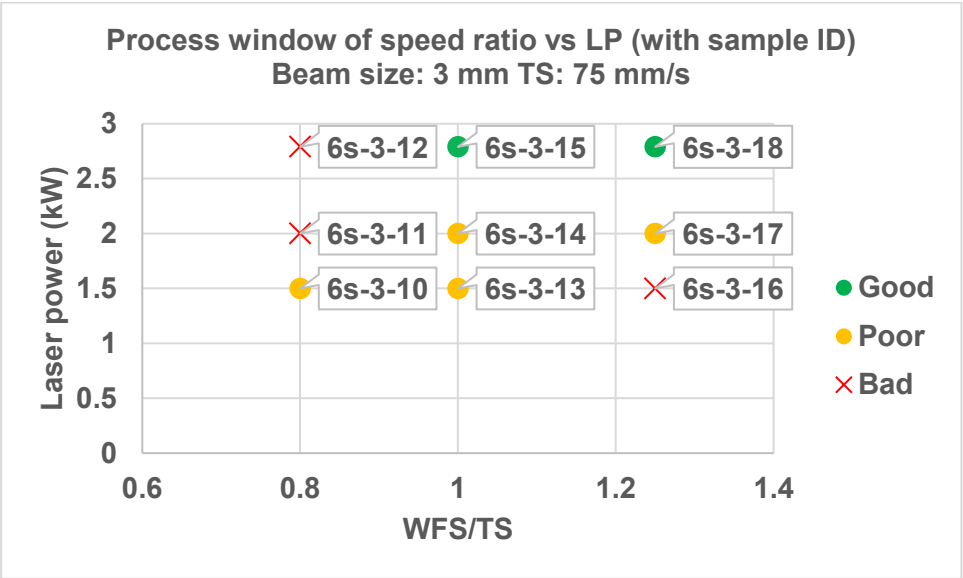


Figure 6-29 Process window of WFS to TS ratio versus LP using a 3.0 mm beam at 75 mm/s of TS.

Table 6-19 The top-view appearance of the bead on plate and the corresponding sample ID processed at 75 mm/s of TS using a 3.0 mm beam.

ID	Top-view appearance (ID sequence corresponds to the process window case)	
6s-3-12		
6s-3-11		
6s-3-10		
6s-3-15		
6s-3-14		
6s-3-13		
6s-3-18		
6s-3-17		
6s-3-16		

10 mm

The process window in Figure 6-28 indicates that using a 3.0 mm laser beam at 2.79 kW of LP with a WFS to TS ratio of 1 under 50 mm/s of the TS (6s-3-6) can have a good deposition performance with good bead condition.

The cases at a speed ratio of 1.25 with 2.00 kW and 3.00 kW of LP (6s-3-8, 6s-3-9) were judged as bad, but actually, as attached top-view images (6s-3-8, 6s-3-9) shown in Table 6-18, the first half part of the bead performed well, the last half part of the bead suffered bead discontinuity, which is related to the deposition experienced the instantaneous laser output drop, this could be explained from two aspects. Firstly, this JK3000 laser has a characteristic of having a higher instantaneous power output when the laser was triggered, then the output started to drop. At this 50 mm/s of TS, the deposition has the chance to experience the laser power output drop; therefore, the bead continuity was interrupted.

Secondly, the received energy for the wire is relatively low compared with the good performance case of 6s-3-6 due to the higher WFS applied, which caused the process to be sensitive to the LP variation. This failure of discontinuity was mainly caused by the wire becoming cold after experiencing the LP dropping down resulting in the difficulty of detaching from the wire tip due to the higher viscosity when the material temperature reduces (Ebrahimi et al., 2022); meanwhile, the melt pool size could have a change, which induced the WFS capacity ability changed.

This issue of discontinuity caused by the LP output drop verifies two critical things, firstly, a higher speed ratio (take a WFS to TS ratio 1.00 with 50 mm/s of TS as the reference point) under a similar TS makes the process more sensitive to the energy variation, this is because a higher volume of material being fed into the melt pool will result in the wire absorbing more energy to melt the wire. In this case, the amount of energy being transferred to the substrate surface becomes lower (based on this, a preheating method applied on the substrate should be very helpful for prompting the success of high-speed deposition with high deposition rate especially beneficial for the high-speed ratio cases). Secondly, the length of the bead designed for experiments at high processing speed is also very critical; a short experimental length can hide the observation of failure, which

will interfere with the real process window determination. Therefore, when designing the experiments for high-speed wire-based laser DED process study, a long enough bead length that allows the deposition to experience a stable laser output is suggested.

When the processing speed increases to 75 mm/s at a 3.0 mm laser beam, Figure 6-29 shows that a higher speed ratio of 1.25 can create a good bead using a 3.0 mm laser beam with 2.79 kW of LP (6s-3-18). This is because firstly, a 3.0 mm laser beam enables the long duration of IT resulting in a high Esp, the wire can be melted completely even if the WFS is increased; secondly, the relatively large size of the melt pool can accommodate more material fed into the melt pool with a still stable performance and good bead appearance, in this case, the tolerance for WFS is higher.

Thirdly, Figure 6-30, and Figure 6-31 show the width of the bead on plate processing at 75 mm/s of TS, 3.0 mm of BD, and 2.79 kW of LP with a speed ratio of 1.00 (sample 6s-3-6) and a WFS to TS ratio of 1.25 (6s-3-9), respectively. Figure 6-32 shows the width of the autogenous laser weld processed under the same parameters. When the WFS to TS ratio reaches 1.25 from 1.00, the bead width changes from similar to the autogenous laser weld to wider than the width of the autogenous laser weld. This indicates that when the WFS to TS ratio reaches 1.25, the more wire being fed absorbs more energy and transfers a portion of this energy to the substrate, which is positive feedback, i.e., feeding more wire, absorbing more energy, enlarging the width, accommodating more melted material.

Fourthly, processing at 75 mm/s of TS avoids the possibility of experiencing the instantaneous output drop, which will interfere with the bead continuity that the 50 mm/s case has experienced.

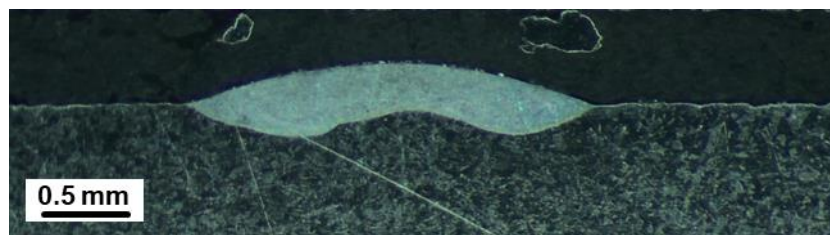
In this case, more energy can be absorbed by the feasibility of feeding more wire at a relatively fast processing speed; all these reasons contribute to the bigger process window at a faster processing speed. This also emphasises that the method of increasing WFS needs the increment of LP accordingly is not always right; increasing the WFS sometimes can enable the wire to absorb more energy

from the laser itself, increasing the WFS and LP accordingly will narrow down the process window.



Width: 2054 μm

Figure 6-30 The width and cross-sectional profile of the bead on plate processing at 75 mm/s of TS, 3.0 mm of BD, and 2.79 kW of LP with a speed ratio of 1.00.



Width: 2284 μm

Figure 6-31 The width and cross-sectional profile of the bead on plate processing at 75 mm/s of TS, 3.0 mm of BD, and 2.79 kW of LP with a speed ratio of 1.25.



Width 2066 μm

Figure 6-32 The width and the cross-sectional profile of the autogenous laser weld processing at 75 mm/s of TS, 3.0 mm of BD, and 2.79 kW of LP.

Moreover, for the case with a WFS to TS ratio of 1.25 (6s-3-9), the depth of penetration is lower than the edge-side part with a convex profile, this should be because the relatively high WFS resulting in feeding more material in the melt pool, absorbing more energy which prevents the energy in the middle section from being transferred downward to reach far depth, this can be beneficial for the wall building due to the less remelting on the previous layer and can reduce the heat input, therefore, refine the crystalized structures.

In this case, the speed-ratio-based process window has been identified. The 3.0 mm laser beam cases performed better than the 2.0 mm beam cases. For the 2.0 mm BD case, only 50 mm/s of the TS cases work; for the 3.0 mm BD case, 75 mm/s of the TS cases performed better than the 50 mm/s cases, but both levels of TS have a good performance range. In this case, in the wall fabrication phase, the feasibility of fabricating millimetre-scale walls will be investigated using the 3.0 mm laser beam with a 50 mm/s of TS for the initial test.

6.5.3 Study of the process repeatability

Because the plume appeared in all the deposition cases which can interfere with the LP projected on the material. And the applied energy is relatively low at a fast processing speed, the deposition could be sensitive to various variations of the factors. In this case, the repeatability was studied using 2.0 mm and 3.0 mm laser beams for the cases with good deposition performance exhibited. The experiments were conducted on either the same substrate or a different substrate to examine the process feasibility.

Table 6-20 summarises the sample identification and processing parameters, and the corresponding substrate used. The overall bead appearance and the corresponding cross-sectional area profile are shown in Figure 6-33 (a) – (d) to Figure 6-36 (a) – (d).

Table 6-20 Summarised sample identification and the corresponding parameters and the substrate identification.

Sample ID	BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Substrate ID
6r-1-A	2.0	2.00	50	50	1
6r-1-B	2.0	2.00	50	50	1
6r-2-C	2.0	2.00	50	50	2
6r-2-D	2.0	2.00	50	50	2
6r-2-E	3.0	2.79	50	50	2
6r-2-F	3.0	2.79	50	50	2
6r-3-G	3.0	2.79	50	50	3
6r-3-H	3.0	2.79	50	50	3

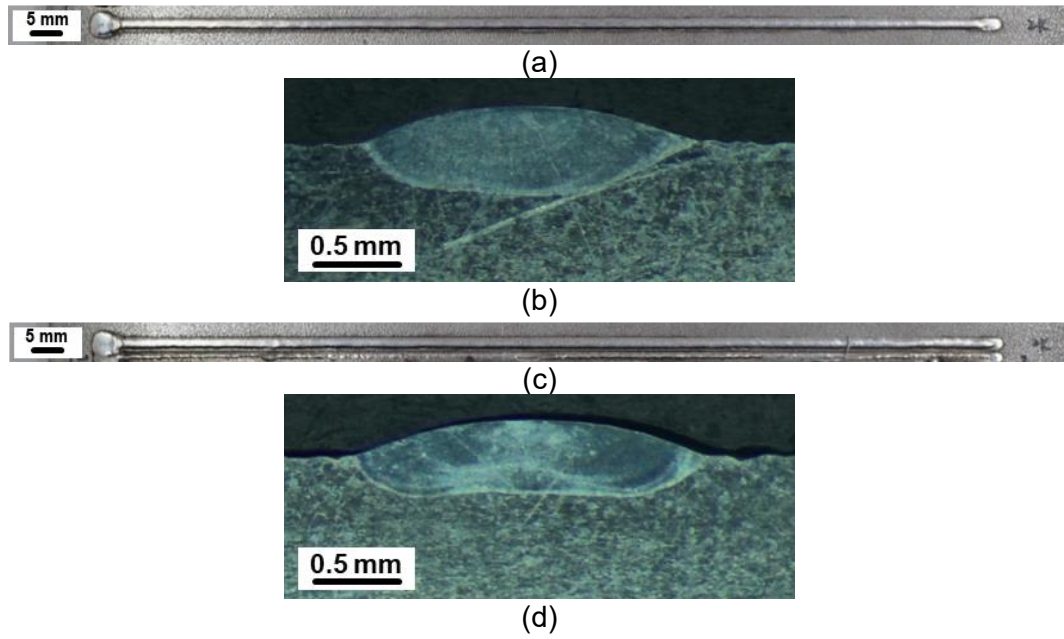


Figure 6-33 Images of (a) overall top view, (b) cross-sectional profile of 6r-1-A, (c) overall top view, (d) cross-sectional profile of 6r-1-B using a 2.0 mm beam to test the repeatability on the same 1# substrate.

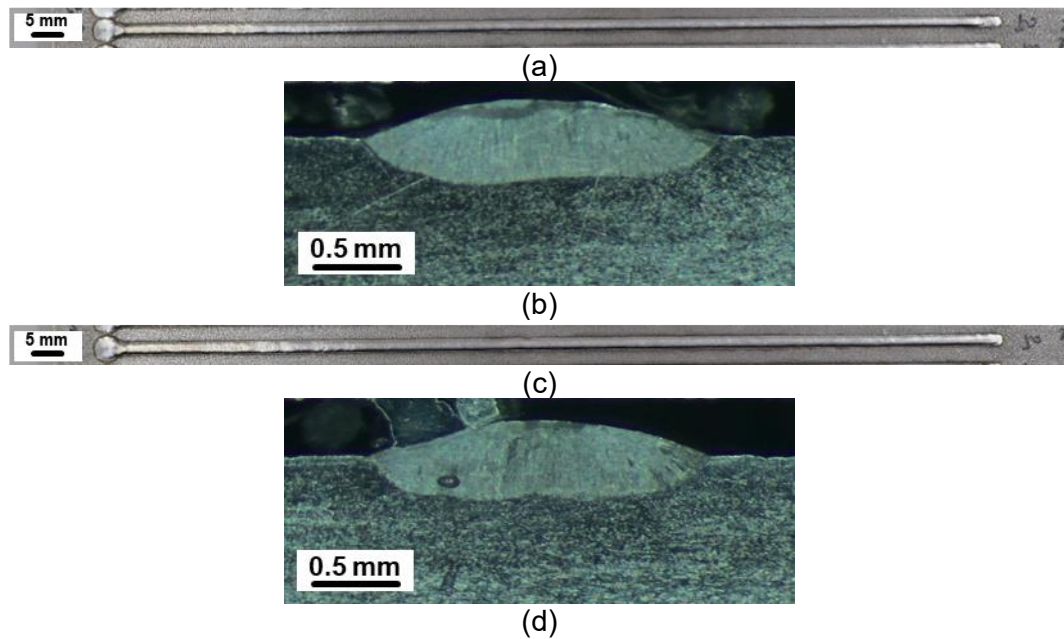


Figure 6-34 Images of (a) overall top view, (b) cross-sectional profile of 6r-2-C; (c) overall top view, (d) cross-sectional profile of 6r-2-D using a 2.0 mm beam to test the repeatability on the same 2# substrate.

