

CRANFIELD UNIVERSITY

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APPLICATION OF FIBRE LASERS IN FABRICATIONS AND
PROCESSING OF THIN GAUGE ALLOYS FOR ENGINEERING
APPLICATIONS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
Welding Engineering and Laser Processing Centre

PhD

Academic Year: 2022-2023

Supervisor: Doctor Supriyo Ganguly
Associate Supervisor: Professor Stewart Williams
October 2022

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gauge alloys for engineering applications

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ABSTRACT

Micro-joining of thin metallic sheets has been growing due to the product weight reduction. Several methods are used to join aluminium and iron-based alloys, but most are limited on the workpiece dimensions, processing time and joint strength. Laser welding was selected as the joining tool for this study as a non-contact, productive and highly flexible process in spatial and temporal resolution of energy application for medical, automotive and aerospace applications.

The digital control of the latest multi-pulse pulsed-wave (MPPW) fibre lasers allows different spatial and temporal resolutions to apply low pulse energy at a high repetition rate and narrow pulse width with high precision. However, it isn't easy to control each parameter's effect on the weld profile without understanding the underpinning science of the laser-material interaction. This study aims to predict the material response and establish a relationship between the total applied energy over a spot, the pulse energy, average peak power and pulse duration. The fundamental laser-material interaction parameters (FLMIP), which have proven to characterise the process in continuous-wave (CW) laser welding, have also been investigated in MPPW seam welding. The performance of MPPW and CW laser modes was compared under like-to-like conditions to correlate penetration and melting efficiency, productivity, joining flexibility and defects generation in the similar and dissimilar joining of 5251 H22 aluminium alloy and 304L austenitic stainless steel. In addition to this, an empirical model was applied in both laser modes to achieve a specific weld profile independent of the beam diameter. In MPPW mode, the weld pool profile could be correlated to the power density and interaction time considering the inter-pulse thermal losses. CW processing was revealed to have better flexibility to control the weld shape and joint strength, higher melting efficiency and productivity when compared to MPPW processing.

Keywords: laser welding, CW and MPPW modes, stainless steel, aluminium, keyhole welding, weld shape, power factor model, dissimilar metal joining.

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LIST OF PUBLICATIONS

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- Industrial Laser Applications Symposium (ILAS) 2019 - conference presentation.

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LIST OF ABBREVIATIONS

a	Thermal diffusivity
A	Absorptivity on the surface
AC	Alternating Current
A _{CS}	Area of the weld cross-section
Al	Aluminium
A _m	Area of the molten metal
A _s	Area of laser spot on the material surface
at	Atomic weight
BPP	Beam Parameter Product
CMT	Cold Metal Transfer
C _{PS}	Specific heat of solid phase
CW	Continuous-Wave
d	Beam diameter
D	Collimated beam diameter
DC	Direct Current
D _c	Duty cycle
d _{waist}	Beam diameter in waist
E	Modulus of Elasticity
E _c	Energy dissipated between pulses
E _{D, CW}	Energy density in continuous-wave mode
EDS	Energy-dispersive X-ray Spectroscopy
E _H	Energy of a single pulse
E _m	Energy per unit length required to melt the weld bead
E _{pulse}	Pulse energy
E _{SP, CW}	Specific point energy in continuous-wave mode
E _{SP, MPPW (new)}	New specific pulse energy in multi-pulse pulsed-wave mode
E _{SP, MPPW (old)}	Old specific pulse energy in multi-pulse pulsed-wave mode
F	Focusing length
f	Foil thickness
Fe	Iron
FLMIP	Fundamental Laser Material Interaction Parameters
FST	Friction Stir Welding

HAZ	Heat Affected Zone
HV	Hardness Vickers
IMC	Intermetallic Compound
I_s	Inter-pulse spacing
l_E	Clamping length
k	Thermal conductivity
Li	Lithium
M^2	Definition of beam quality
Mg	Magnesium
MIG	Metal Inert Gas
MPPW	Multi-Pulse Pulsed-Wave
M_t	Material thickness
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
N_p	Number of pulses
O_F	Overlap factor
P_{Depth}	Penetration depth
P_{Eff}	Penetration efficiency
$P_{F, CW}$	Power factor in CW laser mode
$P_{F, MPPW}$	Power factor in MPPW laser mode
P_L	Average output power
P_{peak}	Average peak power
PRF	Pulse Repetition Frequency
PRF_0	Critical Pulse Repetition Frequency
PW	Pulsed-Wave
P_{width}	Pulse width
Q	Laser power dissipated between pulses
q	Thermal heat capacity
q_p	Average power density
$q_{p, peak}$	Average peak power density
R_{FY}	Clamping restrain intensity
RSW	Resistance Spot Welding
SEM	Scanning Electron Microscopy
SPPW	Single-Pulse Pulsed-Wave
SPR	Self-Piercing Riveting

SS	Stainless steel
T_0	Room temperature
t_0	Characteristic thermal time
T_C	Minimum temperature of the baseplate between pulses
t_c	Cooling time between pulses
T_H	Maximum temperature of the baseplate between pulses
t_H	Cumulative time of material irradiation by multiple pulses
t_i, CW	Interaction time in CW mode
TIG	Tungsten Inert Gas
$t_i, MPPW (new)$	New interaction time in multi-pulse pulsed-wave mode
$t_i, MPPW (old)$	Old interaction time in multi-pulse pulsed-wave mode
$t_i, SPPW$	Interaction time in single-pulse pulsed-wave mode
T_m	Melting temperature
TMAZ	Thermo-Mechanically Affected Zone
T_n	Temperature of the based plate after applying n pulses
T_{n+1}	Temperature of the base plate after applying n pulses plus 1 pulse
T_v	Vaporisation temperature
W_L	Weld length
USW	Ultrasonic Spot Welding
V	Volume of molten metal
v	Travel speed
wfm	Waveform
z	Weld depth
z_0	Distance to which heat can diffuse during the beam interaction
Z_m	Melting efficiency
Zn	Zinc
λ	Wavelength
λ	Thermal conductivity
α	Thermal diffusivity
θ	Divergence angle
Δt	Pulse period
η	Viscosity

1 Introduction

Due to the environmental, economic and performance advantages, thin metal sheets below 2 mm are finding more applications in automotive, aerospace, packaging and medical industries [1]. The main aim is to reduce material consumption by reducing the products' weight and increasing manufacturing productivity and recyclability. Two of the most used structural and functional alloys are aluminium (Al) and stainless steel (SS) due to their cost-effectivity, resistance to corrosion, and versatility to be joined by different techniques, including mechanical fastening, adhesive bonding, solid-state and fusion processing. However, some of these methods have several disadvantages, such as low productivity and tool wearing [2], access to both sides of the joint [3], additional weight added to the structure [4], low productivity, and limitation of the joining partners' maximum [5] or minimum thickness [6].

The non-contact joining processes introduce the innovation needed to fulfil the strict manufacturing requirements. They substitute the traditional tool wearing contact methods, improve productivity through ultra-fast scanning devices [7] and provide joint shape and strength flexibility [8]. Joining processes using a laser as the power source are rapidly developing with new applications such as electro-mobility, extending to new combinations of materials. The single-mode fibre lasers can be focused on a small spot due to their high beam quality, increasing power density, high material vaporisation and small heat-affected zones, which is ideal for laser keyhole welding or cutting. They can also be focused on larger spot sizes, providing a large processing area and a reduced power density, being more suitable for brazing or surface treatment. Nevertheless, in this regime, the risk of distortion is higher due to a longer laser-material interaction.

Several laser temporal outputs and laser welding techniques can be chosen for a particular application, making the selection of the most suitable one a difficult task for similar and dissimilar metal joining. For example, the low pulse energy, high peak power, high repetition rate, and narrow pulse width of the latest generation of nanosecond pulsed lasers offer high cooling and solidification rates. They provide high aspect ratio welds and minimise the distortion risk and the time

for diffusion and growth of the brittle intermetallic compounds (IMCs), usually formed when joining dissimilar metal alloys [9]. The high peak power induces a high material vaporisation and weld pool instability, but the low average power, low duty cycle and thermal losses between pulses create limitations on the maximum thickness of the welded joint. On the other hand, the CW lasers' high average power and continuous power delivery allow the joining of thicker metals and provide stable melt pools and strong joints. Still, the long cooling rate may be a challenge in avoiding the IMCs formation [10]. The energy delivered to the workpiece needs to be understood in both laser temporal modes to allow a like-for-like comparison and determine which one provides better performance, i.e. productivity, quality and mechanical strength, and weld shape flexibility for different applications.

2 Literature review

2.1 Joining processes of thin metallic sheets

2.1.1 Mechanical fastening

Self-piercing riveting (SPR) is considered an ideal joining approach for lightweight materials used in several industries, such as automotive, especially for connecting dissimilar materials [11]. It can usually be accomplished at ambient temperature, and the material doesn't need a pre-drilled hole. An SPR joint is produced by piercing a rivet into two or more substrate materials, which can be similar or not. The rivet is pierced through the top sheet and expands in the bottom sheet to form a mechanical interlock. The operation speed is approximately one second [3], and several experimental trial-and-errors are necessary to optimise the die and rivet geometry and ensure a crack-free joint [12].

One plastic joining process alternative to SPR is mechanical clinching, consisting of sheet metal deformation using a die and punch. The process is shown in Figure 2-1. The main advantage compared to SPR is the lower running costs due to the rivet's absence, although the processing speed is quite similar, and both approaches need access from the sides of the joint [3]. In addition to this, it is only used for applications where a high strength joint is not required. Optimising the clinching tools and the sheet thickness arrangements are essential to achieve a desired joint strength [13] and extend the tool life, which is generally limited to 200,000 operations, similar to SPR [3]. Lambiase et al. investigated a different approach to joining thin sheets with preheating, allowing the application of deeper dies with a reduction of the forming force used, which increased the mechanical strength of the joints and reduced the hydrostatic stresses of the sheets [14]. However, sliding between sheets caused by surface irregularities is likely [3].

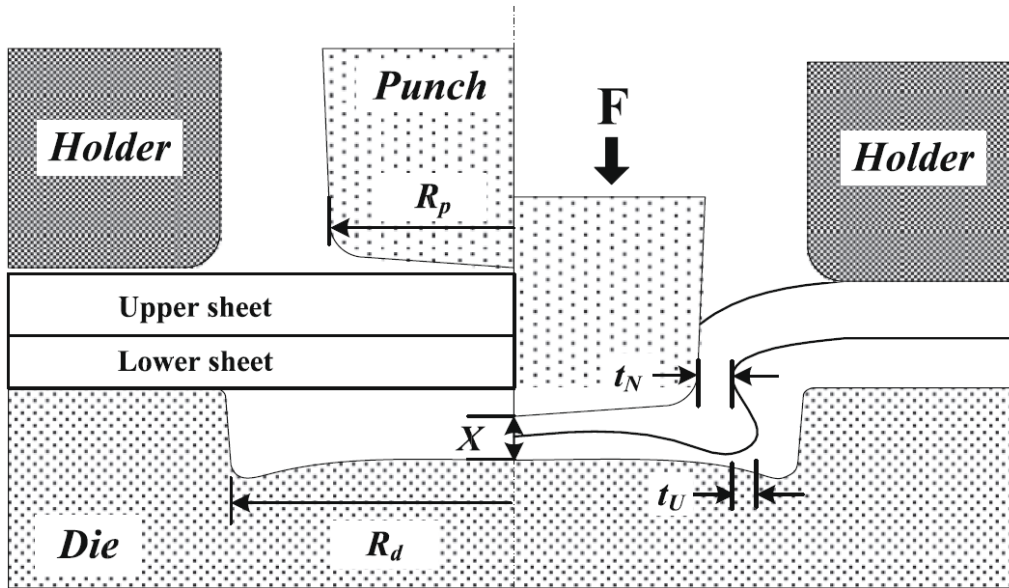


Figure 2-1 Schematic representation of the mechanical clinching process [15].

Fastening using bolts and screws is also customarily used, but the corresponding joints are often weak points of the structure, being the design and manufacturing of these parts critical [16]. Moreover, additional unnecessary weight is added if the joints are over-dimensioned [4]. On the other hand, this kind of mechanical joint is very resistant in peel tests and doesn't need a complex fixturing to support the joints [3].

2.1.2 Adhesive bonding

Adhesive bonding is widely used in the automotive and aerospace industry. It offers good design flexibility to join similar and dissimilar materials [17]. There are several advantages to this joining process. The bond area is uniform compared to other techniques, which improves the joint's stiffness and increases mechanical strength [3]. During the adhesive application, good contact between the joining partners also provides a smooth joint, which seals effectively and reduces the stress concentration, providing high strength in shear and fatigue load requirements. The fixturing to support joints during adhesive curing can be another concern for applying this technique since they are expensive and time-consuming. To achieve a successful joint, removing oils and lubricants from the material's surface is essential to improving adhesion [3]. Environmental, health and safety risks for applying the adhesives and the pre-treatment techniques are

relatively high. Aggressive and toxic chemicals are used, which requires several protective measures, such as special storage, clothing and fumes extraction [18]. One of the biggest challenges of adhesive bonding is the structural joints' durability when they are exposed to a humid environment combined with relatively high loads [3]. After the adhesive curing, the presence of a hot and humid atmosphere is a catalyser for the crack growing of Al [19]. Therefore, pre-treatment is usually required to avoid failure and the adhesive/metal interface in both dry and wet environments, which adds one more step to the process [20][21].

2.1.3 Solid-state processing

2.1.3.1 Friction stir welding

Friction stir welding (FSW) consists of a rotational tool applying a downward force onto two components which generate frictional heat. The base materials are plastically deformed, forming a solid-state weld [22]. A schematic representation of the process is depicted in Figure 2-2. This method helps to join dissimilar metals since the melting phase absence minimises brittle intermetallic compounds' formation by dissolving the hardening precipitates.

The heat input is minor for thinner joining partners, minimising the distortions associated with the high reproducibility of the results, making this process convenient for industry [2]. The welds can be divided into two zones differentiated by the microstructure: the thermo-mechanically affected zone (TMAZ) and the heat-affected zone (HAZ). However, FSW is limited in dimensions of the base materials, joint configuration, and material thickness. The welding time might take some seconds, which is unacceptable for ultra-fast joining processes [2].

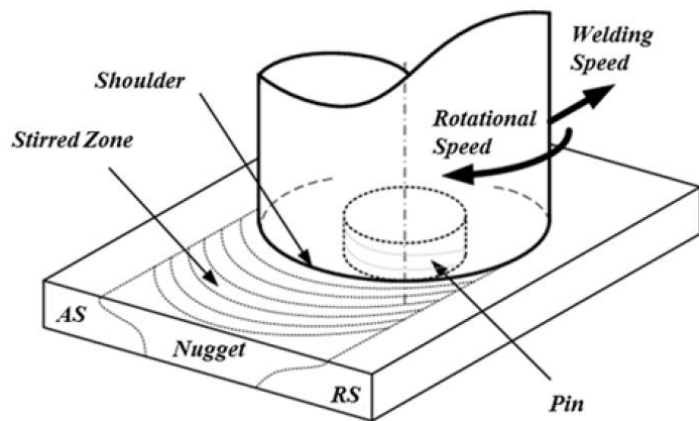


Figure 2-2 Representation of the friction stir welding process [22].

Typically, FSW is associated with thicknesses above 1 mm, but it has been proven to be applicable in thin sheets, being so-called Micro-FSW [23]. Some of the significant drawbacks of this technology are reducing the joints' mechanical resistance, increased heat loss from the workpiece, high forging force requirement and fixturing issues. However, Scialpi et al. found good mechanical properties for 0.8 mm thick sheets in the similar and dissimilar configurations of AA6082-T6 and AA2024-T3 despite defects [24]. Rajawat et al. have also found that this is a pioneering technique for solid-state joining of aluminium alloys, strengthening the mechanical and microstructural properties of the base metal [25]. Moreover, Mohan et al. proved that it is possible to manage heat generation and material deformation at ultra-high rotational speeds [26].

2.1.3.2 Resistance spot welding

Resistance spot welding (RSW) is used to minimise solidification cracking, heat-affected zone, and distortion related problems in the joining of thin metal sheets. Resistive heating and pressure are applied on the joining surfaces at a temperature less than the melting point of metal [27]. Depending on if the material is melted or not in the joint interface, RSW can be categorised into three types: fusion, brazing and solid-state. The process is challenging to apply in materials with specific physical properties since the parent material's high conductivity is the main reason for the degradation of the electrodes [28]. The high energy required per weld (50 – 100 kJ) creates distortions in the material and makes the process expensive, but under optimum conditions, the joints' mechanical

properties are like FSW. Nevertheless, the weld cycle can be relatively long, generally between three and five seconds [29].

2.1.3.3 Ultrasonic spot welding

Ultrasonic spot welding (USW) is a promising energy-efficient technique to join thin sheets up to 3mm, using almost 100 times less energy than the last two processes described in sections 2.1.3.1 and 2.1.3.2 [5]. A schematic representation is depicted in Figure 2-3. Coalescence is produced by applying localised high-frequency vibratory energy and reasonable clamping force. The peak temperature experienced is around 50% of the material's melting point, which avoids regular fusion welding problems, such as cracking and porosity. Furthermore, the heat-affected zone's size is also minimised [30].

The USW systems' success is also dependent on a surface without oxide layers, grease and other residues and the clamping force. The vibration energy used in each weld is highly sensitive to these variables, and an energy-control system is typically used to ensure that the process is replicable [31]. A shear strength up to 3.5 kN was achieved using 0.92 mm thick Al alloy sheet for a welding time of 0.3s [5]. Similar results were observed by Haddadi and Tsivoulas [32]. Defect-free joints were also achieved by Mohammed et al. with solid bonding and grain refinement via dynamic recrystallisation at the weld interface, leading to superior static and fatigue properties [33].

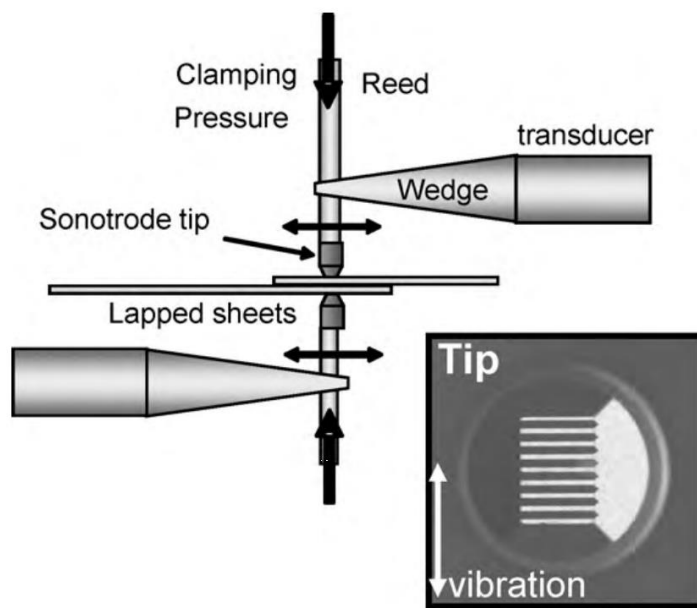


Figure 2-3 Schematic representation of the dual-reed ultrasonic welding machine, with a picture of the sonotrode tip used as an insert [5].

2.1.4 Fusion processing

Reducing the structures' weight has led to the increasing development of thermal fusion processes to join efficiently thinner materials gauges. The main challenge is finding ways to bridge the joint gaps by accurately controlling the heat input in the material without distorting it and avoiding burn-through [34].

The fusion joining techniques are characterised by a high process temperature which can melt at least one of the base metals. Since the melting of both participating alloys is not required to create a joint, this fusion joining process can be divided into two types: brazing and welding. The first one is characterised by melting the third metal without melting the parent metals, and usually, it uses a filler wire. On the other hand, welding involves the melting of the parent metals, and the heat input is higher than brazing, which is crucial in joining thin sheets that are highly sensitive to temperature [34].

Metal inert gas (MIG) welding is used to join thick sections as the high heat input, and the unprecise penetration control are unsuitable for thin sheets. Tong et al. compared alternating current (AC) and direct current (DC) MIG and proved that it is possible to weld 1 mm thick sheets at high speed with low distortions in AC

MIG [35]. By predicting the drop of molten metal's size, the gap between the two sheets can be bridged in a controlled manner [36]. Most recent developments in the welding technology brought a new process free of spatter and characterised by low heat input. Due to its short-circuiting action, the cold metal transfer (CMT) provides less heat accumulation and consequently, smaller material grain sizes and lower hardness after welding [37]. The application of this process in thin sheets showed low distortions and good gap bridging ability [6][38], as depicted in Figure 2-4. However, this process adds unnecessary weight to the structure.

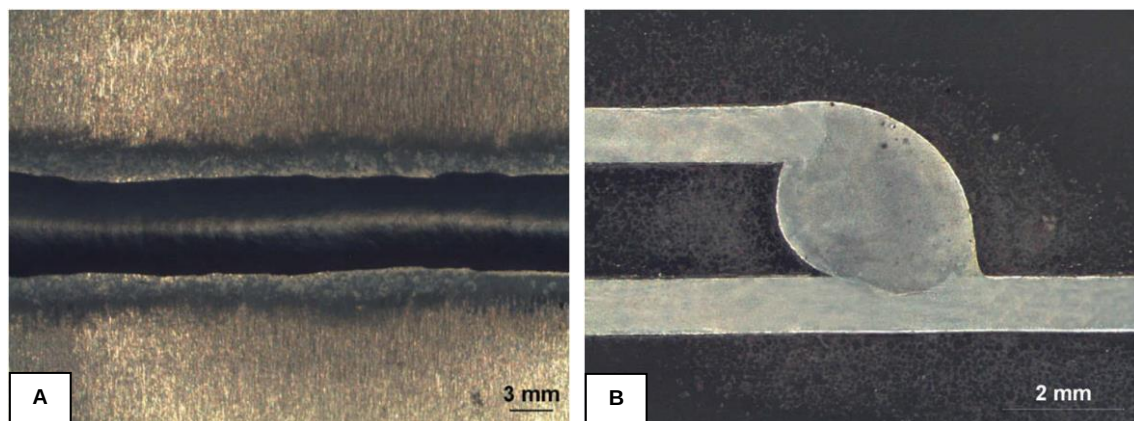


Figure 2-4 Weld seam of CMT process (A) and respective cross-section of a lap joint weld (B) [6].

A laser is another heat source which can be applied in autogenous laser (welding/brazing) , laser + wire (brazing), laser roll welding and bonding (welding/brazing) and hybrid laser-MIG (welding) [39]. Laser welding has excellent potential when compared to other fusion welding processes described previously. They allow increased accuracy and flexibility of spatial and temporal energy resolution

and exact control of the heat input to achieve high penetration/width ratio welds and small heat-affected zone [40]. Thin material gauges can be welded and parts 3D printed, keeping low the thermal distortions and residual stresses in the workpiece when compared to other processes [41]. Lasers can be connected to ultra-fast scanning devices which offer high productivity and meet the demands of some industrial applications with necessary processing times in milliseconds [42].

2.2 Laser welding

2.2.1 Laser-material interaction

There are two main laser temporal modes: pulsed-wave (PW) and continuous-wave (CW). Several combinations of system parameters such as power and travel speed generate different power and energy densities and overall energy application within the laser spot. These parameters are responsible for obtaining the depth of penetration and weld width, which are the main outputs that users wish to control [43]. Depending on the processing conditions, the laser-material interaction can be separated into three operational regimes: conduction, mixed and keyhole [43]. As shown in Figure 2-5, there is a power density transition threshold between conduction and keyhole mode, and therefore, the mixed mode occurs in the transition zone.

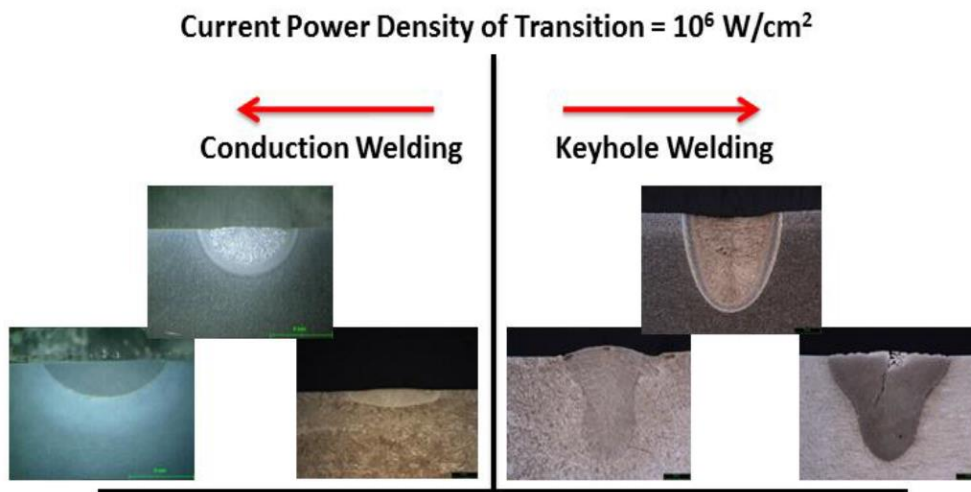


Figure 2-5 Transition between conduction and keyhole welding [44].

No vaporisation takes place in conduction mode. The penetration depth is small, and the coupling efficiency is low when applied in high reflective materials, such as aluminium and copper. On the other hand, the heat input is high, which means higher distortion. If the power density is enough to vaporise the metal, a cavity opens, and the keyhole starts, as depicted in Figure 2-6. If the power density is below the vaporisation point of the material, the keyhole is not formed, and the regime is considered mixed mode .

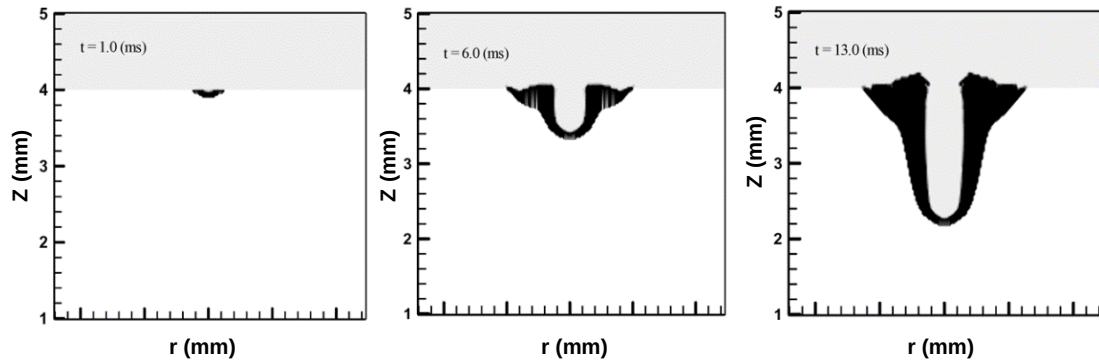


Figure 2-6 Sequence of laser keyhole formation [45].

Several factors must be considered to keep the keyhole open and stable enough to ensure a similar penetration depth and weld width along with the weld bead. The balance between plasma absorption [46], vaporisation pressure [47], heat transfer [48] and hydrodynamic phenomena [49] is critical to obtaining the desired weld profile.

2.2.1.1 Variables controlling the weld shape: Absorption of laser by plasma

In laser keyhole mode, a cavity filled with metal vapor opens due to the interaction of the laser beam with a workpiece. A vapour cloud is formed over the material and interacts with the electric field of the laser beam, accelerating the free electrons. Consequently, the highly energetic electrons collide with the existing atoms and ions, increasing their energy and the metal vapor temperature. Thus, further ionisation occurs, forming a plasma plume, a mixture of ambient gases with ionised metal gases and free electrons [39].

The surrounding ambient pressure affects the vaporisation temperature and the vapour plume's density [50]. As shown in Figure 2-7, the plasma plume's suppression increases the penetration depth as the number of reflections inside the keyhole increases. The cavity walls are considered shiny surfaces that control the absorption of laser light: if the plasma plume is too large, the reflections are reduced, the amount of light reaching the bottom of the keyhole is also reduced, and the penetration depth decreases. The surrounding ambient pressure also affects the vaporisation temperature and the vapour plume's density [50]. Reisgen et al. studied the penetration depth under different vacuum conditions

and at atmospheric pressure using a 16kW laser with a $1\mu\text{m}$ wavelength [51]. The weld depth and quality increases under vacuum compared to laser welding at atmospheric pressures. In vacuum, a lower evaporation temperature was measured, leading to a decline in the pressure difference inside the capillary, specifically of the recoil pressure. A reduction of spatter emission and plasma plume formed was visible, leading to a more effective laser power absorption in the keyhole cavity, being observed deeper welds. At atmospheric pressure, the evaporation temperature is higher and an increase in pressure difference in the capillary leads to more fumes emissions, and consequently, a larger plume. Hence, a reduction of penetration depth for similar laser power applied is evident.

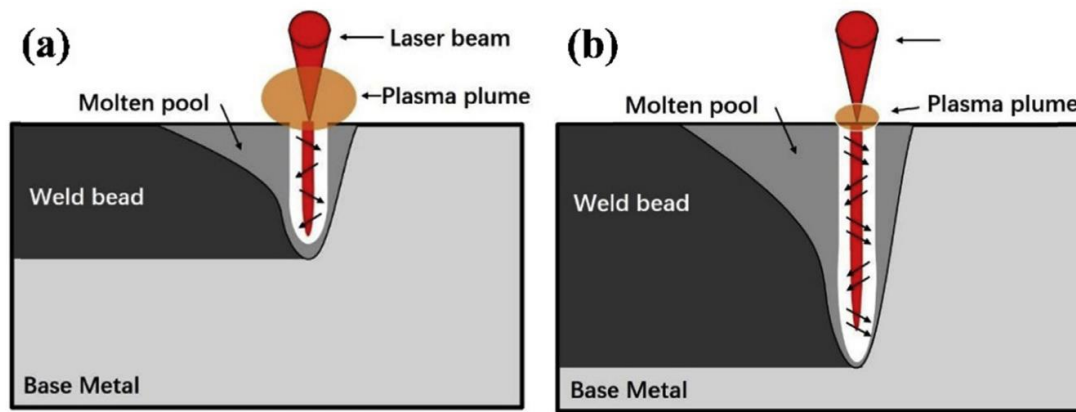


Figure 2-7 Effect of a large plasma plume (a) and suppressed plasma plume (b) on the penetration depth [52].

A high power laser can increase the ionisation state, and consequently, the temperature of the vapour plume due to a considerable absorption of the laser energy by scattered particles of vaporised metal [53]. The laser-material interaction time also affects the plume formation. High speed photography confirmed the change in the inclination angle of the keyhole by increasing the laser interaction time at constant laser power using a 5kW fibre laser with a wavelength of $1\mu\text{m}$ and a beam diameter of $200\mu\text{m}$. Li et al. [54] tried to predict the weld shape based on the spectrum characteristics of the plasma plume and divided the weld penetration in three categories: excessive (exceeding the thickness of the baseplate), moderate (up to the thickness of the baseplate) and partial (less than the thickness of the baseplate). It was found that the penetration

was mainly affected by the plasma height, area and intensity. As shown in Figure 2-8a and b, when the weld was partial and moderate penetration at high interaction times, the keyhole angle was smaller, forming a larger and taller plasma plume erupted mainly from the top part of the weld. On the other hand, for excessive penetration created by high energy input at low interaction times, most of the plasma erupted from the bottom of the workpiece at a higher angle, as shown in Figure 2-8c, creating narrower weld widths.

Figure 2-8 Evolution of plasma eruption location with different penetration states at constant applied power and different welding times: (a) Partial penetration (high interaction time); (b) moderate penetration; (c) excessive penetration (low interaction time) [54].

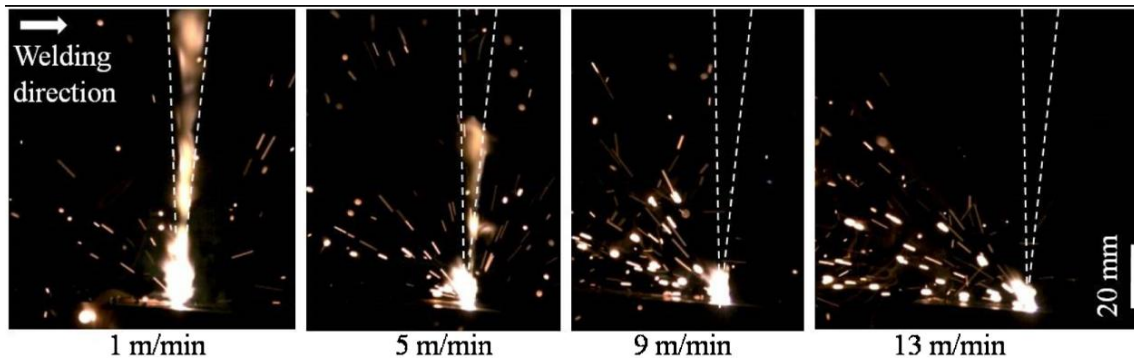


Figure 2-9 Plume morphology changing with welding speed at constant average power of 6 kW and beam diameter of 200 μm [55].

Some methods have been used to avoid the plasma plume effect, such as applying side assisting gas [56] or oscillating the laser beam [57]. However, the use of shielding gas can be an expensive extra cost for the series production of low-value components, which can create some resistance to the adoption of lasers in the industry.

2.2.1.2 Variables controlling the weld shape: Pressure & melt flow dynamics

High power density generates intensive metal vaporisation, induced by increased pressure on the molten metal. This pressure is designated as recoil pressure and provides an ablation force responsible for deep penetration. If the ablation force exceeds the surface tension, it acts like a piston in the molten metal, promoting its expulsion, as demonstrated in Figure 2-10 [58]. The effects on penetration depth by the heat conduction and metal vaporisation can be explained by a balance between surface tension and recoil pressure.

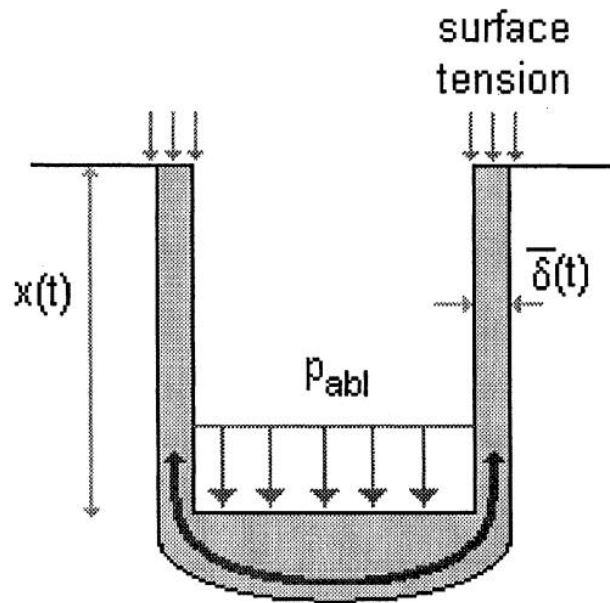


Figure 2-10 Diagram of the forces' action in the liquid layer [58].

The keyhole mode is an unstable and intense hydrodynamic process, described as a capillary surrounded by molten metal. The material displaced under the beam impact zone is subjected to high vapor recoil pressure, but also to a strong thermocapillary force arising on the melt surface, as previously shown in Figure 2-10. The equilibrium between these two forces dictates the final weld shape [59], which is affected by the laser processing conditions applied. The keyhole collapses at high speeds, creating undesired pores [60]., whilst a large melting pool is formed at low speeds, closing the keyhole due to a large amount of molten metal around it. Mizutani and Katayama [61] correlated the keyhole stability with its depth and geometry and distribution of the recoil pressure. As shown in Figure 2-11, they found that deep and narrow cavities were susceptible to high surface tension, but also to a high non-uniform recoil pressure distribution. Consequently, some porosity was visible at the bottom of the welds. On the other hand, lower recoil pressure gradually decreased from the bottom to the weld surface, resulting in a stable keyhole and wide weld widths and no porosity.