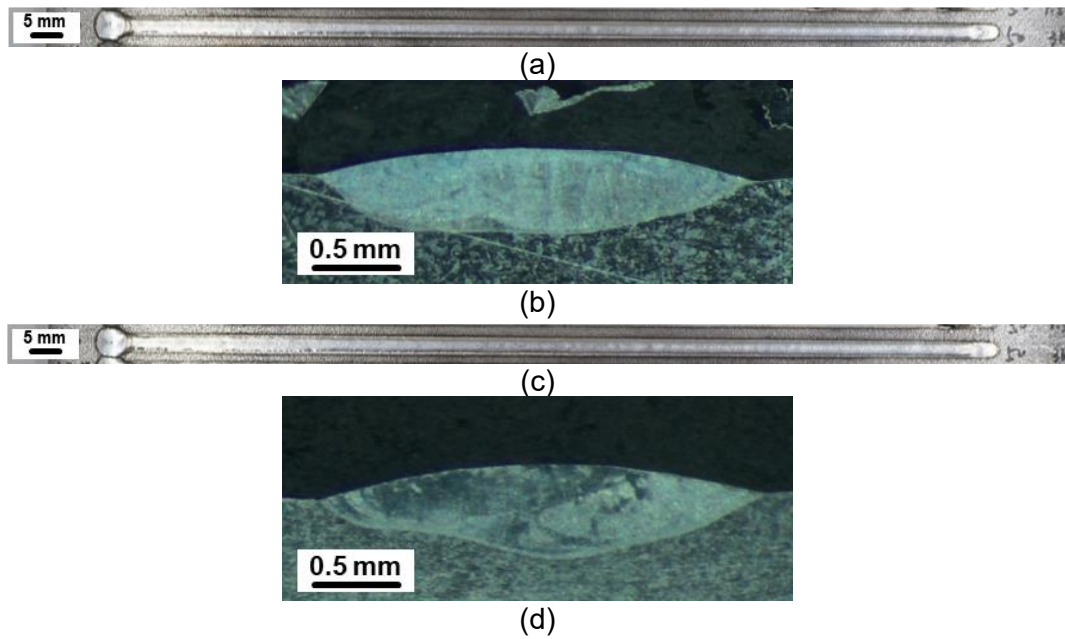


Figure 6-35 Images of (a) overall top view, (b) cross-sectional profile of 6r-2-E; (c) overall top view, (d) cross-sectional profile of 6r-2-F using a 3.0 mm beam to test the repeatability on the same 2# substrate.

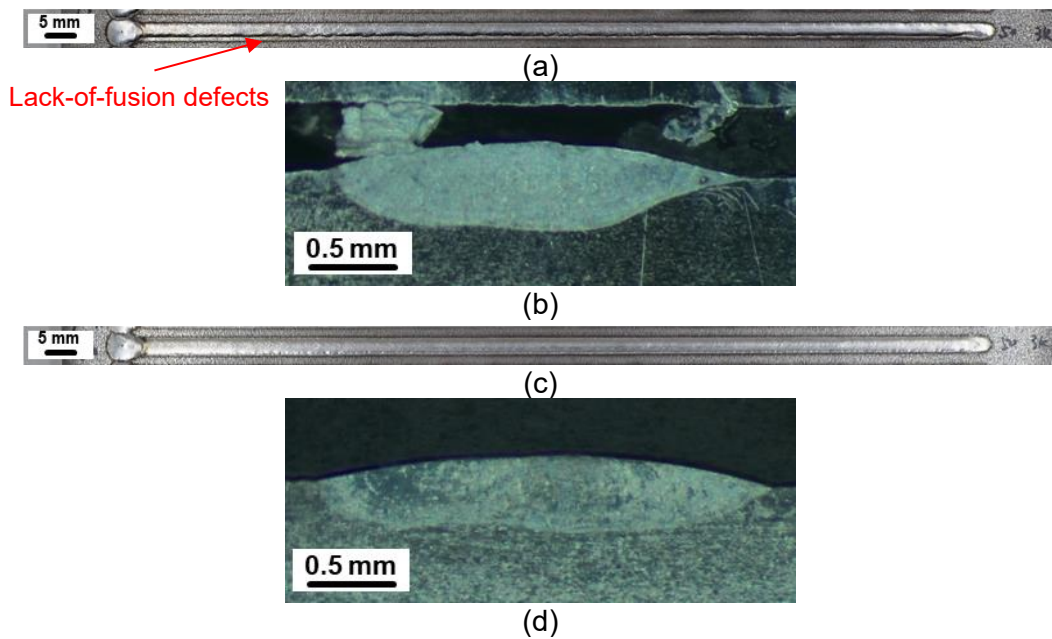


Figure 6-36 Images of (a) overall top view, (b) cross-sectional profile of 6r-3-G; (c) overall top view, (d) cross-sectional profile of 6r-3-H using a 3.0 mm beam to test the repeatability on the same 3# substrate.

Table 6-21 summarises the dimensions of the beads listed in Table 6-20 with the geometry variation percentage compared with the average value.

Table 6-21 Dimensions and the percentage of the geometry variation of the bead on plate for the deposition repeatability study.

Sample ID	Substrate ID	Width (μm)	Width variation	Depth of penetration (μm)	Depth of penetration variation	Reinforcement height (μm)	Reinforcement height variation
6r-1-A	1	1876	3.1%	301	19.7%	206	5.7%
6r-1-B	1	1996		202		231	
6r-2-C	2	1997	1.9%	270	5.7%	213	0.9%
6r-2-D	2	1922		241		209	
6r-2-E	2	2451	0.4%	312	5.9%	167	7.0%
6r-2-F	2	2469		351		192	
6r-3-G	3	2529	1.6%	292	4.6%	167	5.6%
6r-3-H	3	2450		320		187	

The results show that based on the geometry, the deposition repeatability is relatively stable and acceptable on the same and different substrates for both laser beam cases except for the 6r-1-A and 6r-1-B samples with a 19.7% of depth of penetration variation on the same substrate, which were processed at 2.00 kW of LP. This is because when conducting the autogenous laser welding, 2.00 of LP, 2.0 mm of BD were used; this set of parameters induced the keyhole mode profile welds formation for the autogenous welds. When adding the wire to the process, even the conduction mode profile is formed, this kind of conduction mode profile is not stable (the profiles of the bead are obviously different as shown in Figure 6-33 (b) and (d), even the beads in Figure 6-34 exhibit a similar geometry). These processing parameters with the keyhole mode profile appearing in the autogenous laser welds have the potential to cause a significant variance in the depth of penetration resulting in unstable repeatability.

When building the walls, these parameters with keyhole mode appearing in the autogenous weld could cause the energy distribution on the previous layer to be uneven and variate, and even a failure could happen. Therefore, not ideal for wall fabrication, even if the deposition performance and the bead appearance are good.

On top of that, when conducting the experiments at 2.79 kW of LP with a 3.0 mm laser beam, the lack-of-fusion issue is observed in the cases as shown in the Figure 6-36 (a) overall top-view image of sample 6r-3-H with a red arrow pointing at the edge of the bead. Considering the only different factor was the temperature because when the last two trials were repeated, a new 3# substrate was used,

the temperature of the substrate for conducting the first bead was at room temperature, which could have caused the lack-of-fusion defect to appear.

Therefore, to investigate the substrate temperature effect on deposition repeatability, one group of experiments was conducted at room temperature, the other group of experiments were conducted on the substrates with three autogenous laser welds running in advance on the spare place out of the experiments region on the substrate to preheat the substrate (Figure 6-37) to enhance the substrate temperature. Table 6-22 lists the sample identification and specific processing parameters, substrate ID and processing measures.



Figure 6-37 Image of three autogenous laser welds running before the experiments out of the experimental region.

Table 6-22 Summarised sample identifications and corresponding parameters and measures for the different substrate initial temperature study.

Sample ID	BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Substrate ID	Measures
6r-2-J	3.0	2.79	50	50	2	Room Temperature
6r-2-K	3.0	2.79	50	50	2	Room Temperature
6r-2-L	3.0	2.79	75	75	2	Room Temperature
6r-2-M	3.0	2.79	75	75	2	Room Temperature
6r-3-N	3.0	2.79	50	50	3	After three trials pre-run
6r-3-O	3.0	2.79	50	50	3	After three trials pre-run
6r-3-P	3.0	2.79	75	75	3	After three trials pre-run
6r-3-Q	3.0	2.79	75	75	3	After three trials pre-run

Figure 6-38 (a), (b) show that when the trials were conducted under room temperature, the beads were not continuous with lack-of-fusion defects appearing at the edge of the bead, this issue should come from the low temperature of the substrate. When preheating the substrates using the three-trial pre-run strategy to enhance the substrate temperature, the issues were solved (Figure 6-39 (a), (b)). This is attributed to the temperature of the substrate enhancement; meanwhile, as the temperature increases, the laser absorptivity also increases, therefore, more energy can be absorbed by the substrate.

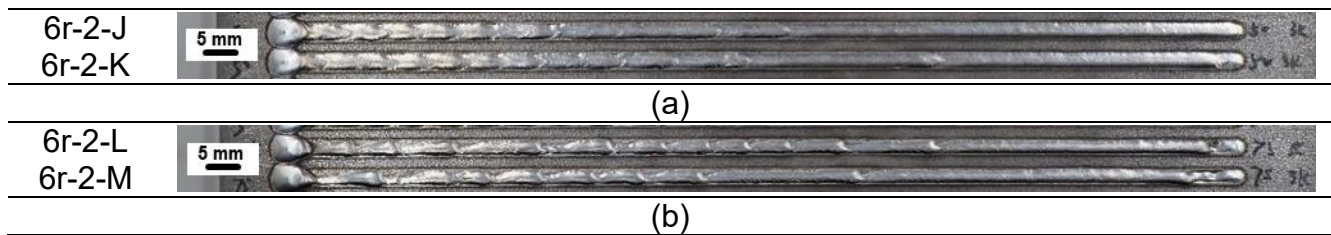


Figure 6-38 Images of two trials conducted under room temperature with 3.0 mm BD, 2.79 kW of LP and (a) 50 mm/s for WFS and TS, (b) 75 mm/s for WFS and TS to test the repeatability.

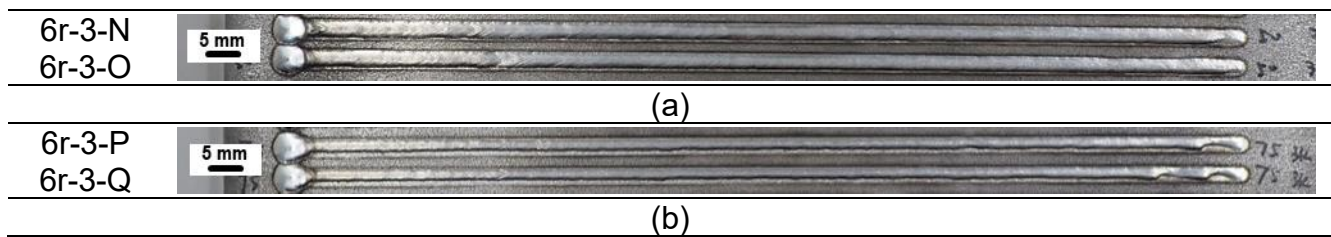


Figure 6-39 Images of two trials conducted after three pre-runs with 3.0 mm BD, 2.79 kW of LP and (a) 50 mm/s for WFS and TS. (b) 75 mm/s for WFS and TS to test the repeatability.

This suggests that this high-speed deposition is sensitive to the substrate's initial temperature, which is because the applied energy at the fast processing speed is relatively low, a slight energy variation will interfere with the deposition performance. Therefore, preheating the substrate before the deposition will be beneficial for this fast-processing speed process.

6.5.4 Effect of BD on wire position sensitivity

To test the wire position sensitivity, the wire was intentionally placed 0.5 mm deviating distance from the middle of the laser spot to compare the performance conducted with the wire placed in the right aligned position.

Two sets of feasible parameters that can achieve good bead deposition were used to study the wire position effect. The detailed wire position and experimental parameters for the BD effect on the wire position sensitivity investigation are listed in Table 3-14. Table 6-23 lists the sample identification and the specific parameters, and the wire relative to the laser spot position for a clear understanding of the content.

Table 6-23 Summarised sample identifications and the corresponding parameters and wire position for the BD effect on the wire position sensitivity study.

Sample ID	BD (mm)	LP (kW)	WFS (mm/s)	TS (mm/s)	Wire position
6p-1	2.0	1.50	50	50	Deviated
6p-2	2.0	1.50	50	50	Aligned
6p-3	3.0	2.79	50	50	Deviated

Results in Figure 6-40 (a) – (c) indicate the deposition performance at the initial, middle, and final phase of sample 6p-1 at 1.50 kW of LP, 50 mm/s of the TS and WFS, using a 2.0 mm laser beam. A slight 0.5 mm deviation of the wire position caused the failure of the deposition (Figure 6-40 (d)). The uneven bead forming intervened in the plume extent, profiles and direction (Figure 6-40 (a) – (c)), i.e., the plume spatial distribution.

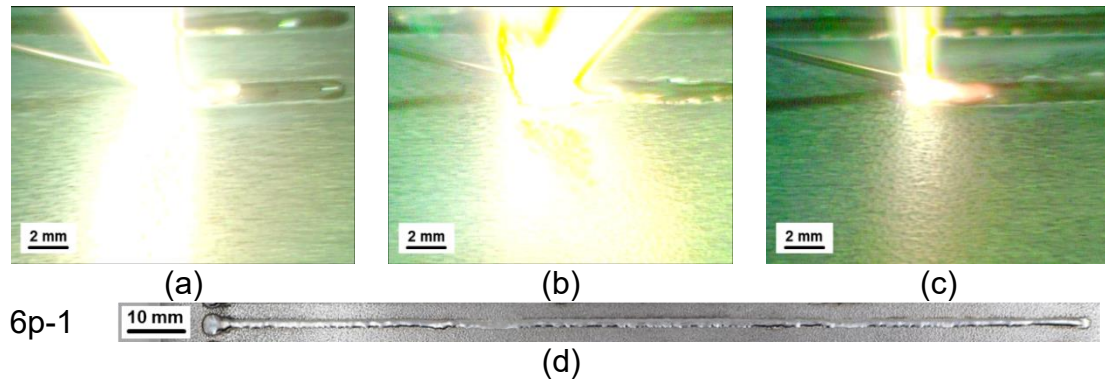


Figure 6-40 Images of the deposition performance and plume levels at the (a) initial, (b) middle, and (c) final phase of the sample 6p-1 with the wire deviation.

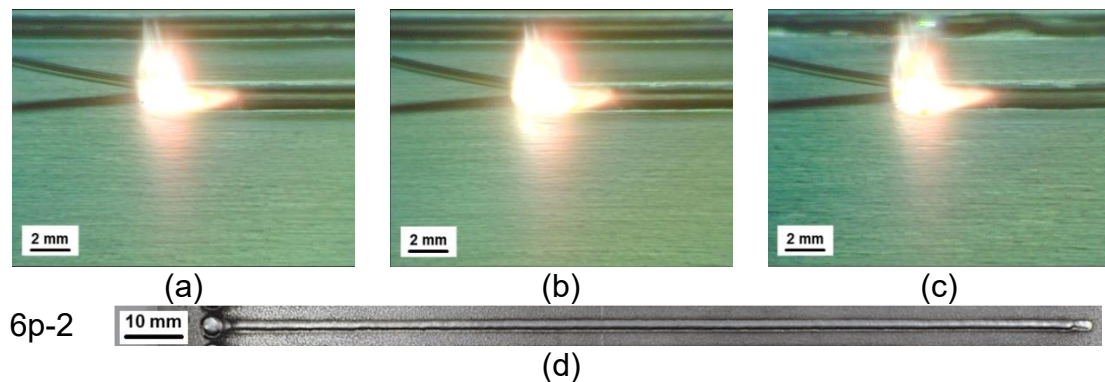


Figure 6-41 Images of the deposition performance and plume levels at the (a) initial, (b) middle, and (c) final phase of the sample 6p-2 with the wire alignment.