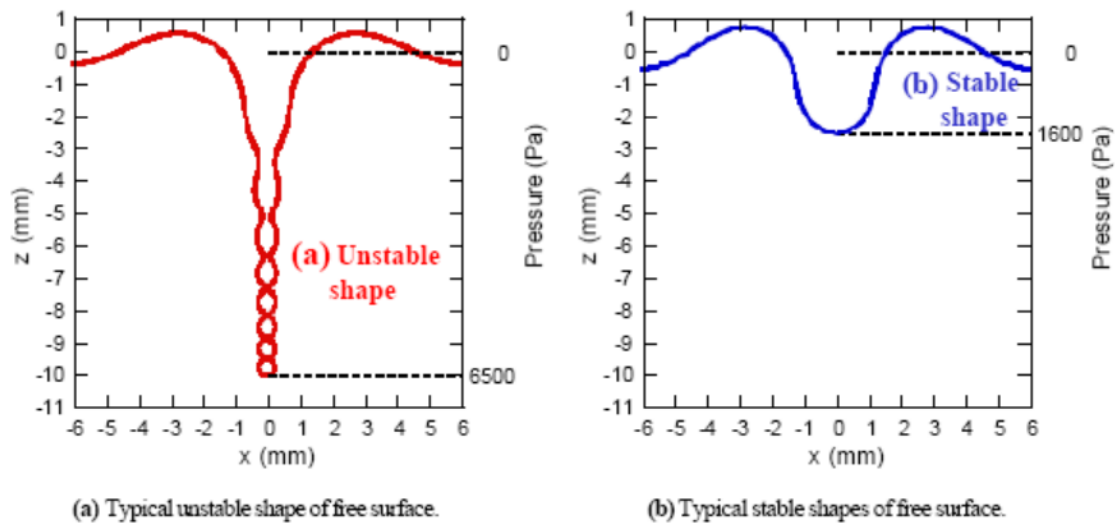


Figure 2-11 Recoil pressure effect on the keyhole formation [61].

As shown in Figure 2-12, the melt pool is subjected to convection flows. A trend of flowing through the root is visible, generating the penetration in the base material. This dynamic set of forces associated with the liquid-gas interaction and the metal viscosity makes the shape of the keyhole variable during the laser processing, which may generate undercut at the surface and fluctuations in the penetration depth and weld width [62]. Thus, the process becomes more stable for wider keyholes since the fumes escape easier without dragging molten metal [63], but the shearing forces of the vapour exiting from the keyhole cavity will originate spatter emissions [64].

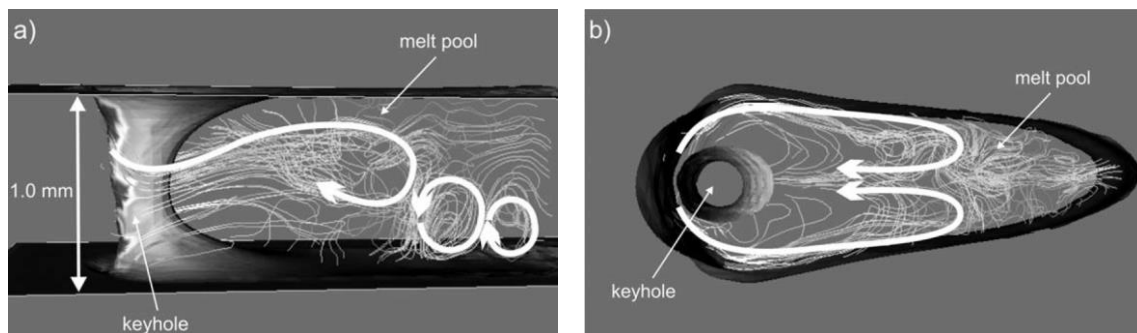


Figure 2-12 Hydrodynamic behaviour of the melt pool: (A) vertical and (B) horizontal view [62].

Based on the flow dynamics of the molten metal, a limitation on the maximum achievable depth of penetration was studied by Lee et al. [66]. It was found that the recoil pressure induces an upward flow of the liquid metal to the top of the keyhole. From a certain depth of penetration, the upward momentum is dissipated by the viscous shearing forces on the keyhole walls. The liquid metal at the bottom of the keyhole cannot be removed anymore, limiting the penetration depth evolution. However, it is possible to achieve deeper penetration, larger melt volume, and lower energy diffusion into the heat affected zone by elongating the beam profile along the welding travel direction. Consequently, the thermocapillary flow is weakened, and the material's deformation is smoothed [65].

2.2.1.3 Variables controlling the weld shape: Heat transfer

Different laser operating regimes impact heat transfer in the weld pool, as studied by Xiao et al. [66]. They showed that in conduction mode, the heat transfer happens predominantly by conduction, and the temperature distribution is regular and smoother. In transition mode, the heat transfer occurs in the radially outward direction of the weld pool. On the other hand, the recoil pressure determines the heat flow when the keyhole is developed. The energy transfer between the laser beam and the material is governed by the reflections inside the keyhole walls and heat conduction. It has been shown that the absorption efficiency of the laser energy is also dependent on the heat conduction inside the keyhole walls [67]. Therefore, the laser absorption efficiency increases if the energy can be thermally radiated inside the keyhole cavity, improving the energy's utilisation from every reflection.

The temperature distribution drives most of the keyhole perturbations since there is an intense thermal gradient at different points inside it, with the highest temperature registered at the bottom [68]. A significant part of the heat is lost by conduction, mainly during the initial stage of the welding. Even before the keyhole opening, the small melt pool formed is subjected to a strong cooling [69]. Therefore, the material's thermal properties determine the maximum temperature that is reached for certain processing conditions [70]. Ayoola et al. [71] used a thermal model proposed by Ashby and Easterling [72] to evaluate the laser

conduction losses, considering the laser average power P_L and beam diameter d , and travel speed v , across the solid surface (Figure 2-13). They used a solid massive enough to keep its average room temperature T_0 unchanged in this analysis. At a point below the centre of the beam, the temperature field $T(z, t)$ was given by an analytical solution of the heat equation expressed in Equation (2-1). A schematic is shown in Figure 2-13.

$$T(z, t) = T_0 + \left[\frac{A * P_L / v}{2\pi\lambda[t(t + t_0)^{1/2}]} \right] \cdot \exp - \left(\frac{(z + z_0)^2}{4\alpha t} \right) [^\circ\text{C}] \quad (2-1)$$

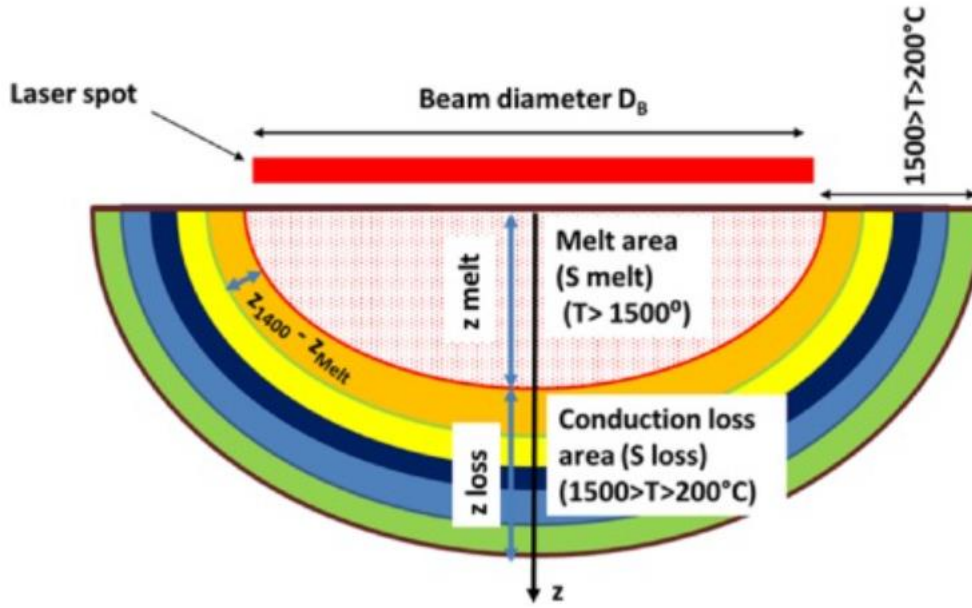


Figure 2-13 Thermal profile of a point below the surface based on the heat equation's analytical solution (Equation (2-1)) [72].

To calculate the thermal losses, the absorptivity of the surface “ A ”, material’s thermal conductivity λ , time t , depth below the surface z , and thermal diffusivity α have also been considered. The constant t_0 was defined as the characteristic thermal time, and it measured the time for heat to diffuse over a distance equal to the beam diameter [72], given by Equation (2-2). The characteristic length z_0 measured the distance over which heat can diffuse during the beam interaction time. It is defined as the square route of the thermal diffusivity multiplied by interaction time, as given by Equation (2-3).

$$t_0 = d^2 / 16\alpha [s] \quad (2-2)$$

$$z_0 = \sqrt{\alpha * t_i} [mm] \quad (2-3)$$

Ayoola et al. [71] found that the ratio of energy for conduction losses to the energy for melting increases for small beam diameters. However, the model is not suitable for keyhole mode as it was developed for conduction mode in steady-state conditions for a point right below the material surface. Moreover, it cannot be used for MPPW mode as it does not consider the laser absorption as a function of temperature, wavelength, pulse duration and frequency of the laser irradiation. These are fundamental variables which must be considered to explain the heat accumulation and cooling between pulses. Kapadia P. and Dowden J. [73] developed a thermal model for keyhole mode but it does not consider the variables described above for MPPW mode. Therefore, its application is limited to the continuous wave laser temporal mode.

2.2.2 Fundamentals of laser welding regimes and parameters

2.2.2.1 Continuous-wave mode

In CW keyhole welding, the process cannot be uniquely described by the system parameters, such as average output power (P_L), travel speed (v) and beam diameter (d) [44]. From the material's perspective, the process is controlled by the fundamental laser-material interaction parameters (FLMIP), independently of the laser source, which determines the thermal field and the resultant molten volume, cooling rate and microstructure changes. The system parameters can be converted into parameters which shape the weld geometry: interaction time ($t_{i, CW}$) controls the weld width, whereas power density (q_p) and specific point energy ($E_{SP, CW}$) are the main ones responsible for the penetration depth [44]. Laser welding is considered a periodic process whose period is the interaction time [74]. Interaction time defines the time when an infinitesimal point is exposed to a circular laser beam moving at a constant travel speed. It is defined as the ratio of beam diameter to travel speed, as given by Equation (2-4) [44]:

$$t_{i, CW} = d/v [s] \quad (2-4)$$

Power density (q_p) is defined by the ratio of the laser average output power to the area of the laser spot on the material surface (A_S), and it is given by Equation (2-5) [44].

$$q_p = P_L / A_S \text{ [MW/cm}^2\text{]} \quad (2-5)$$

A third parameter also characterises laser processing. The total laser energy transferred to the material within a spot was established as the specific point energy ($E_{SP, CW}$) [44]. It is proportional to the product of power density, interaction time, and the laser spot area, as given by Equation (2-6). Dividing the specific point energy by the area of the laser spot on the material surface, the energy density (E_D) can be calculated, as given by Equation (2-7):

$$E_{SP, CW} = q_p * t_{i, CW} * A_S = P_L * t_{i, CW} \text{ [J]} \quad (2-6)$$

$$E_D, CW = E_{SP, CW} / A_S = q_p * t_{i, CW} \text{ [J/mm}^2\text{]} \quad (2-7)$$

The energy rate transferred into the metal depends on the travel speed, which controls energy losses. A typical thermal cycle of a CW weld is shown in Figure 2-14 [75].

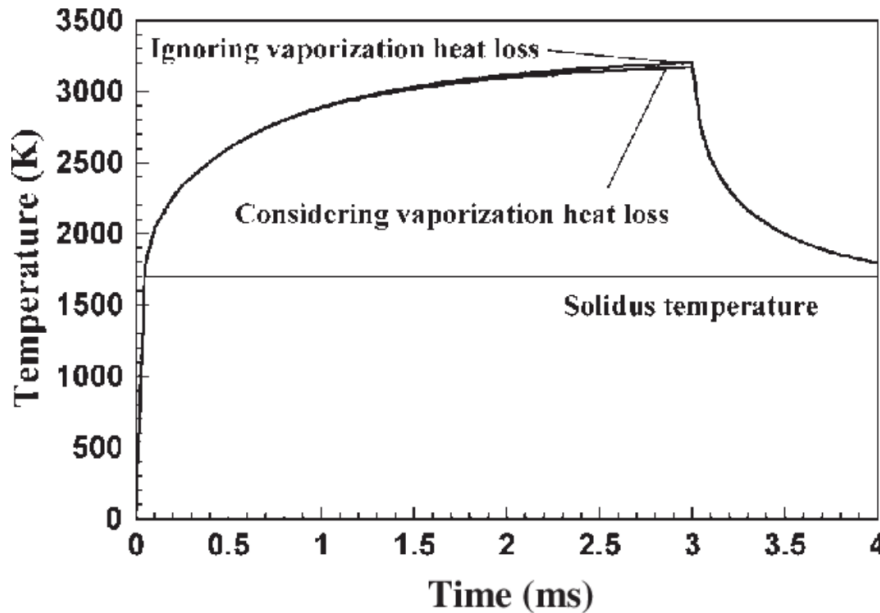


Figure 2-14 Thermal cycle in CW mode on the surface of the centreline of the weld pool [75].

2.2.2.2 Single-pulse pulsed-wave mode

The laser-material interaction time in single-pulse PW mode (SPPW) equals the pulse duration, as given by Equation (2-8). In the conventional SPPW mode, peak power is higher than the average power. Thus, the energy of each pulse (E_{pulse}) can be easily known by calculating the area below each pulse shape, which is the multiplication of pulse width (P_{width}) by the peak power (P_{peak}), as given by Equation (2-9). When more than one pulse is applied, E_{pulse} is determined based on the ratio of average power and pulse repetition frequency (PRF), as given by Equation (2-10) [74].

$$t_{i, SPPW} = P_{Width} [ms] \quad (2-8)$$

$$E_{pulse} = P_{peak} * P_{Width} [J] \quad (2-9)$$

$$E_{pulse} = P_L / PRF [J] \quad (2-10)$$

The pulse shape and the space between pulses play a vital role in controlling the temperature distribution in the metal [76], as the pulse energy can be dissipated entirely before the next pulse arrives. The weld's thermal cycle of a conventional millisecond SPPW laser is the repetition of multiple thermal profiles previously shown in Figure 2-14.

2.2.2.3 Multi-pulse pulsed-wave mode

The application of energy per unit length on the material was established for CW mode, and the process can be described by the fundamental laser-material interaction parameters (FLMIP) [68]. However, in MPPW seam welding, the energy is applied by several pulses at high frequency and with appropriate overlapping for a specific application. The pulse shape can be modulated in the latest generation of multi-pulse PW lasers (MPPW), as shown in Figure 2-15. The power distribution is not constant during the entire pulse duration. Consequently, the average peak power represents the average power distribution within a pulse. Thus, the average peak power is lower than the peak power but higher than the average power [77]. To estimate the pulse's exact energy, the area of its shape needs to be calculated, which represents the integral of the power over time. As

the peak power is instantaneous, the average of the power distribution within a pulse can be used to simplify the calculation of the pulse energy if the pulse shape is always square for any frequency [77], as shown in the previous section for SPPW mode.

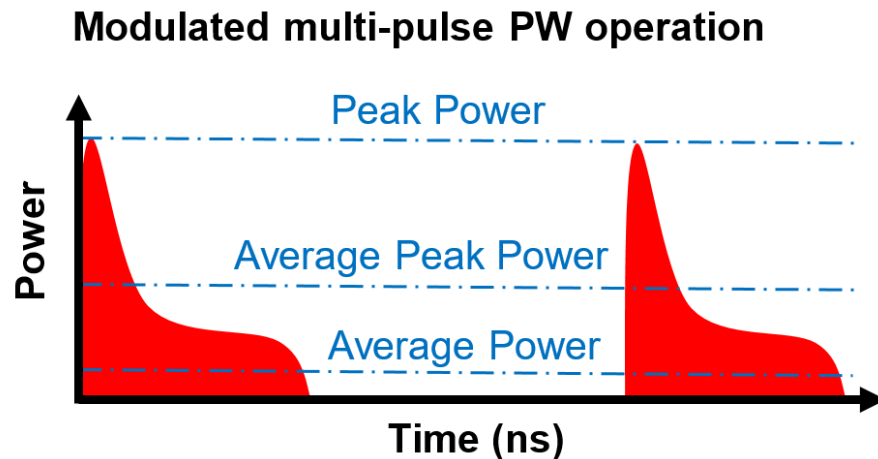


Figure 2-15 Temporal output of a MPPW laser [77].

MPPW lasers enable more refined control of material interaction because the same pulse energy can be applied with different combinations of pulse width, average peak power and pulse energy, as shown in Figure 2-16 [74]. These parameters are combined through various temporal pulse shapes, also known as waveforms (WFM). The power distribution changes with the frequency, being the peak power and pulse energy maximum at a particular critical frequency (PRF_0) and average power. Above PRF_0 , the peak power and pulse energy decrease, and the pulse shape becomes almost square [74].

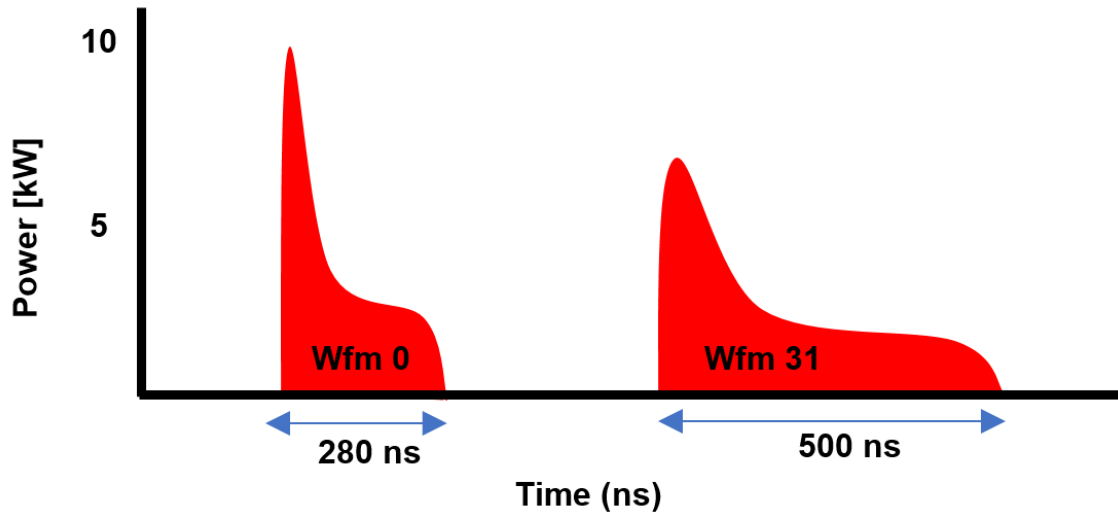


Figure 2-16 Pulse shapes of waveforms 0 and 31 at PRF₀ of 100kHz [74].

The overlap factor represents the percentage of overlap between the consecutive spots, dependent on the travel speed, beam diameter and pulse repetition frequency, as given by Equation (2-11). Therefore, the interaction time in MPPW mode is dependent on the duration of each pulse and the overlap between them, as given by Equation (2-12). At 0% overlap factor, the interaction time equals pulse width, and at 100%, the equation is not applicable since the beam is stationary. Hence, Equation (2-11) is only applicable below 100% of the overlap factor [78]. The influence of $t_{i, MPPW}$ on the weld shape has not yet been tested and compared to the standard definition in CW mode in Equation (2-4).

$$O_F = (1 - v/dPRF) * 100 [\%] \quad (2-11)$$

$$t_{i, MPPW} = P_{Width}/(1 - O_F/100) [ms] \quad (2-12)$$

It was considered that the definition of power density in MPPW mode would follow the exact definition of CW mode in Equation (2-5) [79]. However, it was not evaluated if this definition can be applied in different laser temporal modes. Besides that, the average peak power used in Equation (2-13) assumes square pulses, and it was used in modulated pulses [80][81] without having a study on this approximation. Consequently, the energy transferred to the material followed the definition of CW mode in Equation (2-6) but used Equations (2-12) and (2-13) from MPPW processing, as shown in Equation (2-14).

$$q_{p, peak} = P_{Peak}/A_S [MW/cm^2] \quad (2-13)$$

$$E_{SP, MPPW} = q_{p, peak} * t_{i, MPPW} * A_S = P_{peak} * t_{i, MPPW} [J] \quad (2-14)$$

A single short pulse (10^{-9} s) achieved in pulsed fibre lasers and other solid-state lasers, might be able to create a dimple in the material surface. Nevertheless, certain laser parameter will not lead to melting with a single pulse, being necessary a high duty cycles (D_C), i.e. high frequencies and longer pulse durations (nanoseconds), where enough melting will occur to generate suitable welds for micro joining [80]. The duty cycle is the fraction of time for laser pulse emission. It is defined by the ratio between the pulse width and the pulse period (Δt), as given by Equation (2-15).

$$D_C = P_{Width}/\Delta t [\%] \quad (2-15)$$

As shown in Figure 2-17, there is an energy accumulation between pulses in MPPW mode, which doesn't happen in SPPW [74]. Thus, the inter-pulse spacing significantly affects the thermal behaviour and resultant melt profile. Still, it hasn't been considered in the current FLMIP formulae.

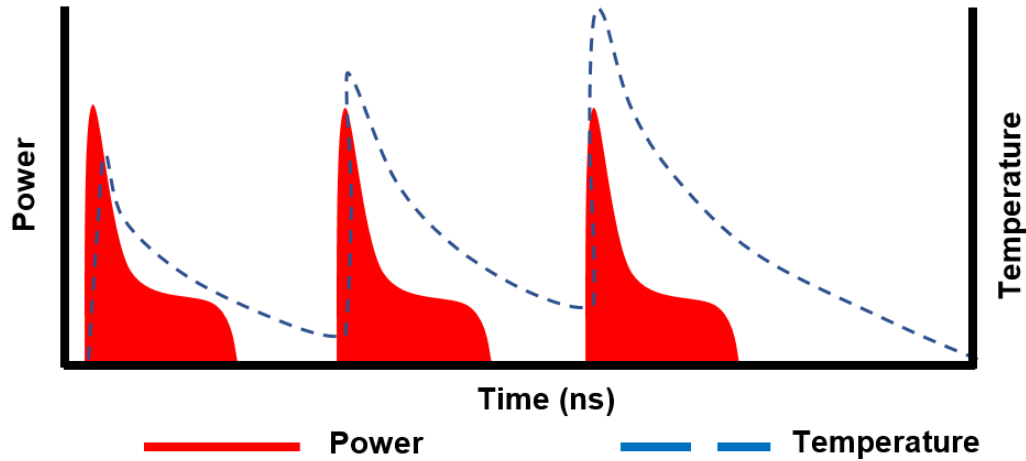


Figure 2-17 Thermal cycles in nanosecond MPPW mode [74].

2.2.3 Power factor model

In CW laser welding, power density and specific point energy control the depth of penetration [44] and depend on the laser beam area. This relationship found that

the penetration depth is proportional to the ratio of laser power to beam diameter, and a new parameter was established, the Power Factor [77][82]. It was defined as the ratio between the laser average output power and the beam diameter, as given by Equation (2-16).

$$P_{F, CW} = P_L/d \text{ [W/m]} \quad (2-16)$$

This definition of power factor generated curves of constant penetration depth, independent of the beam size, as depicted in Figure 2-18. Based on the power factor and interaction time required for a particular weld geometry, it is possible to calculate the laser power and travel speed needed for a specific optical system with a specific beam diameter using Equations (2-16) and (2-4), respectively. However, the laser systems are limited in terms of maximum average output power, beam diameter and travel speed, restricting the combinations of power factor and interaction time, being impossible to achieve unlimited trend lines for higher penetration depths in Figure 2-18.

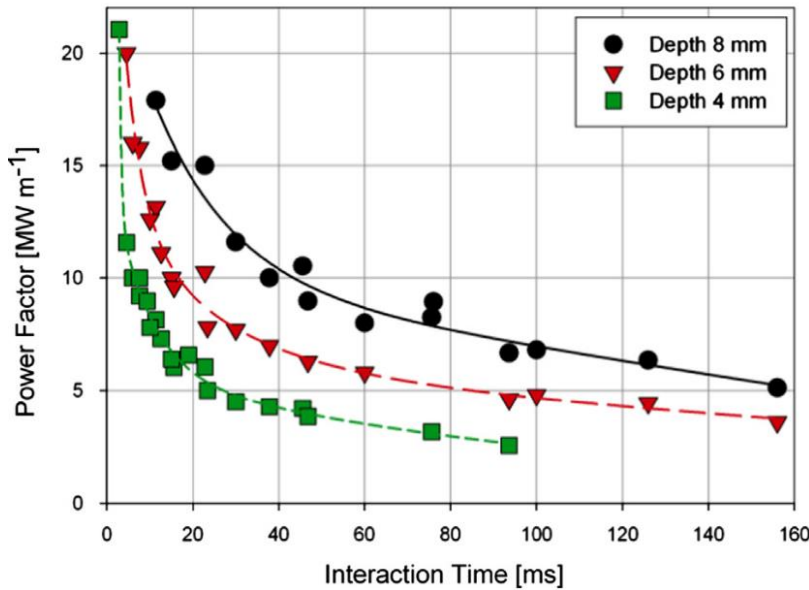


Figure 2-18 Power factor as a function of interaction time for penetration depths of 8 mm, 6 mm and 4 mm (range of beam diameters 0.38 mm to 0.78 mm, average power 1 kW to 8 kW, and travel speed 0.3 m/min to 10 m/min) achieved on S355 low carbon steel using a IPG YLR 8000 W CW multimode fibre laser [82].

Some other limitations have been observed in applying the Power Factor model. It works based on the trade-off between the power density and the specific point energy with an optimum operating range. The optimum conditions registered were in interaction times between 10 ms and 50 ms, as shown in Figure 2-19 [70]. The penetration depth is similar for a beam diameter of 0.5 and 0.78 mm within this range. Above an interaction time of 50 ms, the higher specific point energy achieved with a larger beam diameter provided deeper welds compared to the higher power density in the smaller beam diameter. Below 10 ms of interaction time, the difference in penetration depth reached up to 25%. At these low energy levels, the drilling force was too low, and the trade-off between power density and specific point energy didn't work to maintain deep penetration [70]. The power factor model has been tested and validated for mild steel, and Al [82] in CW macro seam welding for material thicknesses above 10 mm and beam diameters above 0.38 mm. However, when similar values of power factor and interaction time were tested in different material thicknesses [83], the depth of penetration was different from expected based on the model's predictions. The current definition of the model isn't also able to predict the weld geometry for other materials, and it has only been applied in macro-CW welding. So far, no studies have been found for micro-welding in any laser temporal regime. For MPPW mode for example, the trade-off between specific point energy and power density, already validated in CW mode, would need to be tested in a wider variety of parameters. Random combinations of pulse repetition frequencies, overlap factors, pulse durations, travel speeds, beam diameters, pulse energies, peak powers and average powers would need to guarantee similar weld shapes for certain power factors and interaction times.

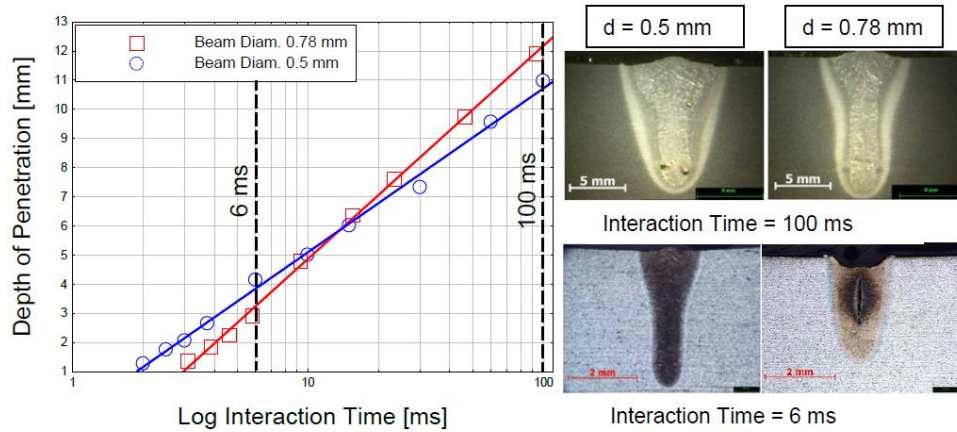


Figure 2-19 Effect of beam diameter at a constant power factor of 10 MW/m for beam diameters 0.5 mm and 0.78 mm at two extreme cases of interaction time: 6 ms and 100 ms [70].

2.2.4 Laser beam quality

Lasers with different wavelengths usually are compared using the M^2 definition. A laser characterised by an M^2 value of 1.5 will provide a larger beam diameter by 50% compared to a laser with a perfect beam ($M^2 = 1$) [39]. On the other hand, the beam parameter product (BPP) characterises the focus-ability of a specific laser system. The higher the beam quality (low BPP), the smaller the beam diameter achieved with a given optical arrangement. Both definitions of M^2 and BPP are based on the divergence angle of a laser source shown in Figure 2-20 and are described in Equations (2-17) and (2-18), respectively [39].

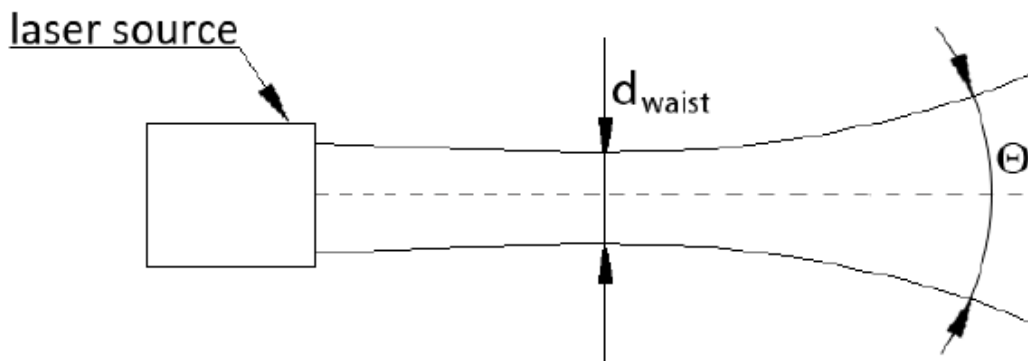


Figure 2-20 M^2 definition [70].

$$M^2 = \pi * d_{waist} * \theta / 4\lambda \quad (2-17)$$

$$BPP = M^2 \lambda / \pi = d_{waist} * \theta / 4 \text{ [mm.mrad]} \quad (2-18)$$

d_{waist} – Beam diameter in waist; θ - full divergence angle; λ – wavelength

The beam diameter of the laser system can be calculated based on the *BPP*, the collimated beam diameter (*D*) at the focusing lens entrance and the focusing length (*F*), as given by Equation (2-19) [79]. A high-power density applied on the optical lens can induce a thermal load for highly focused laser beams, changing its refractive index. This leads to a change of the focal point (also defined as focal shift) and, consequently, the applied laser power density modification. Therefore, an extended focal depth is desired in cutting and welding, allowing a higher tolerance for a constant beam diameter on the surface, ensuring repeatable results [70].

$$d = 4F * (BPP/D) \text{ [}\mu\text{m]} \quad (2-19)$$

2.2.5 Laser welding techniques

2.2.5.1 Laser spot welding

Laser spot welding uses a pulse of light with an accurate, repeatable and controllable energy duration to create a single weld spot to join metals. The material absorbs a fraction of energy during each pulse to generate melting in the conduction regime or is vaporised in the keyhole regime. If the solidification time is lower than the interpulse spacing, the material solidifies, and the keyhole closes at the end of each pulse. The process lasts only a few milliseconds and is characterised by its small weld pool size and high heating and cooling rates, delivering minimum energy to small components with high precision [84]. The frequency or pulse width can be increased to achieve a higher duty cycle if a longer cooling rate is required. It usually requires high pulse energy to generate melting with each pulse with 10^{-3} s. An example of a spot lap joint is shown in Figure 2-21.

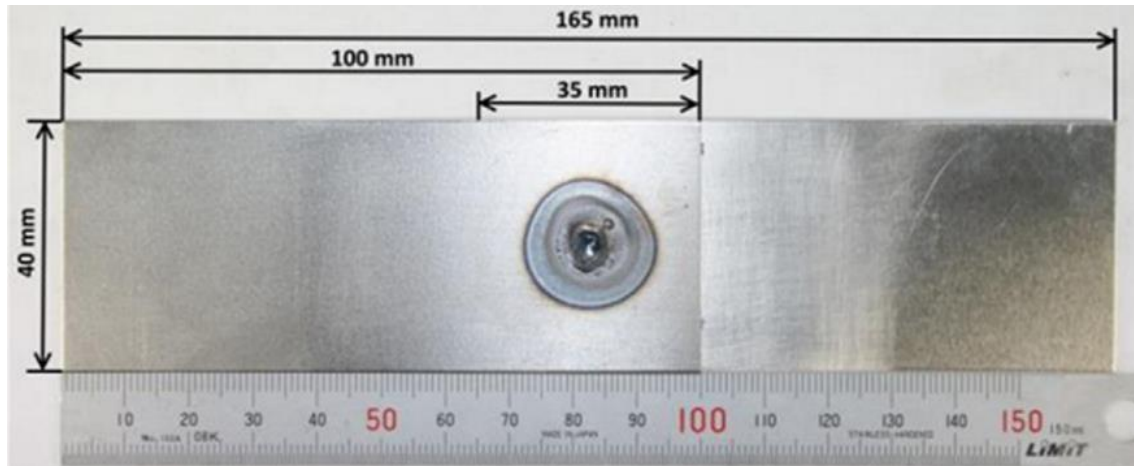


Figure 2-21 Example of laser spot welding [85].

2.2.5.2 Laser wobbling

Welding with laser beam oscillation (wobbling) occurs when the laser beam oscillates to enlarge the melt pool. The oscillation pattern is a secondary motion that overlaps the laser beam's main feeding motion along the welding path. A schematic of different oscillating patterns is shown in Figure 2-22. The ratio between travel speed and the laser beam's oscillation frequency defines the weld bead shape along the path of the laser beam. High oscillation frequency leads to an overlap of the track. The material is partially remelted and generates a continuous bead.

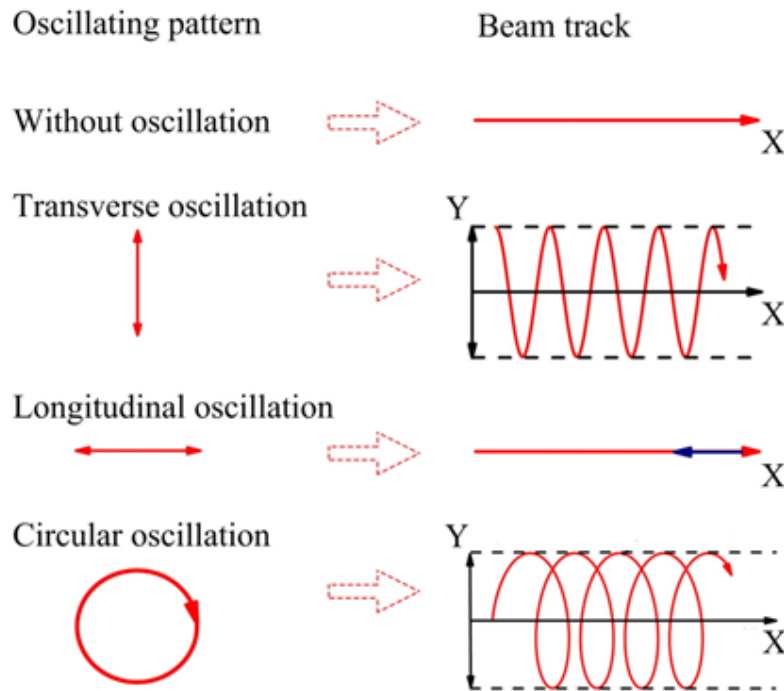


Figure 2-22 Schematic diagrams of different beam oscillating patterns [86].

Laser wobbling demonstrates several benefits in higher fit-up tolerance, less effort for pre-welding preparation and gap minimisation, and higher coupling efficiency of reflective metals by influencing the temperature profile inside the melt pool [7]. Thiel et al. have studied the influence of laser beam oscillation for Al welding using CW laser [7]. They compared cross-sections for different oscillation properties and concluded the same weld depth can be achieved with or without oscillation. In addition to this, the surface quality was not affected when laser beam oscillation was applied, as shown in Figure 2-23. Nevertheless, different oscillation patterns showed different results in the process stability. It can also be observed that for a spot diameter of 200 μm without beam oscillation, the porosity content and size are smaller than a spot of 100 μm due to lower power density. The process quality can be improved with or without oscillation if the processing parameters are optimised, mainly the power density. Barbieri et al. achieved similar conclusions where butt and lap joint welding were investigated in automotive Al alloys using a wobble welding head with a 2-kW CW fibre laser [87]. The wobbling process generally helps in minimising the porosity when combined with an optimised set of welding parameters. However, additional variables are to consider in this process, such as amplitude and

frequency of oscillation. Adding these parameters to the standard system parameters from CW and PW seam welding makes it even harder to analyse the individual effect of each one on the weld profile. Therefore, it isn't easy to make a fair comparison between laser wobbling and seam welding without having fundamental parameters established in both techniques.