On the contrary, when placing the wire at the right aligned position (sample 6p-2), the deposit performance was good, stable. A continuous bead was achieved

(Figure 6-41 (d)). The plume and plume column did not disturb the good bead appearance (Figure 6-41 (a) and (c)).

When using a 3.0 mm laser beam, 2.79 kW of LP, and 50 mm/s for both the WFS and TS, a slight 0.5 mm wire deviation from the middle of the laser spot (sample 6p-3) did not cause an obvious failure of the deposition as encountered in the 2.0 mm laser beam case (sample 6p-1), the bead on plate is continuous with some of the lack-of-fusion defects appearing at the edge of the bead (as pointed by the arrow shown in Figure 6-42).

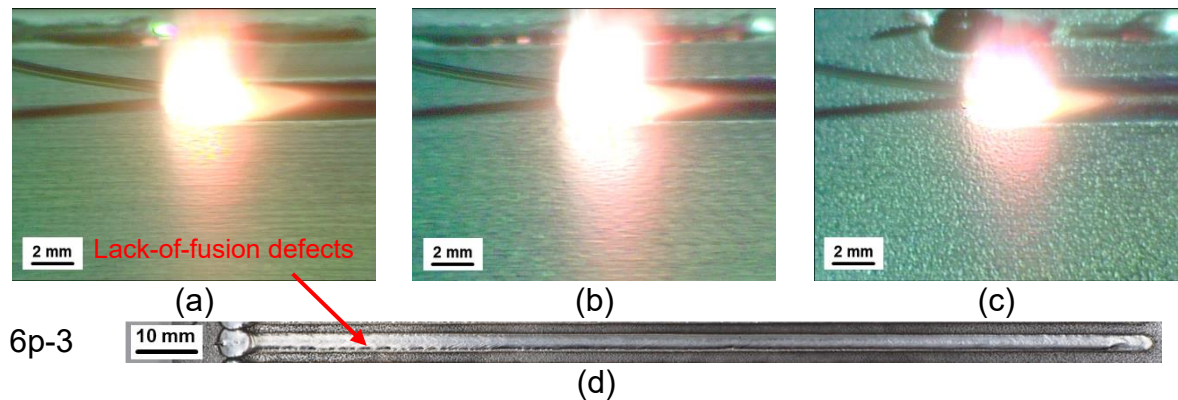


Figure 6-42 Images of the deposition performance and plume levels at the (a) initial, (b) middle, and (c) final phase of the sample 6p-3 with the wire deviation.

Therefore, the wire position sensitivity was mitigated due to the use of a 3.0 mm laser beam combining a higher level of LP. In this case, the D-ratio is 5.00. This means a fast-processing process can restore the wire position sensitivity when using a 2.0 mm laser beam (D-ratio equals 3.33, the same as the 500 W case when using a 2.0 mm laser beam). However, increasing the beam size to 3.0 mm with a D-ratio equals 5.00 can reduce the wire position sensitivity relative to the laser beam again. Therefore, at a fast-processing speed, a higher D-ratio is required; the values above 5.00 should be considered.

6.6 High deposition rate wall manufacturing – Strategy, repeatability, feasibility, geometry, and deposition rate

In this section, after the feasible parameters for bead on plate with good performance have been down-selected, the feasibility of fabricating millimetre to submillimetre-scale walls at a high deposition rate with a good deposition

performance and wall appearance was studied. Initially, the feasibility of manufacturing the wall was examined, considering the general research sequence and procedure of gradually enhancing the processing speed and deposition rate. In this case, a lower TS of 50 mm/s was chosen to conduct the wall manufacturing. Table 6-24 lists the wall identifications and the specific strategy.

Table 6-24 Summarised wall identifications and the corresponding parameters and strategies for the feasibility and repeatability study.

Wall ID	BD (mm)	WFS (mm/s)	TS (mm/s)	Number of layers	Strategy
w-1	3.0	50	50	10	Layer 1-5 2.79 kW
					Layer 6-10 2.75 kW
w-2	3.0	50	50	20	Layer 1-5 2.79 kW
					Layer 6-10 2.75 kW
					Layer 11-20 2.50 kW

Figure 6-43 (a) shows that the wall can be successfully deposited with a good straightness and surface finish. From the cross-sectional image of the wall (Figure 6-43 (b)), the left side of the wall exhibits a straighter net-shape profile along the vertical direction compared with the right side. There are no obvious defects, such as pores or lack-of-fusion defects observed. After 10 layers of deposition, the total height is about 1.56 mm, therefore, the average layer height is about 156 μm .

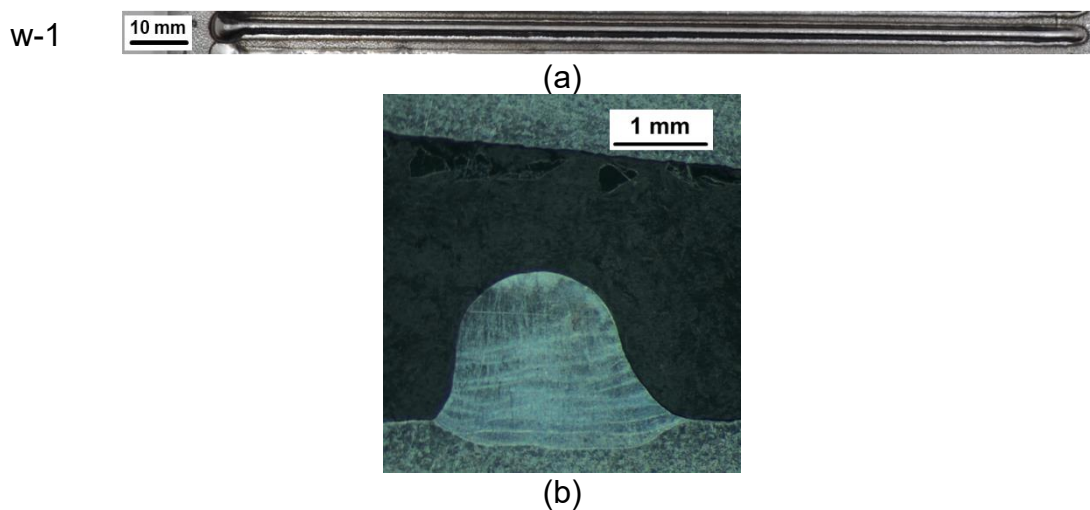


Figure 6-43 Images of the (a) overall top view of wall w-1 and the corresponding (b) cross-sectional profile.

Thereafter, a higher wall with 20 layers was manufactured to see the deposition performance, and process stability. Due to the wall's left side and right side looking uneven as shown in Figure 6-43 (b), the fabrication repeatability was examined simultaneously.

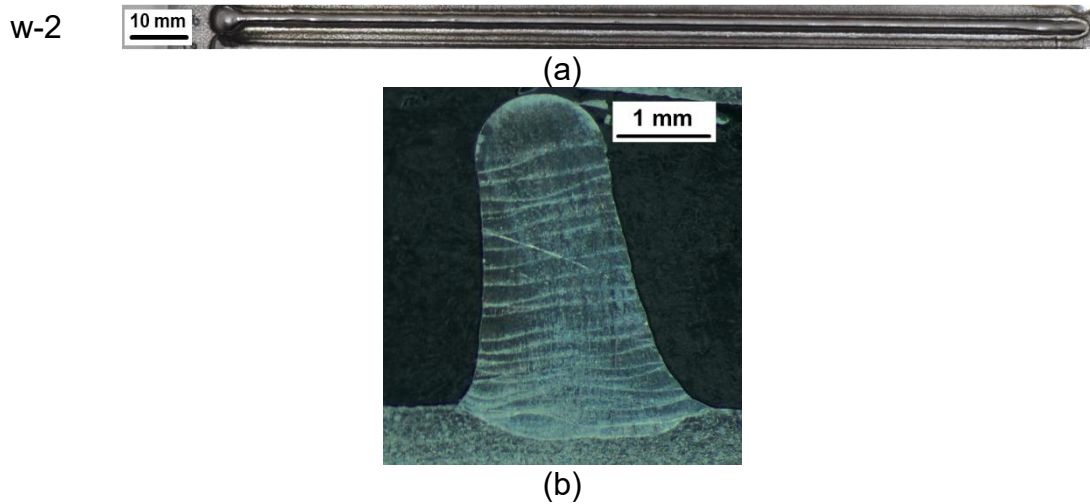


Figure 6-44 Images of the (a) overall top view of wall w-2 and the corresponding (b) cross-sectional profile.

Figure 6-44 (a) shows that the 20-layer wall can also be successfully deposited with a good straightness and surface finish.

Table 6-25 The linear dimensions of the two walls for the manufacturing feasibility and repeatability study.

Dimensions	Wall-1	Wall-2	Variation percentage
1 st layer Width (μm)	2765	2713	2%
Depth of penetration (μm)	313	357	14%
Wall height (μm)	1566	3294	/
Average layer height (μm)	157	165	5%

Table 6-25 lists the linear dimensions of these two walls for comparing the wall fabrication repeatability. Table 6-26 lists the EWW, TWW, effective width ratio and the deposition efficiency of the wall-2, respectively.

It can be seen that a similar bottom part profile (Figure 6-43 (b), Figure 6-44 (b)) and a similar first-layer width (Table 6-25) were achieved, which proved the process repeatability was high. After 20 layers, the total height reached 3.29 mm, the average layer height was maintained at about 165 μm , which is similar to the

average layer height of 157 μm achieved after 10-layer fabrication (5% of the layer height variation), which exhibited a stable layer height increment.

The effective wall width of 1.29 mm can be achieved after 20 layers' deposition as indicated in Table 6-26, which indicates the feasibility of fabricating the millimetre-scale wall features, and still shows the potential for effective width reduction (submillimetre-scale fabrication) if building more layers or using other strategies such as reducing the LP in an earlier layer's deposition, applying more LP reduction than the current level used.

Table 6-26 Geometrical dimensions, the effect width ratio, and the deposition efficiency of the wall-2.

Wall-2			
EWV (μm)	TWV (μm)	Effect width ratio	Deposition efficiency
1290	2713	48%	80%

The deposition efficiency is about 80%. This is lower than the 500 W cases with a deposition efficiency ranging from 85% to 94% mentioned in the previous chapter. However, as the layer continues building up, and when the width is constantly maintained at a millimetre-scale level, the deposition efficiency will increase due to the machined-off material being less, if the net shape achieved upward, even no machining is needed for the upper part, therefore, the deposition efficiency will be increased by building more layers upward.

Currently, 80% of the deposition efficiency is mainly because of the uneven right-side surface which causes the total machined-off material to increase. This uneven side surface should come from the wire feed nozzle misaligning along the deposition direction as shown in Figure 6-45 (yellow dotted line). It is difficult to perceive this misalignment from the side direction. If accurately and correctly align the wire feed nozzle along the deposition direction, the profile of the wall should be closer to the net shape with a higher deposition efficiency and a more even surface.

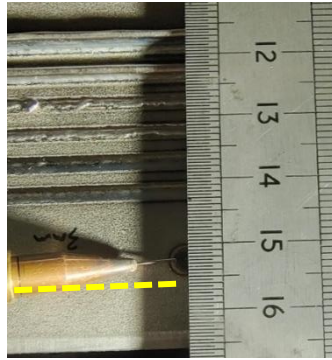


Figure 6-45 Image of the wire feed torch misalignment with the deposition direction.

Finally, the deposition rate was calculated, and it shows a rate that can reach 400 g/h when carrying out the deposition under 50 mm/s of the WFS. And shows the possibility of reaching 750 g/h if applying 93.75 mm/s of the WFS at 75 mm/s of the TS to fabricate the walls, this amount of deposition rate exceeds the case of a conventional powder-based DED process with 600 g/h (Z. Li et al., 2022). Moreover, compared with the previous 500 W LP case, the deposition rate is increased by ten times from 40 g/h to 400 g/h.

Table 6-27 summarises some wire-based laser DED works with the deposition rate calculation. It can be seen that to achieve the small-sized size wall, usually a small-sized wire has to be chosen, which inevitably induces a low deposition rate in nature significantly because a two times wire thickness reduction causes quadruple deposition rate reduction, which is more obvious than the linear WFS increment based on the deposition rate formula (5-4).

Table 6-27 Summarised deposition rates, wire size used, and the corresponding effective wall width of some wire-based laser DED works.

Material	Wire size (mm)	WFS (mm/s)	Deposition rate (kg/h)	Wall width (mm)	Reference
SS 304	0.1	7.85	0.001	0.5 – 1.0	(Shaikh et al., 2020)
Ti-6Al-4V	0.4	17 – 20	0.03 – 0.04	1.5 – 1.7	(Du et al., 2019)
Ti-6Al-4V	1.2	64	1.15	< 5.0	(X. Wang et al., 2021)
Ti-6Al-4V	1.2	17, 33	0.3, 0.6	< 7.0	(Mok, Bi, Folkes, Pashby, et al., 2008)
Ti-6Al-4V	1.0	15	0.19	< 2.0	(Mortello & Casalino, 2021)

Considering this 0.6 mm size wire, achieving above 400 g/h should already be regarded as compatible. If using a 1.2 mm in diameter wire, the deposition rate

will reach 3.00 kg/h and 1.61 kg/h when 93.75 mm/s and 50 mm/s of WFS are used, respectively. Therefore, above 400 g/h of the deposition rate for the 0.6 mm in diameter wire is promising for the millimetre to submillimetre-scale features fabrication in high deposition rate applications.

Therefore, millimetre-scale walls were successfully fabricated at higher levels LP, and larger laser beam conditions with a high deposition rate of reaching 400 g/h and still show the potential to achieve submillimetre-scale features at a potential deposition rate of 750 g/h.

6.7 Melting efficiency (500 W LP cases added)

Melting efficiency is defined as the ratio of the energy required to melt the weld (deposit) metal to the energy actually absorbed by the base metal (Sabbaghzadeh et al., 2008). The calculation is based on the formula 6-5 given below:

$$\text{Melting efficiency: } \frac{A * v * \rho * [Cp * (Tm - T0) + L]}{(1 - R) * LP} \quad (6-5)$$

Where A, v, ρ , Cp, Tm, T0, L, and R represent average fusion zone area (m²), processing speed (m), material density (kg/m³), heat capacity (J/kg⁻¹K⁻¹), liquidus temperature (K), initial room temperature (K), latent heat of fusion (kJ/kg), and laser reflectivity (use 0.7 (Chowdhury et al., 2020) for calculation), respectively.

Due to the appearance of the transition and keyhole modes, and considering that the laser absorption rate varies across different working regimes. Also, due to the large beam size used, the melted area can be very large, an improper choice of laser reflection efficiency could cause the melting efficiency to exceed 100%, which is impossible. In this case, the total power is applied for the melting efficiency calculation without discounting the reflected power. This enables the comparison between different mode cases even if the calculated melting efficiency based on total LP is lower.

Therefore, the melting efficiency formula 6-6 below is used for calculation, of which the case of using full power for calculation is also found and used in (Quintino et al., 2007).

$$\text{Melting efficiency} = \frac{A * v * \rho * [Cp * (Tm - T0) + L]}{LP} \quad (6-6)$$

In this case, the melting efficiency of the weld zone of autogenous laser welds will be compared with the melting efficiency of the total area, reinforcement area, and substrate melt area of the bead on plate to investigate whether the melting efficiency will be increased after adding the wire, which can provide the supported evidence for the absorptivity increment of the wire.

6.7.1 500 W LP situation

Figure 6-46 shows the melting efficiency of the bead on plate with different levels of WFS versus the IT at 1.50 mm and 2.00 mm laser beam cases.

Compared with the autogenous laser welds (WFS = 0 mm/s), the melting efficiency has been enhanced when adding the wire to the process.

This helps verify that the wire can absorb more energy compared with the substrate due to the higher laser absorptivity of the wire. This is because the wire does not have enough extra, but the same media to dissipate the heat resulting in less waste of the heat, the applied energy can be absorbed by the wire significantly. In this case, the temperature of the wire is higher resulting in the absorptivity being higher; the absorptivity increases as the temperature increases (Ebrahimi et al., 2022).

To examine if the increase in melting efficiency comes from the added material, the melting efficiency of the reinforcement area and the substrate area after adding the wire was calculated. Figure 6-47 shows the melting efficiency of the reinforcement, substrate melted area of the bead and autogenous laser weld melted area.

One observation is that when using a 1.50 mm laser beam, adding wire with 4 mm/s of WFS, the melting efficiency of the reinforcement is lower than that of the autogenous laser weld case; this means for the 1.50 mm laser beam, adding the wire with 4 mm/s of WFS, the melting efficiency increment is not only coming from the added material but also relies on the substrate melted area. When the WFS increases to 7 mm/s, the melting efficiency of the reinforcement area becomes

similar to the melting efficiency of the autogenous laser weld melted area, the melting efficiency of the substrate area reduces. Therefore, from this point, the melting efficiency increment comes from the added material, but this comes at the cost of energy being taken from the substrate.

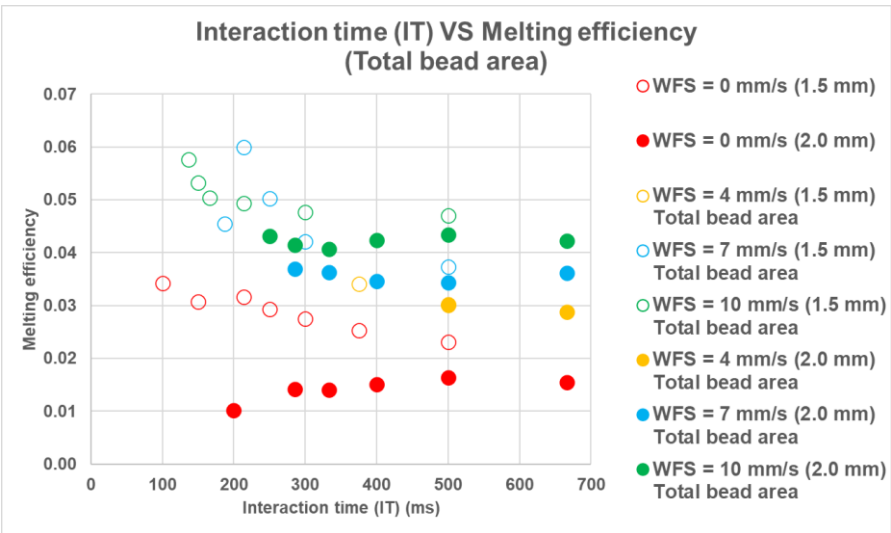


Figure 6-46 Image of the melting efficiency of bead on plate processed at different levels of WFS and the melting efficiency of the autogenous laser weld against the IT processed at the 1.5 mm and 2.0 mm laser beams.

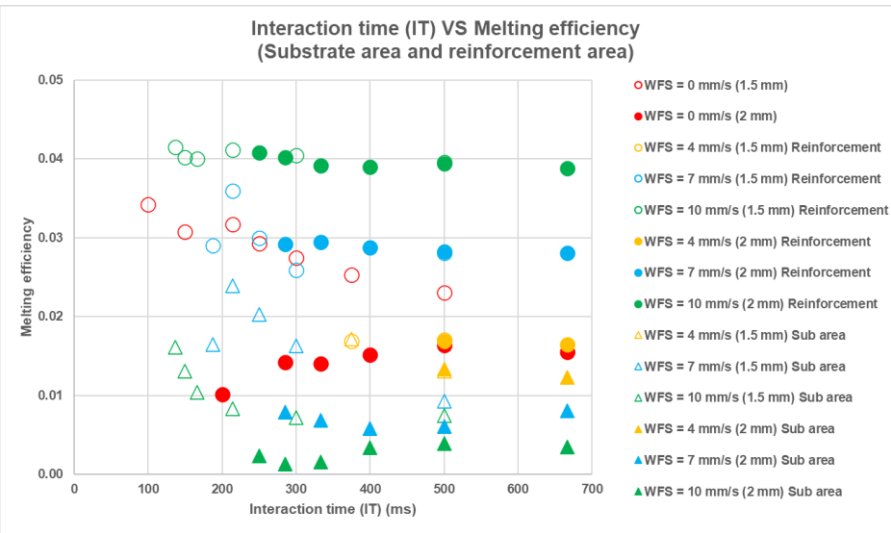


Figure 6-47 Image of the melting efficiency of reinforcement area and substrate area processed at different levels of WFS and the melting efficiency of the autogenous laser weld against the IT processed at the 1.5 mm and 2.0 mm laser beams.

For the 2.00 mm laser beam, adding the wire with 4 mm/s of WFS, the melting efficiency of the reinforcement is similar to that of the autogenous laser weld case. This means the melting efficiency increment for the 2.00 mm laser beam, when the WFS exceeds 4 mm/s, comes from the added material, but this also comes at the cost of energy being taken from the substrate.

6.7.2 High-level LPs situations

For the high-level LP cases, Table 6-28 lists the bead on plate average total cross-sectional area of all the cases with good performance, the corresponding average area of the autogenous laser weld, the average reinforcement area, the average substrate area of the bead on plate, respectively, and the corresponding melting efficiency.

It can be seen that within the IT range of 40 to 60 ms, similar as the 500 W LP case, the laser is more efficient in wire-added process, a larger bead on plate cross-sectional area compared with the autogenous cross-sectional area was achieved, except in the case with 2.00 kW of LP and 2.0 mm laser beam. In this case of the autogenous laser weld, the keyhole mode profile appeared causing a larger melted area. This is because the large laser beam and high-level LP were used; the cross-sectional area was propagating widely sideward as well as downward, resulting in a large cross-sectional area. When adding the wire to the process, more energy was absorbed by the wire, resulting in the energy that can be transferred to the substrate being mitigated. Therefore, the total cross-sectional area of the bead-on-plate is reduced.

Table 6-28 Specific cross-sectional area of the total bead, total weld, reinforcement, and substrate region of all the cases with good performance, and the corresponding melting efficiency.

Area type	BD (mm)	WFS (mm/s)	TS (mm/s)	IT (ms)	Speed ratio	LP (kW)	PD (kW/cm ²)	Average cross- sectional area (mm ²)	Melting efficiency
Total bead	2.0	50.00	50	40	1.00	1.50	47.75	0.50	0.13
Total weld	2.0	0.00	50	40	0.00	1.50	47.75	0.37	0.10
Reinforcement	2.0	50.00	50	40	1.00	1.50	47.75	0.27	0.07
Substrate	2.0	50.00	50	40	1.00	1.50	47.75	0.23	0.06

Total bead	2.0	50.00	50	40	1.00	2.00	63.66	0.65	0.13
Total weld	2.0	0.00	50	40	0.00	2.00	63.66	1.11	0.22
Reinforcement	2.0	50.00	50	40	1.00	2.00	63.66	0.26	0.05
Substrate	2.0	50.00	50	40	1.00	2.00	63.66	0.39	0.08
Total bead	3.0	50.00	50	60	1.00	2.79	39.47	0.87	0.11
Total weld	3.0	0.00	50	60	0.00	2.79	39.47	0.74	0.10
Reinforcement	3.0	50.00	50	60	1.00	2.79	39.47	0.29	0.04
Substrate	3.0	50.00	50	60	1.00	2.79	39.47	0.58	0.08
Total bead	3.0	75.00	75	40	1.00	2.79	39.47	0.52	0.10
Total weld	3.0	0.00	75	40	0.00	2.79	39.47	0.45	0.09
Reinforcement	3.0	75.00	75	40	1.00	2.79	39.47	0.27	0.05
Substrate	3.0	75.00	75	40	1.00	2.79	39.47	0.25	0.05
Total bead	3.0	93.75	75	40	1.25	2.79	39.47	0.50	0.10
Total weld	3.0	0.00	75	40	0.00	2.79	39.47	0.45	0.09
Reinforcement	3.0	93.75	75	40	1.25	2.79	39.47	0.32	0.06
Substrate	3.0	93.75	75	40	1.25	2.79	39.47	0.17	0.03

Similarly, for these good performance cases, the higher efficiency of melting the wire is not caused by the added material only; it is the case of added material plus the substrate area, but at the cost of energy being taken from the substrate.

The case with 93.75 mm/s of WFS exhibits a relatively high wire melting efficiency and a high capacity of accommodating the melted wire. In the previous chapter, this case has been addressed due to the width of the bead being wider than the autogenous weld. When the 75 mm/s of WFS was being used, a similar width of the bead as the autogenous weld was achieved. This means that when increasing the WFS from 75 mm/s to 93.75 mm/s, the wire absorbs more energy to melt this amount of the wire and still has the leftover energy to convey to the melt pool at this set of processing parameters. Therefore, still has the potential to accommodate more wire fed at a higher WFS. Then, as the WFS continues to increase, the bead size becomes smaller than the autogenous weld until failure happens. This reveals that at a set of constant LP, and TS, as the WFS increases, this amount of wire can absorb more energy from the laser itself; it is unnecessary to increase the LP accordingly, which may deteriorate the wire absorbing more energy behaviour itself unintentionally.

This case also has the least substrate area melting efficiency, which means the process spends the least of energy on melting the substrate to prompt a stable bonding, therefore, the process is relatively colder than other cases in terms of

remelting the previous layer when building the wall, this should be the advantage for wall building.

6.8 Chapter summary

In this chapter, the feasibility of manufacturing millimetre-scale wall features using high-level LP ranging from 1.00 kW to 2.79 kW with a 2.00 mm to 3.00 mm laser beams was investigated along with the corresponding autogenous laser welds study, which can guide the set of parameter selection for the wire adding process. Several points are concluded below:

- Using 1.5 mm to 3.0 mm laser beams with higher LP ranging from 1.50 kW to 2.79 kW, a 1.0 mm autogenous laser weld width still can be achieved, which is achieved by processing faster to create a width smaller than the laser beam size.
- Using linear energy density (EI) can analyse the LP effect, but needs FLMIPs to explain the performance reason. When it comes to the BD effect, due to the longer IT at a larger BD, different IT durations can interfere with the real BD effect; using EI should be avoided. Using Esp instead of EI can get the real BD and LP effect. And the width development trend can be explained through the analysis of FLMIPs directly.
- Owing to the fast-processing speed operated, the applied energy is relatively low, which causes the mitigation of many factors' influence on the width variation, such as IT, Esp, and EI. Therefore, the feasibility of similar width independent of LP can appear at a low level of energy.
- At fast processing speed, to achieve the autogenous laser weld width less than 1.0 mm using large BD, high peak-PD plays a critical role in width development, of which the width is mainly formed by the thermal length. In this case, A Gaussian-type fibre laser could be an advantage to achieve a wall width far less than the BD used. An even energy distribution of a top-hat profile case could make the feasibility of manufacturing millimetre to submillimetre-scale walls to become difficult.

- Due to the high levels of LP used, at a width close to 1.0 mm region, a smaller BD controls a wider width situation does not appear from the perspective of surface ED. A large BD always has a wider width.
- Processing at a higher LP and a faster speed to conduct the deposition, a larger D-ratio is required; the previous D-ratio worked well for the low-level LP situation can introduce back the wire position sensitivity.
- The millimetre-scale walls at higher levels LP, larger laser beam conditions have been achieved. The deposition rate has been extended from 40 g/h to 400 g/h and still shows the potential to have a better net-shape submillimetre profile and a higher deposition rate of 750 g/h.
- The high deposition rate process is repeatable, and the process performance is relatively stable.
- Adding the wire can enhance the melting efficiency of the process compared with the conduction mode autogenous laser welding process. This is because of a higher energy utilisation rate of the wire without much energy dissipating resulting in a higher temperature of the wire. Meanwhile, a higher temperature of the wire causes a higher laser absorptivity for the wire, resulting in more material being melted to form a larger cross-sectional area, therefore, resulting a higher melting efficiency.

7 Conclusions

The feasibility of manufacturing millimetre to submillimetre-scale wall features using from 250 W to 500 W low levels to 1.0 kW to 2.79 kW high levels of LP, from a 1.0 mm small beam to 1.5 mm – 3.0 mm large beams have been investigated. Several critical conclusions can be drawn as follows:

- Millimetre to submillimetre-scale wall features can be deposited using large beam diameters.
- A 1.0 mm small laser beam size with a small D-ratio of 1.67 makes the process sensitive to the LP variation due to the steep laser beam profile distribution. Small D-ratio caused the difficulty of achieving a stable deposition process with good repeatability due to many issues introduced, such as plume, defects, wire positioning sensitivity and tolerance.
- The wire position tolerance is increased by using a higher D-ratio. This ratio should be greater than 2.5.
- To enable higher deposition rates for millimetre-scale wall features fabrication, a high-power laser is needed along with larger beam sizes and much higher processing speeds to compensate for the high LP applied. This can reintroduce the process sensitivity; a higher D-ratio is needed to reduce the process sensitivity.
- 400 g/h of deposition rate can be achieved for now and has the potential to reach 750 g/h for the 0.6 mm in diameter 316L Si stainless steel wire.

8 Future work

- Investigation of using a 1.2 mm wire to deposit submillimetre-scale features.
 - Keep the parameter used in Chapter 6 constant, to observe whether the plume extent can be reduced when using a thicker wire.
 - Keep the D-ratio constant to study the large beam size effect on deposition performance.
- Optimise the parameters with a better strategy to extend the high deposition rate millimetre features to the submillimetre scale.
- Update the setup of the 3-kW laser with a better wire feed nozzle alignment along the processing direction to test the wall surface waviness, maybe combine with an automatically positioning device to position the wire.
- Try other materials such as Titanium, Aluminium, and Magnesium alloys.
- Identify the maximum beam size boundary for manufacturing millimetre to submillimetre-scale wall features using this 3-kW laser system.
- Apply preheating to the substrate and wire for higher deposition rates.
- Place the wire vertically and laser laterally to study whether the energy utilisation efficiency can be enhanced for large laser beams.
- Place the laser head with a larger tilted angle, for instance, 10°, 30°, 45°, etc to enlarge the beam length projected on the substrate along the deposition direction to enable higher values of FLMIPs but keep at the constant system parameters used in this thesis.
- Calculate the energy efficiency based on the inverse of the formula of the heat input index.