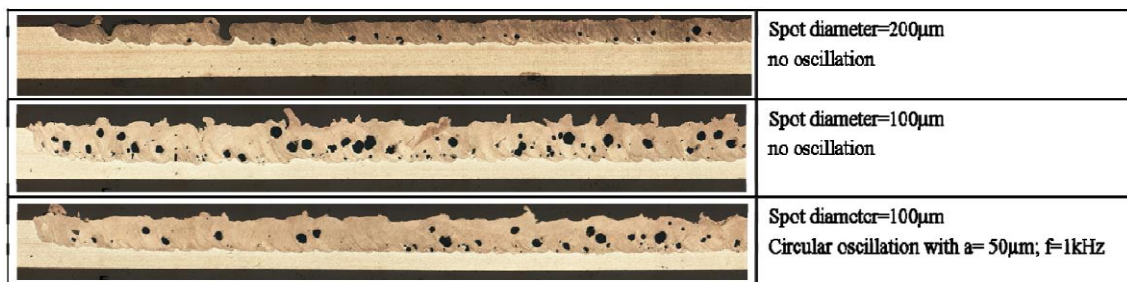


Figure 2-23 Longitudinal sections of Al6110 weld seams ($v = 5 \text{ m/min}$, $P = 1.3 \text{ kW}$) [7].

2.2.5.3 Pulsed-wave laser seam welding

Typically for pulsed welding, the pulse time is between 10^{-3} to 10^{-9} s. In single-pulse pulsed-wave (SPPW) laser welding, the energy is delivered in relatively long pulses (milliseconds) at low frequency and travel speed, high and constant peak power, and high pulse energy and low average power [74]. If many pulses are applied with an overlap, then a seam weld is produced, as shown in Figure 2-24.

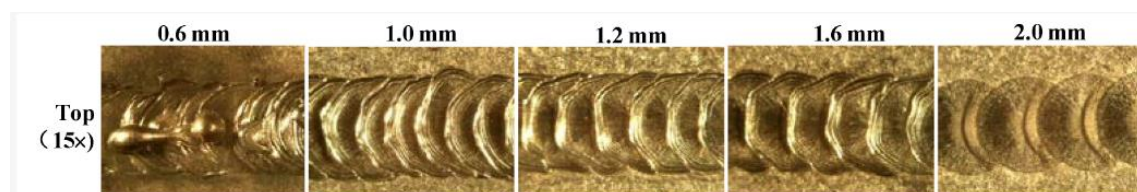


Figure 2-24 Nd:YAG laser weld of steel [88].

Laser welding using a nanosecond MPPW laser is only possible with a high overlap of single pulses. Although a single pulse's energy is low but sufficient to create a dimple in the substrate, a high overlap factor is necessary to create enough energy accumulation to melt it, as depicted in Figure 2-25 [81]. The energy is deposited into the material mainly during the peak power period, dispersed by conduction when the laser is off. Thus, the low heat input is applied

rapidly to enhance the laser absorptivity, but generates cracks, spatter, spike-like welds, and vaporisation of volatile elements. Therefore, Mg, Zn and Li in some Al alloys substantially contribute to the keyhole instability, increasing the likelihood of porosity in the weld pool [89].

The pulse duration is also responsible for controlling the heat input, reducing the amount of molten metal for shorter pulses [90]. The effect of pulse shaping variation in laser spot welding of Al using a 220 W Nd:YAG pulsed laser has been studied by Hajavifard et al. [91]. They found that for equal pulse width, pulse energy and peak power, the depth of penetration was similar and independent from the pulse shape. However, most of this study was done through system parameters, being difficult to compare these results with other laser systems.

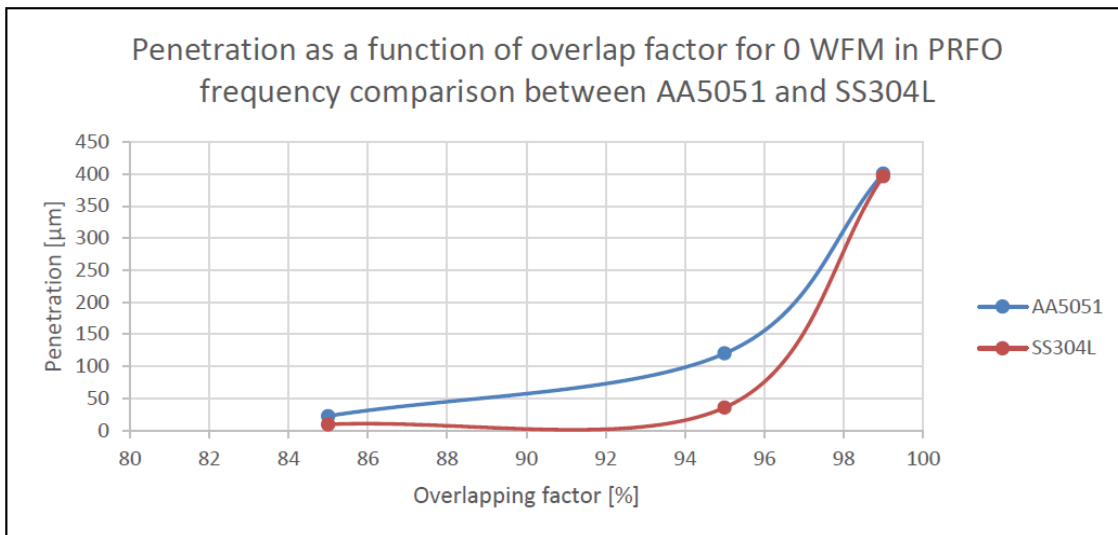


Figure 2-25 Penetration depth as a function of overlap factor for 0 WFM in nanosecond pulsed wave laser processing of AA5051 and SS304L [81].

2.2.5.4 Continuous-wave laser seam welding

CW lasers have a flexible application in a broader range of material thicknesses due to their higher average power [77]. The increased penetration and weld quality of the CW mode in the laser welding of Al alloys is attributed to the stable heat conduction due to a constant peak power during the irradiation time, which is not the case in PW mode [77]. However, the selection of parameters is shorter in CW lasers, and for micro-welding applications, they are generally operated at

high processing speeds to minimise the heat input [92]. For low welding speed, the alloying elements are more likely to vaporise, decreasing the joint's mechanical properties. Porosity can also be caused by the keyhole collapsing due to the imbalance between liquid forces and vapour recoil pressure. It leads to elongated defects, evident as blowholes [93], having a detrimental effect on the welds' fatigue life and strength [94]. When the processing conditions such as power density and applied energy are carefully controlled, the right amount of vaporisation and melting is ensured, and good weld quality can be obtained. This was observed in CW seam welding of Al [8] and SS [95], being possible to achieve welds without undercutting, spatter and pores.

Pulse wave and continuous-wave laser processing are equally applied in micro joining [96]. Most of the literature's experimental works reported results for a specific processing mode and did not compare the different operating regimes based on the incident energy. Hence, there is limited knowledge of understanding which temporal mode is more efficient. Fuershbach and Eisler [96] analysed both CW and SPPW lasers and concluded that CW has higher penetration than SPPW laser. However, only power density was used as the comparison parameter, omitting the effect of the laser-material interaction time, which also contributes to the energy density. Assuncao and Williams [79] have studied both processes at equal interaction time and power density and concluded that millisecond SPPW laser achieved higher penetration depth than CW processing, as observed in Figure 2-26. However, it is essential to note that the authors compared SPPW spot welds with CW seam welds. This fact could have contributed to the difference in penetration depth due to the difference in surface tension gradient and its effects on the fluid dynamics of the melt pool. In addition to this, the impact of the pulse repetition frequency and overlap factor for SPPW laser was not taken into consideration since the laser beam was stationary concerning the substrate. Therefore, the welds were performed with single pulses and the interaction time of each pulse was controlled by the pulse duration only.

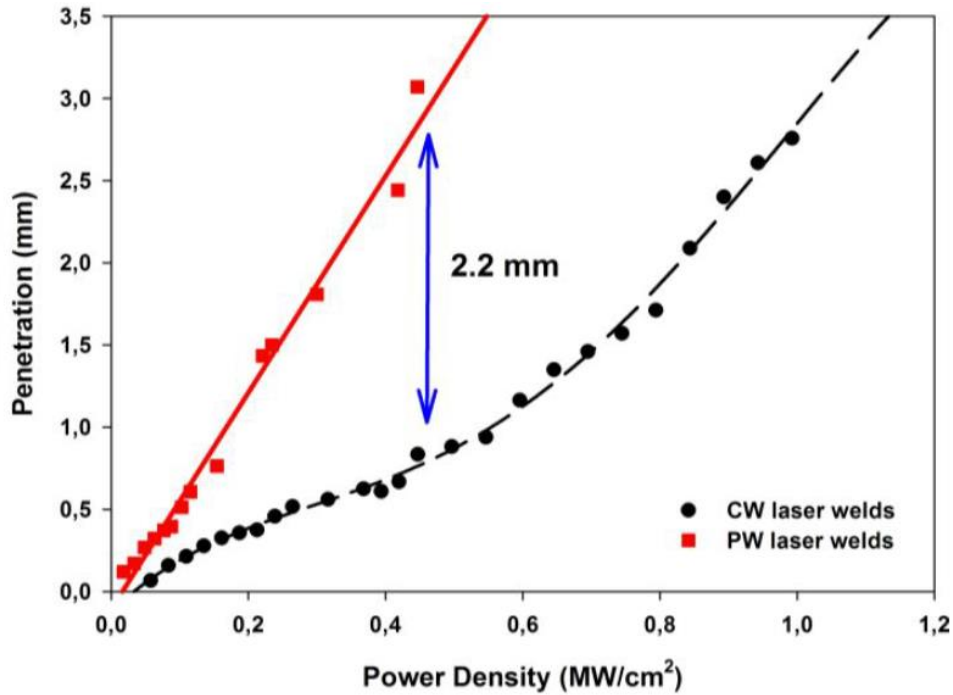


Figure 2-26 Penetration depth versus power density for an interaction time of 10 ms, a beam diameter of 0.95 mm for the CW welds, and a beam diameter of 0.9 mm for the PW [79].

A comparison between MPPW and CW lasers was performed by Demir et al.[97]. The authors concluded that the high power densities of the MPPW laser are more suitable for thin structures where precise heat input is required. In contrast, the CW laser provided a superior weld quality with less porosity. In a different study, it has also been observed that CW welding provides larger weld pools and better mechanical properties in comparison to MPPW welding [41]. Despite the several scientific articles available either for continuous or pulsed wave laser modes, they don't compare both at similar welding conditions. The only exception found was the work developed by Assuncao et al. [79]. Most of the reported studies were based on different system parameters, such as spot size, travel speed, and average power, resulting in entirely different applied energies and power densities, making the temporal mode effect challenging to unravel. Moreover, none of them considers the material's physical properties and the thermal losses between pulses, which may significantly impact the weld shape, even if similar parameters are used.

2.3 Dissimilar metal joining of aluminium with steel

Innovative structures and components are manufactured with several materials that better satisfy the requirements of mechanical strength, weight, or corrosion resistance [98]. The combination of dissimilar materials such as SS to Al offers many advantages at an economical, performance or environmental level in several industries: maritime, automotive, aerospace and packaging. The product weight reduction without compromising structural integrity is the main focus of these industries [99]. Aluminium and SS are widely used in the packaging industry, for example, and any small material saving will have a high impact on the manufacture of millions of components. However, due to the different physical properties such as thermal conductivity, melting temperature, and thermal expansion [90], both materials lack solid solubility. This leads to the formation of brittle intermetallic compounds (IMCs) and residual stresses, generating crack propagation, which compromises the mechanical strength [100]. According to the binary Fe-Al phase diagram depicted in Figure 2-27, different intermetallic compounds are formed depending on the temperature of the melt pool and the participation of various alloying elements of the weld metal.

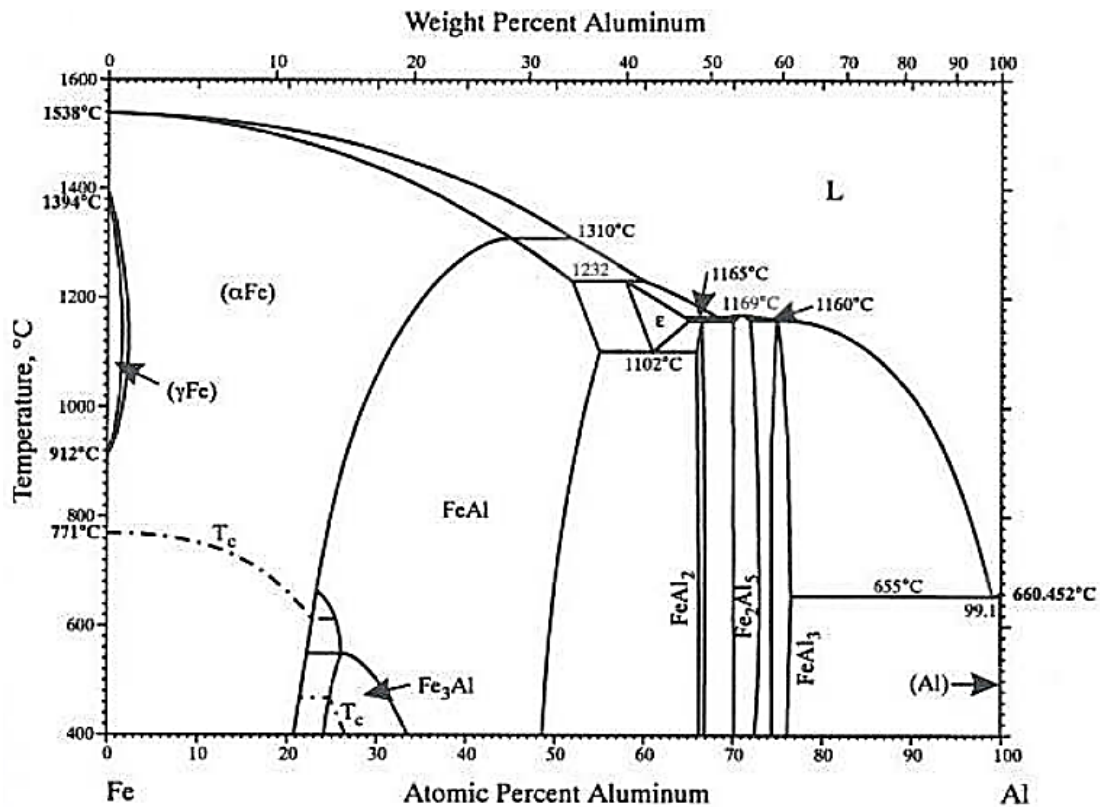


Figure 2-27 Binary Fe-Al phase diagram [101].

Aluminium has about 20 at.% solid solubility in Iron (Fe), but Fe has zero solid solubility in Al, resulting in the formation of brittle intermetallic phases, which can be organised into two groups. Iron-rich IMCs (FeAl and Fe₃Al) have some toughness and ductility, whereas Al-rich IMCs (FeAl₂, Fe₂Al₅ and FeAl₃) are hard and brittle [102]. The hardness of each IMC is shown in Table 2-1. The iron-rich IMCs have good high-temperature corrosion resistance [103] and relatively high ductility, being used in the form of coatings to increase structural parts' wear resistance [104]. However, the Al-rich IMCs are undesired, and their formation needs to be avoided. The analysis of the IMC may be more complicated if a third element is introduced. Stainless steel contains chromium, and Al-Cr-Fe multi-phase is usually formed, being brittle in the Al-rich parts of the Al-Fe (Al₂Fe, Al₂Fe and Al₅Fe₂) and Al-Cr (Al₄Cr, Al₈Cr₅ and Al₉Cr₄). The phase diagram is shown in Figure 2-28.

Table 2-1 Fe-Al phases and Vickers microhardness [101][105].

	Phase	Al [at%]	HV
	Fe (solid solution)	0-45	-
	Fe (γ)	0-1.3	-
Fe-rich IMCs	Fe_3Al (β_1)	23-34	250-350
	FeAl (β_2)	23-55	400-520
Al-rich IMCs	Fe_2Al_3 (ϵ)	58-65	-
	FeAl_2 (ζ)	66-66.9	1000-1050
	Fe_2Al_5 (η)	70-73	1000-1100
	FeAl_3 (θ)	74.5-76.5	820-980
	Al (solid solution)	99.998-100	-

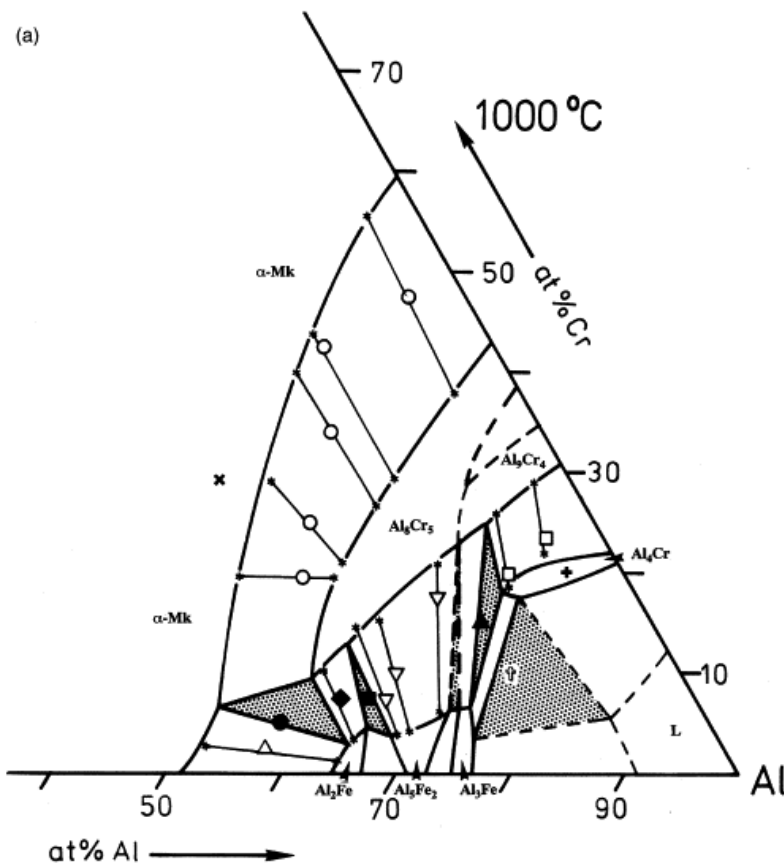


Figure 2-28 Phase diagram of Al-Cr-Fe at 1000°C [106].

Steel and aluminium can be joined in liquid-liquid, solid-liquid and solid-solid physical conditions, being the alloys' physical state critical for the formation of

IMCs due to the diffusivity of the atoms of the participating alloys [34]. Time and temperature are the main factors influencing the formation and growth of the IMCs [34]. The proper combination of both parameters can form a thin and continuous layer of IMC along the weld joint, giving good mechanical strength [107].

Several welding techniques have been used for joining dissimilar materials. Tungsten Inert Gas (TIG) is commonly used for welding thin material thicknesses in lap and butt-joint configurations [108]. It has been used for brazing steel to Al in overlap configuration, but poor quality and low tensile strength have been observed [109]. Another process used is friction stir welding (FSW), allowing solid-state reaction between the steel to Al [24][110], avoiding macroscopic melting and consequently cracking, porosity and volatile solute losses. However, this process generates differential deformation of the two dissimilar alloys and, hence, asymmetry in stress formation [111]. Explosion welding is a solid-state process used to clad large steel areas by Al via an explosion bonded hybrid transition joint. The process is speedy, and there is almost no time for heat transfer, limiting the diffusion of Al into Fe and, consequently, the formation of intermetallic compounds [112][113], [114]. Ultrasonic spot welding can also be successfully used to join dissimilar materials with a certain thickness and minimise the IMCs [114][115] since the process is operated at temperatures lower than the melting temperature.

Lasers are versatile and allow flexibility in dissimilar metals' joining processes, applied in welding, brazing, or welding-brazing. They offer a minimal heat affect zone, reasonable control of the total applied energy on the substrate, and high cooling and solidification rates, which minimises diffusion and growth of the IMCs. Different temporal output laser energies were used to join Al to steel: high power CW [9] and millisecond SPPW welding [90]. Both base materials were mixed in the liquid state, and the reaction between Fe and Al was enhanced, being formed Al-rich and Fe-rich thick IMCs. Sierra et al. found that by limiting the penetration depth to below 500 μm , as observed in Figure 2-29 (a) and (b), Fe-on-Al dilution could be restricted and, consequently, the weld's hardness could be confined.

Such penetration depths led to a maximum tensile strength of 250 N/mm, with failure located in the Al interfaces composed of Fe_2Al_5 and FeAl_3 IMCs, with a thickness between 5 and 20 μm . As shown in Figure 2-29 (c) and (d), increasing the penetration led to a reduction of the mechanical strength. However, even though micrographs (c) and (d) were achieved with similar welding parameters, the penetration depth is entirely different, which the authors justify as keyhole instabilities [9].

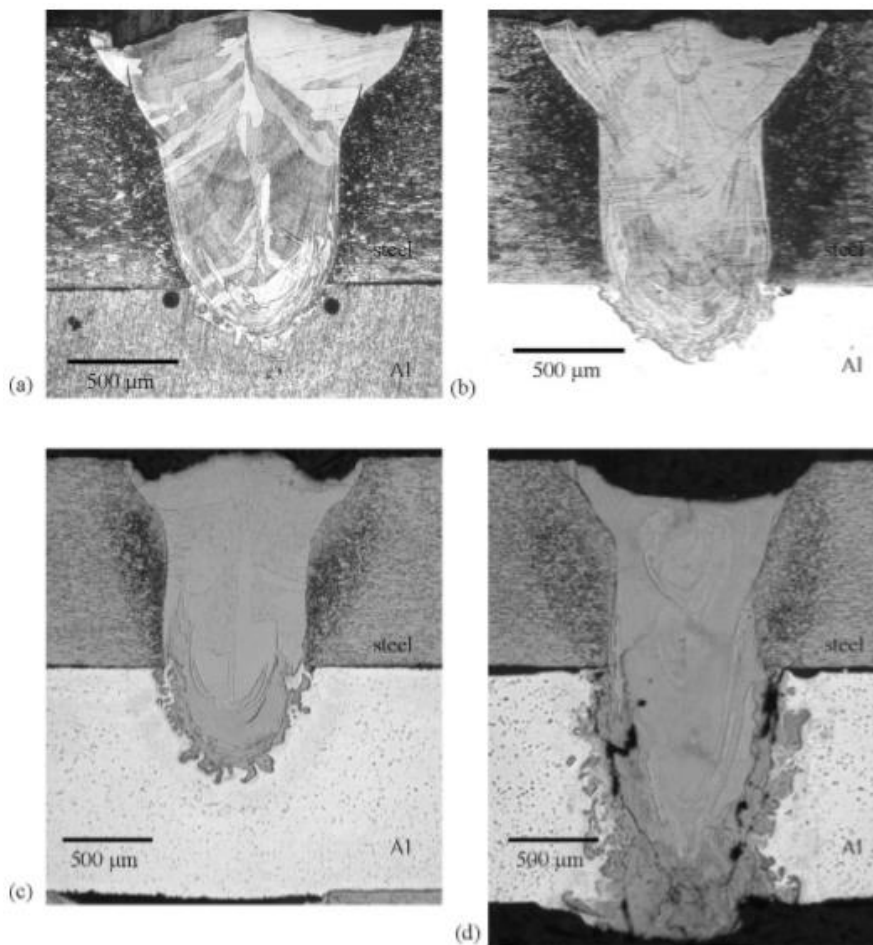


Figure 2-29 Cross-sections of steel-on-aluminium CW joints realised with (a), (c) and (d) a 200mm focal lens and (b) a 150mm focal lens. (a) $P=3.1\text{kW}$, $S=5.5\text{m/min}$, penetration = 250 μm , (b) $P = 2.25\text{kW}$, $v = 4.5\text{m/min}$, penetration = 380 μm , (c) $P = 3.1\text{kW}$, $v = 5\text{m/min}$, Penetration = 580 μm and (d) $P=3.1\text{kW}$, $S=5\text{m/min}$, Penetration = 1100 μm [9].

Nanosecond MPPW lasers can also be used to enhance the joining of 1 mm thick Al to 0.85 mm thick steel sheet by texturing the sample before welding with CW

laser [85]. The maximum tensile-shear load can be improved by increasing the bonding area with textured surfaces. A similar laser was used in a separate study to 0.125 mm thick sheets of Al to 0.5 mm thick SS in keyhole mode [80]. The low average power, high peak power and short pulse duration demonstrated good results by accurate control of the energy delivered to the joint. This laser produced good quality joints of these two alloys, as shown in Figure 2-30 [80]. The intermetallic distribution along the weld depth could be controlled by controlling the power density, and maximum tensile shear strength of 13.3 N/mm for one weld line was registered. However, a comparison between CW and PW mode under similar processing parameters was not performed, and the author recommended further research on this topic.

It would be helpful to understand which temporal mode provides better weld quality and joint strength. Even though in the results from Sierra et al., maximum tensile shear strength of 250 N/mm has been achieved in CW mode [9], which is almost 20x higher than the 13.3 N/mm performed in PW processing [80], the welding parameters cannot be compared. Once the fundamental parameters in MPPW seam welding are established, a fair comparison with CW processing can be made.

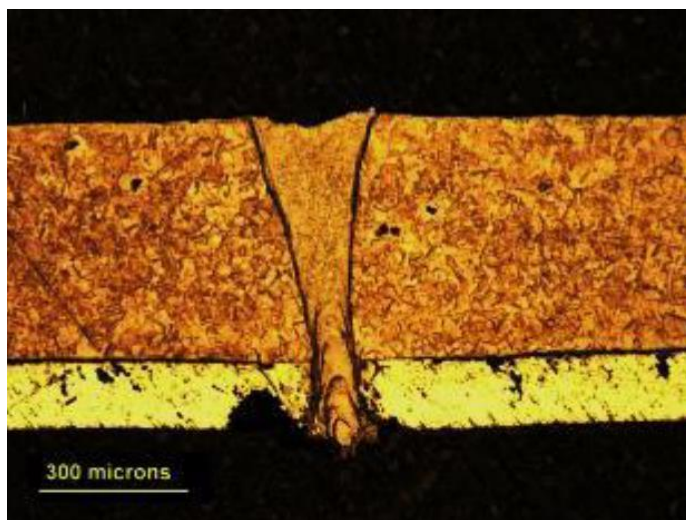


Figure 2-30 Micrograph from a nanosecond pulsed laser processing of stainless steel to aluminium using waveform 0 (pulse duration 240 ns, peak power 13 kW and pulse energy 1 mJ at 70 kHz), beam diameter 102 μm , travel speed 7.14 mm/s, specific point energy 1 J and overlap factor 99.9% [80].

2.4 Scaling effects of joining of thin sheets

Thermal processing for the fabrication of several macro, micro and nanoscale devices is taking the challenge of creating strong, safe and optimised joints to a higher level. Nonetheless, the appearance of thermally induced distortions and weld defects are almost inevitable when joining thin metallic sheets. The heat input, setup conditions and heat sinking design are crucial variables that must be precisely controlled to avoid them. A schematic representation of the deformations in a bead-on-plate weld is depicted in Figure 2-31. Typically, longitudinal and transverse thermal strains are responsible for distortions [115].

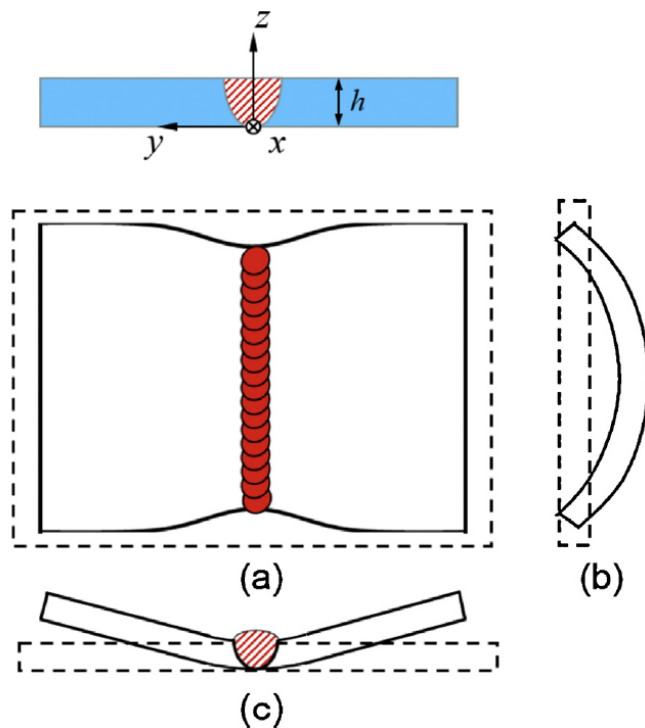


Figure 2-31 Deformation of a welded sheet: shrinkage in the plane (a), longitudinal bending (b) and transverse bending (c)[115].

The development of temperature gradients in the workpiece generates internal welding stresses and distortion. This phenomenon can be counteracted by the clamping system, which is essential in the micro-welding process to create a homogeneous and continuous weld seam [116][117][118]. During the welding process, the material is subjected to expansion and shrinking forces contained by several factors. There are two different regimes in shrinkage behaviour that

can be considered: local and global. The first one is caused by the colder material around the fusion zone, which prevents the expansion of the metal during the welding process. The global restraint to expansion is caused by the surrounding material and the clamping fixture. It defines the restraint intensity and the clamping length. According to Zhou et al., this is defined by Equation (2-20) which relates the modulus of elasticity E , the thickness of the foil f and the clamping length l_E [119]. The formula is as follows:

$$R_{F_Y} = E * f / l_E \text{ [MPa]} \quad (2-20)$$

Equation (2-20) is an indicator of the likelihood of cracking. As the clamping length is reduced, the mean residual welding stresses grow transversely to the seam while distortion decreases proportionally. However, the residual stresses and distortion can be suppressed simultaneously by maximising the clamping length, increasing the material thickness, and applying a localised clamping force in the joining zone [119]. An efficient technique to reduce the joint's temperature and consequently avoid distortion is utilising a copper backing bar underneath the weld joint [34].

2.5 Summary

Industry aims to reduce material consumption by decreasing their products' body weight and increasing productivity by optimising and developing fast joining processes. However, selecting the most appropriate joining method to meet all the manufacturing requirements is difficult since plenty are available. It is necessary to understand the advantages and limitations of each. Most of them are limited in processing time and joint strength or only applicable to a specific range of material thicknesses.

The mechanical fastening techniques can be used to join similar and dissimilar materials. However, in some cases, unnecessary weight is added, access to both sides of the joint is required, and the processing time is close to one second, which is not suitable for ultra-fast applications. Adhesive bonding is widely used in several industries, allowing a flexible joint design. Nevertheless, there are several environmental, health and safety risks to applying adhesives. Moreover,

the durability of the joints is highly sensitive to the environment. Solid-state joining includes friction stir welding, resistance spot welding and ultrasonic spot welding, amongst other processes. Most of them require mechanical contact, which creates tool-wearing and slows down the process, being impossible to reach the millisecond scale. Fusion welding such as cold metal transfer (CMT) has proven suitable for joining thin metallic sheets. However, a filler material is required, which makes the structure heavier. Laser welding, a fusion process and a non-contact joining technique, introduces the innovation needed to substitute the traditional tool wearing contact methods and improves productivity through ultra-fast rotating mirror scanners, allowing flexibility of the joint-shaped mechanical properties [120]. Due to the high energy density, it has a high potential in micro joining, resulting in a precise heat input control and high aspect ratio welds compared to other fusion welding processes. Therefore, it was the process selected to be investigated in this study.

Different laser temporal modes and laser welding techniques complicate the selection process for a specific welding application. Both CW and PW lasers have been demonstrated to be suitable for similar and dissimilar metal joining of Al and SS in keyhole and conduction mode. Laser welding using a nanosecond multi-pulse pulsed-wave laser applies the energy at a high rate, generating spike-like welds in Al. However, the pulse shape can be flexibly controlled, and good weld quality has been observed in SS. In CW keyhole welding, the intense vaporisation of the alloying elements of Al results in a reduction of the joint's mechanical properties. On the other hand, the weld quality in Al and SS can be improved by optimising the processing parameters. When joining both alloys together using either CW or PW mode, a reaction between Fe, Cr, and Al occurs, forming brittle intermetallic compounds (IMCs), which become thicker for higher energy power density levels. Among all the welding techniques available in laser welding, such as seam, spot or wobbling, seam welding is easy to apply, doesn't involve extra system parameters and allows identical welding conditions in both processing modes, being the one chosen in this work.

An intricate balance between vaporisation pressure, heat transfer, laser absorption and hydrodynamic phenomena influences weld pool formation. From the material's perspective, the process is controlled by the fundamental laser material-interaction parameters (FLMIP), which include interaction time, power density and specific point energy. These parameters are independent of the laser source and control the depth of penetration and weld width in CW welding. When the processing conditions are carefully chosen, the right amount of vaporisation and melting can be obtained, and phenomenological models like the power factor can predict the desired weld shape for an individual application. The clamping fixture plays a critical role in preventing distortion and residual stresses. Using a copper backing bar underneath the weld joint and a thicker sheet of metal are efficient techniques to avoid distortion during the study of new welding parameters.

2.6 Knowledge gaps found in science

The continuous application of energy per unit length was established for continuous-wave (CW) mode through the Fundamental Laser-Material Interaction Parameters (FLMIP). Low pulse energy, high peak power, and low average power multi-pulse pulsed-wave (MPPW) fibre lasers can deliver the same energy as CW through several nanosecond pulses overlapped at very high frequencies. However, it is not clear the benefit of such high frequencies near CW operation for micro welding. Therefore, it is necessary to study the individual effect of each parameter on the weld profile, i.e. depth of penetration and weld width.

Most of the research was done in pulsed-wave and continuous-wave lasers separately. No study was found in the literature review comparing MPPW and CW seam welding. There is a lack of studies for both laser types under similar processing conditions to understand which one is the most productive and efficient and offers better flexibility on the weld shape control. Thus, the characterisation of the MPPW laser is required to establish the correct FLMIP formulae to allow a like-for-like comparison for similar metal joining first. Then, this comparison should be explored to dissimilar welding to study the effect of

each laser on the intermetallic compound's formation, joint configuration, and weld strength.

In CW laser, the travel speed determines the energy rate transferred into the material, which controls the thermal losses of the melt pool. On the other hand, short individual pulses operated at high-duty cycles are needed to increase the energy accumulation to generate melting in MPPW welding. The thermal field, and consequently, the melt pool and cooling rate developed, are influenced by the inter-pulse spacing, the energy rate delivered in several consecutive pulses, and the material's physical properties. Thus, the thermal losses created by the different laser temporal modes applied in various materials with other physical properties impact the thermal weld cycle and must be captured in the FLMIP formulae.

The power factor is a phenomenological model of parameters validated in CW macro seam welding, which works based on the FLMIP. The trade-off between power density and specific point energy limits the model's applicability. It is necessary to investigate if the power factor model can be used in micro-welding, where the magnitude of the FLMIP values and the thermal field generated are entirely different. Moreover, the model could also be tested and extended to MPPW mode.

2.7 Project aim

This work aims to enable the selection of the most productive, efficient, and robust laser welding processing mode for joining thin, similar and dissimilar structural alloys by comparison under like-to-like conditions.

2.8 Research objectives and thesis structure

2.8.1 Research objectives

The following objectives will allow the investigation of different process variables and parameters for the application of lasers in the processing of thin structural alloys.

- Characterisation of the MPPW laser: measure and calculate the real pulse energy, average peak power and average power of the modulated pulses and compare the values from the theoretical formulas established for the SPPW laser.
- Establish the fundamental laser-material interaction parameters (FLMIP) in MPPW micro-welding.
- Application of a simple model to predict the thermal profile in PW processing of SS.
- Compare the productivity, penetration efficiency, melting efficiency, weld quality and mechanical strength of CW and MPPW welding of Al and SS using similar processing parameters.
- Investigate the laser system parameters' transferability in CW and MPPW micro seam welding through the power factor model.
- Investigate the brittle IMCs formation and distribution in MPPW and CW dissimilar welding of SS to Al and Al to SS and correlate with the joints' mechanical properties and welding defects.

2.8.2 Thesis structure

- Chapter 2 begins by reviewing the existing literature on different welding processes and techniques used in similar and dissimilar metal joining of aluminium and stainless steel, the aim and objectives of this research.
- Chapter 3 describes the experimental procedure and setup used in bead-on-plate laser welding of Al and SS and overlapped dissimilar welding of Al on SS and vice-versa. It also shows the methodology applied to the metallographic analysis and the tensile shear tests performed.
- Chapter 4 characterises the nanosecond MPPW laser used in this work. The average power, average peak power and pulse energy are compared with the laser manufacturer's reference tables and with the theoretical formulas established for SPPW laser. The individual effect of each FLMIP on the weld geometry is analysed. A simple thermal model is used to understand the

necessary applied energy per unit length to generate the base material's vaporisation.