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Appendices

Appendix A Ethical approval letter



4 December 2024

Dear Mr Wang ,

Reference: CURES/24002/2024

Project ID: 27330

Title: INVESTIGATION OF WIRE-BASED LASER DIRECTED ENERGY DEPOSITION (DED) PROCESS FOR HIGH-RESOLUTION SUBMILLIMETRE FEATURES

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/24002/2024 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

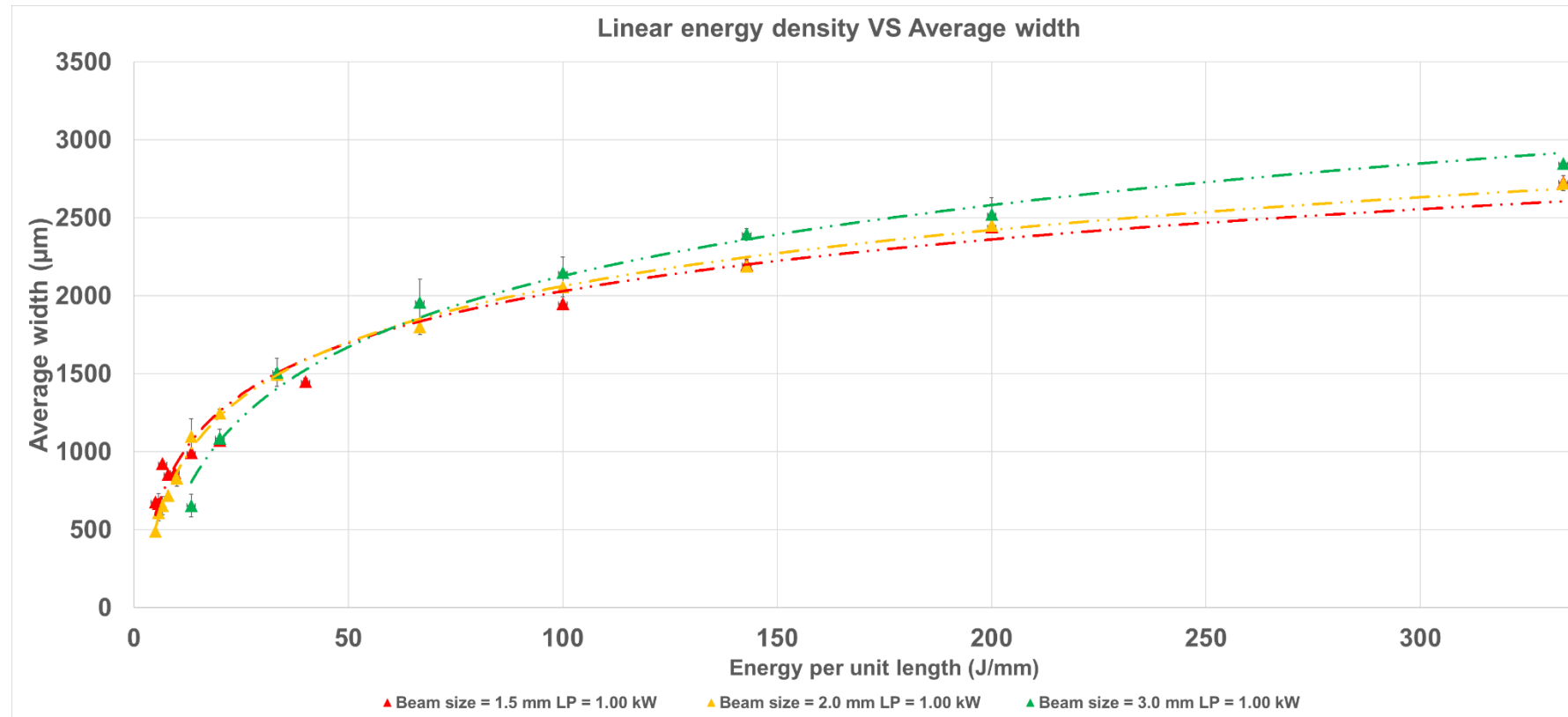
We wish you every success with your project.

Regards,

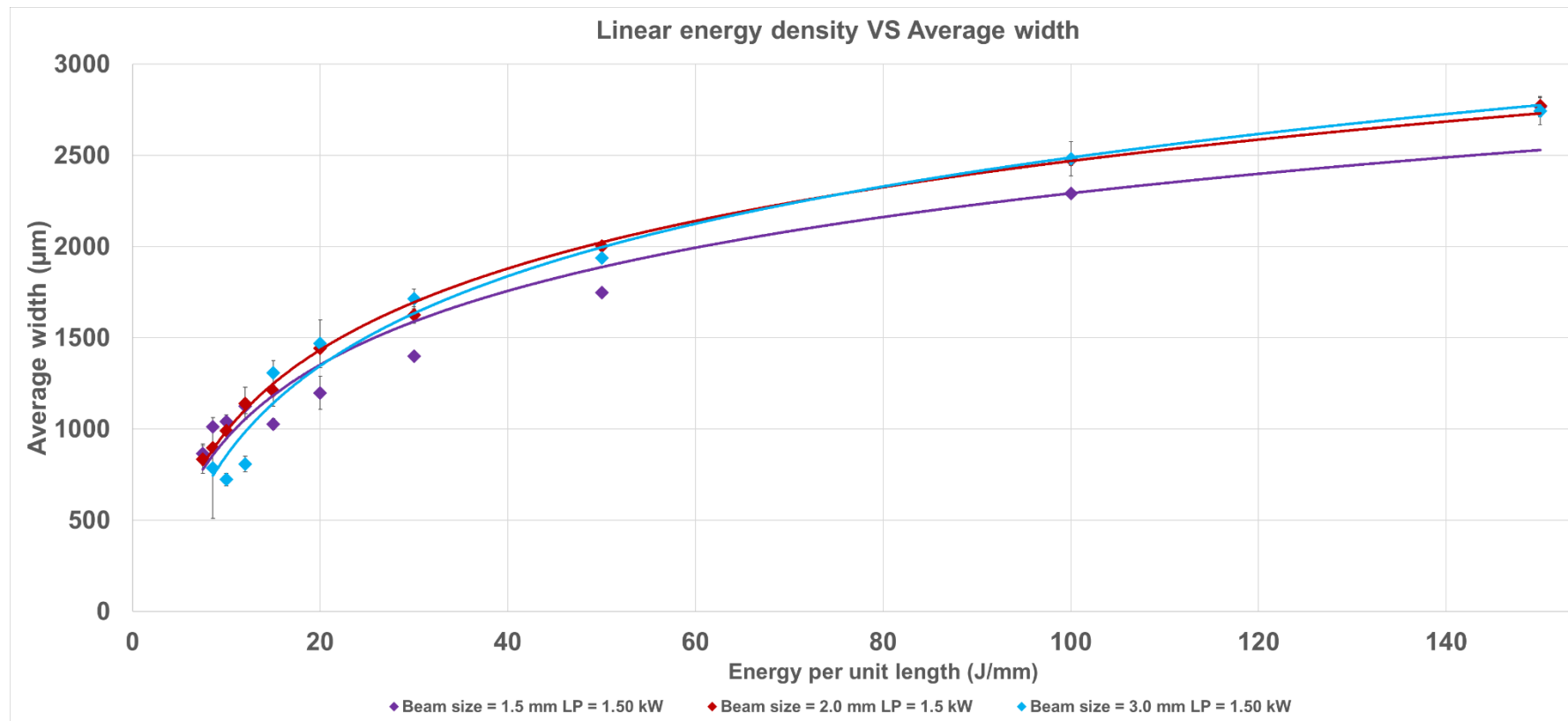
CURES Team

Figure_Apx A-1 Image of ethical approval letter.

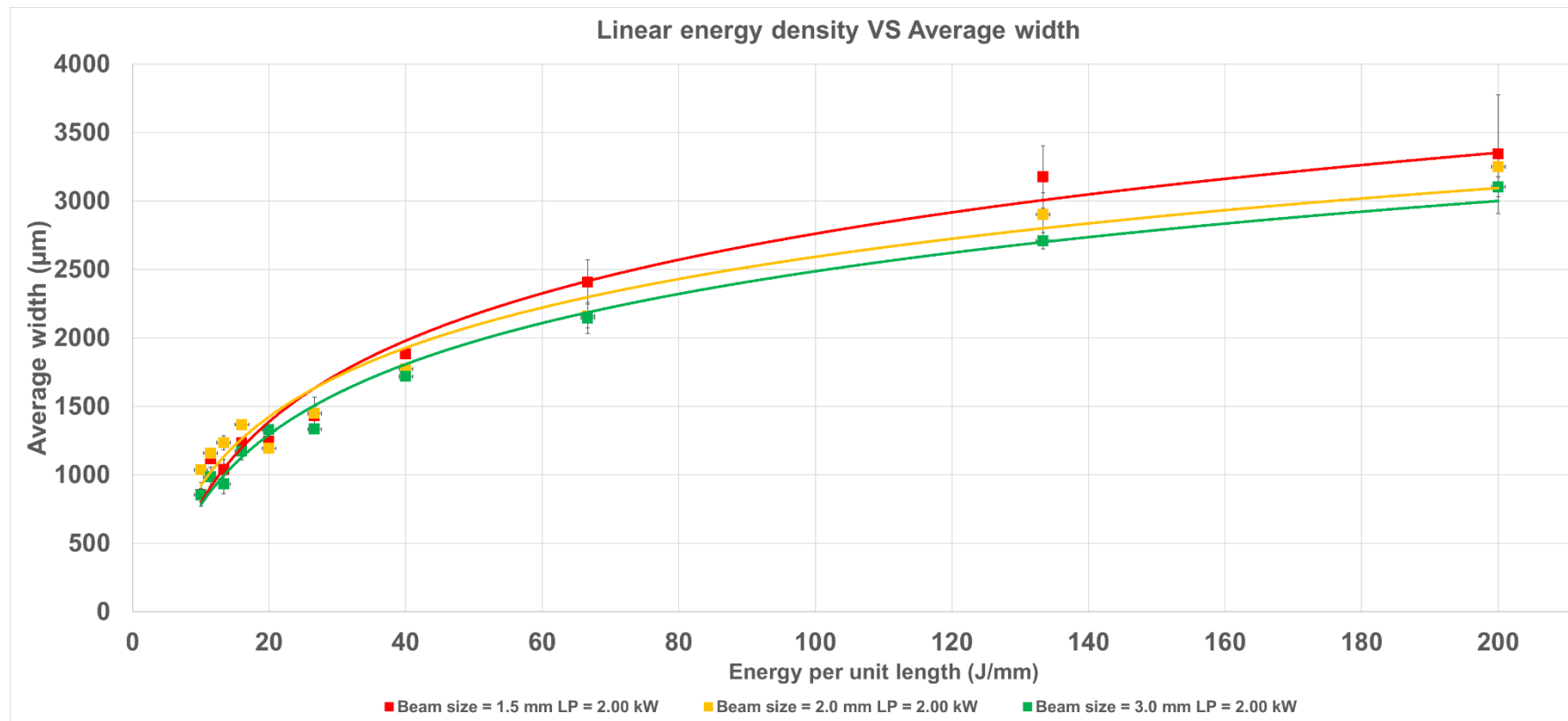
Appendix B



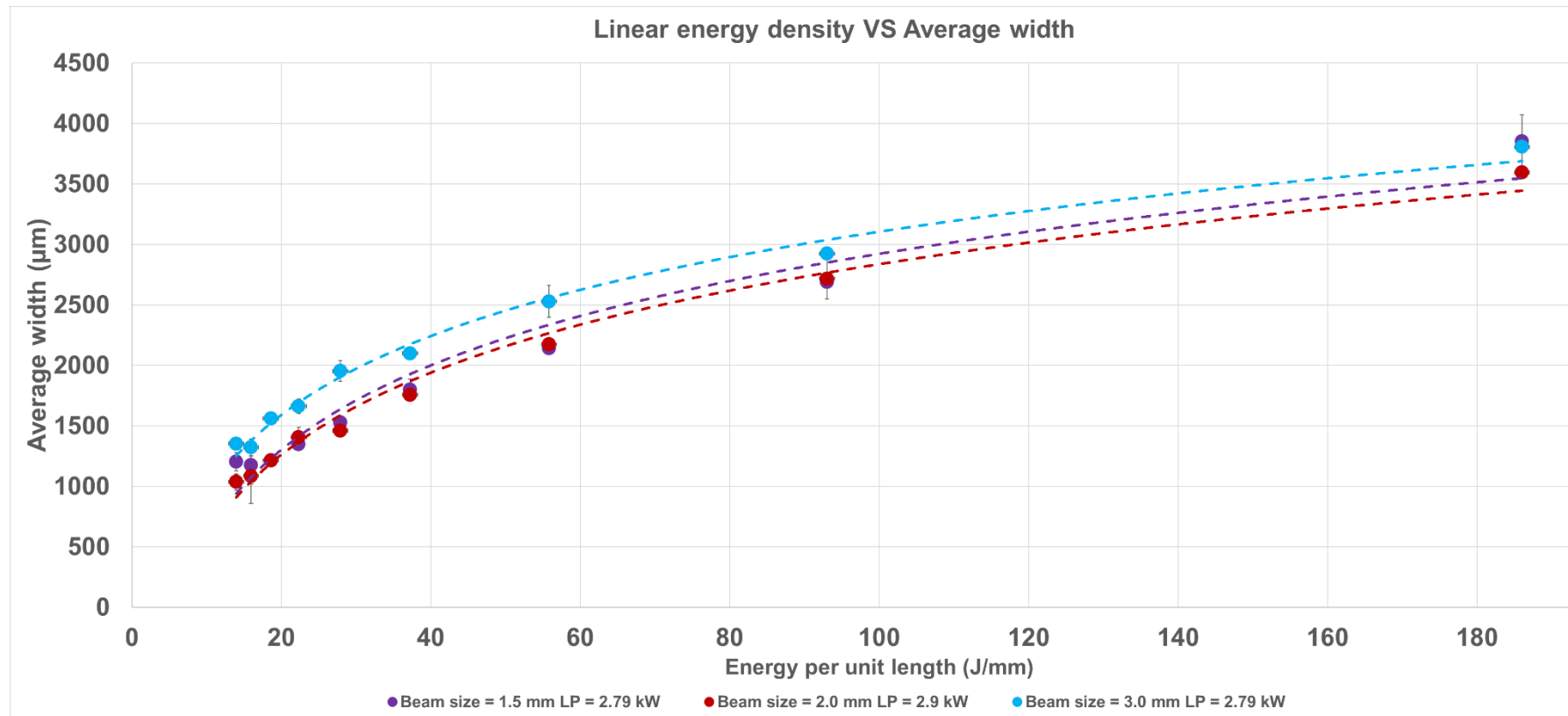
Figure_Apx B-1 Image of EI versus average width at 1.00 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