- Chapter 5 investigates the selection of different waveforms in MPPW welding. The application of the FLMIP in various pulse shapes with different pulse duration, average peak power and similar pulse energy is analysed. The effect of the duty cycle on the weld profile is studied.
- Chapter 6 compares MPPW and CW lasers under similar processing conditions. A new model which describes the energy received by the material to compare both lasers for like-to-like conditions is used. The productivity, penetration efficiency, melting efficiency and weld shape control are analysed in the bead-on-plate seam welding of SS and Al.
- Chapter 7 extends the Power Factor model to CW micro seam welding. The interdependence between average power, travel speed and beam diameter are analysed in this model, optimising the system parameters to achieve the desired weld shape for a specific application.
- Chapter 8 follows the same principle and methodology used in chapter 7, but for MPPW micro seam welding. However, in this temporal mode, the standard definition of Power Factor was redesigned, being correlated with average peak power, pulse energy, pulse repetition frequency, pulse width and beam diameter to obtain a particular weld profile.
- Chapter 9 compares both MPPW and CW lasers for overlapped dissimilar joining of Al to SS and SS to Al. Several tensile shear tests were performed to determine which temporal mode better controls the IMC formation and provides stronger welds at similar processing conditions.
- Chapter 10 proposes a new definition of interaction time to compare different laser temporal modes by capturing the thermal losses.
- Chapter 11 sums up the entire work. An overall discussion, the main conclusions, and the contribution to knowledge are presented.
- In the last section are the references utilised throughout this work.

3 Experimental procedure

The process selected to be used in this work was autogenous laser seam welding. The experimental setup, laser systems and equipment to characterise the laser source are presented in this chapter. The materials' chemical composition, physical and mechanical properties, and sample preparation procedure are also shown.

3.1 Materials

The welds were made in 5251 H22 aluminium (Al) alloy and austenitic stainless steel (SS) 304L. Their chemical compositions are shown in Table 3-1 and Table 3-2. These alloys' mechanical and physical properties are shown in Table 3-3 and Table 3-4, respectively.

Table 3-1 Chemical composition in %wt of 5251 H22 aluminium alloy [121].

Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
Max 0.4	Max 0.5	Max 0.15	0.1 – 0.5	1.7 – 2.4	Max 0.15	Max 0.15	Max 0.15	Bal.

Table 3-2 Chemical composition in %wt of 304 L austenitic stainless steel [122].

Si	Fe	C	Mn	P	N	Ni	Cr
Max 1.0	Bal.	Max 0.03	Max 2.0	Max. 0.05	Max 0.11	8.0-11	18-20

Table 3-3 Mechanical properties of the base materials [121][122].

Material	Proof Stress [MPa]	Tensile Strength [MPa]	Elongation at failure [%]
Al 5251 H22	120 min	190 - 230	15 - 20
SS 304L	220 min	520 - 700	45 min

Table 3-4 Physical properties of the base materials [121][122].

Property	Symbol	Units	Al 5251 H22	SS 304L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Vaporisation Temperature	T_v	W.(m.K) ⁻¹	2790	3023
Thermal conductivity	k	W m ⁻¹ K ⁻¹	134	16.2
Thermal diffusivity	α	m ² s ⁻¹	5.7 x 10 ⁻⁵	5.5 x 10 ⁻⁶
Modulus of Elasticity	E	GPa	70	193

3.1.1 Clamping system

The clamping system is essential to ensure the reproducibility of the experiments. The following characteristics were considered:

- Setup time: Due to the large number of experiments required in this work, a low setup time to clamp the substrate is necessary. Thus, the number of screws used has been minimised.
- The cooling rate of the welds: According to the literature, the brittle intermetallic compounds (IMCs) grow with temperature and time. A copper heat sink can extract the heat from the joint due to its high thermal conductivity, reducing the growth of the IMCs and the likelihood of distortion [34]. Therefore, a 5 mm thick copper backing bar has been used.
- Applied force along the substrate: To achieve a constant weld seam in every experiment, the force applied by the clamping device must be uniform. Thick clamping bars (10 mm) of steel have been designed in order to avoid their deformation after several cycles of clamping and unclamping of the substrate. Hence, good contact between the substrate and the copper backing bar can also be ensured to maximise the cooling efficiency and minimise the risk of distortion.

The clamping system was designed based on the previous characteristics. It is schematically shown in Figure 3-1 and Figure 3-2.

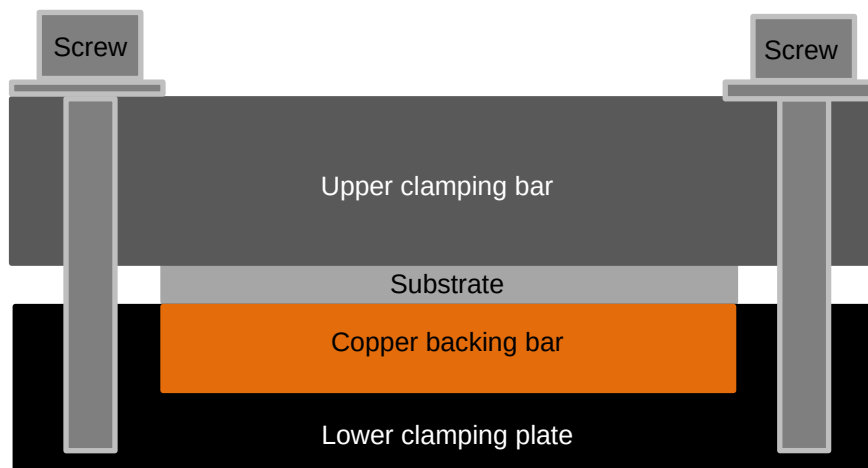


Figure 3-1 Cross-section representation of the clamping system.

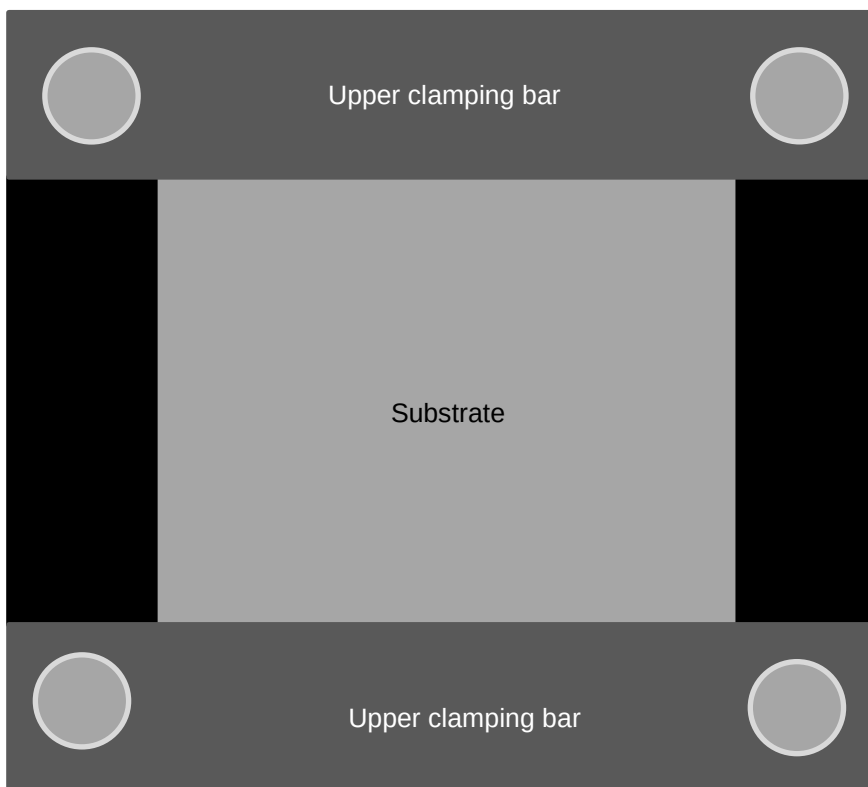


Figure 3-2 Schematic representation of the clamping system (front view).

3.1.2 Welding configuration

Different welding configurations were used. Bead-on-plate welds of Al and SS (Figure 3-3) were performed in chapters 4 to 8. The overlapped welding of Al-SS and SS-Al (Figure 3-4) was conducted in chapter 9. Therefore, a copper backing bar was used in both similar (Figure 3-3) and dissimilar joining (Figure 3-4) to keep the processing conditions as identical as possible in both cases. The Al and SS plates were ground and then degreased with acetone.

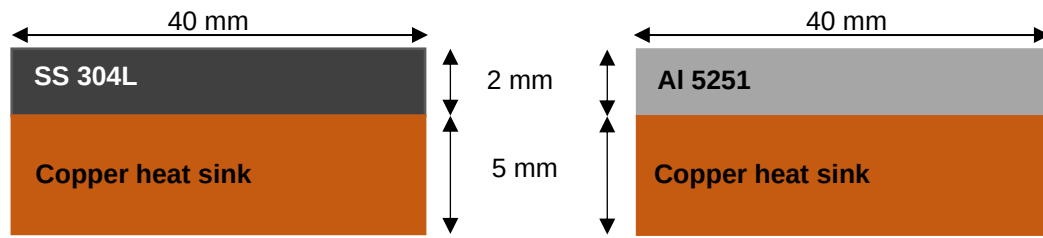


Figure 3-3 Weld configuration of bead-on-plate welds of SS and Al.

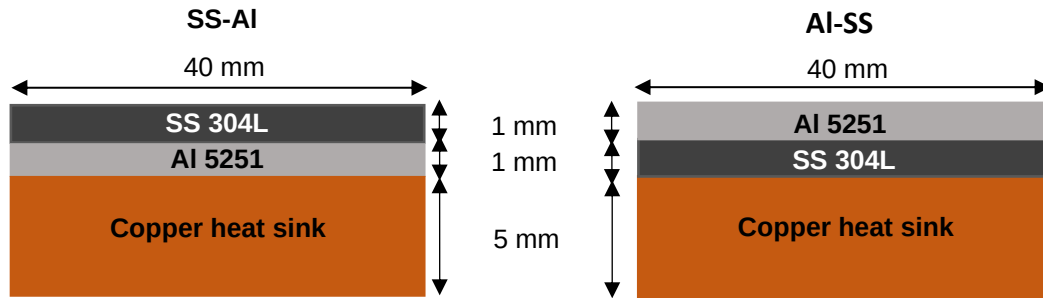


Figure 3-4 Weld configuration of overlap welds of SS-Al and Al-SS.

3.1.3 Laser processing

Two different types of fibre lasers were used with a wavelength of 1 μm : a JK500FL JK Laser (now Trumpf) 500 W output power continuous wave and a SPI Laser SP-100P-A-EP-Z-B-Y (now Trumpf) G4 nanosecond multi-pulse pulsed-wave (Z-type) with an average output power of 100 W, a maximum peak power of 10 kW, maximum pulse energy of 1 mJ, and maximum pulse duration of 500 ns. The laser beam was delivered through an optical fibre of 50 μm diameter, and the delivery fibres of both lasers were connected to the same galvo-scanner (RAYLASE SUPERSCAN IIE) equipped with an f-theta focusing lens with a focal length of 160 mm. An air knife was used with compressed gas to protect the lens from spatter, and no shielding gas was applied to the substrate. The experimental

setup is depicted in Figure 3-5. The schematic representation of the experimental setup is shown in Figure 3-6.

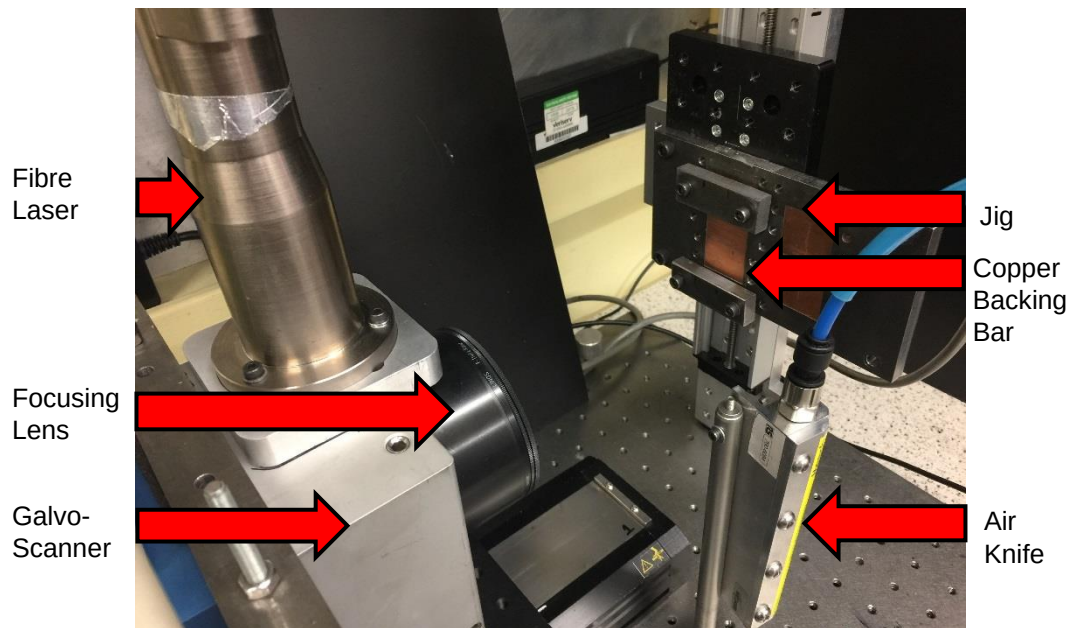


Figure 3-5 Experimental setup.

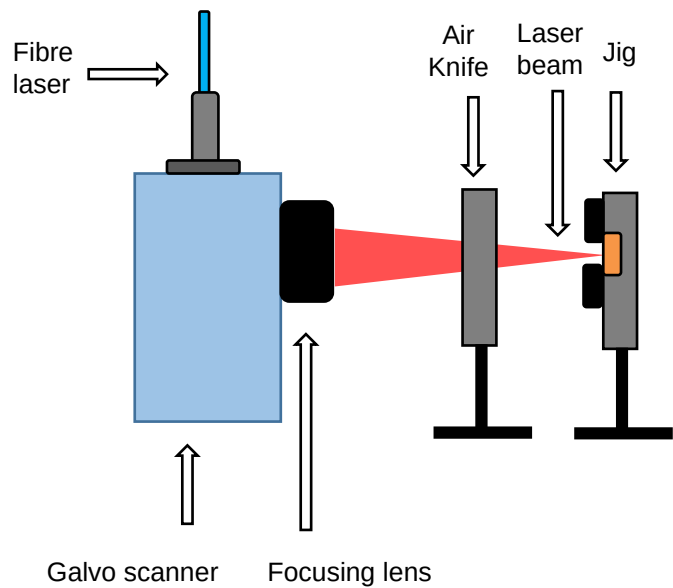


Figure 3-6 Schematic representation of the experimental setup.

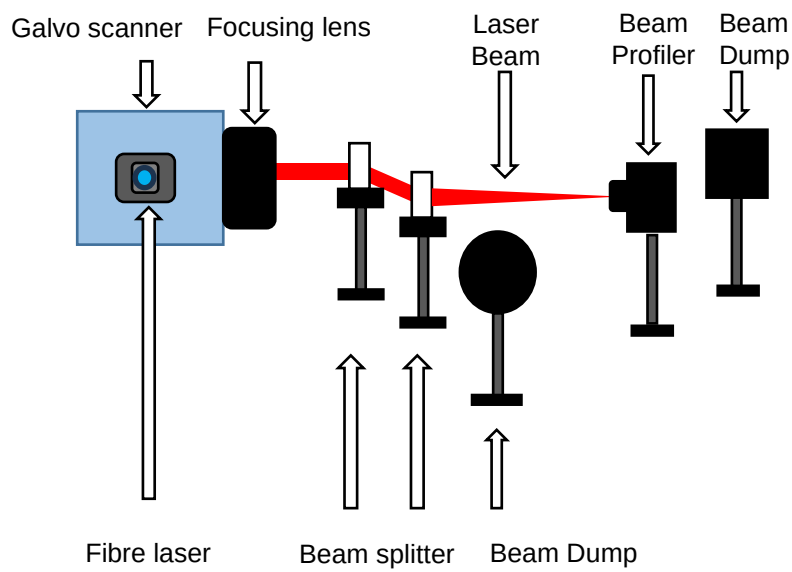


Figure 3-8 Schematic representation of the experimental setup for beam profiling.

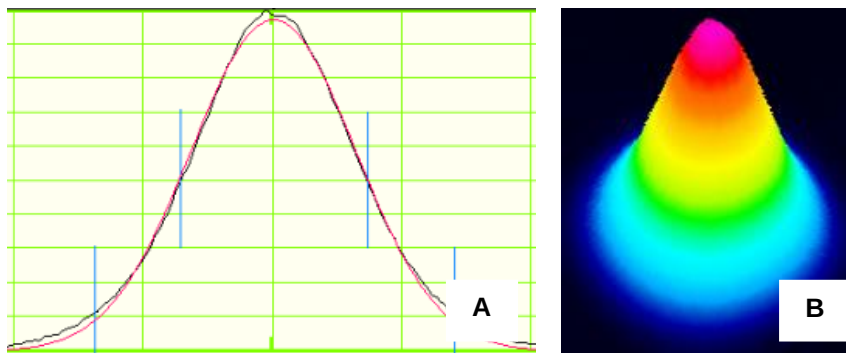


Figure 3-9 Gaussian profile (A) and 3D profile (B) of the CW laser for a beam diameter of 35 μm .

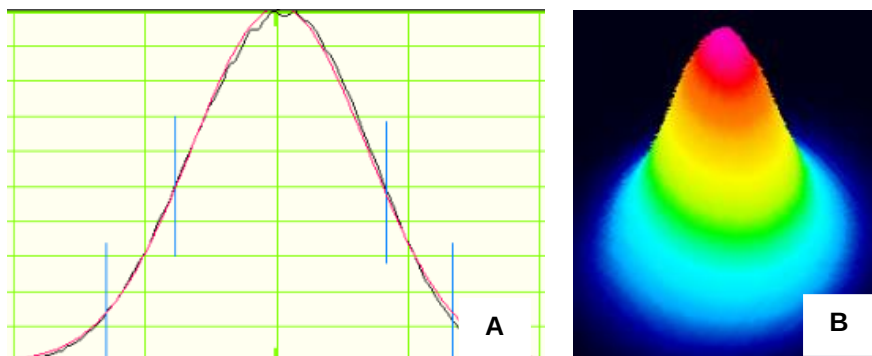


Figure 3-10 Gaussian profile (A) and 3D profile (B) of the MPPW laser for a beam diameter of 35 μm .

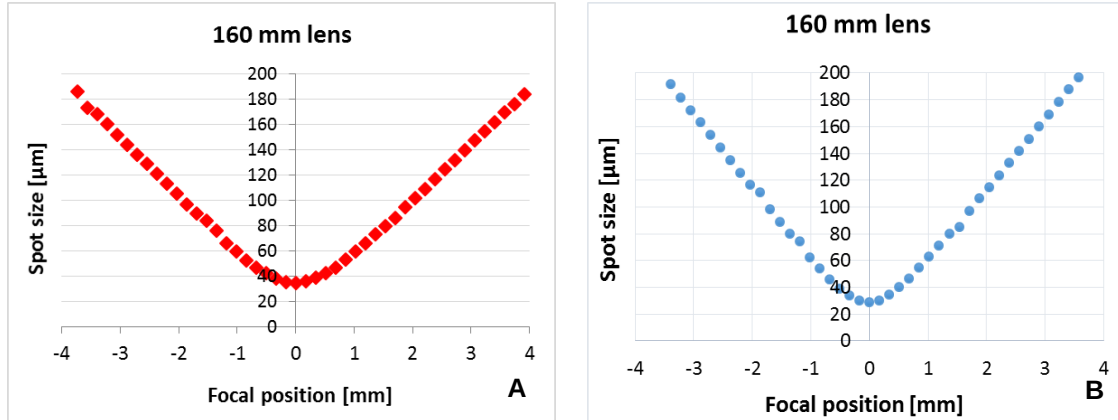


Figure 3-11 Beam profiles of A) MPPW (35 μm on focus) and B) CW lasers (30 μm on focus).

The laser power was measured by a power meter (Laserpoint A-600-D40-HPB), and showed less than 1% variation compared to the laser source. The beam diameter was maximised to reduce the energy density and avoid thermal damage of the sensor. A schematic of the setup is shown in Figure 3-12.

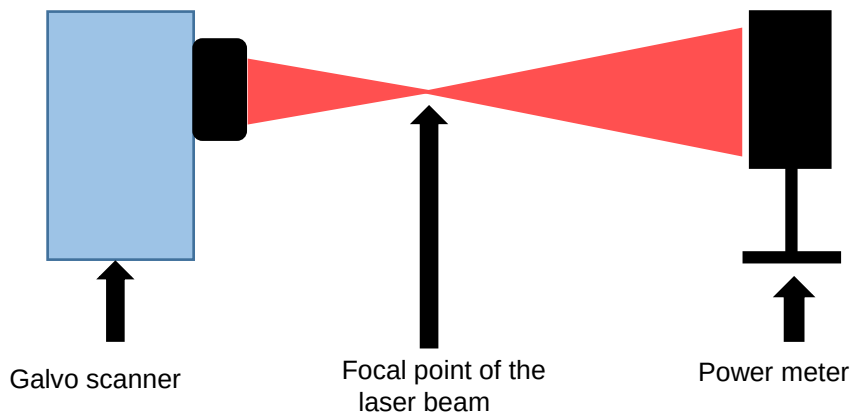


Figure 3-12 Schematic diagram of the power meter setup.

For MPPW processing, the laser radiation's temporal response was measured using a high-speed photodetector (Model APD310 from MenloSystems) connected to an oscilloscope with 1GHz bandwidth and 5GS/s sample rate (Model: MDO3102 from Tektronix). The CW laser output stability and response were also tested. The high-speed camera (Phantom Miro ex1) was used without any illumination at 500 frames-per-second (fps) to analyse if the processing speeds shown by the galvo-scanner's software corresponded to the real values. The experimental setup is shown in Figure 3-13 and Figure 3-14.

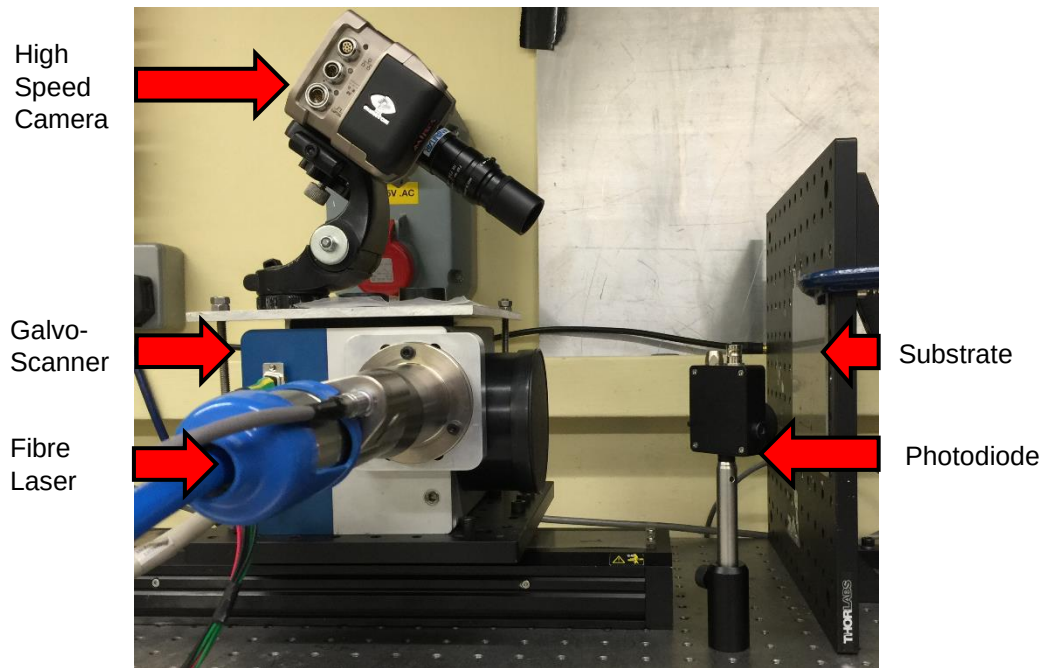


Figure 3-13 Experimental setup for the analysis of the temporal response of the laser.

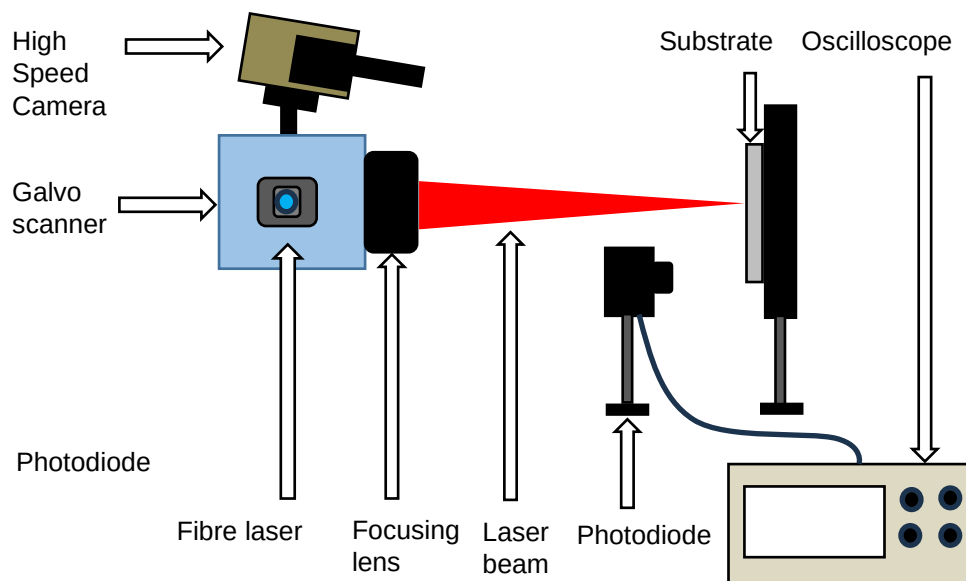


Figure 3-14 Schematic representation of the experimental setup for the analysis of the temporal response of the laser.

3.3 Metallographic analysis

Bead-on-plate welds were cross-sectioned in two different samples (A and B) to analyse the weld geometry, as shown in Figure 3-15. On the other hand, dissimilar welds were cross-sectioned in three samples: A and B for analysis of the weld geometry and IMC distribution, and sample C for the tensile shear test, as shown in Figure 3-16.

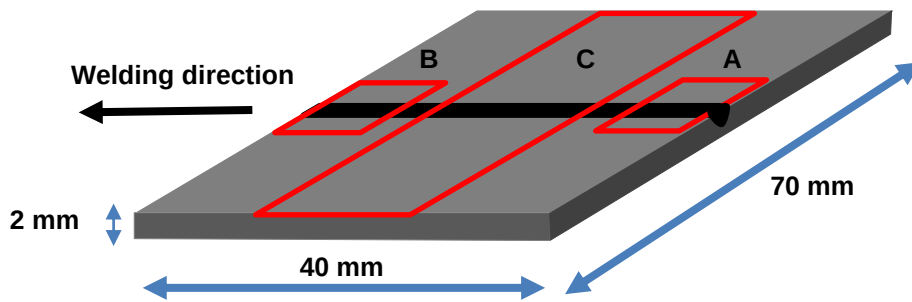


Figure 3-15 Schematic representation of the samples A and B extracted from the bead-on-plate welds for metallography analysis, and sample C for mechanical testing.

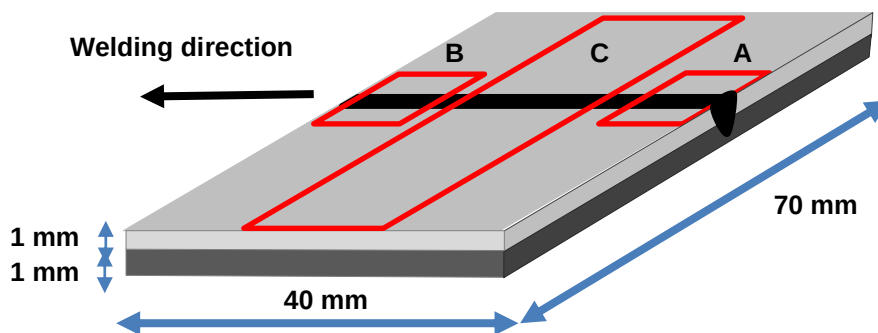


Figure 3-16 Schematic representation of the samples A and B extracted from the dissimilar metal welds for metallography analysis, and sample C for mechanical testing.

All welds were mounted in plastic moulds using an epoxy resin mixed with a hardener. The samples were mechanically ground in an automatic polisher in three steps using different grades of sanding paper: 240, 1200 and 2500. Next,

the polishing using 9 μ m diamond suspension was performed, followed by 5 μ m diamond paste. Finally, 1 μ m colloidal silica suspension was used. The Al microstructure was revealed by etching its surface with Keller's reagent (5 mL HNO₃, 3 mL HCl, 2 mL HF, and 190 mL Distilled Water) [123], whereas SS was electrolytically etched (60 seconds at 15V per sample) with 10% of oxalic acid (C₂H₂O₄) [124]. Micrographs were taken with an Optiphot optical microscope with total magnification ranging from 2.5x to 40x. Scanning electron microscope (SEM) equipment was also used to investigate the IMC's composition and distribution in the fusion zone of the welds with integrated energy-dispersive X-ray spectroscopy (EDS).

3.4 Mechanical testing

Tensile shear tests were conducted at room temperature using an electromechanical Instron 5500 machine, with a load cell of 3 kN and a crosshead displacement of 0.5 mm/min perpendicular to the weld direction. The setup used is shown in Figure 3-17, where the strength of the dissimilar joints of Al-SS and SS-Al were tested. The geometry and dimensions of the cross weld lap tensile-shear test specimens were parallel edge with 25 mm wide and 160 mm long (80 mm long Al sheet on 80 mm long SS sheet and vice-versa, with 40 mm overlap length) according to ISO 14273:2001 standards for mechanical tensile-shear testing of seam welds [125]. Figure 3-18 shows the weld line patterns used for tensile testing. Each sample was aligned without any spacers and the weld start and stop points were positioned outside of it. A different number of 25 mm long horizontal weld line patterns were used: (a) single line, (b) 2 lines and (c) 4 lines, separated by 5 mm each. The parent metals' elongation was measured using laser extensometer model LE-15 for a gauge length of 30 mm.

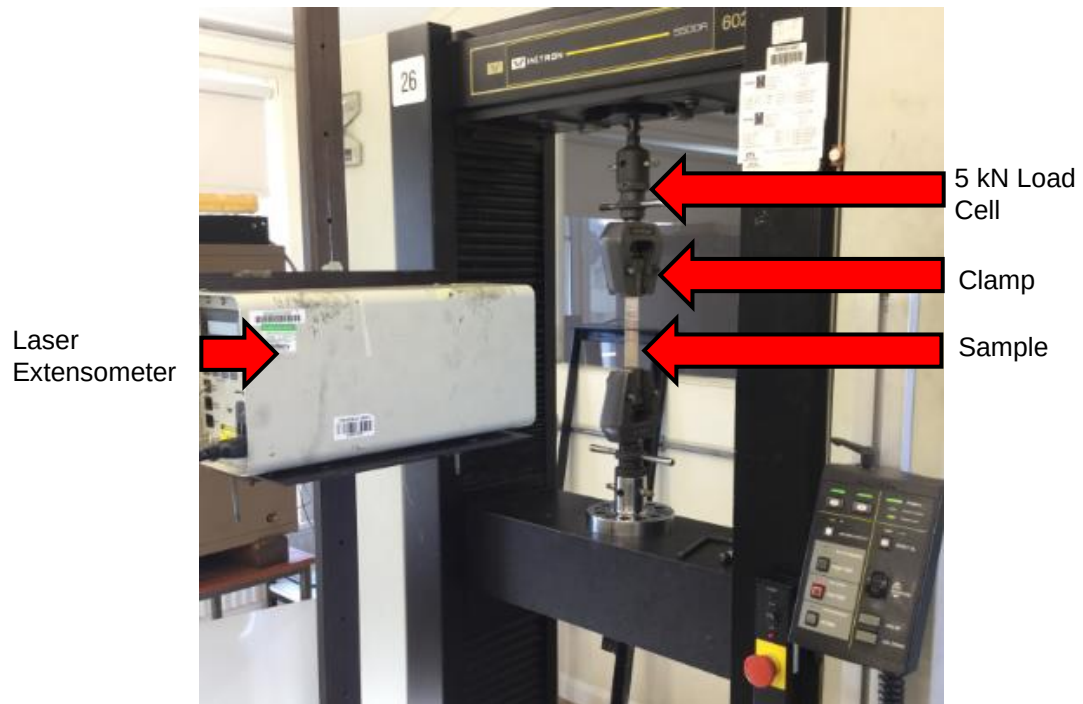


Figure 3-17 Setup for the tensile test.

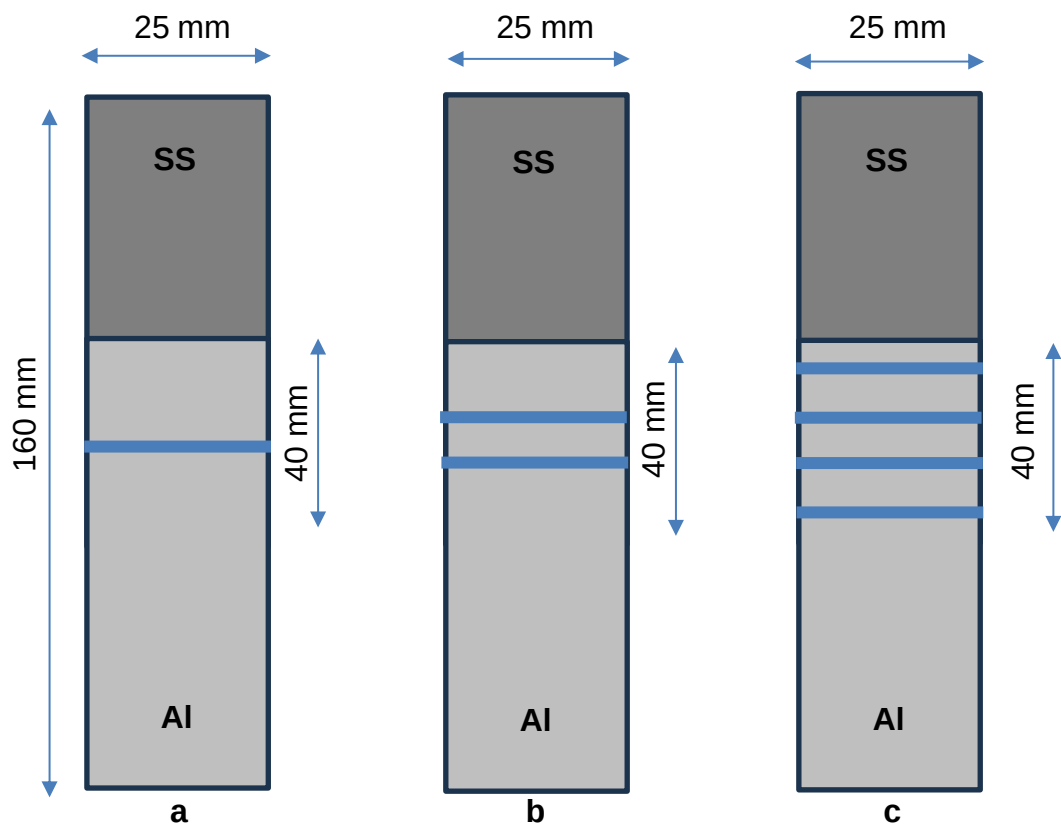


Figure 3-18 Patterns of weld lines used for tensile testing.

4 Characterisation of the multi-pulse pulsed-wave laser

Part of this chapter is based on the following publication:

Coroado J*, Ganguly S., Suder W., Williams S., Meco S., Pardal G. (2021) ‘Selection of parameters in nanosecond pulsed wave laser micro-welding’, *The International Journal of Advanced Manufacturing Technology*, 115, pp. 2929–2944, <https://doi.org/10.1007/s00170-021-07251-8>.

4.1 Introduction

This work aims to fully characterise the MPPW laser and understand if the existing definitions of the fundamental laser-material interaction parameters (power density, specific point energy and interaction time), initially developed to control the welding process in continuous wave mode [44], are also applicable. The objectives are as follows:

- Acquisition of the pulse shape and measurement of the laser temporal response.
- Determination of the actual pulse energy and average peak power based on the measurements of the laser temporal response.
- Investigation of the influence of the system, calculated and fundamental laser-material interaction parameters on the weld profile.
- Investigation of the laser’s duty cycle on the weld shape using a simplistic thermal model.

4.2 Experimental procedure

4.2.1 Material

The material used in the experiments was a 2mm thick plate of SS304 L. Its chemical composition, and physical properties are shown in section 3.1 in Table 3-2 and Table 3-4, respectively.

4.2.2 Methodology and experimental setup

The bead-on-plate welds were produced with a 100 W average output power nanosecond multi-pulse pulsed-wave fibre laser, whose output’s characterisation

is shown in Figure 4-1. It can be seen that at a particular pulse repetition frequency (PRF_0), the average power and pulse energy are maximum. Below PRF_0 , the average power decreases linearly, and the pulse energy remains constant, whereas above PRF_0 , the pulse energy decreases with the increment in PRF , and the average power remains constant. The experimental setup is shown in section 3.

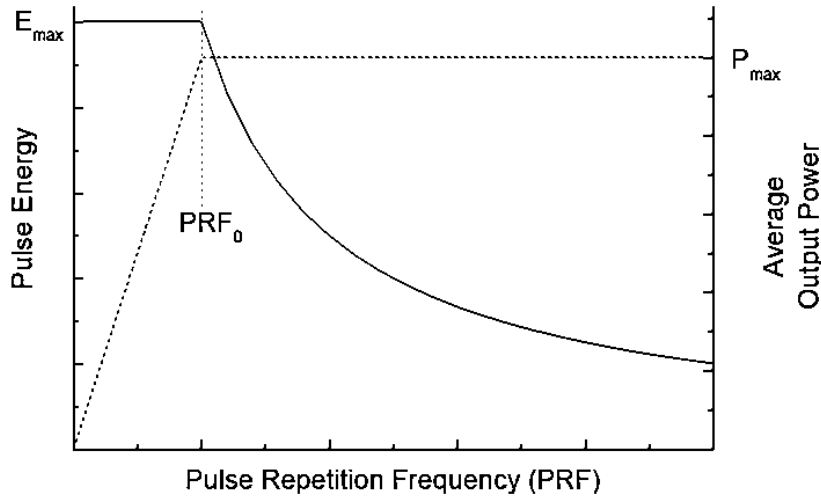


Figure 4-1 Output characterisation of the nanosecond MPPW laser according to the manufacturer [126].

This MPPW laser allows the selection of 31 different waveforms, characterised by specific pulse duration and power distribution. The properties of the waveforms used in this chapter are presented in Table 4-1.

Table 4-1 Properties of waveforms 0, 27 and 31 at PRF_0 and at a maximum average power of 100W [126].

Waveform	Pulse duration [ns]	Pulse repetition frequency [kHz]	Average power [W]	Pulse Energy [mJ]	Peak power [kW]
wfm	P_{width}	PRF_0	P_L	E_{pulse}	-
0	280	100	100	1	10
27	350	100	100	1	7
31	500	100	100	1	7

The laser radiation's temporal response was measured using a photodiode and oscilloscope shown in Figure 4-2. The pulse shape of each waveform at different frequencies was acquired in the oscilloscope in Volts and then normalised to

Watts for each measured point throughout the pulse. The peak power at PRF_0 from Table 4-1 was used as a reference equivalent to the maximum voltage measured, being all the other values normalised accordingly.

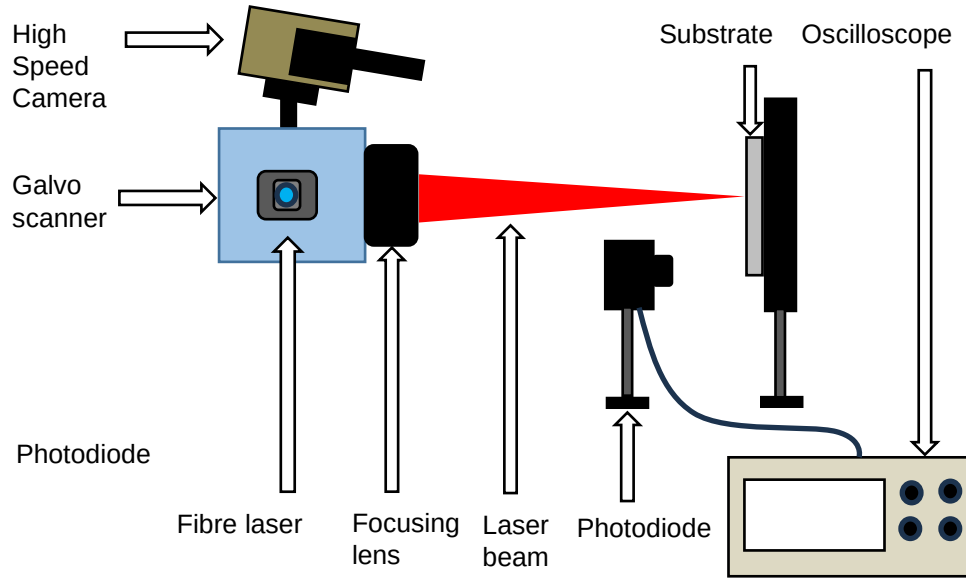


Figure 4-2 Schematic representation of the experimental setup for the analysis of the temporal response of the laser.

4.2.2.1 Mapping of the actual pulse energy and average peak power for different pulse durations

The total energy delivered within one pulse is represented by the area of its shape, which corresponds to the integral of the power over the entire pulse duration. The power distribution is not constant within the pulse duration, and the average power distribution is designated as the average peak power, as depicted in Figure 4-3. However, the laser manufacturer [126] only provides the pulse energy and peak power for maximum average power (100 W) at PRF_0 (100 kHz), as previously shown in Table 4-1.

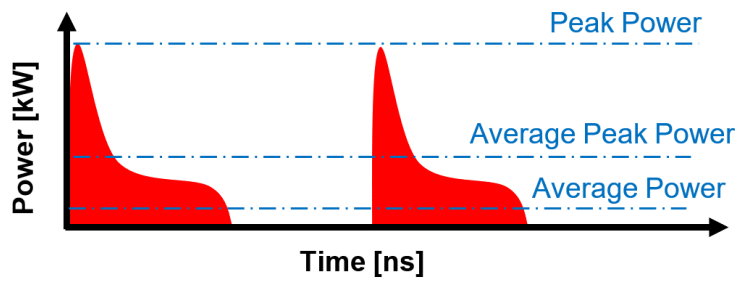


Figure 4-3 Temporal output of a nanosecond MPPW laser [126].

To investigate the variation of the pulse energy and the average peak power for different pulse widths, pulse repetition frequencies and average powers, a set of experiments was performed based on the parameters in Table 4-2. A photodiode was used to measure the pulse shape for each combination of parameters, and an oscilloscope recorded the different values. Since the data acquired by the oscilloscope was in voltage, it was normalised to watts according to the reference of each waveform at PRF_0 previously shown in Table 4-1.

Table 4-2 System parameters used for waveforms 0, 27 and 31.

Waveform	Pulse width [ns]	Average Power [W]	Pulse repetition frequency [kHz]
wfm	P_{width}	P_L	PRF
0	280	50 - 100	50 - 300
27	350	50 - 100	50 - 300
31	500	50 - 100	50 - 300

4.2.2.2 Effect of average peak power density, specific point energy and interaction time on the weld shape

The application of energy is well defined for CW mode, and the process can be described by the fundamental laser-material interaction parameters (FLMIP). It includes the interaction time ($t_{i, CW}$), average power density (q_p) and specific point energy ($E_{SP, CW}$) [44]. Nevertheless, the definitions and application of these parameters in MPPW mode are not well established yet and need to be understood or developed.

A summary of the mathematical formulae of the FLMIP used to define the laser temporal output is presented in Table 4-3. In CW mode, the average power density (q_p) is defined as the ratio of the average power (P_L) to the area of the

laser spot on the material's surface (A_s) [44]. As observed in Figure 4-4, in MPPW mode, the average power is different from the average peak power, and a new power density needs to be defined: the average peak power density ($q_{p, peak}$). This concept has been previously used in a millisecond SPPW laser [79], and nanosecond MPPW laser [80][81].

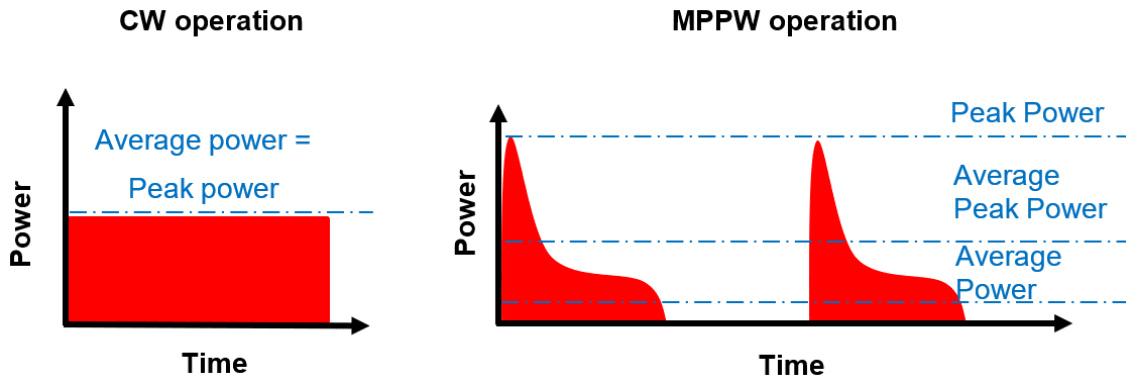


Figure 4-4 Temporal output of a CW and nanosecond MPPW lasers [126].

The energy transferred to the material is also different from the standard definition in CW mode for two reasons: first, in CW mode, the interaction time ($t_{i, CW}$) only considers the ratio between travel speed and beam diameter and in MPPW mode, it is also necessary to consider the pulse repetition frequency and pulse width [80]; second, in MPPW mode a new power density needs to be defined to accommodate the effect of the average peak power. Hence, a new definition of specific point energy also needs to be considered: ($E_{SP, MPPW}$). This concept has also been previously used, but the definition was never distinguished from CW [80][81]. Moreover, the definition of interaction time established for MPPW mode was never compared to CW mode's existing formula. Therefore, these definitions need to be tested in order to understand their individual effect on the penetration depth and weld width and then be established as the corresponding FLMIP in MPPW micro seam welding. A summary of the different FLMIP used in MPPW and CW laser modes is shown in Table 4-3.

Table 4-3 FLMP equations applied in different laser temporal modes.

Laser temporal mode	Interaction time [ms]	Power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]
CW	d/v	P_L/A_S	P_L/A_S	$q_p \cdot t_{i, CW} \cdot A_S$
MPPW	$P_{width}/(1-O_F/100)$	P_L/A_S	P_{Peak}/A_S	$q_{p, peak} \cdot t_{i, MPPW} \cdot A_S$

This section investigates the effect of the proposed new set of parameters on the shape of MPPW bead-on-plate welds using a fixed beam diameter, average power and pulse width. The set of system parameters and corresponding calculated and fundamental laser-material interaction parameters are presented in Table 4-4 and Table 4-5, respectively.

Table 4-4 System parameters and corresponding calculated and FLMP used in MPPW laser for a beam diameter of 89 μm , a pulse width of 500 ns and average power of 100 W.

System Parameters					Calculated Parameters			
Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Duty cycle [%]	Overlap Factor [%]
d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}	D_c	O_F
89	500	100	0.9-1780	100 - 400	0.25 – 1	0.5 - 2	5 - 20	95-99.99

Table 4-5 System parameters and corresponding FLMP used in MPPW laser for a beam diameter of 89 μm , a pulse width of 500 ns and average power of 100 W.

System Parameters							Fundamental Laser Material Interaction Parameters			
Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]	Interaction time [ms]
d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$	$t_{i, \text{MPPW}}$
89	500	100	0.9-1780	100 - 400	0.25 – 1	0.5 - 2	1.6	8 – 32	5 - 10000	0.01 - 5

4.2.2.3 Effect of the duty cycle on the weld shape

According to the nanosecond pulsed MPPW laser's output characterisation in Figure 4-1, for similar pulse width, when *PRF* increases, the average power remains constant, but the pulse energy decreases. Hence, the duty cycle of the laser increases, but less energy is applied per pulse. In this section, the pulse energy is kept constant, and the effect of the laser's duty cycle on the weld geometry is studied. The set of parameters used is presented in Table 4-6 and Table 4-7.

Table 4-6 Calculated parameters and corresponding system parameters used in MPPW laser for a beam diameter of 35 μm , a pulse duration of 500 ns and different average powers.

Calculated Parameters		System Parameters						
Duty cycle [%]	Overlap Factor [%]	Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]
D_c	O_F	d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}
1.25	99.5	35	500	25	4.4	25	1	2
2.5	99.5	35	500	50	8.8	50	1	2
5	99.5	35	500	100	17.6	100	1	2

Table 4-7 Calculated parameters and corresponding FLMIP used in MPPW laser for a beam diameter of 35 μm , a pulse duration of 500 ns and different average powers.

Calculated Parameters		Fundamental Laser Material Interaction Parameters			
Duty cycle [%]	Overlap Factor [%]	Average power density [MW/cm^2]	Average peak power density [MW/cm^2]	Specific point energy [mJ]	Interaction time [ms]
D_c	O_F	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$	$t_{i, \text{MPPW}}$
1.25	99.5	2.6	208	200	0.1
2.5	99.5	5.2	208	200	0.1
5	99.5	10.4	208	200	0.1

A simple thermal model has been used to evaluate each pulse's cumulative heat effect when the laser's duty cycle is varied at constant pulse energy and pulse width. A MPPW laser of average power P_L and beam diameter d has been used in steady position to understand how the laser duty cycle affects the weld thermal cycle to melt a desired volume of metal. The baseplate with a thickness of 2mm

is considered in this study at a room temperature T_0 of 293 K. The cumulative temperature of multiple pulses applied on the material (T_n) can be calculated by a simple thermal balance; the difference between the maximum temperature reached after each pulse heating up the material's surface (T_H), and the minimum temperature that the material reaches during the cooling time between pulses (T_C), as given by in Equation (4-1). T_H can be calculated as the laser duty cycle (D_C) multiplied by the ratio of the applied energy on the baseplate of a single pulse (E_H) by the product of the volume of molten metal (V), its density (ρ) and the specific heat capacity (C_{PS}), plus room temperature (T_0), as given by Equation (4-2). On the other hand, T_C is given by the laser duty cycle multiplied by the ratio of the dissipated energy (E_C), and the product of V , ρ and C_{PS} , plus T_0 , as given by Equation (4-3).

$$T_n = T_H - T_C [K] \quad (4-1)$$

$$T_H = (E_H / (V * \rho * C_{PS}) + T_0) * D_C / 100 [K] \quad (4-2)$$

$$T_C = (E_C / (V * \rho * C_{PS}) + T_0) * D_C / 100 [K] \quad (4-3)$$

The volume of molten metal considered is the area of the laser beam multiplied by the weld depth (z), as shown in Equation (4-4). E_H is calculated as the time that the laser irradiates the metal (t_H) multiplied by the laser average peak power (P_{peak}) and the material absorptivity when exposed to a certain wavelength at a certain temperature (A), as shown in (4-5). For the MPPW laser used in this study with a wavelength of 1 μm , the absorptivity of stainless steel is 0.65 at room temperature [127].

The laser irradiation time (t_H) is calculated as the product of pulse duration (P_{width}) by the number of pulses applied on the material (N_p), as given by Equation (4-6). The average peak power is the ratio between the pulse energy (E_{pulse}) and pulse duration, as given by .

$$V = \pi * \left(\frac{d}{2}\right)^2 * z [mm^3] \quad (4-4)$$

$$E_H = t_H * P_{peak} * A [J] \quad (4-5)$$

$$t_H = P_{width} * N_p [s] \quad (4-6)$$

$$P_{peak} = E_{pulse}/P_{width} [kW] \quad (4-7)$$

The energy dissipated when the laser is off, is provided by the product of the time between pulses, also defined as interpulse spacing (I_S), and the laser power dissipated between pulses (Q), as given by Equation (4-8). Therefore, the time for cooling when the laser is off is given by (4-9) as the product between I_S and the number of pulses applied (N_P). I_S depends on the laser duty cycle (D_C) and the pulse repetition frequency (PRF), as given by Equation (4-10). The duty cycle is the fraction of time for laser pulse emission. It is defined by the ratio between pulse width and the pulse period (Δt), as given by Equation (4-11).

$$E_C = I_S * Q * N_p [J] \quad (4-8)$$

$$t_C = I_S * N_p [J] \quad (4-9)$$

$$I_S = (1 - D_C)/PRF [s] \quad (4-10)$$

$$D_C = P_{width}/\Delta t [\%] \quad (4-11)$$

When the laser is not irradiating the metal, the energy is dissipated by conduction to the baseplate. Therefore, the laser cooling power lost between pulses (Q) can be calculated as the product between the material thermal conductivity (K), area irradiated by the laser beam (A_S), and the material temperature difference between two consecutive pulses ($T_{n+1} - T_n$), divided by the material thickness (M_t), as given by Equation (4-12). The area of the weld cross-section (A_{CS}) depends on the laser beam diameter (4-13).

$$Q = K * A_{CS} * (T_{n+1} - T_n)/M_t [W] \quad (4-12)$$

$$A_{CS} = \pi * \left(\frac{d}{2}\right)^2 [mm^2] \quad (4-13)$$

The thermal cycle has been calculated based on a selection of parameters previously presented in Table 4-6 and Table 4-7.

4.2.3 Weld shape characterisation

The depth of penetration and weld width were accurately characterised using an optical microscope. More details are presented in section 3.

4.3 Results and discussion

4.3.1 Mapping of the actual pulse energy and average peak power for different pulse durations

The variation of the pulse energy and average peak power is investigated in this section for different pulse repetition frequencies and constant pulse width. Figure 4-5 shows only one pulse from waveform 0 ($P_{width} = 280$ ns) at different pulse repetition frequencies, between 50 and 300 kHz. The peak power of 10 kW at PRF_0 of 100 kHz is characteristic in the first nanoseconds of the pulse duration, tailing down immediately after reaching its maximum. The peak power decreases for frequencies above 100 kHz, whereas, below PRF_0 , it is kept constant (10 kW), according to the laser output characteristic, as previously depicted in Figure 4-1.

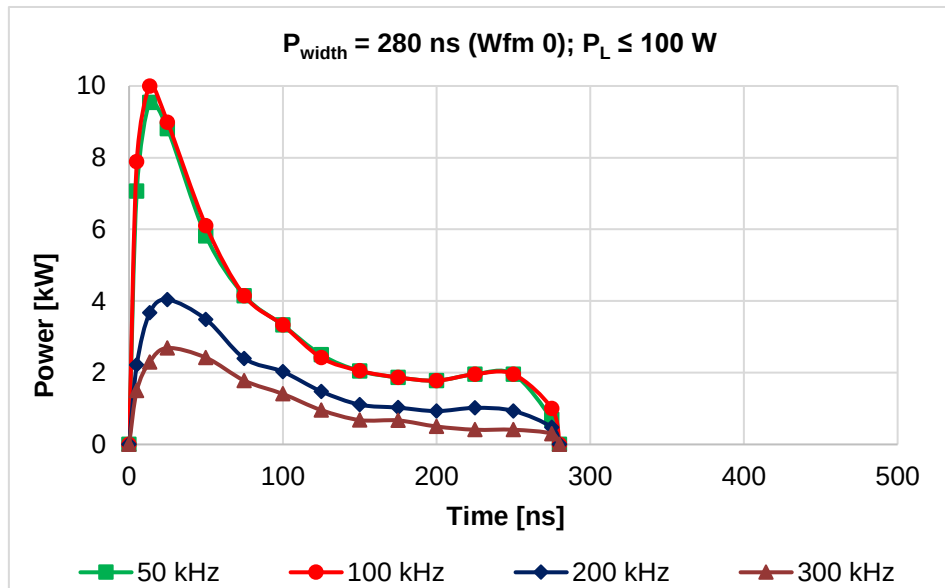


Figure 4-5 Pulse shapes of waveform 0 for different pulse repetition frequencies at a maximum average power of 100W.

Figure 4-6 shows the calculated pulse energy (E_{pulse}) from the pulse shapes previously shown in Figure 4-5. As expected, and according to the reference in

Figure 4-1, until 100 kHz (PRF_0), the maximum pulse energy of 1 mJ is achieved, decreasing after this frequency. It is also shown in Figure 4-6 the corresponding average peak power (P_{peak}) for each pulse energy.

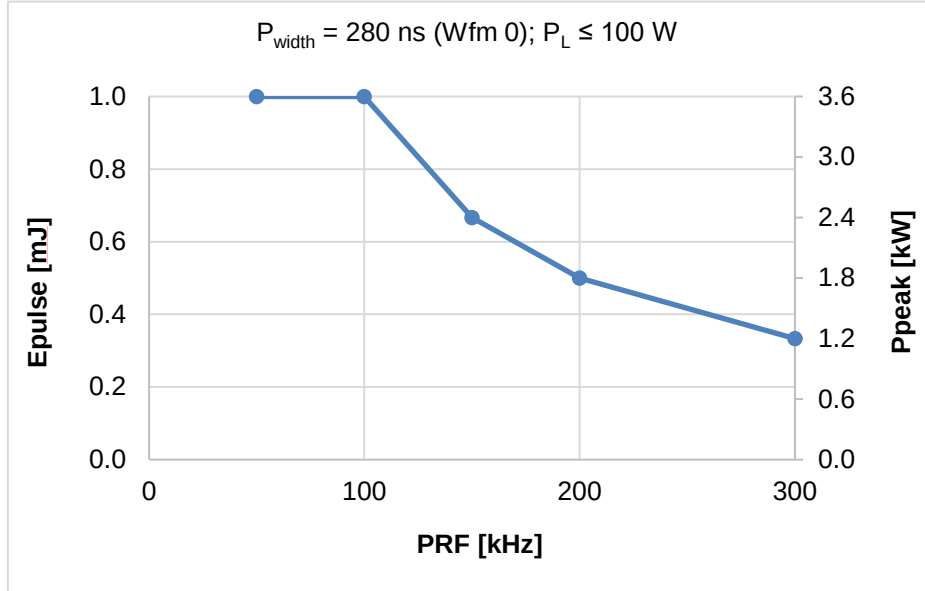


Figure 4-6 Pulse energy and average peak power of waveform 0 for different pulse repetition frequencies at a maximum average power of 100 W.

Figure 4-7 is plotted for similar pulse width and pulse energy, comparing modulated and square pulses from MPPW and SPPW lasers, respectively. The average power distribution over the entire modulated pulse duration, designated as average peak power (P_{peak}), is 3.6 kW, the same as the square pulse. Thus, for the pulse width of 280 ns, each pulse shape's calculated areas represent the energy of 1 mJ. These results match the calculations from Equations (2-9) ($E_{pulse} = P_{peak}P_{width}$) and (2-10) ($E_{pulse} = P_L/PRF$), both designated for square pulses but also applicable for modulated pulses in MPPW mode.

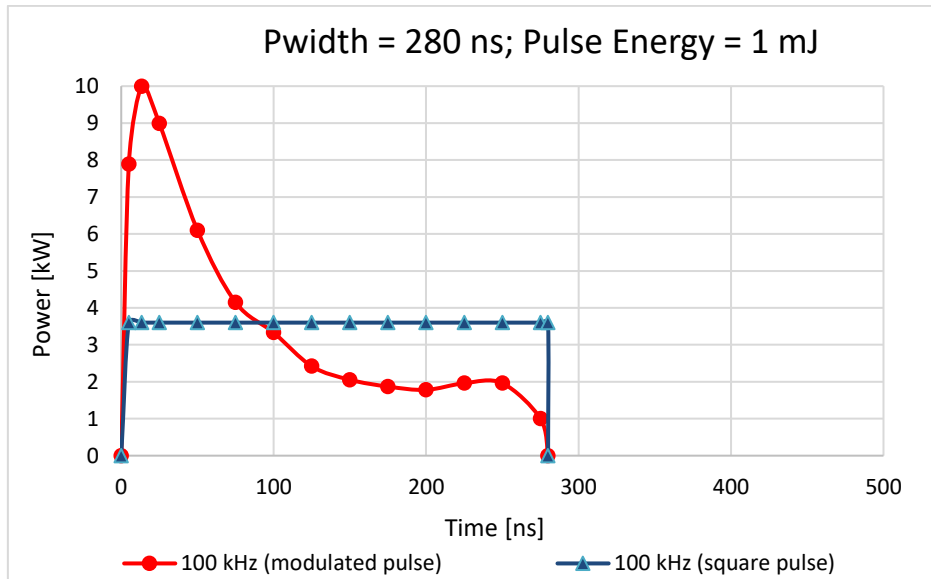


Figure 4-7 Modulated (MPPW laser) and square (SPPW laser) pulse shapes at a constant pulse width of 280 ns, pulse repetition frequency of 100 kHz, pulse energy of 1 mJ and average peak power of 3.6 kW.

Each waveform is unique, i.e., specific pulse duration, peak power, and pulse energy. Therefore, the laser has a different temporal response to the pulse duration and frequency selected. Figure 4-8 shows the pulse shapes of waveform 31 (pulse duration of 500 ns) at pulse repetition frequencies between 50 and 300 kHz. Similarly to waveform 0 (280 ns) in Figure 4-5, the peak power is constant until 100 kHz, reaching only 7 kW in Figure 4-8. Comparing the pulse shapes in Figure 4-5 and Figure 4-8, the peak reduction is more intense for the longest pulse of 500 ns, being the pulse shape almost rectangular at 300 kHz.

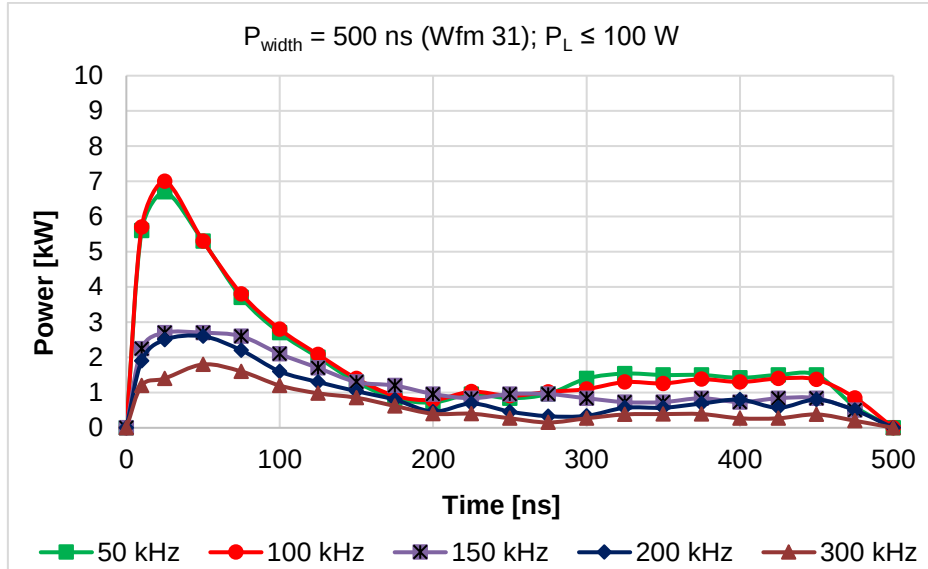


Figure 4-8 Pulse shapes of waveform 31 for different pulse repetition frequencies at a maximum average power of 100W.

The mapping of pulse energy (E_{pulse}) and average peak power (P_{peak}) for a pulse duration of 500 ns, at frequencies between 50 and 300 kHz, is shown in Figure 4-9. The maximum pulse energy of 1 mJ and average peak power of 2 kW are achieved until 100 kHz (PRF_0), decreasing after this value, which is according to Figure 4-1. Doubling the frequency to 200 kHz, the pulse energy is reduced to 0.5 mJ and the average peak power to 1 kW.

The E_{pulse} and P_{peak} calculated directly from the modulated pulse shapes match with the theoretical formulae for square pulses in Equations (2-9) and (2-10), which means they can be correctly applied in this process for any pulse duration and any pulse repetition frequency.

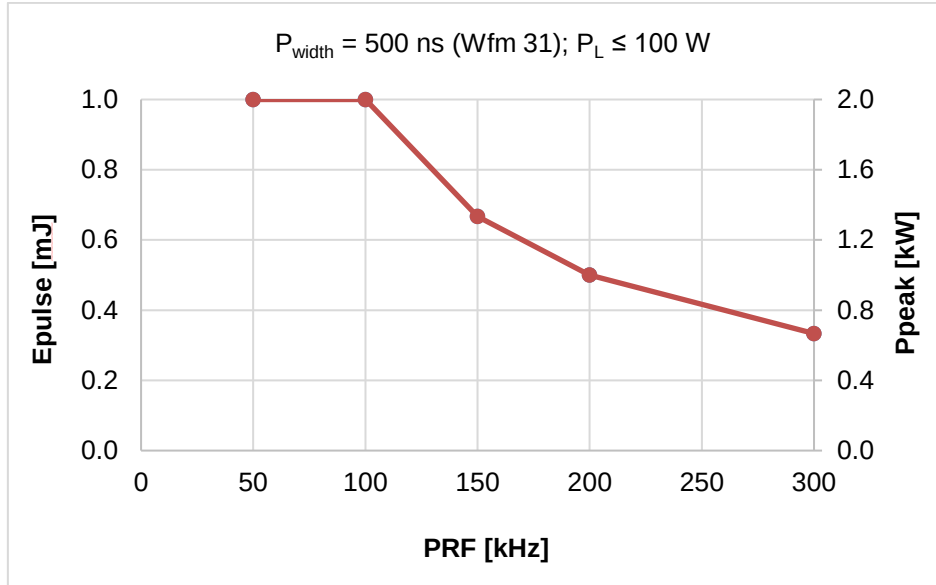


Figure 4-9 Pulse energy and average peak power of waveform 31 for different pulse repetition frequencies at a maximum average power of 100 W.

The average power is one of the system parameters which can be selected, allowing flexible control of the total energy delivered to the workpiece. The maximum pulse energy (1 mJ) can be achieved at a maximum average output power (100 W) and a PRF_0 of 100 kHz. The reference values of each pulse width are presented only according to this value, as shown in Table 4-1. However, the laser manufacturer doesn't supply any reference to other average output powers used in this laser and how it behaves at different frequencies [126].

According to Equation (2-10) ($E_{pulse} = P_L / PRF$), when the average power is reduced at a constant frequency, the pulse energy also decreases in the same ratio. Consequently, according to Equation (2-9) ($E_{pulse} = P_{peak} * P_{width}$), average peak power also decreases. Figure 4-10 shows the pulse shapes of waveform 31 for an average output power below 50 W. Peak power of 2 kW is achieved until 100 kHz, being the PRF_0 fixed and independent from the average power selected.

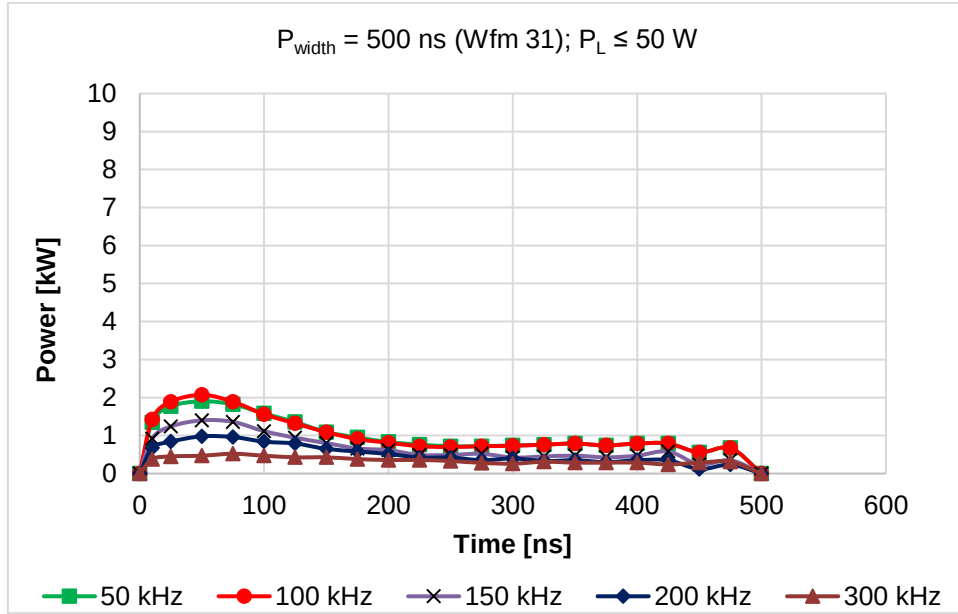


Figure 4-10 Pulse shapes of waveform 31 for different pulse repetition frequencies at a maximum average power of 50 W.

A new mapping of the pulse energy (E_{pulse}) and average peak power (P_{peak}) for a pulse duration of 500 ns at frequencies below and above PRF_0 and average output powers equal and below to 100 W is shown in Figure 4-11 and Figure 4-12, respectively.

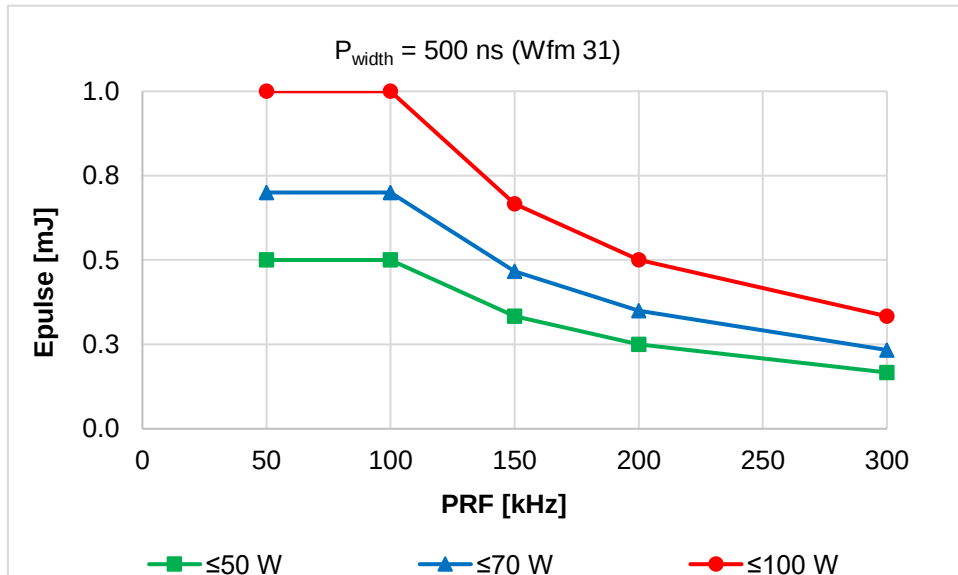


Figure 4-11 Pulse energies for a pulse width of 500 ns at pulse repetition frequencies between 50 and 300 kHz and maximum average powers of 50, 70 and 100 W.

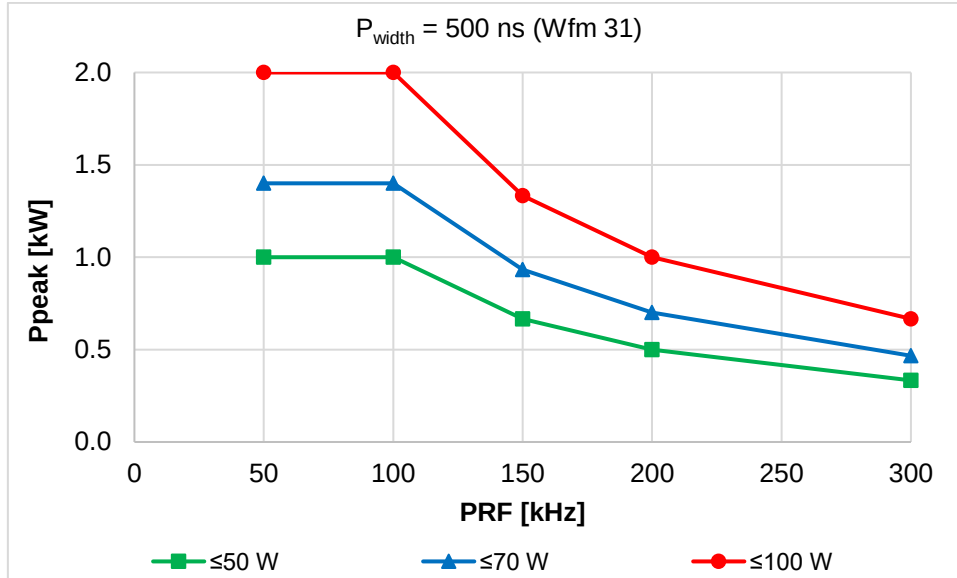


Figure 4-12 Average peak powers of a pulse width of 500 ns at pulse repetition frequencies between 50 and 300 kHz and maximum average powers of 50, 70 and 100 W.