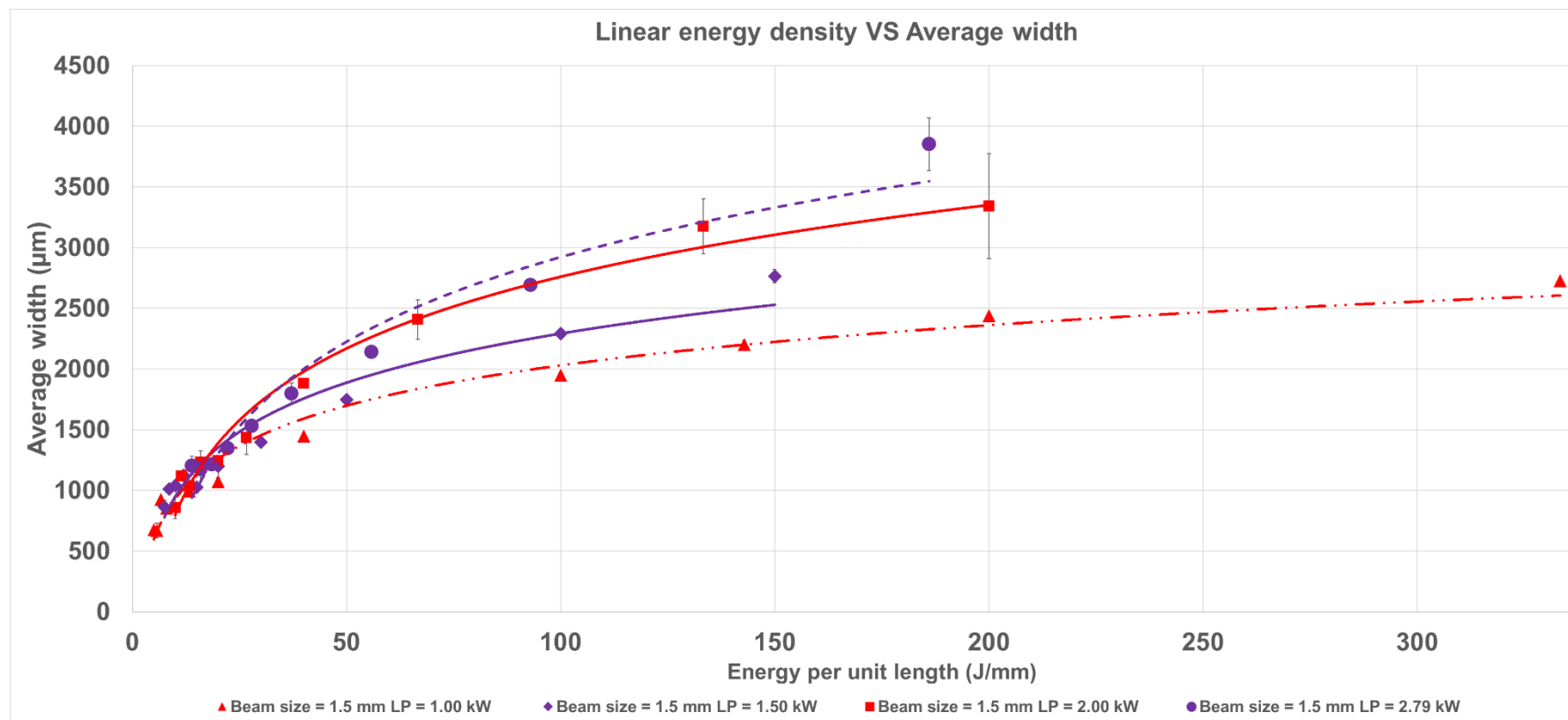
Figure_Apx B-2 Image of EI versus average width at 1.50 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



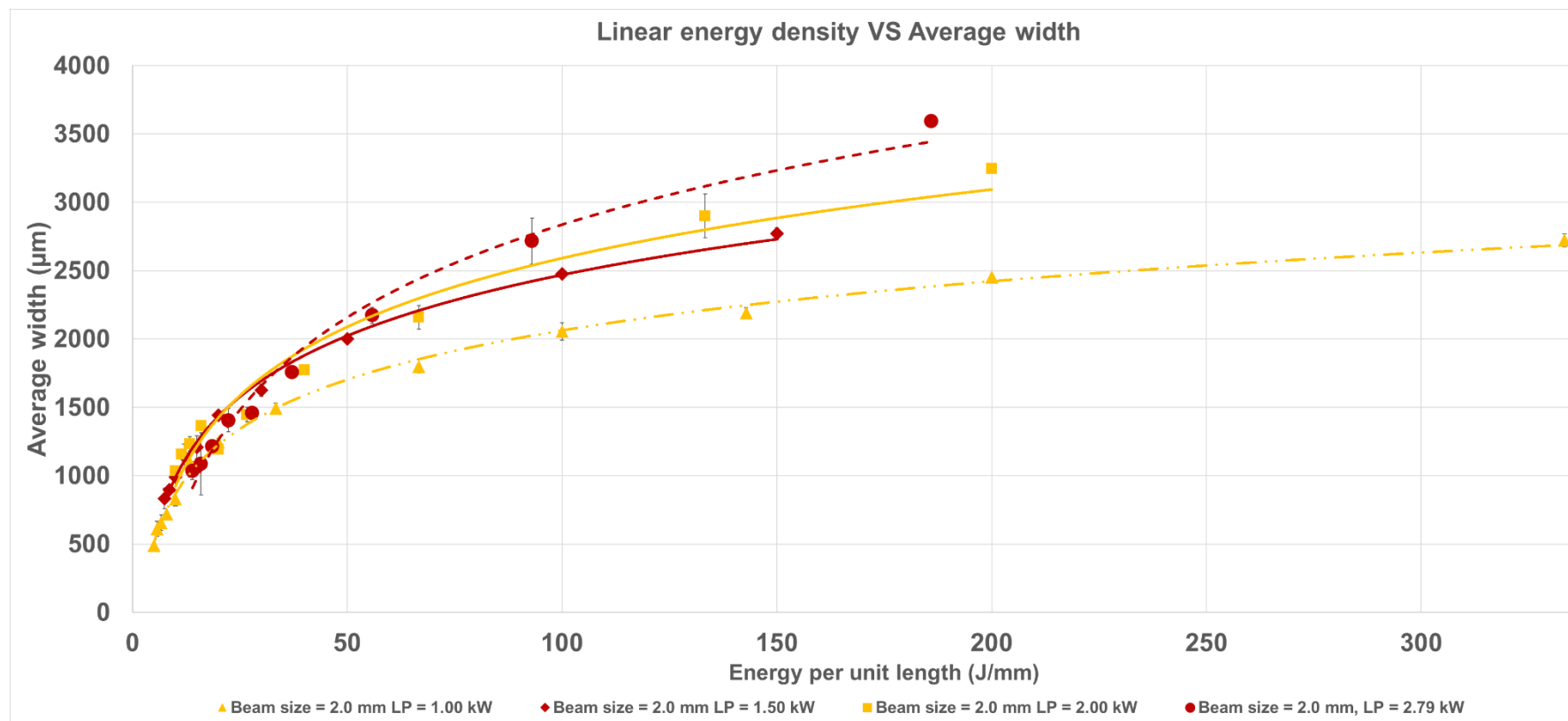
Figure_Apx B-3 Image of EI versus average width at 2.00 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



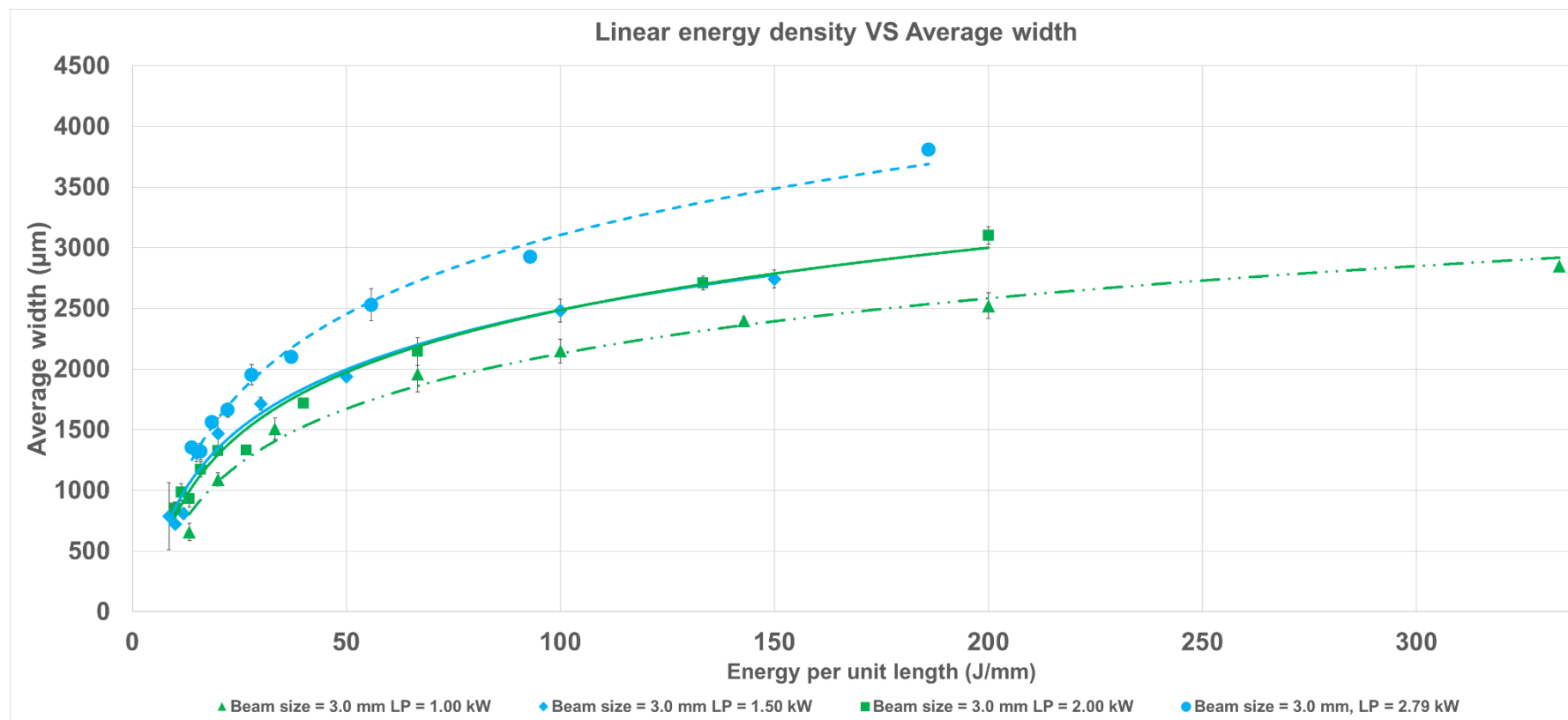
Figure_Apx B-4 Image of EI versus average width at 2.79 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



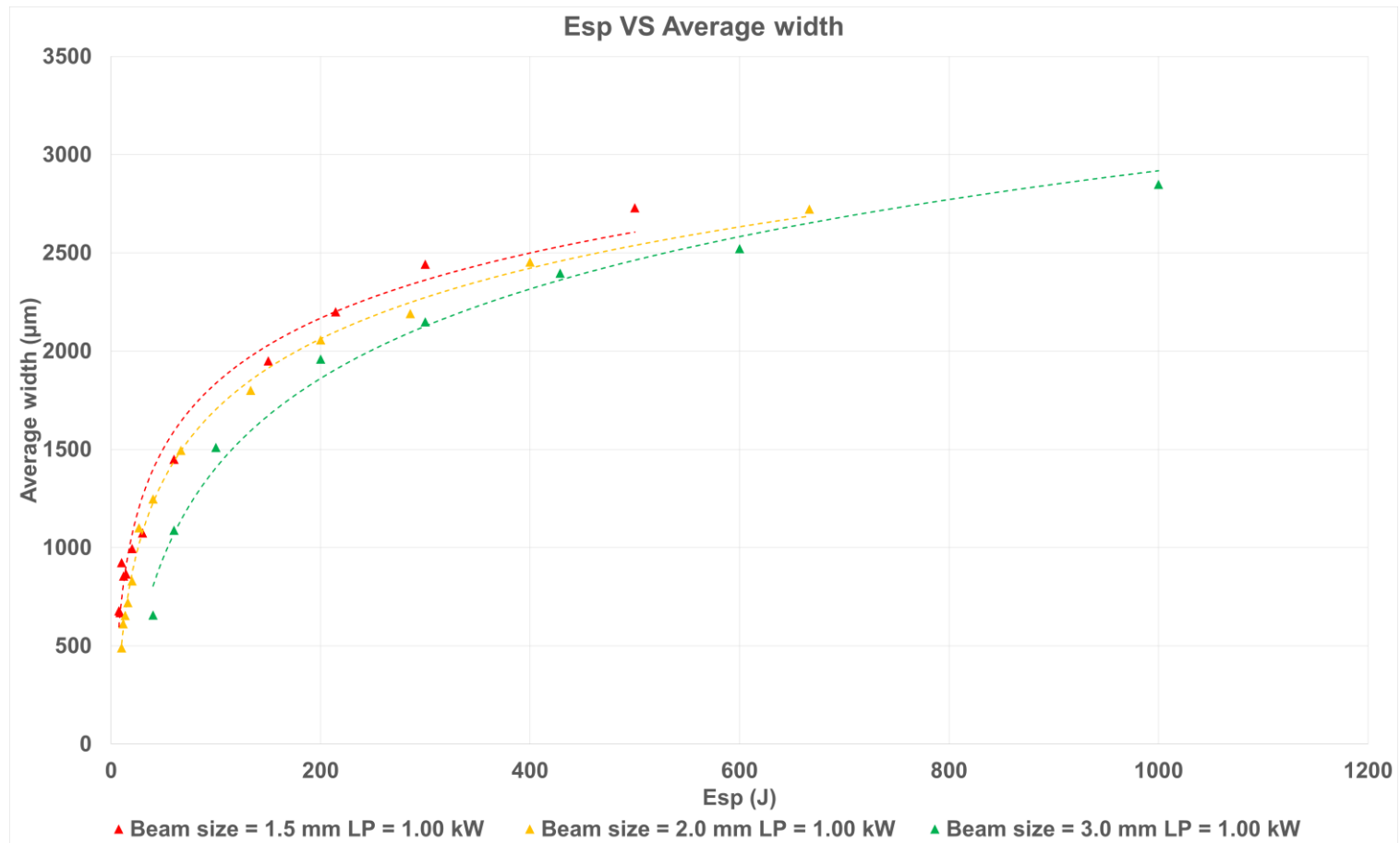
Figure_Apx B-5 Image of EI versus average width using a 1.5 mm BD with LP ranging from 1.00 kW to 2.79 kW.