The ratio of peak power by average peak power for similar frequencies and average powers in waveform 31 is shown in Figure 4-13. For an average power of 100W, the ratio decreases by 30% when the frequency increases from 100 to 200 kHz, stabilising after that as the pulse shape becomes almost square, as previously shown in Figure 4-8. On the other hand, for an average power of 50W, the ratio decreases only 5% for the same range of frequencies. This correlation highlights the importance of the average power of the MPPW laser to maximise the potential impact of the peak power on material vaporisation. However, this impact might be more relevant for a short range of frequencies close to PRF_0 . The peak power effect might not have any relevant effect for frequencies beyond PRF_0 and average powers below 100 W.

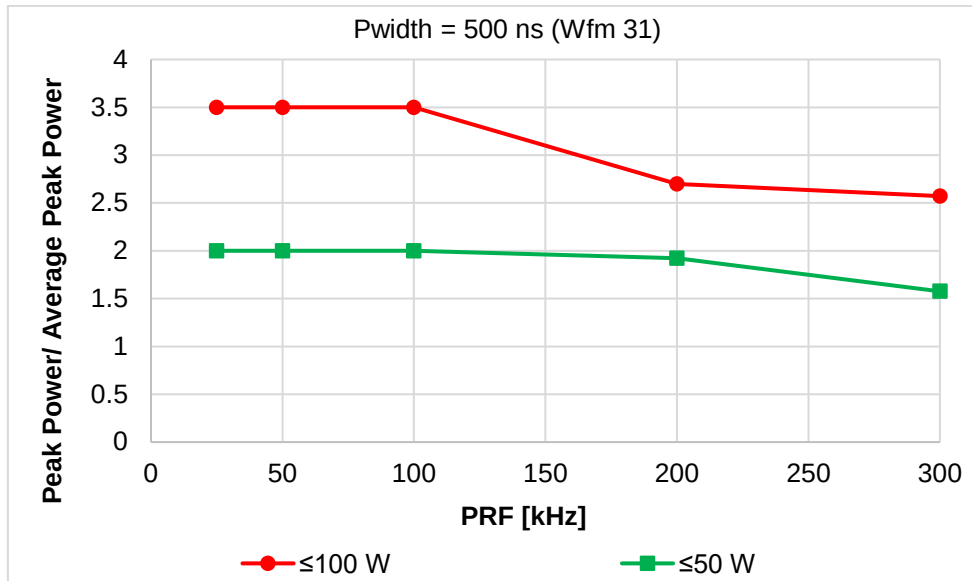


Figure 4-13 Ratio between the peak power and the average peak power for different pulse repetition frequencies at a maximum average power of 100 W and 50 W.

The trend lines of average peak power (P_{peak}) as a function of pulse energy (E_{pulse}) for different pulse widths at a constant average power of 100 W are plotted in Figure 4-14. It can be seen that a linear offset of average peak power between waveforms at constant pulse energies and pulse repetition frequencies, being on top the shortest and at the bottom the longest. Pulse energy can be changed by changing the pulse repetition frequency, as previously seen in Figure 4-10.

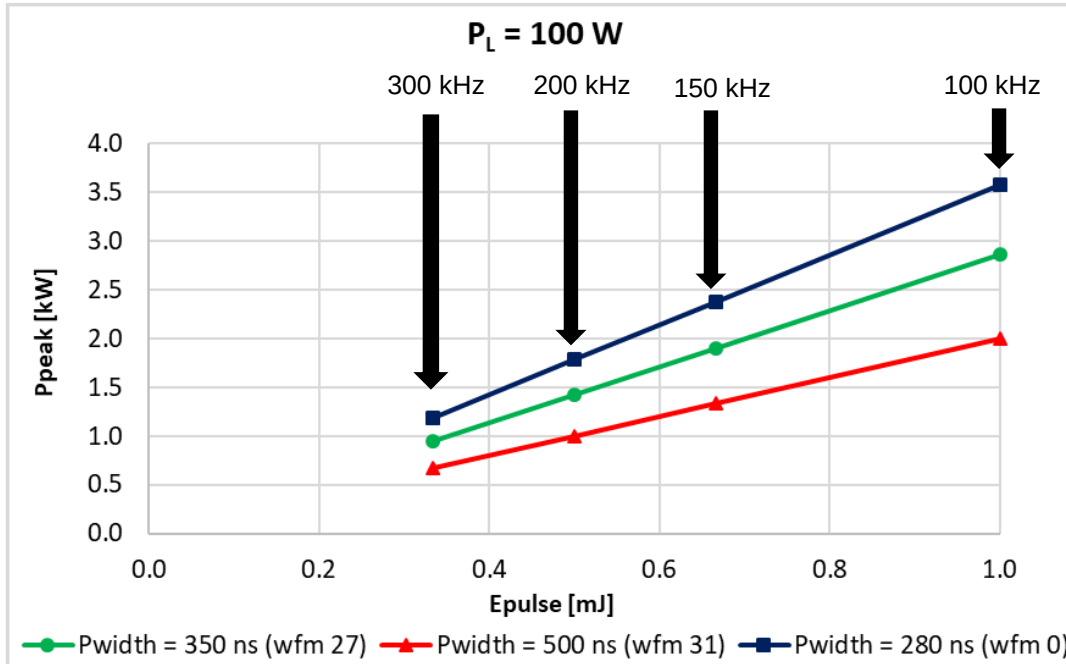


Figure 4-14 Average peak power (P_{Peak}) versus pulse energy (E_{Pulse}) for pulse widths of 280, 350 and 500 ns at a constant average power of 100 W.

4.3.2 Effect of average peak power density, specific point energy and interaction time on the weld shape

The laser-material interaction was analysed by correlating the weld geometry, i.e. depth of penetration and width, with system, calculated and fundamental laser-material interaction parameters (FLMIP). The definitions of the FLMIP in MPPW mode, i.e. average peak power density, specific point energy and interaction time, were tested to understand if they can individually control the welding process. The parameters used in this chapter are shown in Table 4-8 and Table 4-9 and correlated with the weld geometry of the micrographs shown in Figure 4-16 to Figure 4-19.

Table 4-8 System and calculated parameters and corresponding micrographs' number used for a beam diameter of 89 μm , a pulse width of 500 ns and average power of 100 W.

System Parameters						Calculated Parameters			
Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Duty cycle [%]	Overlap Factor [%]	Micrograph
d	P _{width}	P _L	v	PRF	E _{pulse}	P _{peak}	D _C	O _F	
89	500	100	445	100	1	2	5	95	4-1
89	500	100	890	200	0.5	1	10	95	-
89	500	100	1780	400	0.25	0.5	20	95	-
89	500	100	89	100	1	2	5	99	4-2
89	500	100	178	200	0.5	1	10	99	-
89	500	100	356	400	0.25	0.5	20	99	4-5
89	500	100	4.5	100	1	2	5	99.95	4-3
89	500	100	8.9	200	0.5	1	10	99.95	-
89	500	100	17.9	400	0.25	0.5	20	99.95	4-6
89	500	100	0.9	100	1	2	5	99.99	4-4
89	500	100	1.8	200	0.5	1	10	99.99	-
89	500	100	3.6	400	0.25	0.5	20	99.99	4-7
89	500	100	71	200	0.5	1	10	99.6	4-8
89	500	100	71	400	0.25	0.5	20	99.8	4-9

Table 4-9 System parameters, FLMIP and corresponding micrographs' number used for a beam diameter of 89 μm , a pulse width of 500 ns and average power of 100 W.

System Parameters						Fundamental Laser Material Interaction Parameters					
Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Average power density [MW/cm^2]	Average peak power density [MW/cm^2]	Specific point energy [mJ]	Interaction time [ms]	Micrograph
d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$	$t_{i, \text{MPPW}}$	
89	500	100	445	100	1	2	1.6	32	20	0.01	4-1
89	500	100	890	200	0.5	1	1.6	16	10	0.01	-
89	500	100	1780	400	0.25	0.5	1.6	8	5	0.01	-
89	500	100	89	100	1	2	1.6	32	100	0.05	4-2
89	500	100	178	200	0.5	1	1.6	16	50	0.05	-
89	500	100	356	400	0.25	0.5	1.6	8	25	0.05	4-5
89	500	100	4.5	100	1	2	1.6	32	2000	1	4-3
89	500	100	8.9	200	0.5	1	1.6	16	1000	1	-
89	500	100	17.9	400	0.25	0.5	1.6	8	500	1	4-6
89	500	100	0.9	100	1	2	1.6	32	10000	5	4-4
89	500	100	1.8	200	0.5	1	1.6	16	5000	5	-
89	500	100	3.6	400	0.25	0.5	1.6	8	2500	5	4-7
89	500	100	71	200	0.5	1	1.6	16	125	0.125	4-8
89	500	100	71	400	0.25	0.5	1.6	8	125	0.250	4-9

Figure 4-15 shows the effect of specific point energy ($E_{SP, MPPW}$) on penetration depth for constant average peak power densities ($q_{p, peak}$) at constant pulse width, beam diameter and average power.

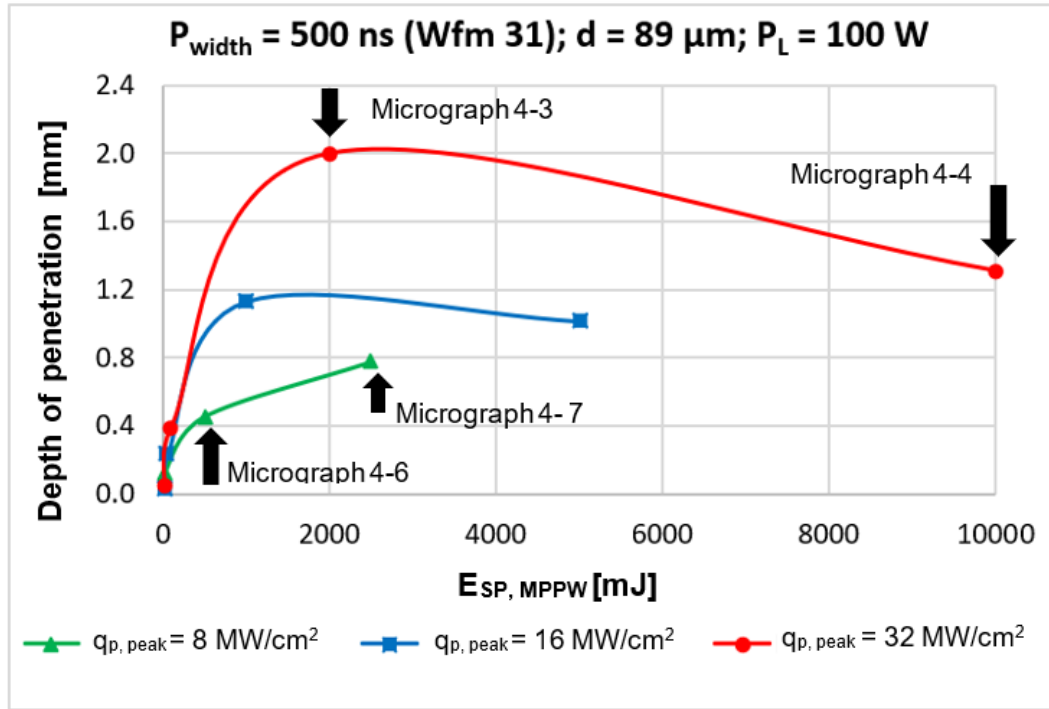


Figure 4-15 Effect of specific point energy ($E_{SP, MPPW}$) on the penetration depth for different average peak power density ($q_{p, peak}$) at a constant pulse duration of 500 ns, beam diameter of 89 μ m and average power of 100 W.

As shown in Figure 4-15, the penetration depth increases with $E_{SP, MPPW}$, dropping from a certain threshold. At constant $E_{SP, MPPW}$, higher penetrations are achieved at higher $q_{p, peak}$. According to Table 4-9, at constant $q_{p, peak}$, $E_{SP, MPPW}$ increases with interaction time. This is only possible by increasing the overlap between pulses, which happens by decreasing the travel speed at constant pulse repetition frequency, pulse duration and beam diameter, as shown in Table 4-8.

The micrographs from Figure 4-15 are shown in Figure 4-16 to Figure 4-19. In micrograph 4-1 from Figure 4-16, there is only ablation of the surface for low energy levels. Hence, when processing at low energy levels, using this material thickness or above, this laser cannot be used for welding or cutting, but only for marking. The difference in penetration depth is visible by increasing the specific point energy at constant average peak power density from micrograph 4-1 to 4-

2. Due to an increase of overlap between pulses at a constant frequency and beam diameter, the travel speed decreased 5x, from 445 to 89 mm/s. Consequently, the number of pulses applied per unit length and the laser-material interaction time increase in the same proportion. As the laser irradiation time rises 5x, from 0.01 to 0.05 ms, the total energy applied to the metal increases in the same ratio, from 20 to 100 mJ. Thus, the heat transfer rate from the hot surface to the cold bottom is much higher, enough to build up the temperature of the material to such a level where a keyhole is formed.

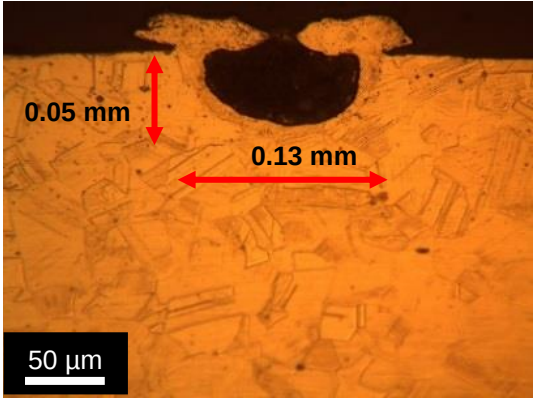
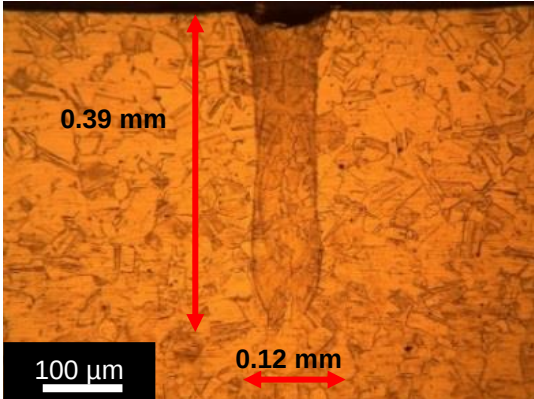
$P_{width} = 500 \text{ ns}$ (Wfm 31); $d = 89 \text{ }\mu\text{m}$; $P_L = 100 \text{ W}$; $DC = 5\%$	
Micrograph 4-1	Micrograph 4-2
$E_{SP, MPPW} = 20 \text{ mJ}$; $q_{p, peak} = 32 \text{ MW/cm}^2$	$E_{SP, MPPW} = 100 \text{ mJ}$; $q_{p, peak} = 32 \text{ MW/cm}^2$
$t_{i, MPPW} = 0.01 \text{ ms}$	$t_{i, MPPW} = 0.05 \text{ ms}$
	
Depth = 0.05 mm; Width = 0.13 mm	Depth = 0.39 mm; Width = 0.12 mm

Figure 4-16 Micrographs of bead-on-plate welds achieved at different specific point energies, a similar average peak power density of 32 MW/cm^2 , pulse duration of 500 ns, beam diameter of $89 \text{ }\mu\text{m}$ and average power of 100 W.

The penetration depth increased from micrograph 4-2 in Figure 4-16 to micrograph 4-3 in Figure 4-17 by increasing the specific point energy at constant average peak power density. After that, the penetration drops, as seen in micrograph 4-4. This can be explained by laser absorption of the intense plasma generated from the metal when irradiated at a high energy level [128]. At the highest energy of 10000 mJ in micrograph 4-4, the weld metal area is 0.32 mm^2 , much higher in comparison to the other micrographs. In this situation, the recoil pressure exerted at the bottom of the keyhole is high, and the capacity to eject

metal from the cavity is reduced [128]. Hence, the molten metal gets entrapped, allowing lateral heat losses, enlarging the width of the melt pool, reducing its depth and increasing the overall weld metal area. For that reason, no matter how much the energy is increased by increasing the interaction time through the overlap between pulses, if the average peak power density remains constant, the penetration depth won't increase anymore from a certain threshold, but only the weld width gets larger. Thus, in MPPW mode, it is necessary to have a trade-off between $E_{SP, MPPW}$ and $q_{p, peak}$ to have enough material vaporisation and guarantee a certain penetration depth.

From Figure 4-17 to Figure 4-18, the $E_{SP, MPPW}$ and $q_{p, peak}$ were reduced. Despite the increase in $E_{SP, MPPW}$ at constant $q_{p, peak}$ from micrographs 4-5 to 4-7 in Figure 4-18, it is not visible any drop in the penetration depth. The average peak power density applied is not high enough to create intense vaporisation and, consequently, high aspect ratio welds. An increase in applied energy leads to higher inter-pulse thermal losses, an enlargement of the weld pool, and a marginal increase in penetration depth, but for higher energy levels, the penetration depth would have eventually dropped. This is an explicit limitation of the FLMIP as it would be expected much higher penetration as the applied energy increases significantly, as previously shown in Figure 4-15.

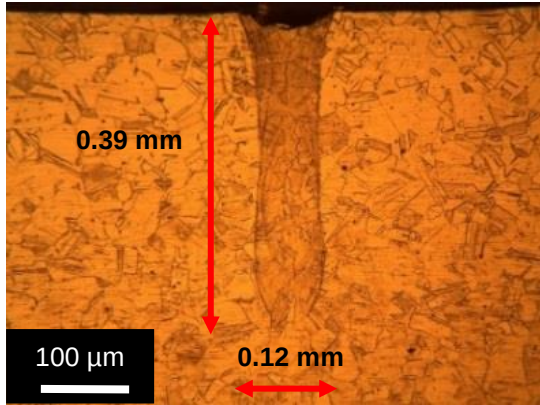
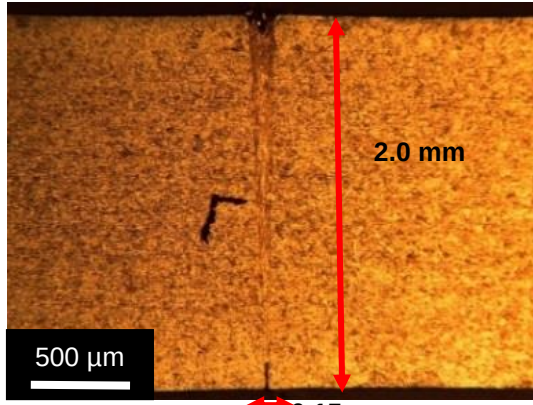
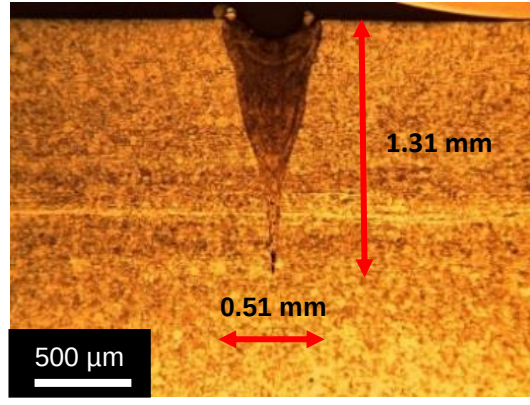
$P_{width} = 500 \text{ ns (Wfm 31)}; d = 89 \mu\text{m}; P_L = 100 \text{ W}; D_c = 5\%$		
Micrograph 4-2	Micrograph 4-3	Micrograph 4-4
$E_{SP, MPPW} = 100 \text{ mJ}; q_{p, peak} = 32 \text{ MW/cm}^2$	$E_{SP, MPPW} = 2000 \text{ mJ}; q_{p, peak} = 32 \text{ MW/cm}^2$	$E_{SP, MPPW} = 10000 \text{ mJ}; q_{p, peak} = 32 \text{ MW/cm}^2$
$t_{i, MPPW} = 0.05 \text{ ms}$	$t_{i, MPPW} = 1 \text{ ms}$	$t_{i, MPPW} = 5 \text{ ms}$
		
Depth = 0.39 mm; Width = 0.12 mm	Depth = 2.0 mm; Width = 0.15 mm	Depth = 1.31 mm; Width = 0.51 mm
Weld metal area: 0.045 mm^2	Weld metal area: 0.14 mm^2	Weld metal area: 0.32 mm^2

Figure 4-17 Micrographs of bead-on-plate welds achieved at different specific point energies, a constant average peak power density of 32 MW/cm^2 , pulse duration of 500 ns, beam diameter of $89 \mu\text{m}$ and average power of 100 W.

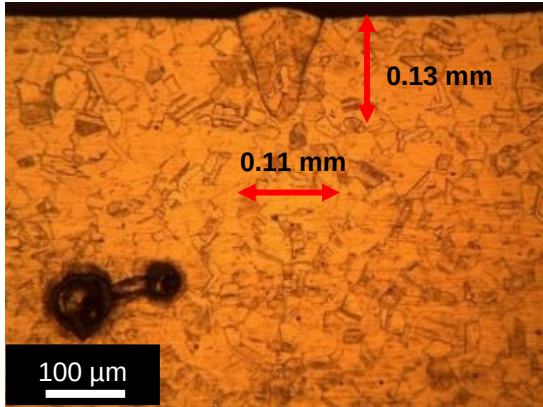
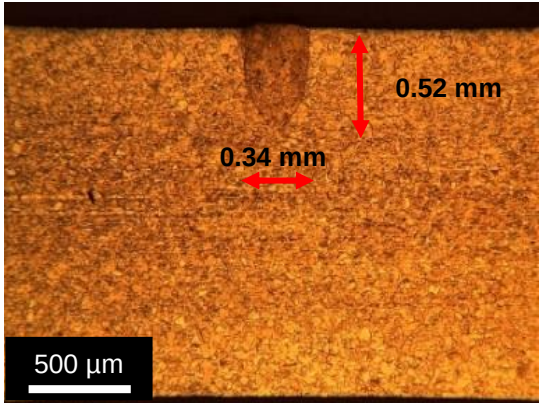
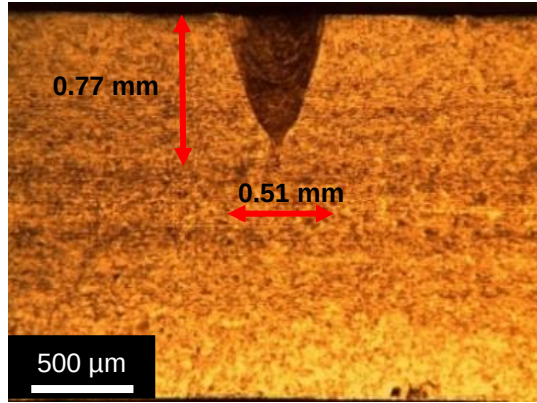
P_{width} = 500 ns (Wfm 31); d = 89 μm; P_L = 100 W; D_c = 20%		
Micrograph 4-5	Micrograph 4-6	Micrograph 4-7
E _{SP, MPPW} = 25 mJ; q _{p, peak} = 8 MW/cm ²	E _{SP, MPPW} = 500 mJ; q _{p, peak} = 8 MW/cm ²	E _{SP, MPPW} = 2500 mJ; q _{p, peak} = 8 MW/cm ²
t _{i, MPPW} = 0.05 ms	t _{i, MPPW} = 1 ms	t _{i, MPPW} = 5 ms
		
Depth = 0.13 mm; Width = 0.11 mm	Depth = 0.52 mm; Width = 0.34 mm	Depth = 0.77 mm; Width = 0.51 mm
Weld metal area: 0.0091 mm ²	Weld metal area: 0.16 mm ²	Weld metal area: 0.19 mm ²

Figure 4-18 Micrographs of bead-on-plate welds achieved at different specific pulse energies, a similar average peak power density of 8 MW/cm², pulse duration of 500 ns, beam diameter of 89 μm and average power of 100 W.

In Figure 4-19, micrographs 4-8 and 4-9 were achieved at similar applied energy and different average peak power densities. From micrograph 4-8 to 4-9, the pulse repetition frequency increased 2x and consequently, E_{pulse} and P_{peak} were reduced to half (Table 4-8). As the frequency was doubled at constant travel speed and beam diameter, the overlap between pulses increased, doubling the interaction time from 0.125 ms to 0.250 ms. By doubling the interaction time and halving the average peak power density from 16 MW/cm² to 8 MW/cm², a constant $E_{SP, MPPW}$ of 125 mJ was possible to be obtained in both cases. Nevertheless, the penetration depth decreased from micrographs 4-8 and 4-9, as the inter-pulse thermal losses created by the reduction in $q_{p, peak}$, cannot be compensated by an increase in the duty cycle in the same proportion. From Figure 4-19 can be concluded that $q_{p, peak}$ is the second FLMP responsible for controlling the penetration in MPPW micro seam welding. A schematic of this explanation is depicted in Figure 4-20.

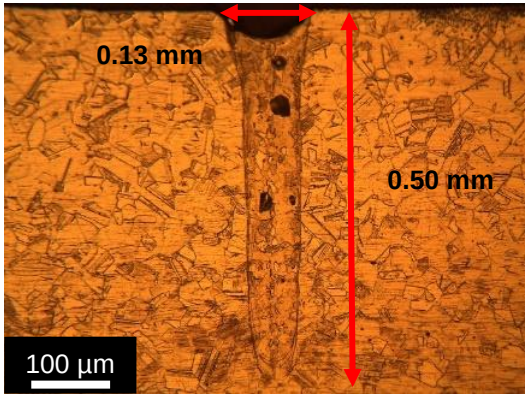
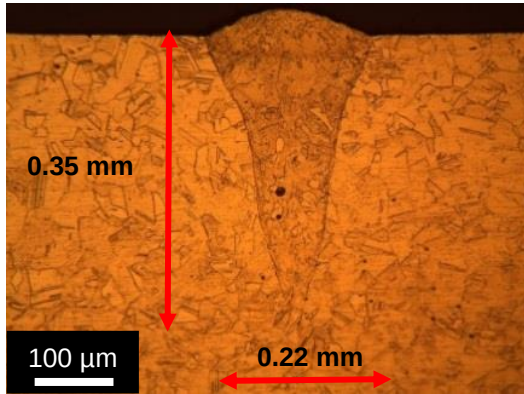
$P_{width} = 500 \text{ ns (Wfm 31)}; d = 89 \text{ } \mu\text{m}; v = 71 \text{ mm/s } P_L = 100 \text{ W}$	
Micrograph 4-8	Micrograph 4-9
$E_{SP, MPPW} = 125 \text{ mJ}; \text{Peak } q_p = 16 \text{ MW/cm}^2$	$E_{SP, MPPW} = 125 \text{ mJ}; \text{Peak } q_p = 8 \text{ MW/cm}^2$
$t_{i, MPPW} = 0.125 \text{ ms}; D_C = 10\%$	$t_{i, MPPW} = 0.250 \text{ ms}; D_C = 20\%$
	
Depth = 0.5 mm; Width = 0.13 mm	Depth = 0.35 mm; Width = 0.22 mm
Weld metal area: 0.062 mm ²	Weld metal area: 0.069 mm ²

Figure 4-19 Micrographs of bead-on-plate welds achieved at different average peak power densities, similar specific point energy of 125 mJ, pulse duration of 500 ns, beam diameter of 89 μm and average power of 100 W.

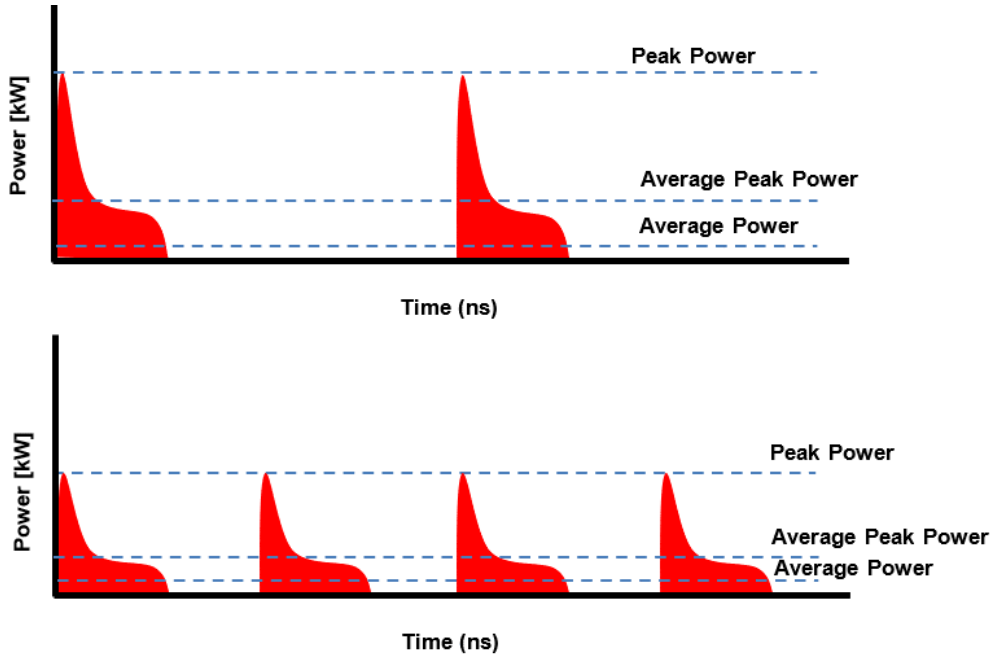


Figure 4-20 Temporal output of an MPPW laser at a constant pulse width, different duty cycles, pulse energies and average peak powers.

The effect of specific point energy ($E_{SP, MPPW}$) on the weld width for different levels of average peak power density ($q_{p, peak}$) is plotted in Figure 4-21. For constant $q_{p, peak}$, the weld width increases with $E_{SP, MPPW}$ due to an increase in interaction time through the overlap factor (Table 4-8 and Table 4-9). However, at constant $E_{SP, MPPW}$, larger widths are observed for lower $q_{p, peak}$ due to an increase of interaction time through the pulse repetition frequency (PRF). In addition to this, the weld width remains constant, independently of the $E_{SP, MPPW}$ and $q_{p, peak}$, as long as the interaction time ($t_{i, MPPW}$) remains constant, as observed in the micrographs 4-4 and 4-7 from Figure 4-17 and Figure 4-18, respectively. This means that in MPPW mode, similarly to CW mode [44], interaction time is the FLMIP responsible for controlling the weld width. However, there is a critical value of $E_{SP, MPPW}$ for a certain $q_{p, peak}$ above which the heat losses are much higher, and $t_{i, MPPW}$ cannot control the weld width anymore. As observed in micrographs 4-6 and 4-3 from Figure 4-18 and Figure 4-17, respectively, even though the interaction time is 1 ms in both cases, the weld width is much narrower in micrograph 4-3.

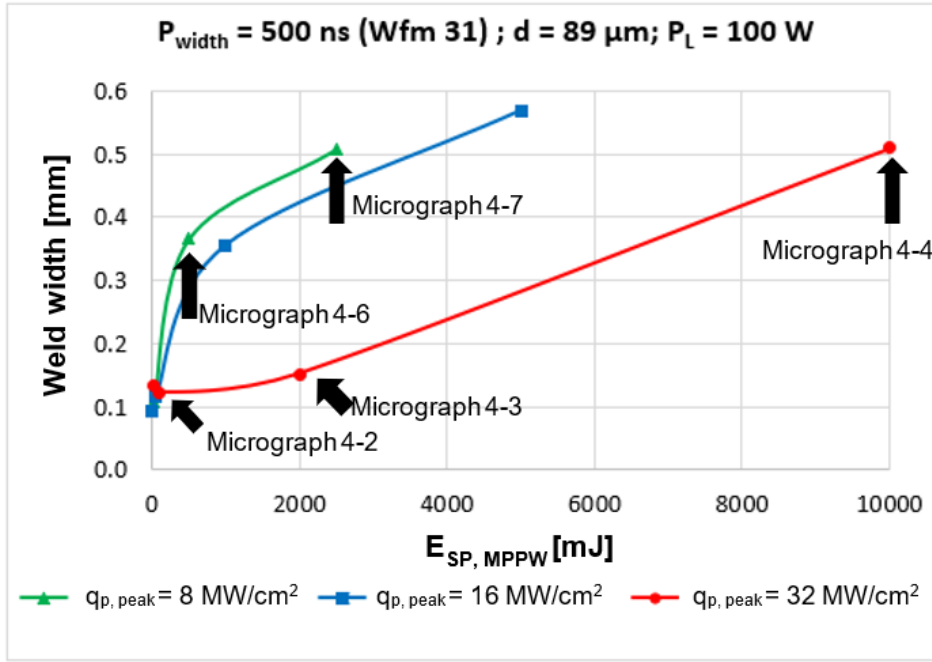


Figure 4-21 Effect of specific pulse energy on the weld width for different average peak power density levels and constant pulse width of 500 ns, beam diameter of 89 μm and average power of 100 W.

In Figure 4-15 and Figure 4-21, there is a trade-off between penetration depth and weld width. At constant $E_{SP, MPPW}$, a higher penetration can be achieved at higher $q_{p, peak}$, but narrow weld widths are obtained. On the other hand, lower penetrations and wider widths can be reached at similar $E_{SP, MPPW}$ and lower $q_{p, peak}$. As per Equation (2-12), interaction time depends on the overlap factor and pulse width. However, as per Equation (2-11), the overlap factor depends on pulse repetition frequency (PRF), beam diameter (d) and travel speed (v). Both the PRF and pulse width control the laser's duty cycle ($D_C = PRF \times P_{width}$). In contrast, the ratio between the beam diameter and travel speed defines the interaction time in CW mode ($t_{i, CW}$), according to Equation (2-4). Thus, the definition of interaction in MPPW mode can be simplified by the product of the duty cycle and the standard definition of interaction time in CW mode, as given by Equation (4-14). As shown in Table 4-10, this allows a direct comparison between both modes, assuming the duty cycle in CW mode is always 100%.

$$t_{i, MPPW} = [P_{width} * (1 - O_F/100)] = (D_C * d/100v) [ms] \quad (4-14)$$

Table 4-10 Laser-material interaction times in MPPW and CW laser modes.

Pulse width [ns]	Beam diameter [μm]	Travel speed [mm/s]	Frequency [kHz]	Duty cycle in MPPW [%]	Overlap Factor [%]	Interaction time in MPPW mode [ms]	Interaction time in CW mode [ms]	Micrograph
P_{width}	d	v	PRF	D_c	O_F	$t_{i, MPPW} = P_{width}(1 - O_F/100) = D_c(d/100v)$	$t_{i, CW} = D_c(d/100v)$	-
500	89	445	100	5	95.0	0.01	0.2	4-1
500	89	89	100	5	99.0	0.05	1	4-2
500	89	356	400	2	99.0	0.05	0.25	4-5
500	89	4.5	100	5	99.95	1	20	4-3
500	89	17.9	400	20	99.95	1	5	4-6
500	89	0.9	100	5	99.99	5	100	4-4
500	89	3.6	400	20	99.99	5	100	4-7
500	89	71	200	10	99.60	0.125	1.25	4-8
500	89	71	400	20	99.80	0.250	1.25	4-9

4.3.3 Effect of the duty cycle on the weld shape

The previous section concluded that the interaction time depends on the laser's duty cycle. However, it was impossible to study the individual effect of the duty cycle on the weld profile since the specific point energy and average peak power density were not kept constant.

In this section, the laser's duty cycle was investigated by changing the frequency at a constant pulse duration, keeping the applied energies and average peak powers unchanged. The laser-material interaction was analysed by correlating the weld geometry, i.e. depth of penetration and width, with system, calculated and fundamental laser-material interaction parameters (FLMIP). The parameters used in this chapter are shown in Table 4-11 and Table 4-12, and correlated with the micrographs in Figure 4-22.

Table 4-11 Calculated parameters and corresponding system parameters and micrographs' number used for a beam diameter of 35 μm , pulse duration of 500 ns and different average powers.

Calculated parameters		System parameters							
Duty cycle [%]	Overlap factor [%]	Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Micrograph
D_c	O_F	d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}	-
1.25	99.5	35	500	25	4.4	25	1	2	4-10
2.5	99.5	35	500	50	8.8	50	1	2	4-11
5	99.5	35	500	100	17.6	100	1	2	4-12

Table 4-12 Calculated parameters and corresponding FLMIP used for a beam diameter of 35 μm , pulse duration of 500 ns and different average powers.

Calculated parameters		Fundamental laser material interaction parameters				
Duty cycle [%]	Overlap factor [%]	Power density [MW/cm^2]	Average peak power density [MW/cm^2]	Specific point energy [mJ]	Interaction time [ms]	Micrograph
D_c	O_F	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$	$t_{i, \text{MPPW}}$	-
1.25	99.5	2.6	208	200	0.1	4-10
2.5	99.5	5.2	208	200	0.1	4-11
5	99.5	10.4	208	200	0.1	4-12

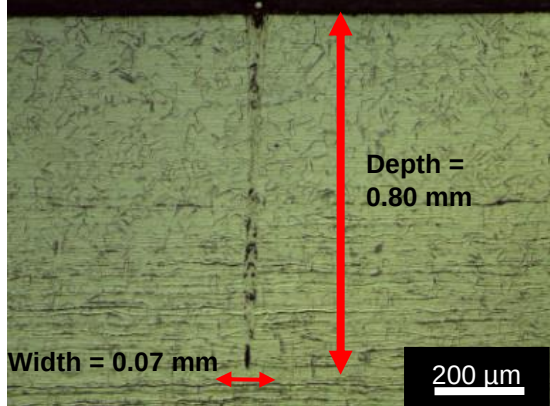
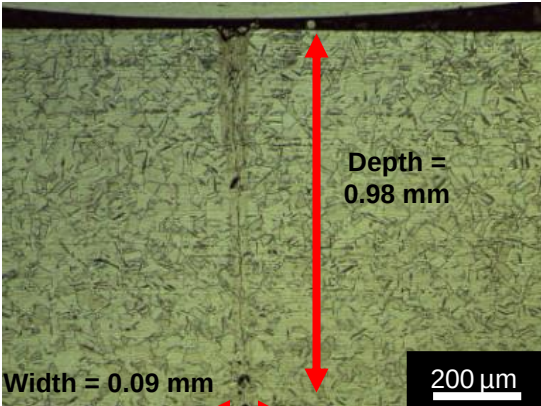
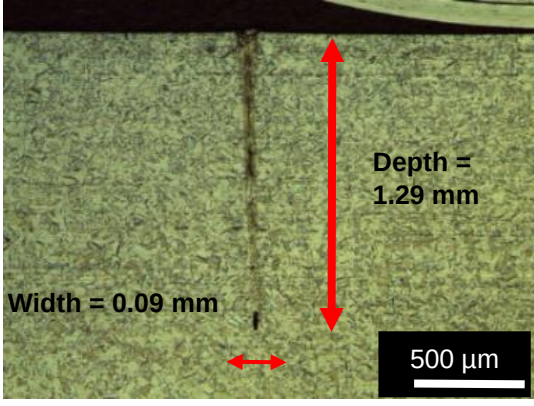
P_{width} = 500 ns (Wfm 31); d = 35 μm; t_{i, MPPW} = 0.1 ms		
Micrograph 4-10	Micrograph 4-11	Micrograph 4-12
D _c = 1.25%; q _p = 2.6 MW/cm ²	D _c = 2.5%; q _p = 5.2 MW/cm ²	D _c = 5%; q _p = 10.4 MW/cm ²
E _{SP, MPPW} = 200 mJ; q _{p, peak} = 208 MW/cm ²	E _{SP, MPPW} = 200 mJ; q _{p, peak} = 208 MW/cm ²	E _{SP, MPWW} = 200 mJ; q _{p, peak} = 208 MW/cm ²
		
Depth = 0.8 mm; Width = 0.07 mm	Depth = 0.98 mm; Width = 0.09 mm	Depth = 1.29 mm; Width = 0.09 mm
Weld metal area: 0.051 mm ²	Weld metal area: 0.091 mm ²	Weld metal area: 0.11 mm ²

Figure 4-22 Micrographs of bead-on-plate welds made at different duty cycles and average power densities, a constant pulse width of 500 ns, beam diameter of 35 μm and interaction time of 0.1 ms.

From micrographs 4-10 to 4-12 in Figure 4-22, the duty cycle has been increased from 2.5% to 5% at constant pulse energy and average peak power by increasing the average power and pulse repetition frequency in the same ratio (Table 4-11). The overlap between pulses has been kept constant by increasing the frequency and travel speed in the same proportion (Table 4-11). Consequently, the average power density (q_p) has been increased from 1.25 to 10.4 MW/cm² at constant E_{SP} , $MPPW$ of 200 mJ and $q_{p, peak}$ of 208 MW/cm² (Table 4-12).

As depicted in Figure 4-23, by doubling the duty cycle at constant pulse energy and average peak power, the inter-pulse spacing decreases 2x, and the average power increases in the same proportion. Therefore, for constant E_{SP} , $MPPW$ and $q_{p, peak}$, by increasing the duty cycle, the thermal losses between pulses are lower, leading to an increase in penetration depth and the overall melting efficiency as well, as observed in micrographs 4-10 to 4-12 from Figure 4-22. In the same micrographs, it can also be seen that for a constant interaction time of 0.1 ms, the weld width remains almost unchanged, which shows once again that for high aspect ratio welds, the lateral heat losses are low.

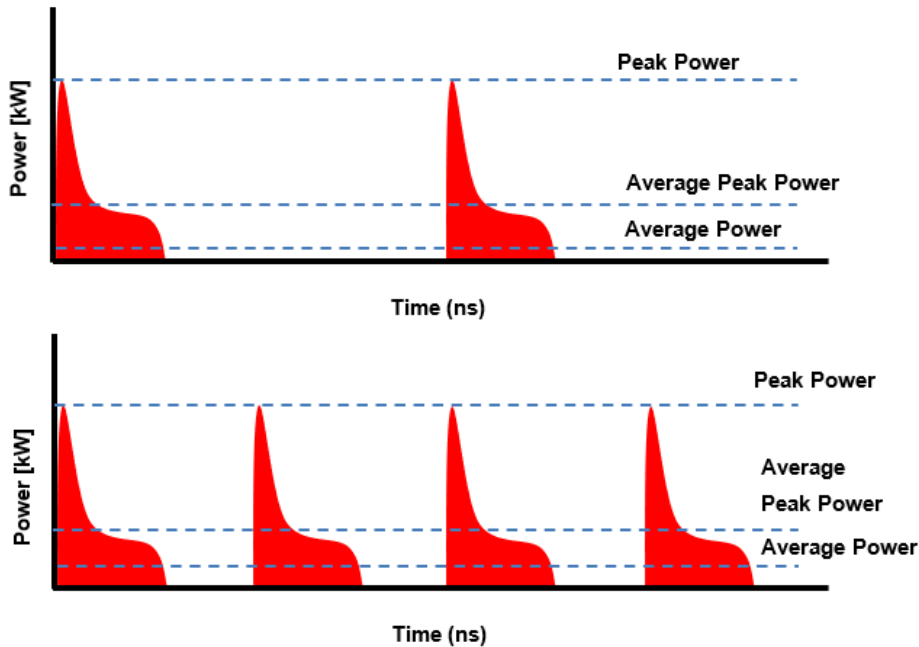


Figure 4-23 Temporal output of an MPPW laser at different duty cycles, constant pulse energy and average peak power.

The duty cycle plays an essential role in determining penetration depth when other conditions remain constant. However, as observed in Figure 4-17 and Figure 4-18 in the previous section, an increase in the duty cycle at constant average power density doesn't contribute to the rise in the penetration depth. Therefore, it can be concluded that the average power density independently controls the depth of penetration in MPPW micro seam welding.

The observations in Figure 4-22 can also be explained by a simple thermal model that describes the heat accumulation between pulses at different laser duty cycles from Figure 4-24 to Figure 4-29. As the MPPW laser utilises high overlap factors and pulse repetition frequencies, this thermal model considers a stationary laser beam to understand how many pulses are needed to melt $9.6 \times 10^{-5} \text{ mm}^3$ of metal, which corresponds to the area of the laser spot multiplied by a point 0.1 mm below the surface ($V = A_s \cdot z$). The absorptivity (A) of stainless steel of 0.65 to the MPPW laser wavelength of $1 \text{ } \mu\text{m}$ [127] is also taken in consideration in this analysis. Figure 4-24 shows the material thermal cycle irradiated by a $35 \text{ } \mu\text{m}$ spot size at an average power of 25 W and a laser duty cycle of 1.25%. Between pulses, the material volume of $9.6 \times 10^{-5} \text{ mm}^3$ decreases 3.9 K, and when the next pulse arrives, it increases 26.1 K, being dissipated 0.17 W by thermal conduction losses. When 20 pulses are applied, the temperature builds up above 493 K, still far from the melting point of stainless steel of 1723 K (Table 3-4 from section 3.1).

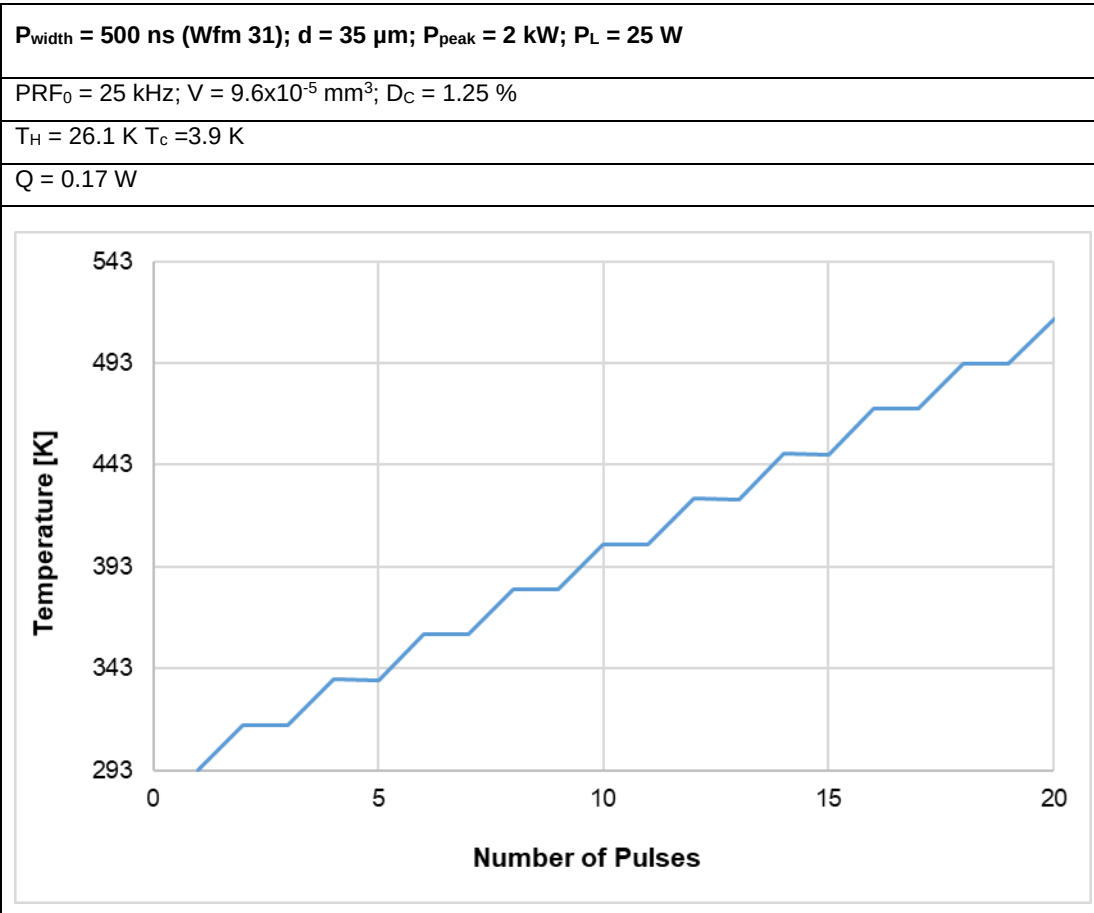


Figure 4-24 Thermal profile of a volume of metal when irradiated by 20 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 25 kHz and DC of 1.25%.

Figure 4-24 is repeated in Figure 4-25, but 146 pulses were applied on the same volume of metal with the same processing parameters. As shown in Figure 4-25, it's necessary 135 pulses to reach the melting temperature of 1723 K. The laser parameters used are also similar to the ones in micrograph 4-10 from Figure 4-22. In micrograph 4-10, for a travel speed of 4.4 mm/s and a PRF of 25 kHz, 199 pulses are emitted to irradiate the area of the laser spot and initiate melting. Therefore, this theoretical model is a good approximation to the experimental results.

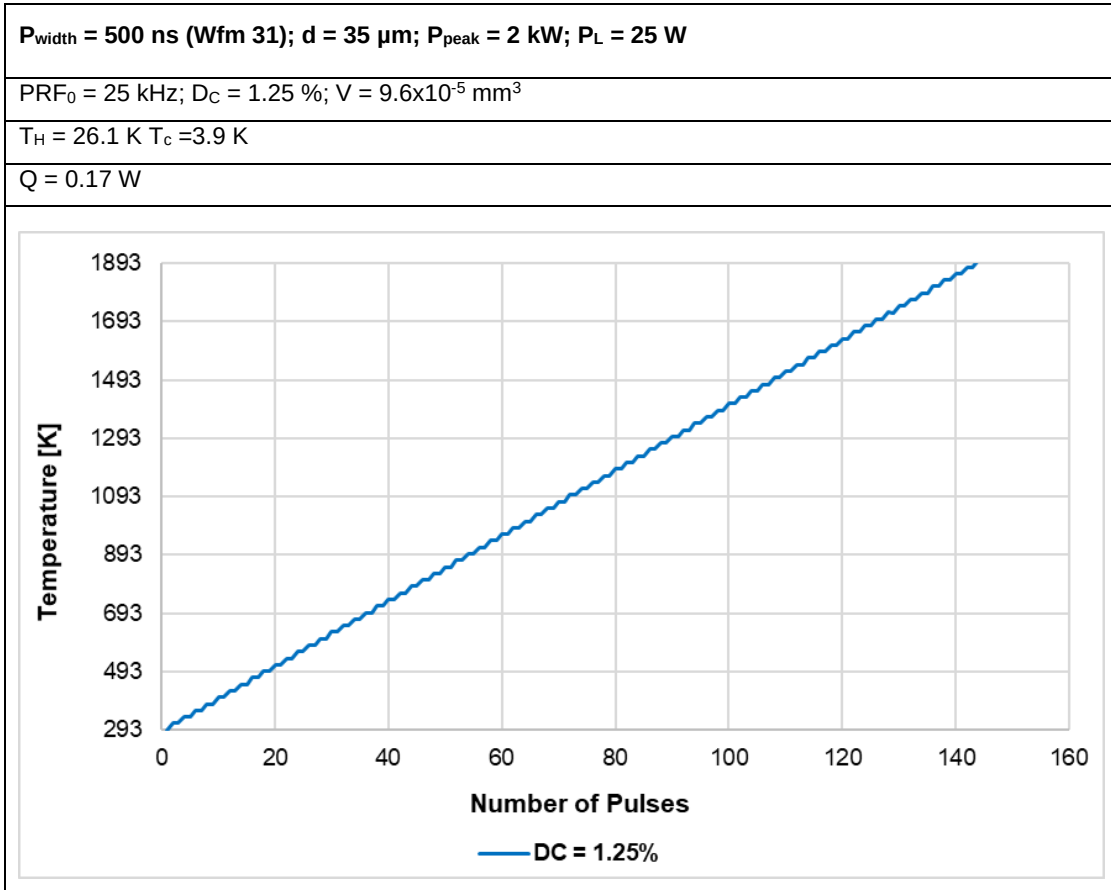


Figure 4-25 Thermal profile of a volume of metal when irradiated by 146 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 25 kHz and DC of 1.25%.

Increasing the average power to 50 W and the laser duty cycle to 2.5% in Figure 4-26, the maximum temperature between pulses (T_H) is higher in comparison to Figure 4-25. Consequently, the same temperature of 493K is reached with half the number of pulses. As the thermal gradient is higher, the power dissipated between pulses increases, but the energy accumulates much faster, being necessary half the pulses to reach the melting temperature, as shown in Figure 4-26. The processing parameters from Figure 4-25 and Figure 4-26 are similar to the ones to achieve micrograph 4-11 from Figure 4-22. In micrograph 4-11, the penetration depth increased in comparison to micrograph 4-10, as expected. Although the interaction time is similar in both cases (0.1 ms), the laser's duty cycle doubled from 1.25 to 2.5%. Therefore, the higher heat accumulation between pulses is reflected by an increase of the average power density from 2.6 MW/cm^2 to 5.2 MW/cm^2 , which is captured by this thermal model.

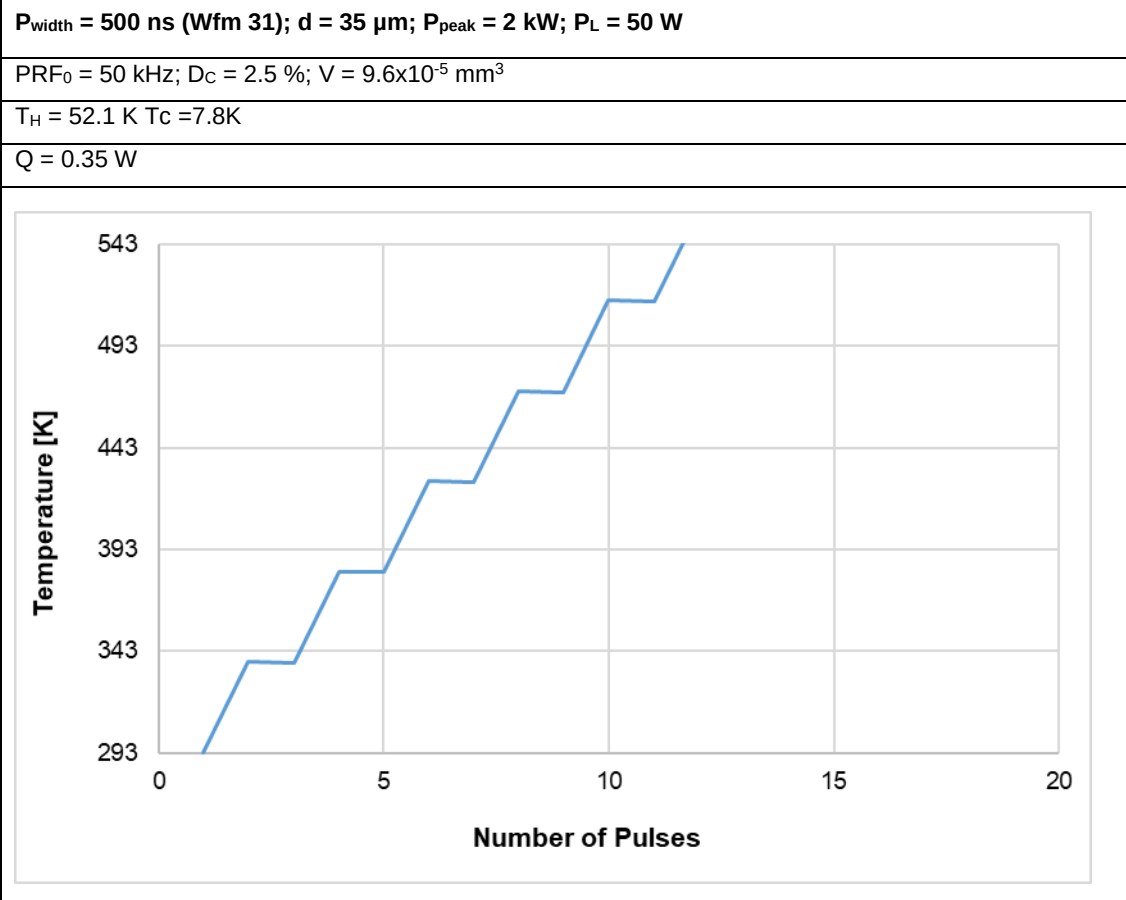


Figure 4-26 Thermal profile of a volume of metal when irradiated by 12 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 50 kHz and DC of 2.5%.

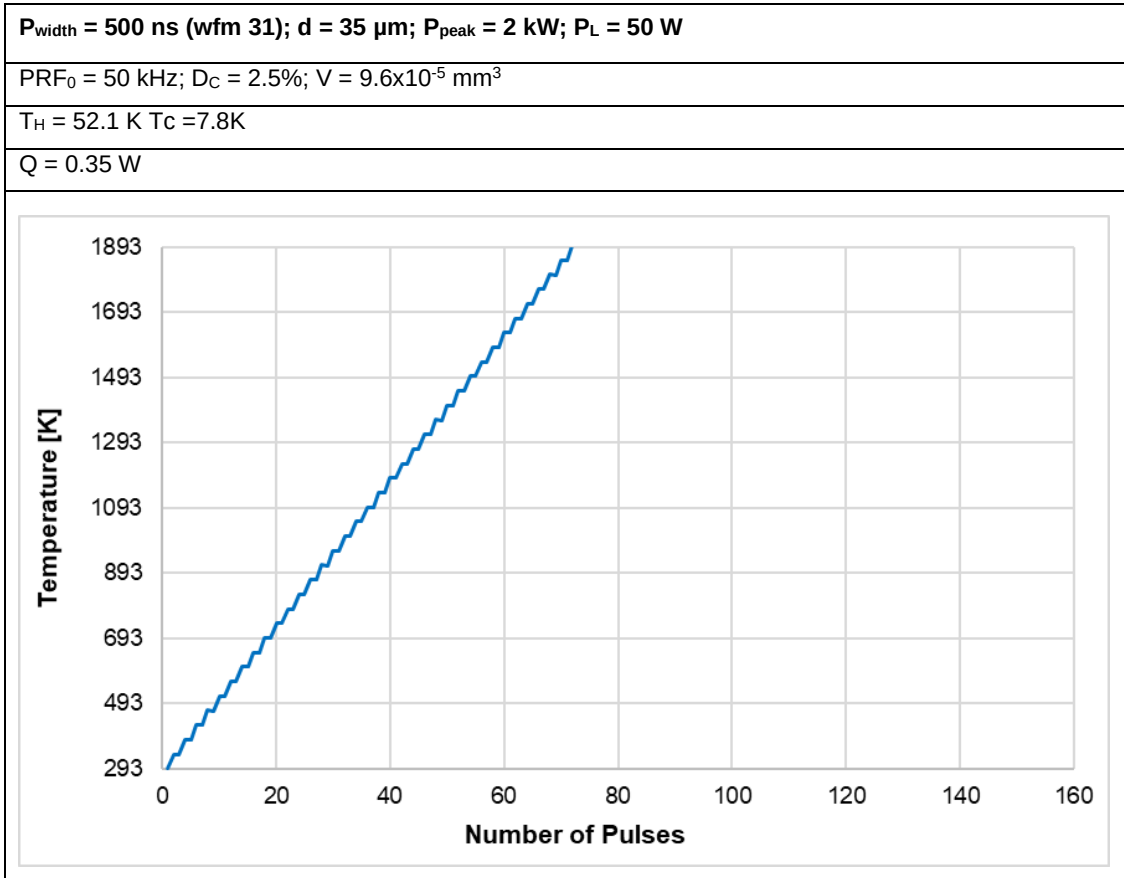


Figure 4-27 Thermal profile of a volume of metal when irradiated by 73 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 50 kHz and DC of 2.5%.

The average power of 100 W has been used at 100 kHz in Figure 4-28 and Figure 4-29. In Figure 4-28, the temperature of 493 K is reached with only 6 pulses, and in Figure 4-29 the melting temperature is reached with 35 pulses. The period between pulses is now $1 \times 10^{-5} \text{ s}$, allowing lower inter-pulse thermal losses and a higher heat accumulation, as shown in micrograph 4-12 from Figure 4-22 for the same processing parameters. A penetration depth of 1.29 mm has been achieved, which is 0.31 mm deeper than in micrograph 4-11.

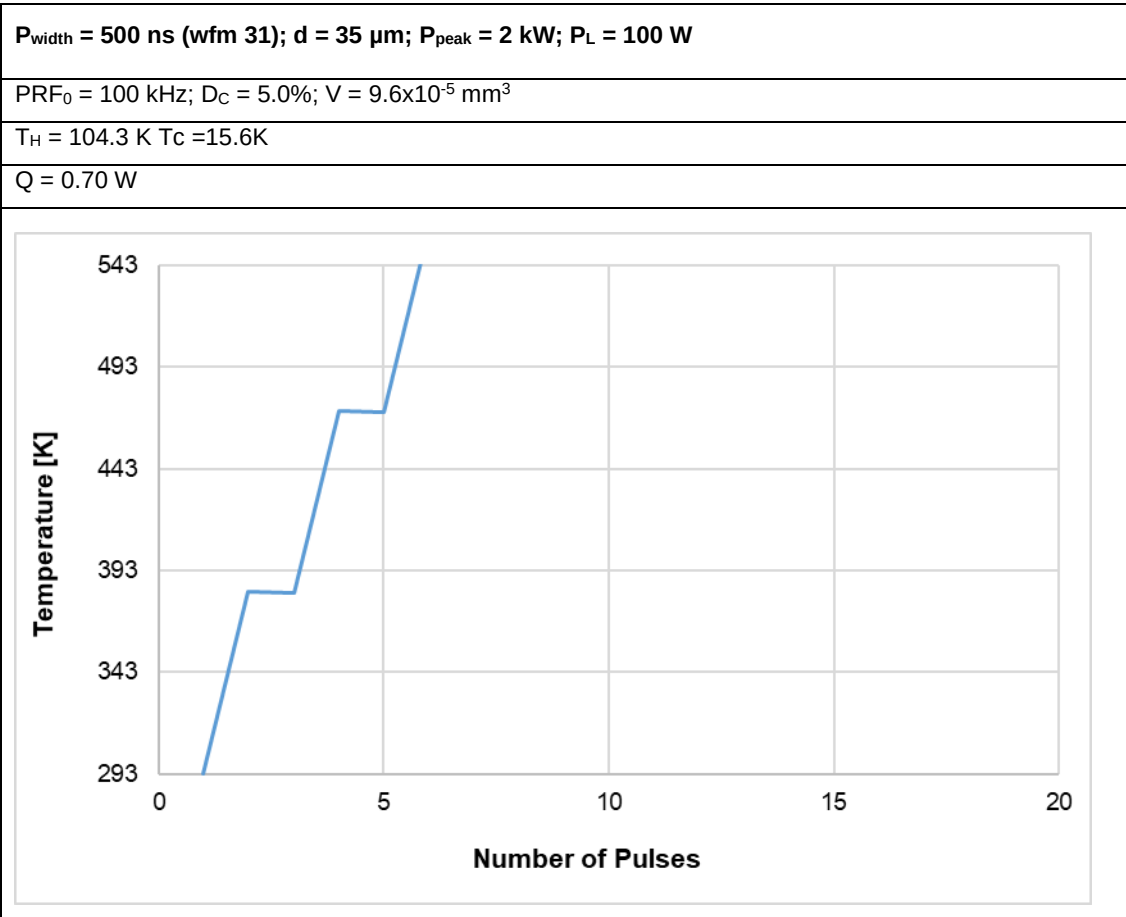


Figure 4-28 Thermal profile of a volume of metal when irradiated by 6 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 100 kHz and DC of 5%.

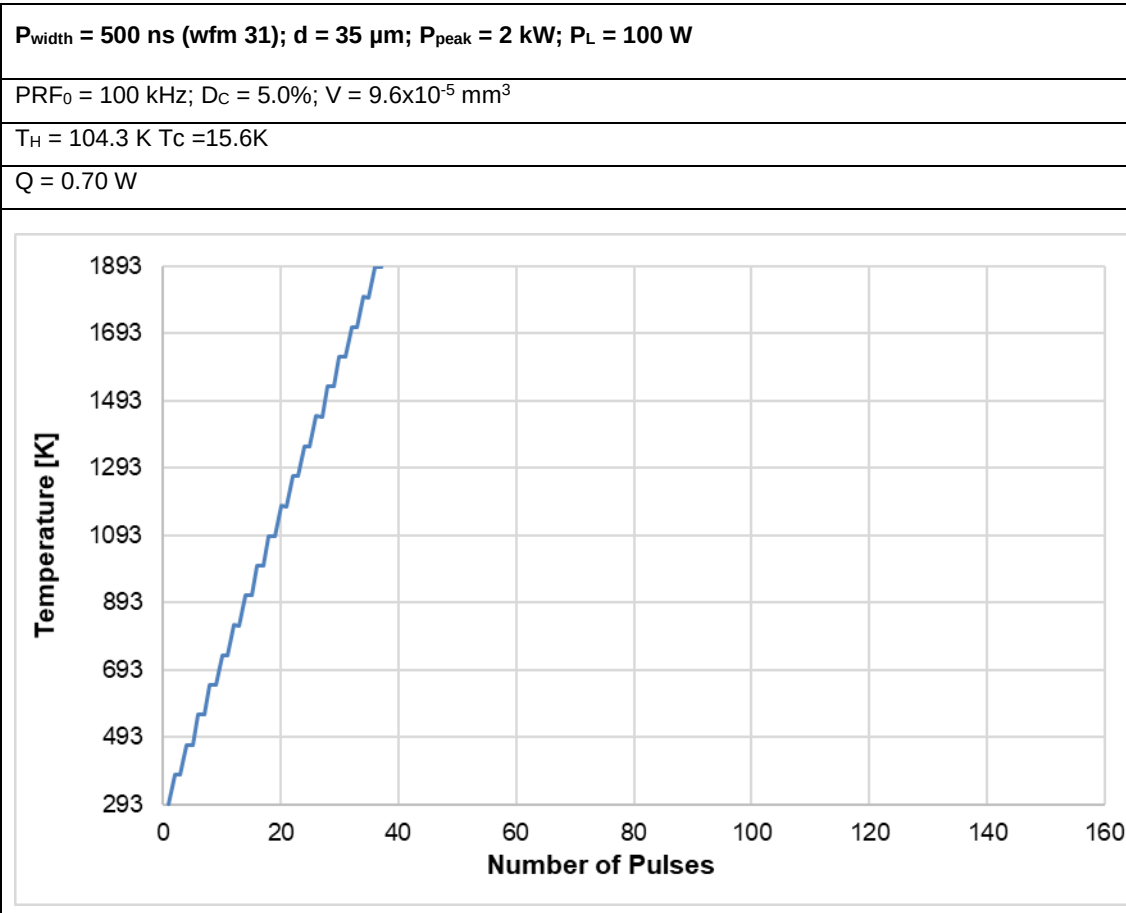


Figure 4-29 Thermal profile of a volume of metal when irradiated by 38 pulses at an average peak power of 2 kW with a beam diameter of 35 μm , pulse duration of 500 ns, pulse repetition frequency of 100 kHz and DC of 5%.

This thermal model shows how the application of each pulse and the material's properties influence the temperature build up and down in the material, creating a "jigsaw blade" effect for different laser duty cycles, as shown in Figure 4-30.

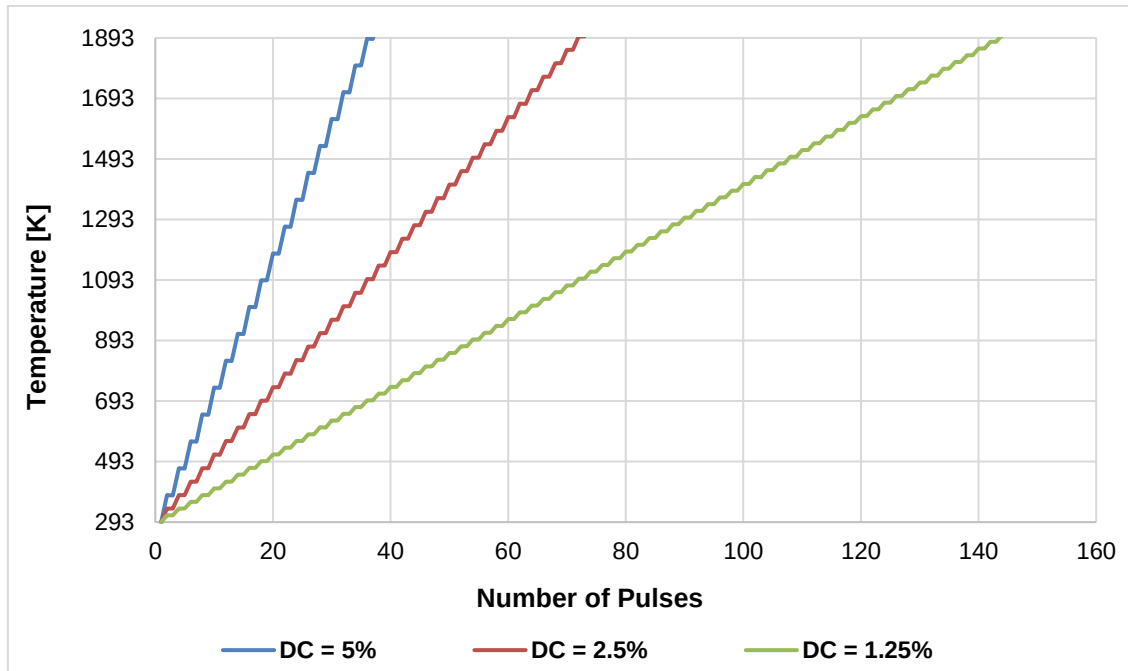


Figure 4-30 Thermal profile of a volume of metal irradiated by a laser beam diameter of 35 μm , pulse duration of 500 ns, average peak power of 2 kW and DC of 5%, 2.5% and 1.25%.

According to the FLMIP definitions, similar energy per unit length can be applied with the same number of pulses within the same laser-material interaction time, as shown in Figure 4-22. However, the effect on the weld profile is entirely different depending on how fast the pulses are applied and the heat is dissipated, as shown from Figure 4-24 to Figure 4-29. A higher laser duty cycle (shorter inter-pulse spacing) leads to higher heat accumulation, and higher penetration depth. Therefore, this should be considered in the formulae of the FLMIP, especially if we want to compare different metals and laser temporal modes like MPPW and CW, where the duty cycle is different. Still, the overall applied energy and laser-material interaction time might be the same.

Further computer simulations are required to extend this simplistic thermal model and foresee the depth of penetration and weld width based on the thermal cycle of the weld, which is out of the scope of this study.

4.4 Summary of discussions

A mapping of pulse energy (E_{pulse}) and average peak power density (P_{peak}) has been plotted for different pulse durations, pulse repetition frequencies and average powers of modulated pulse shapes. The values acquired from the photodiode and oscilloscope match the theoretical values from the mathematical formulae previously defined for square pulse shapes. The new definitions of the fundamental laser-material interaction parameters (FLMIP) have been established in MPPW welding. Their influence on the depth of penetration and weld width has been shown:

- The average power density (q_p), average peak power density ($q_{p, peak}$) and specific point energy ($E_{SP, MPPW}$) independently control the penetration depth.
- The interaction time controls the weld width.
- The inter-pulse thermal losses create a limitation on the applicability of the FLMIP from a certain trade-off between $q_{p, peak}$ and $E_{SP, MPPW}$.
- It is necessary to have a trade-off between $E_{SP, MPPW}$, $q_{p, peak}$ and q_p to have enough material vaporisation and guarantee a certain penetration depth.
- At constant $E_{SP, MPPW}$ and constant q_p , higher penetration can be achieved at higher $q_{p, peak}$, but narrow weld widths are obtained. On the other hand, lower penetrations and wider widths can be reached with similar $E_{SP, MPPW}$ and q_p and lower $q_{p, peak}$.

A simple thermal model showed that the FLMIP could be correlated with the thermal cycle in the substrate to predict the necessary energy per unit length to melt SS. However, the inter-pulse spacing should be considered in the formulae of the FLMIP to account for the thermal losses effect between pulses for various metals. In the next chapter, an analysis of the impact of the pulse width of different waveforms on the weld geometry will be carried out.

5 Selection of waveforms in multi-pulse pulsed-wave micro-welding

Part of this chapter is based on the following publication:

Coroado J.*, Ganguly S., Suder W., Williams S., Meco S., Pardal G. (2021) 'Selection of parameters in nanosecond pulsed wave laser micro-welding', *The International Journal of Advanced Manufacturing Technology*, 115, pp. 2929–2944, <https://doi.org/10.1007/s00170-021-07251-8>.

5.1 Introduction

The nanosecond MPPW laser used in this study allows the selection of 31 different waveforms with different pulse durations, pulse energies and peak powers, which provide different duty cycles. As concluded in the previous chapter, the laser duty cycle plays an essential role in determining penetration depth and weld widths when the pulse duration, pulse energy and average peak power remain constant for an identical waveform. This section aims to understand the impact of different waveforms on the weld profile and correlate the results with the corresponding laser duty cycles and fundamental laser-material interaction parameters. The objectives are as follows:

- Variation of the duty cycle in different waveforms at a constant frequency, pulse energy, and different peak powers and pulse widths.
- Variation of the frequency, pulse energy and pulse width in different waveforms at constant average peak power and duty cycle.
- Correlation of the laser duty cycle and fundamental laser-material interaction parameters with the weld geometry.

5.2 Experimental procedure

5.2.1 Material

The material used in the experiments was a 2 mm thick plate of SS304 L. Its chemical composition, and physical properties are shown in section 3.1 in Table 3-2 and Table 3-4, respectively.