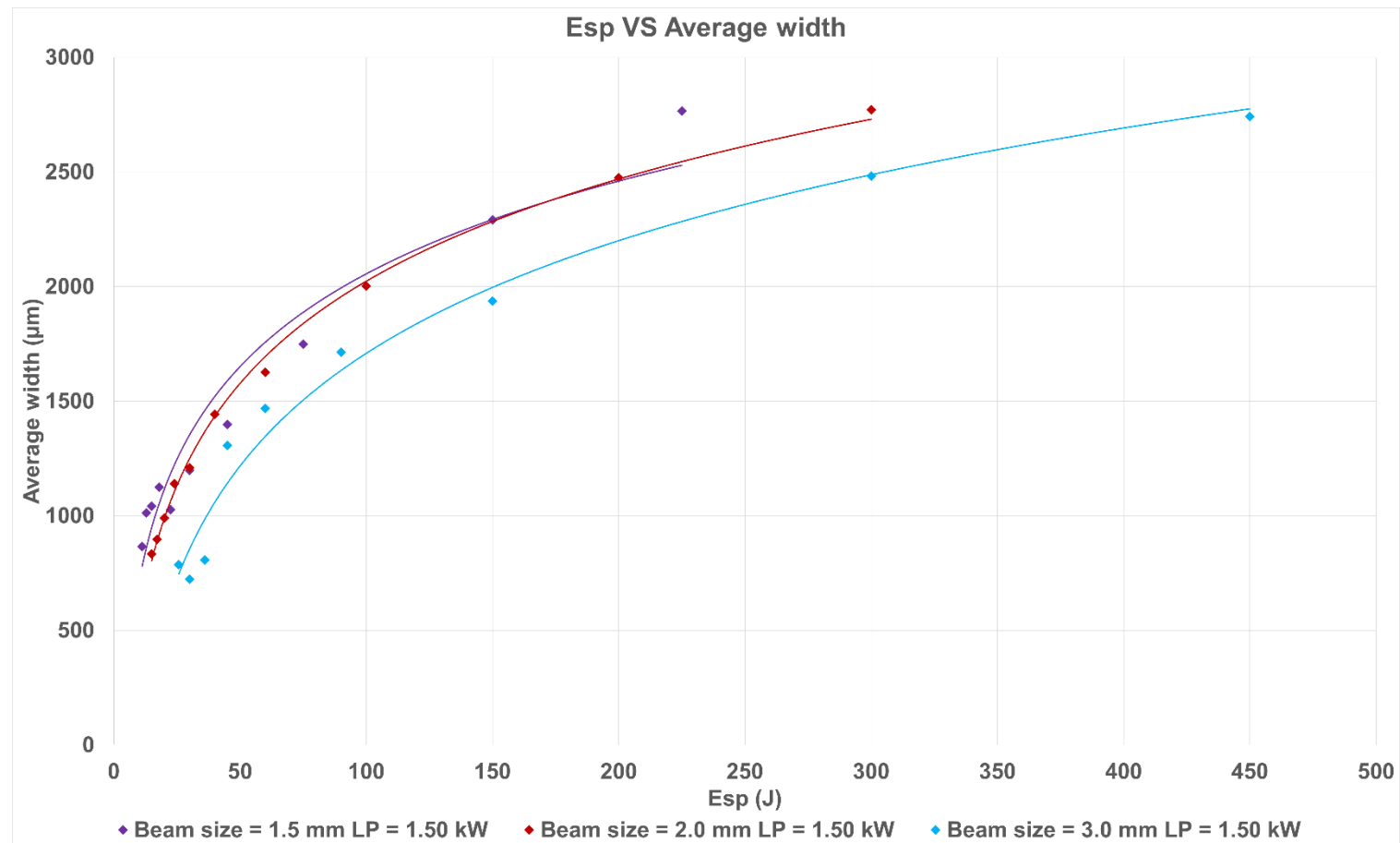
Figure_Apx B-6 Image of EI versus average width using a 2.0 mm BD with LP ranging from 1.00 kW to 2.79 kW.



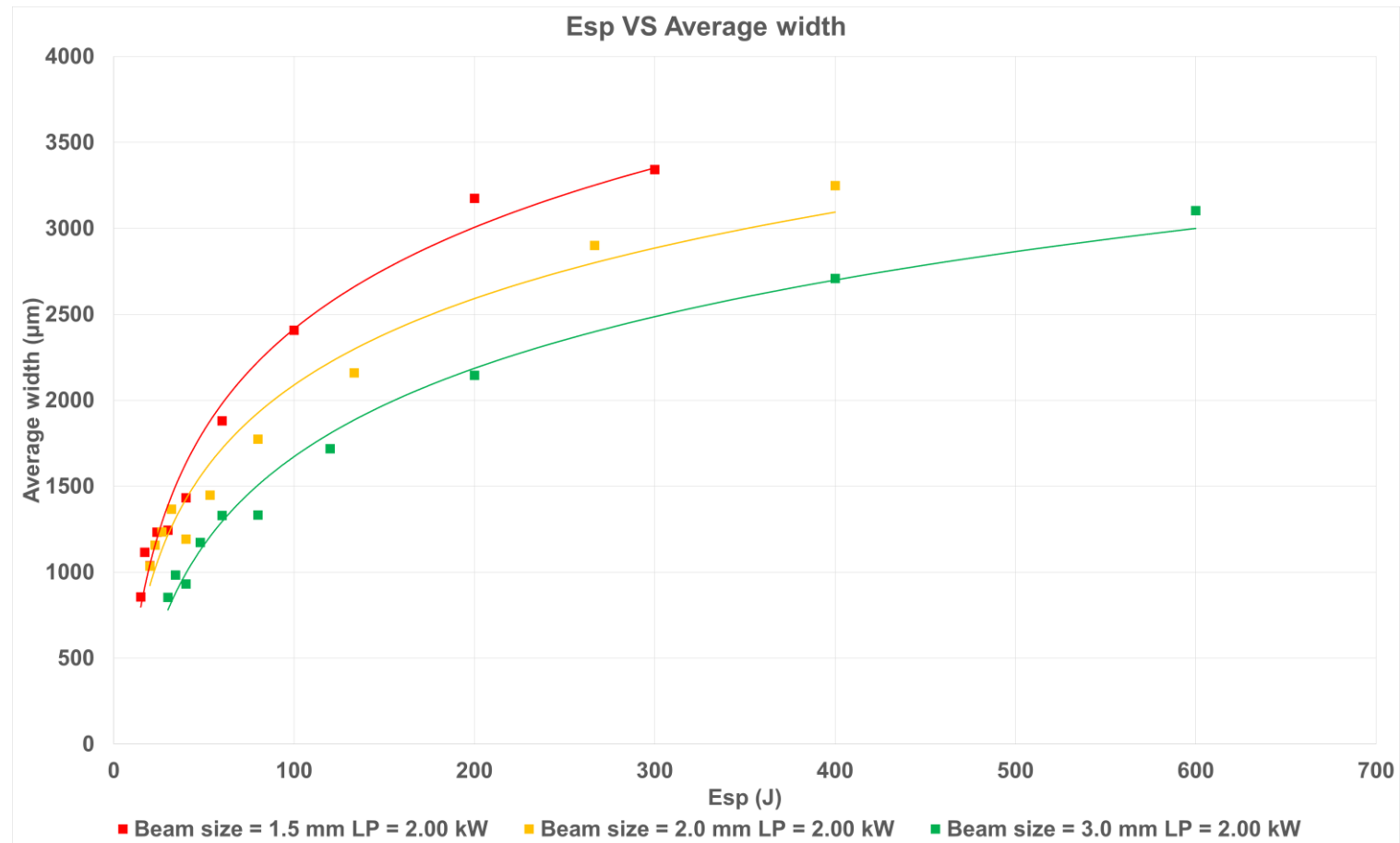
Figure_Apx B-7 Image of EI versus average width using a 3.0 mm BD with LP ranging from 1.00 kW to 2.79 kW.



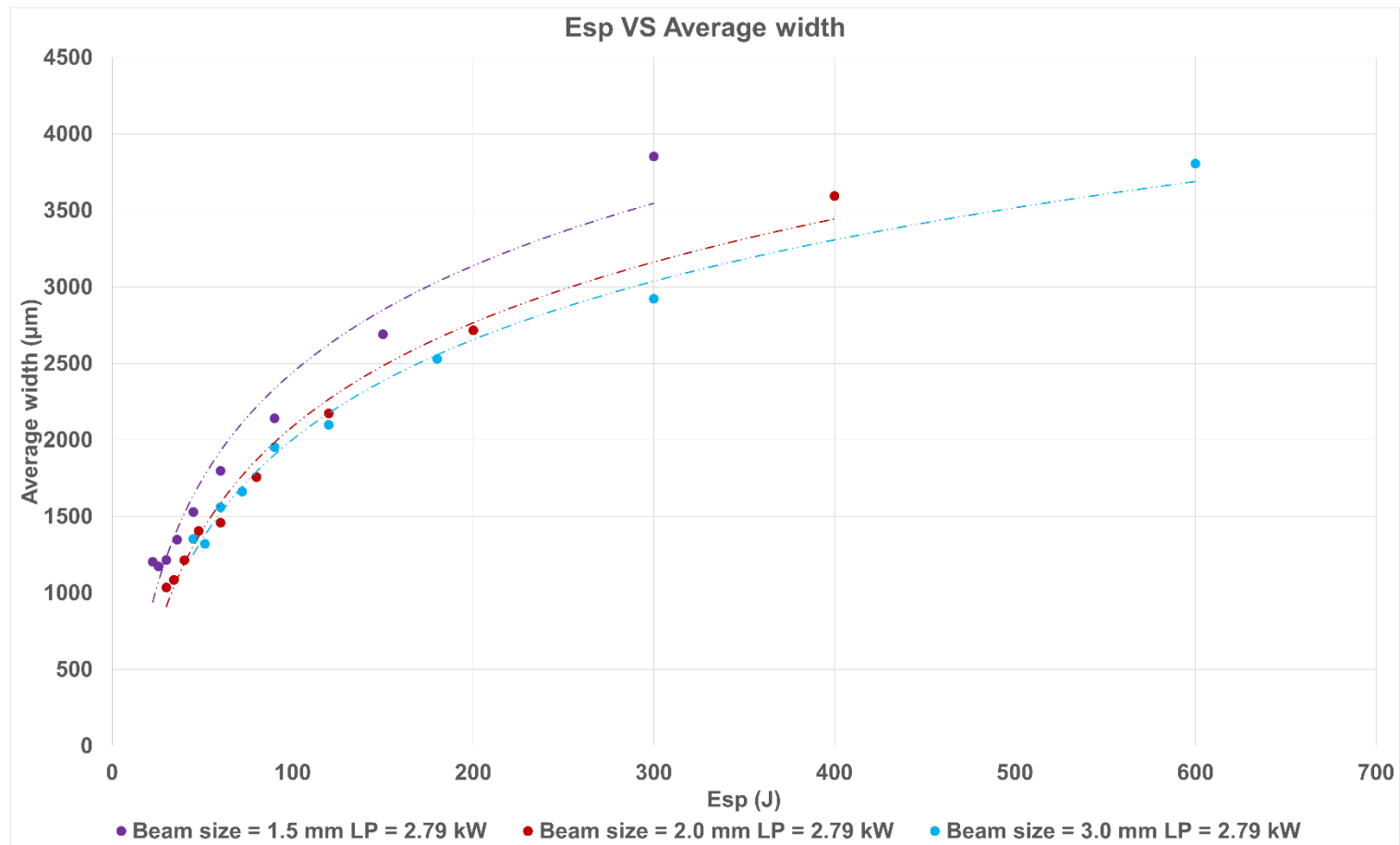
Figure_Apx B-8 Image of Esp versus average width at 1.00 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



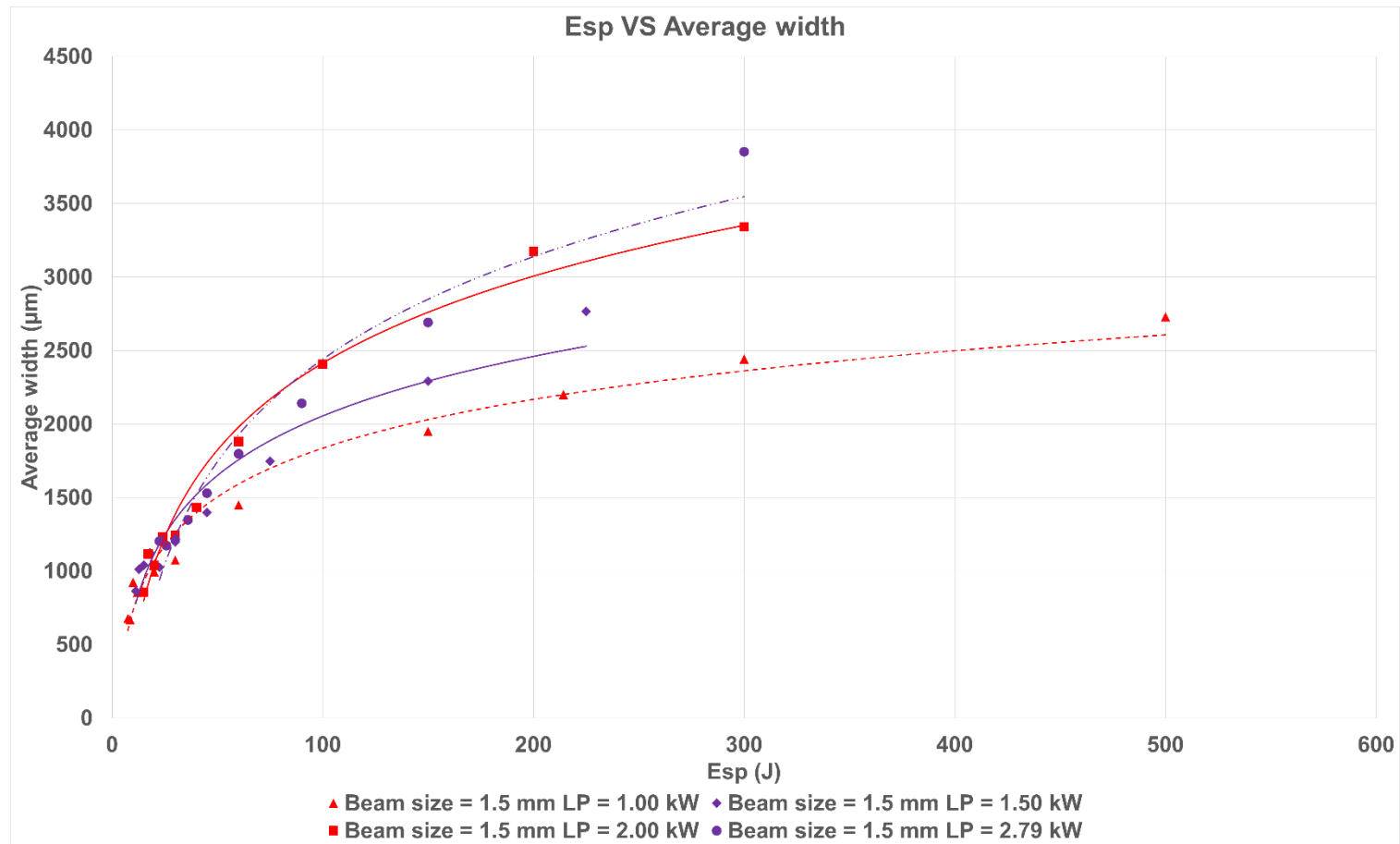
Figure_Apx B-9 Image of Esp versus average width at 1.50 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



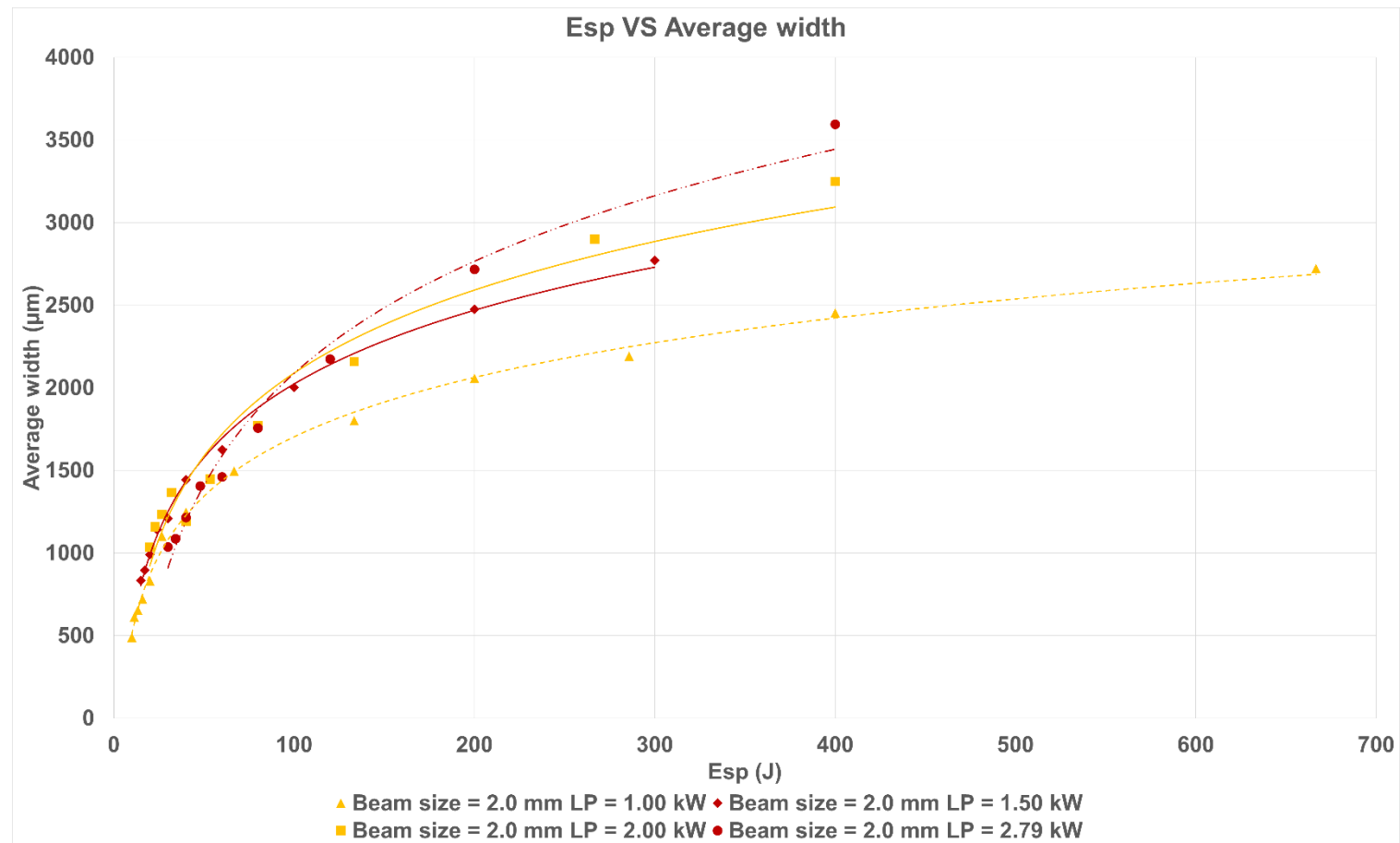
Figure_Apx B-10 Image of Esp versus average width at 2.00 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



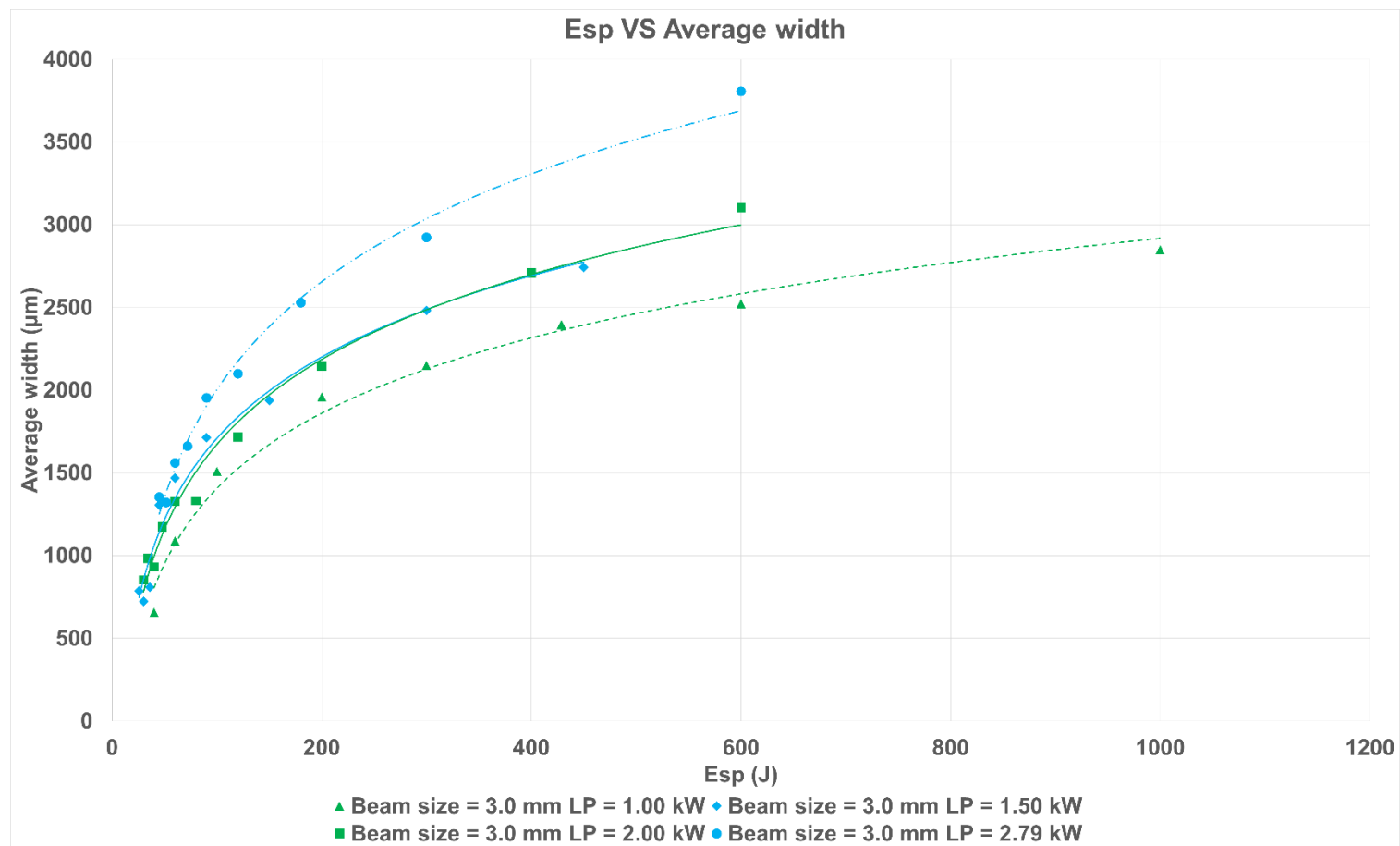
Figure_Apx B-11 Image of Esp versus average width at 2.79 kW of LP with three levels of BD ranging from 1.5 mm to 3.0 mm.



Figure_Apx B-12 Image of Esp versus average width using a 1.5 mm BD with LP ranging from 1.00 kW to 2.79 kW.



Figure_Apx B-13 Image of Esp versus average width using a 2.0 mm BD with LP ranging from 1.00 kW to 2.79 kW.



Figure_Apx B-14 Image of Esp versus average width using a 3.0 mm BD with LP ranging from 1.00 kW to 2.79 kW.

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COLUMBUS STAINLESS (Pty) Ltd Subsidiary of ACERINOX, S.A. SWB: +27 13 247 9111 FAX: +27 13 246 1681 http://www.columbus.co.za PO BOX 133 MIDDELBURG 1050 MPUMALANGA SOUTH AFRICA		 by Accredited Body		Abnahmeprüfzeugnis INSPECTION CERTIFICATE ACCORDING TO EN 10204 3.1 Prüf - Nr. 67 2021 2535 10001 E Inspection No. <small>*Zustimmungsschreiben des TÜV Baden vom 21. Februar 1983* Letter of approval from the TÜV Baden dated 21-2-83 *Laut Schreiben des TÜV Baden v. v. vom 26. Juni 1.989 wird auf die Gegenseignung verzichtet.* TÜV Baden renounce to the countersignature according their letter dated 26-6-89</small>										
Besteller - Customer ASC METALS LTD		Auftrags Nr - Our order n° MA 548		Bestellung Nr - Your order n° GS 7952/Dec21										
Prüfgegenstand - Article BLECH AUS BAND (SHEET)		Werkstoff Nr und Lieferzustand - Material n° and Condition of Delivery 1.4401/1.4404 2B												
Werkstoff - Normbez Standard - Grade of Material X5CrNiMo 17-12-2/X2CrNiMo 17-12-2		Werksbez - Works Grade Acr - 240		Erschmelzungsart - Steelmaking Process A = AOD Verfahren - AOD Process										
Anforderungen - Technical requirements EN 10028-7/AD W01T00 100/AD2000 W2W10/PE0 2014/08/IEU		Kennzeichnung - Marking Schmelzenummer - N° of coil												
Zeichen des Lieferwerks - Brand of the manufacturer		 Stempel des Sachverständigen - Inspector's stamp												
Pos Nr. Item N°	Stückzahl Quantity	Abmessung - Dimensions mm		Schmelze Nr Heat N°	Probe Nr Test N°									
2	42	2,000 x 1.000,00 x 2.000,00		N00027	N000434 A02CB01 C / F									
Chemische Analyse - Chemical Composition (%)														
Schmelze Nr Heat N°	C	CR	MN	MO	N	NI	P	S	SI					
Anforderungen Requirements	0,030	16,500 18,500	2,000	2,000 2,500	0,100	10,000 13,000	0,045	0,015	1,000					
N00027	0,019	17,000	1,590	2,000	0,060	10,100	0,032	0,010	0,470					
Mechanische Eigenschaften - Mechanical Properties Pr. Temp/T. Temp. 20° C														
Probe Nr Test N°	Prob.-Lage Pos of Test	Abmessungen des Probekörpers Dim. of specimen		Rm. MPa	Rp 0.2 MPa	Rp 1.0 MPa	A50 %	A80 %	HRB HRBW	A262-E				
Anforderungen Requirements		Breite x Dicke Width x Thickness mm		530,00 680,00	240,00	270,00	40,00	40,00	95,00					
N000434A02CB01 N000434A02CB01	C T F T	20,000 20,000	2,00 2,00	628,00 650,00	310,00 366,00	337,00 402,00	49,00 45,00	49,00	80,00 86,00					
Beschäftigung und Masskontrolle wurden durchgeführt: O.B. Surface and dimensions controlled: O.K. Der Werkstoff ist beständig gegen interkristalline Korrosion gemäss The material is resistant to intergranular corrosion test according to Spektroskopische Identitätsprüfung: O.B. Spectrometrical identity test: O.K. Wärmebehandlung: Glühen bei 1050 - 1100 °C Heat treatment: Und Abschrecken mit Luft, cooling with air. Die Lieferung entspricht der Bestellung. The delivery is in accordance with the order Issued in agreement with TÜV SÜD Industrie Service GmbH (02/1983)										WERKSACHVERSTÄNDIGER WORK INSPECTOR				
Zeugnis ist per EDV erstellt und ohne Unterschrift gültig gemäss E-Norm 10204										Middelburg, 16. November 2021				

FDT0014

Figure_Apx B-15 Image of the chemical composition of the 2 mm-thick 316L stainless steel sheet substrate.

Sold to

OUTOKUMPU STAINLESS LTD, Outokumpu
Europa Link, SL2 Building, Door 51
Stainless Distribution
Europa Link, SL2 Building, Door 51
SHEFFIELD S9 1TZ
UNITED KINGDOM

Product

Stainless Steel Hot Rolled Plate, Silt
edge, Supra 316L/4404

Grade

1.4401
1.4404
TYPE 316 / UNS S31600
TYPE 316L / UNS S31603

Finish

1D

Ship to

Outokumpu Stainless Distribution
Plate Service Centre
Door 57, Europa Link
SHEFFIELD
S9 1TZ
UNITED KINGDOM

Requirements

AD 2000 W 2, Aug. 01.2020, W 10, Aug. 01.2020 & EN 10028-7:2016
ASME SA-240/SA-240M BPVC.II.A-2021
ASTM A240/A240M - 20a
EN 10028-7:2016
EN 10088-2:2014
EN 10088-4:2009
NACE MR0103/ISO 17945:2015
NACE MR0175/EN ISO 15156-1:2020 & NACE MR0175/EN ISO 15156-3:2020

Mark of manufacturer

outokumpu

Process

E+AOD

Inspector's Stamp

AJA

ASME SA-480/SA-480M BPVC.II.A-2021
ASTM A480/A480M - 20a
EN ISO 9444-2:2010

Sales order item

Dimensions

Quantity (pcs)

Weight

Heat No.

Lot No.

Identification No. of Product

Customer's Material No.

20

6,00 X 2000,0 X 4000 mm

16

6090 kg

520525

4

520525-4

Chemical Composition

Heat No. 520525	Country of Melt Sweden	C % 0,018	Si % 0,45	Mn % 1,27	P % 0,030	S % 0,001	Cr % 17,1	Ni % 10,1	Mo % 2,03	N % 0,039	
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Test Results (1=Beginning, 2=Middle, 3=End, T=Transverse, L=Longitudinal, D=Diagonal, RT=Room temperature)

		EN ISO 6892-1 / ASTM A370 (RT)						ASTM E10 / EN ISO 6506-1	
Identification No. of Product	Sample ID	RP0.2 MPa	RP1.0 MPa	RM MPa	A5 %	A50 %	HARDNESS HBW		
	Minimum	220	290	530	40	40			
	Maximum			680			217		
520525-4	1 T 796100	319	366	616	52	52	178		
520525-4	3 T 796101	314	362	612	54	54	174		
		EN ISO 3851-2 A		PMI					
Identification No. of Product	Sample ID	INTERGRANULAR CORROSION		PMI					
	Minimum								
	Maximum								
520525-4	1 T 796100	OK		OK					
520525-4	3 T 796101			OK					

Figure_Apx B-16 Image of the chemical composition of the 6 mm-thick 316L stainless steel plate substrate.

Chemical composition of 150 mm x 100 mm x10 mm and 150 mm x 150 mm x 10 mm plates was obtained from the following website as the reference.

<https://www.azom.com/article.aspx?ArticleID=2868>

Chemical composition of 0.6 mm 316L silicon stainless steel wire was obtained from the following website as a reference.

<https://www.inverterfusion.co.uk/app/uploads/2023/11/high-alloyed-solid-wires-inertfil-316lsi-oerlikon-en-TN130038.pdf>