5.2.2 Methodology and experimental setup

The bead-on-plate welds were produced with a 100 W average output power nanosecond MPPW fibre laser. Only three waveforms, whose corresponding properties are presented in Table 5-1, were selected and studied in this chapter. The joint dimensions and experimental setup are shown in section 3.

Table 5-1 Properties of waveforms 0, 27 and 31 at PRF₀ of 100 kHz and average power of 100W [126].

Waveform	Pulse duration [ns]	Pulse repetition frequency [kHz]	Average power [W]	Pulse Energy [mJ]	Peak power [kW]
wfm	P _{width}	PRF ₀	P _L	E _{pulse}	-
0	280	100	100	1	10
27	350	100	100	1	7
31	500	100	100	1	7

5.2.2.1 Effect of different duty cycles in different waveforms

This section studied the duty cycle's effect on the weld profile, i.e. penetration depth and weld width, in three different waveforms. The average peak power was varied at constant frequency and pulse energy for each waveform. The correlation of the various duty cycles with the system parameters and corresponding fundamental laser-material interaction parameters are shown in Table 5-2 and Table 5-3, respectively.

Table 5-2 Calculated and system parameters, and corresponding micrographs' number used in waveforms 0, 27 and 31.

Calculated Parameters			System Parameters							
Waveform	Duty cycle [%]	Overlap Factor [%]	Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	Micrograph
Wfm	D _C	O _F	d	P _{width}	P _L	v	PRF	E _{pulse}	P _{peak}	-
0	0.7	99.5	35	280	25	4.4	25	1	3.6	5-1
27	0.875	99.5	35	350	25	4.4	25	1	2.9	5-2
31	1.25	99.5	35	500	25	4.4	25	1	2	5-3
0	1.4	99.5	35	280	50	8.8	50	1	3.6	5-4
27	1.75	99.5	35	350	50	8.8	50	1	2.9	5-5
31	2.5	99.5	35	500	50	8.8	50	1	2	5-6
0	2.8	99.5	35	280	100	17.6	100	1	3.6	5-7
27	3.5	99.5	35	350	100	17.6	100	1	2.9	5-8
31	5	99.5	35	500	100	17.6	100	1	2	5-9

Table 5-3 Calculated and fundamental parameters, and corresponding micrographs' number used in waveforms 0, 27 and 31.

Calculated Parameters			Fundamental Laser Material Interaction Parameters				
Waveform	Duty cycle [%]	Overlap Factor [%]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]	Interaction time [ms]	Micrograph
Wfm	D _C	O _F	q _p	q _{p, peak}	E _{SP, MPPW}	t _{i, MPPW}	-
0	0.7	99.5	2.6	371	200	0.056	5-1
27	0.875	99.5	2.6	297	200	0.07	5-2
31	1.25	99.5	2.6	208	200	0.10	5-3
0	1.4	99.5	5.2	371	200	0.056	5-4
27	1.75	99.5	5.2	297	200	0.070	5-5
31	2.5	99.5	5.2	208	200	0.10	5-6
0	2.8	99.5	10.4	371	200	0.056	5-7
27	3.5	99.5	10.4	297	200	0.070	5-8
31	5	99.5	10.4	208	200	0.10	5-9

5.2.2.2 Effect of constant duty cycles in different waveforms

This section studied the effect of a constant duty cycle on the weld profile at different pulse repetition frequencies and pulse widths. The pulse energy was varied at constant average peak power for each waveform. The correlation of the various duty cycle values with the system parameters and corresponding fundamental laser-material interaction parameters (FLMIP) is shown in Table 5-4 and Table 5-5, respectively.

Table 5-4 Calculated and system parameters, and corresponding micrographs' number used in waveforms 0, 27 and 31.

Calculated Parameters			System Parameters							Micrograph
Waveform	Duty cycle [%]	Overlap Factor [%]	Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]	
Wfm	D _C	O _F	d	P _{width}	P _L	v	PRF	E _{pulse}	P _{peak}	
0	5	99.72	35	280	100	17.5	179	0.56	2	5-10
27	5	99.65	35	350	100	17.5	143	0.7	2	5-11
31	5	99.5	35	500	100	17.5	100	1	2	5-12
0	7.5	99.72	35	280	100	26.3	268	0.37	1.3	5-13
27	7.5	99.65	35	350	100	26.3	214	0.47	1.3	5-14
31	7.5	99.5	35	500	100	26.3	150	0.67	1.3	5-15
0	10	99.72	35	280	100	35	357	0.28	1	
27	10	99.65	35	350	100	35	286	0.35	1	
31	10	99.5	35	500	100	35	200	0.5	1	

Table 5-5 Calculated and fundamental parameters, and corresponding micrographs' number used in waveforms 0, 27 and 31.

	Calculated Parameters		Fundamental Laser Material Interaction Parameters				
Waveform	Duty cycle [%]	Overlap Factor [%]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]	Interaction time [ms]	Micrograph
Wfm	D _C	O _F	q _p	q _{p, peak}	E _{SP, MPPW}	t _{i, MPPW}	-
0	5	99.72	10.4	208	200	0.10	5-10
27	5	99.65	10.4	208	200	0.10	5-11
31	5	99.5	10.4	208	200	0.10	5-12
0	7.5	99.72	10.4	139	133	0.10	5-13
27	7.5	99.65	10.4	139	133	0.10	5-14
31	7.5	99.5	10.4	139	133	0.10	5-15
0	10	99.72	10.4	104	100	0.10	
27	10	99.65	10.4	104	100	0.10	
31	10	99.5	10.4	104	100	0.10	

5.2.3 Weld shape characterisation

The weld geometry analysis was based on optical microscopy to measure the fusion zone geometry, i.e. depth of penetration and weld width. More details are presented in section 3.

5.3 Results and discussion

5.3.1 Effect of different duty cycles in different waveforms

According to the results presented in section 4, below a critical pulse repetition frequency (PRF_0), the pulse energy and average peak power remain maximum. Consequently, the average laser power decreases with the duty cycle. From the measurements of the pulse shapes previously acquired, it can be seen in Figure 5-1 the variation of the average peak power with pulse repetition frequency (PRF) and average power (P_L) for different pulse widths (P_{width}) at a constant pulse energy of 1 mJ. The corresponding duty cycle variation is shown in Figure 5-2. For similar PRF , P_L and pulse energy, the average peak power is higher for shorter pulse widths, whereas the duty cycle is shorter.

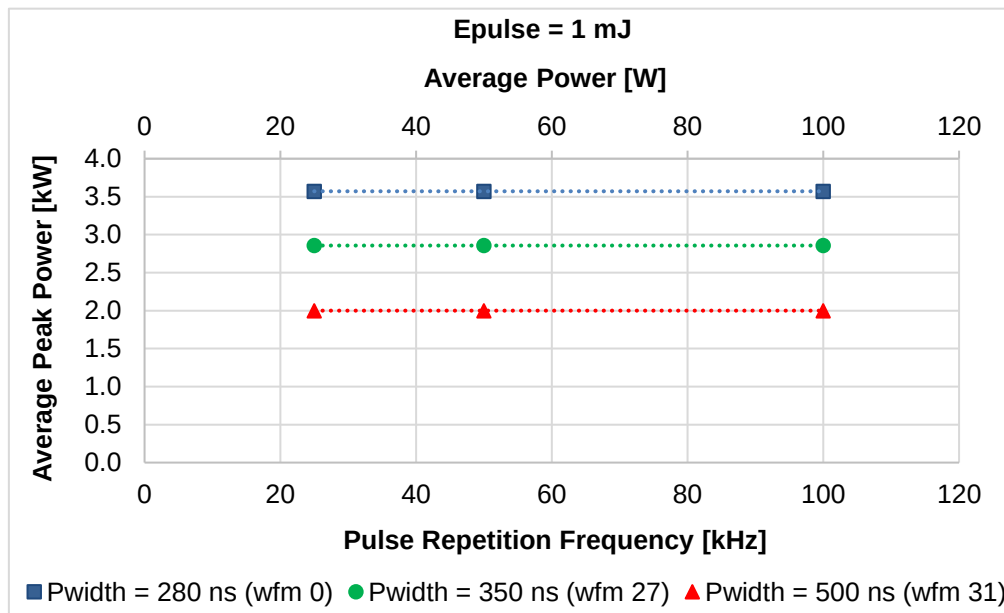


Figure 5-1 Average peak power (P_{Peak}) versus pulse repetition frequency (PRF) versus average power (P_L) for different pulse widths at a constant pulse energy of 1 mJ.

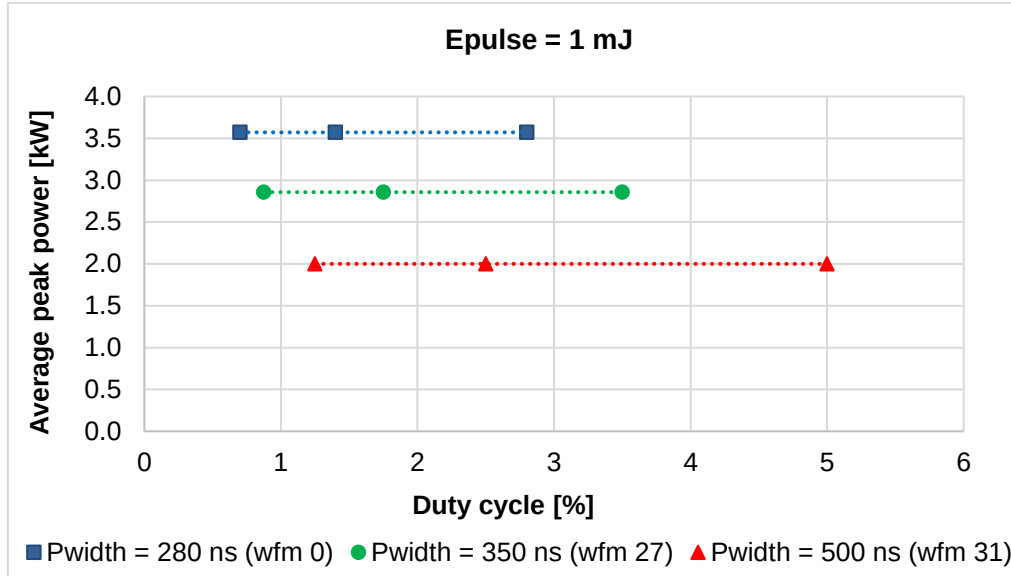


Figure 5-2 Average peak power (P_{Peak}) versus duty cycle (Dc) for different pulse widths at a constant pulse energy of 1 mJ.

According to Table 5-2 and Table 5-3, different pulse widths (P_{width}) and similar pulse repetition frequencies (PRF) allow different duty cycles at constant pulse energy and different peak powers in waveforms 0, 27 and 31. Thus, at constant average power, beam diameter and travel speed, similar average power densities and specific point energies are possible to replicate independently of the waveform selected.

The effect of the average peak power density and average power density on the depth of penetration for different waveforms at constant applied energy is shown in Figure 5-3. The corresponding micrographs are shown in Figure 5-4, Figure 5-6 and Figure 5-7. It can be observed in Figure 5-3 that the penetration depth increases with the average peak power density and average power density, independently of the waveform selected. Moreover, the penetration depth is similar in all waveforms for constant average peak power density, average power, and specific point energy.

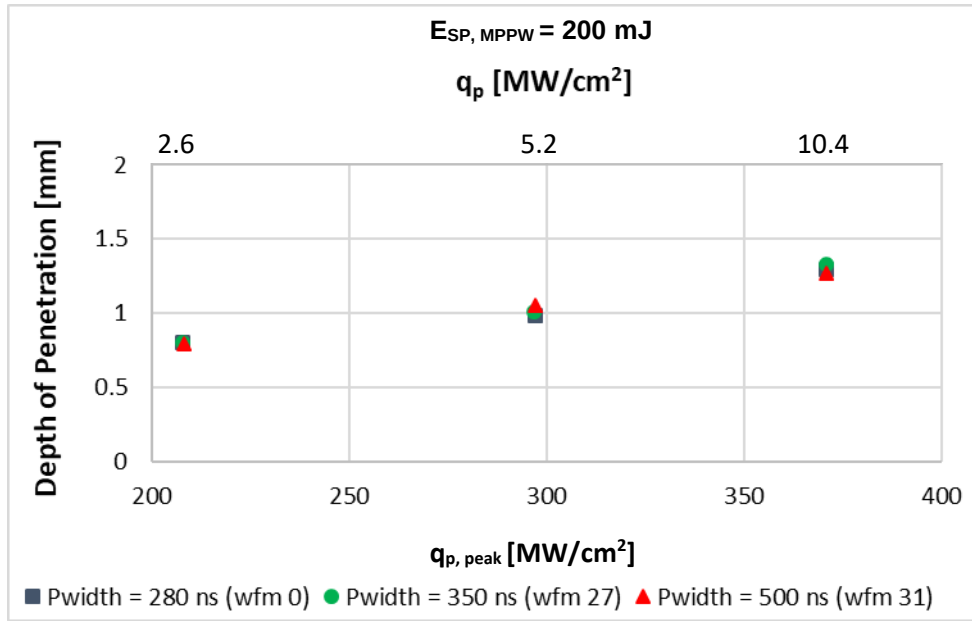


Figure 5-3 Depth of penetration versus average peak power density ($q_{p, peak}$) versus average power density (q_p) for different pulse widths at constant specific point energy ($E_{SP, MPPW}$) of 200 mJ.

Micrograph 5-1 in Figure 5-4 was achieved with the shortest pulse duration of 280 ns (waveform 0) and the highest average peak power density of 371 MW/cm² compared to the micrographs 5-2 and 5-3. From micrograph 5-1 (waveform 0) to 5-2 (waveform 27), the pulse duration was increased from 280 ns to 350 ns at a constant pulse repetition frequency of 25 kHz (Table 5-2). Consequently, the laser's duty cycle raised from 0.7% to 0.875%, and the interaction time also increased by the same percentage (25%) (Table 5-3). There is also a difference of 25% in $q_{p, peak}$ from waveform 27 (297 MW/cm²) to waveform 0 (371 MW/cm²), which is exactly the same percentage of the duty cycle increase.

In micrograph 5-1 from Figure 5-4, for a travel speed of 4.4 mm/s and a pulse repetition frequency of 25 kHz (Table 5-2), the laser emitted approximately 5682 pulses in 1 mm. In micrograph 5-2, at equal travel speed and pulse repetition frequency, a similar number of pulses have been emitted in the same domain. Looking at the pulse energy in both cases, it was 1 mJ. Multiplying 5682 pulses by 1mJ, it is equal to 5.7 J. Thus, the same energy was delivered per unit length on the material in both cases, being the overall specific pulse energy 200 mJ.

However, the average peak power (P_{peak}) given by each pulse was much higher in micrograph 5-1 (Table 5-2), which represents a higher average peak power density ($q_{p, peak}$). Therefore, to achieve constant penetration depth with different waveforms at constant q_p and $E_{SP, MPPW}$, a higher $q_{p, peak}$ is required to compensate for the thermal losses created by the lower duty cycle (micrograph 5-1). On the other hand, as $q_{p, peak}$ decreases from micrograph 5-1 to 5-3, the duty cycle increases and the thermal losses are lower, being possible to keep the penetration depth unchanged. It can be concluded that the duty cycle is more important than the average peak power density in controlling the inter-pulse thermal losses and, consequently, the weld shape.

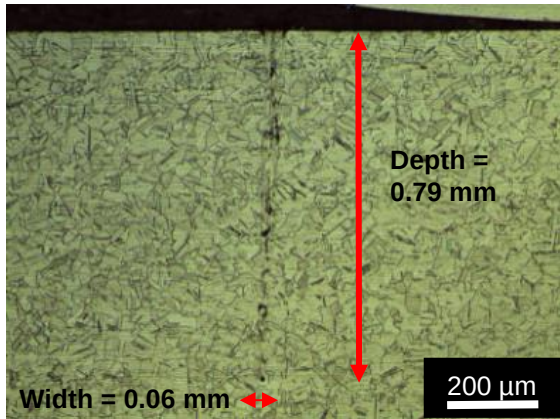
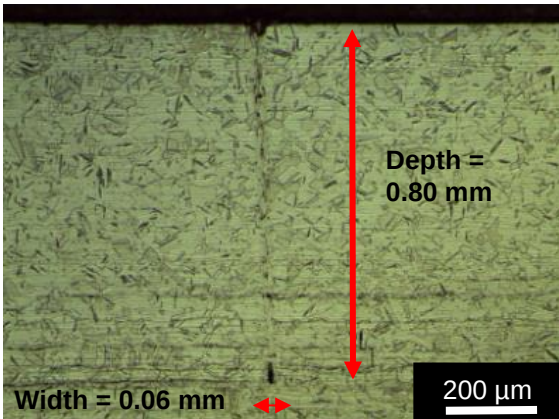
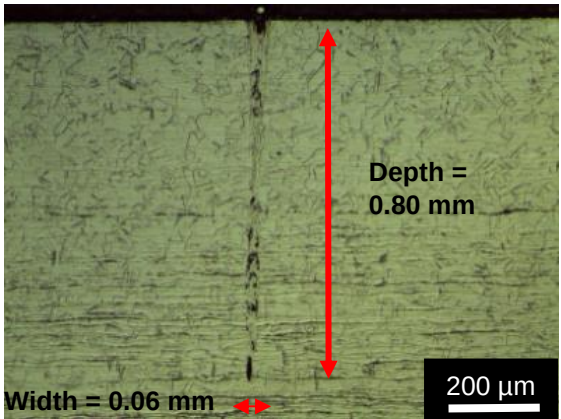
$q_p = 2.6 \text{ MW/cm}^2$; $E_{SP, \text{MPPW}} = 200 \text{ mJ}$		
Micrograph 5-1	Micrograph 5-2	Micrograph 5-3
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 350 \text{ ns (Wfm 27)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$D_C = 0.7\%$; $t_{i, \text{MPPW}} = 0.057 \text{ ms}$	$D_C = 0.875\%$; $t_{i, \text{MPPW}} = 0.07 \text{ ms}$	$D_C = 1.25\%$; $t_{i, \text{MPPW}} = 0.1 \text{ ms}$
$q_{p, \text{peak}} = 371 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 297 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 208 \text{ MW/cm}^2$
		
Depth = 0.79 mm; Width = 0.06 mm	Depth = 0.80 mm; Width = 0.06 mm	Depth = 0.80 mm; Width = 0.06 mm
Weld metal area = 0.043 mm^2	Weld metal area = 0.042 mm^2	Weld metal area = 0.046 mm^2

Figure 5-4 Micrographs of bead-on-plate welds made at a constant average power density of 2.6 MW/cm^2 and specific point energy of 200 mJ.

A schematic representation of the previous explanation is depicted in Figure 5-5. For similar pulse repetition frequency, higher average peak power in waveform 0 is needed to compensate for the higher thermal losses created by the lower duty cycle (and higher inter-pulse spacing) in comparison to waveform 31. On the other hand, the lower peak power of waveform 31 is compensated by a higher duty cycle (and lower inter-pulse spacing). Thus, the thermal losses are reduced and allow a constant penetration depth, as previously observed in Figure 5-4. This is only possible as the pulse energy, represented by the area in red, is identical in both waveforms. However, this observation is not captured by the FLMIP formulae as it would be expected a shallower penetration depth in micrograph 5-3 for a lower $q_{p, peak}$ and similar $E_{SP, MPPW}$ and q_p in comparison to micrographs 5-1 and 5-2. A similar conclusion was drawn in section 4.

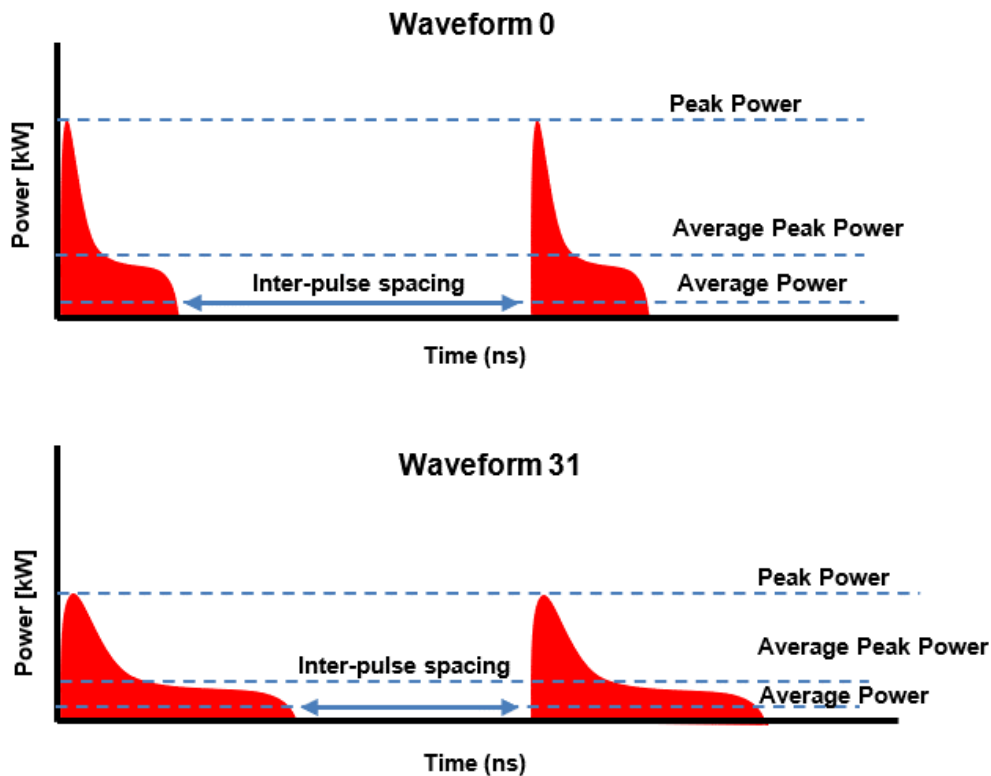


Figure 5-5 Temporal output of an MPPW laser at a constant pulse repetition frequency, average power and pulse energy applied in different waveforms: waveform 0) high average peak power and short pulse duration; waveform 31) low average peak power and long pulse duration.

From Figure 5-4 to Figure 5-6, the pulse repetition frequency increased from 25 to 50 kHz, and the average power increased in the same ratio for all pulse

durations (Table 5-2 and Table 5-3). Consequently, $E_{SP, MPPW}$ and $q_{p, peak}$ remained constant, and q_p increased from 2.6 to 5.2 MW/cm². The overlap between pulses remained constant by increasing the frequency and travel speed in the same proportion, the interaction time being similar in each waveform. In Figure 5-6, 5682 pulses have been applied in the length of 1 mm for a pulse repetition frequency of 50 kHz. A travel speed of 8.8 mm/s multiplied by pulse energy of 1 mJ equals 5.7J of total energy applied per unit length, the same as in Figure 5-4. Thus, *the* $E_{SP, MPPW}$ has been kept constant for each waveform in both figures.

The duty cycle increased from Figure 5-4 to Figure 5-6, which is reflected by a higher q_p . Consequently, the thermal losses between pulses were reduced, leading to a homogeneous increase in penetration depth, as seen in all micrographs from Figure 5-6 compared to Figure 5-4. Similar phenomena can be observed in Figure 5-7 as the average power and pulse repetition frequency were further increased.

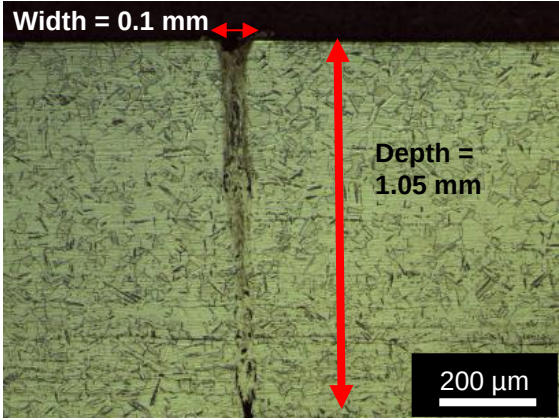
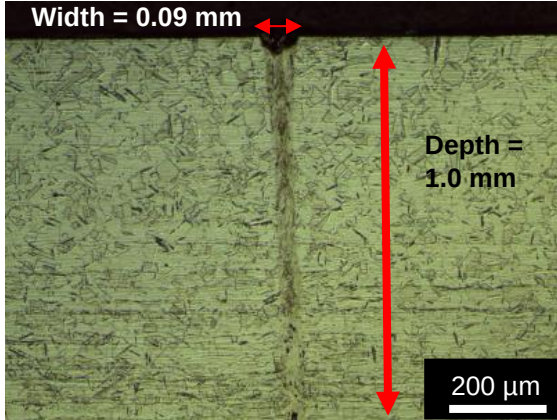
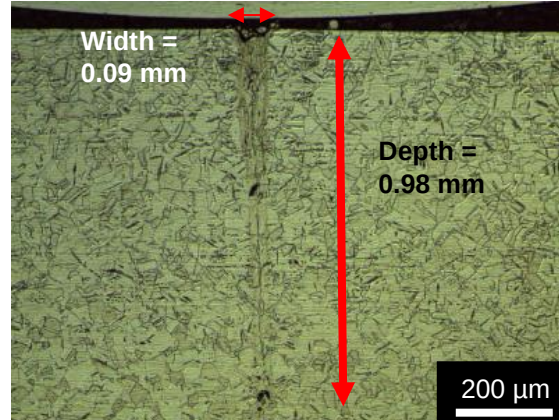
$q_p = 5.2 \text{ MW/cm}^2$; $E_{SP, \text{MPPW}} = 200 \text{ mJ}$		
Micrograph 5-4	Micrograph 5-5	Micrograph 5-6
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 350 \text{ ns (Wfm 27)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$D_C = 1.5\%$; $t_{i, \text{MPPW}} = 0.057 \text{ ms}$	$D_C = 1.75\%$; $t_{i, \text{MPPW}} = 0.07 \text{ ms}$	$D_C = 2.5\%$; $t_{i, \text{MPPW}} = 0.1 \text{ ms}$
$q_{p, \text{peak}} = 371 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 297 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 208 \text{ MW/cm}^2$
		
Depth = 1.05 mm; Width = 0.10 mm	Depth = 1.0 mm; Width = 0.09 mm	Depth = 0.98 mm; Width = 0.09 mm
Weld metal area = 0.091 mm^2	Weld metal area = 0.085 mm^2	Weld metal area = 0.087 mm^2

Figure 5-6 Micrographs of bead-on-plate welds made at a constant average power density of 5.2 MW/cm^2 and specific point energy of 200 mJ.

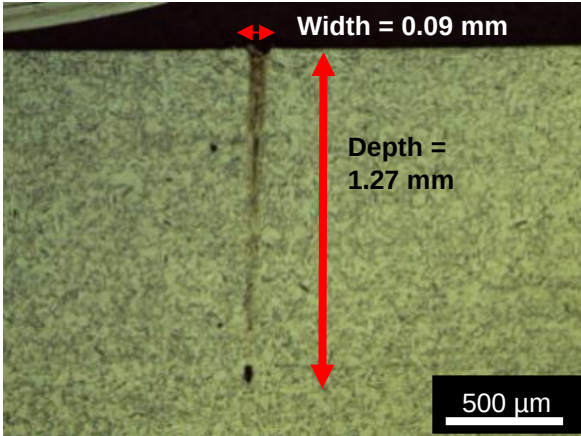
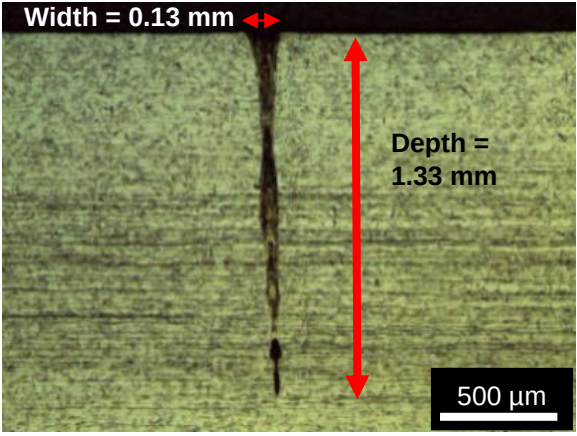
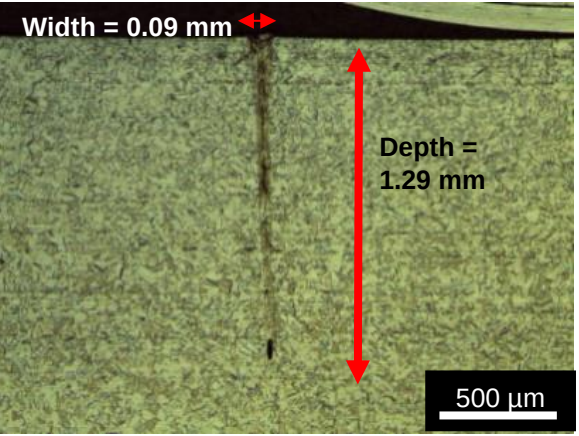
$q_p = 10.4 \text{ MW/cm}^2$; $E_{SP, \text{MPPW}} = 200 \text{ mJ}$		
Micrograph 5-7	Micrograph 5-8	Micrograph 5-9
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 350 \text{ ns (Wfm 27)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$D_C = 2.8\%$; $t_{i, \text{MPPW}} = 0.057 \text{ ms}$	$D_C = 3.5\%$; $t_{i, \text{MPPW}} = 0.07 \text{ ms}$	$D_C = 5\%$; $t_{i, \text{MPPW}} = 0.1 \text{ ms}$
$q_{p, \text{peak}} = 371 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 297 \text{ MW/cm}^2$	$q_{p, \text{peak}} = 208 \text{ MW/cm}^2$
		
Depth = 1.27 mm; Width = 0.09 mm	Depth = 1.33 mm; Width = 0.13 mm	Depth = 1.29 mm; Width = 0.09 mm
Weld metal area = 0.11 mm^2	Weld metal area = 0.12 mm^2	Weld metal area = 0.10 mm^2

Figure 5-7 Micrographs of bead-on-plate welds made at a constant average power density of 10.4 MW/cm^2 and specific point energy of 200 mJ.

5.3.2 Effect of constant duty cycles in different waveforms

It was shown in the previous section that it's possible to achieve similar weld shapes with different waveforms if the duty cycle compensates for the thermal losses effect between pulses. This section investigates if similar weld shapes can be achieved with different waveforms when a constant duty cycle is reached through a trade-off between pulse width (P_{width}) and pulse repetition frequency (PRF).

The average peak power variation with pulse repetition frequency for different pulse widths can be seen in Figure 5-8. The corresponding pulse energies (E_{pulse}) and duty cycles (D_C) are shown in Figure 5-9. The pulse repetition frequency was increased for shorter pulse widths to achieve similar average peak power in different waveforms. Consequently, the pulse energy decreased, and the duty cycle remained constant. The calculated parameters and corresponding system parameters and FLMIP applied in waveforms 0, 27 and 31 are shown in Table 5-4 and Table 5-5, respectively. The corresponding micrographs are shown in Figure 5-11 and Figure 5-12.

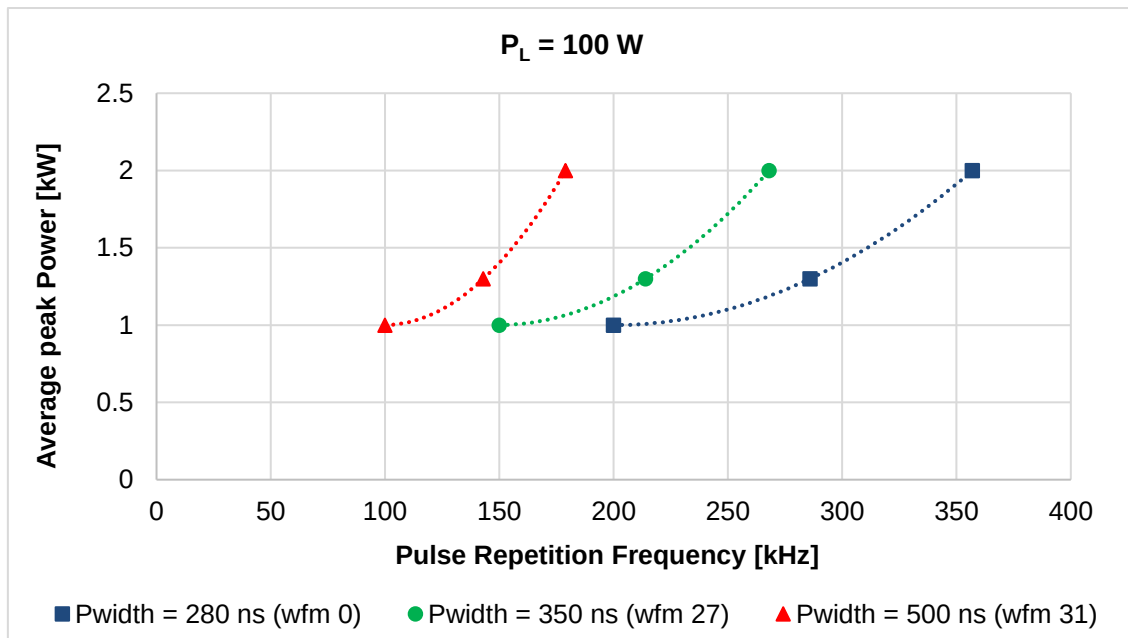


Figure 5-8 Average peak power (P_{Peak}) versus pulse repetition frequency (PRF) for different pulse widths at a constant average power of 100 W.

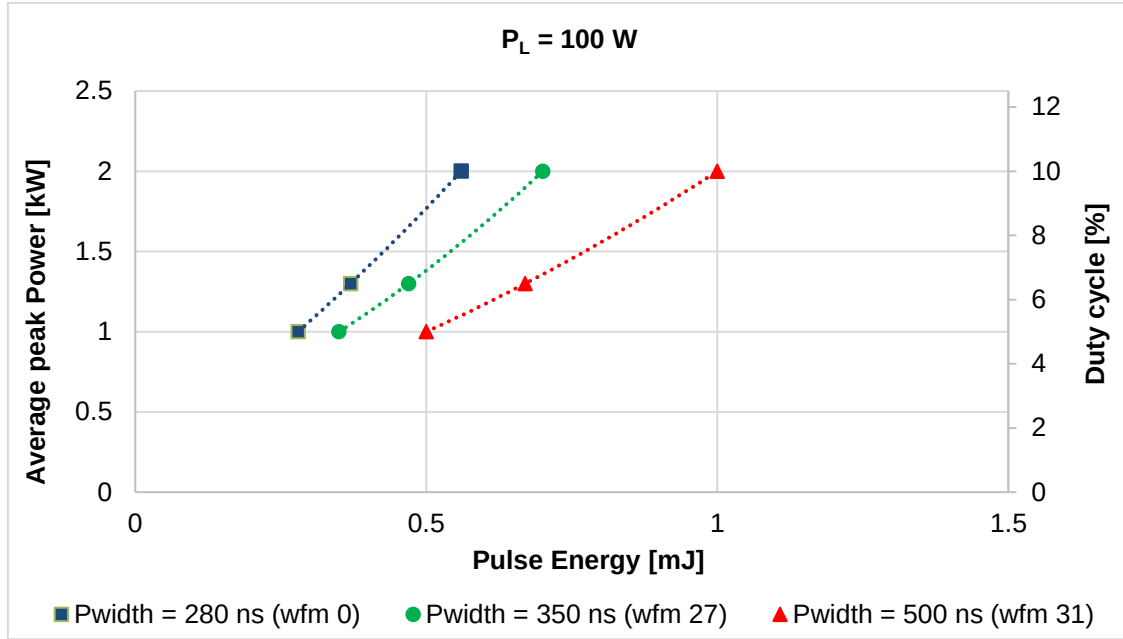


Figure 5-9 Average peak power (P_{Peak}) versus pulse energy (E_{pulse}) versus duty cycle (D_C) for different pulse widths at a constant average power of 100 W.

Table 5-4 and Table 5-5 show that a trade-off between pulse width (P_{width}) and pulse repetition frequency (PRF) allows a constant duty cycle and average peak power in waveforms 0, 27 and 31. Thus, at constant average power, beam diameter and travel speed, similar average power density, average peak power densities, specific pulse energies and interaction time were possible to replicate independently of the waveform selected.

The effect of $E_{SP, MPPW}$, $q_{p, peak}$ and D_C on the penetration depth for different waveforms at constant q_p and $t_{i, MPPW}$ is shown in Figure 5-10. The corresponding micrographs are shown in Figure 5-11 and Figure 5-12. As shown in Figure 5-10, the penetration depth increases with $E_{SP, MPPW}$ and $q_{p, peak}$, independently of the waveform selected. Besides that, at constant q_p , $q_{p, peak}$, $t_{i, MPPW}$, $E_{SP, MPPW}$, and D_C , the depth of penetration obtained is similar in all waveforms.

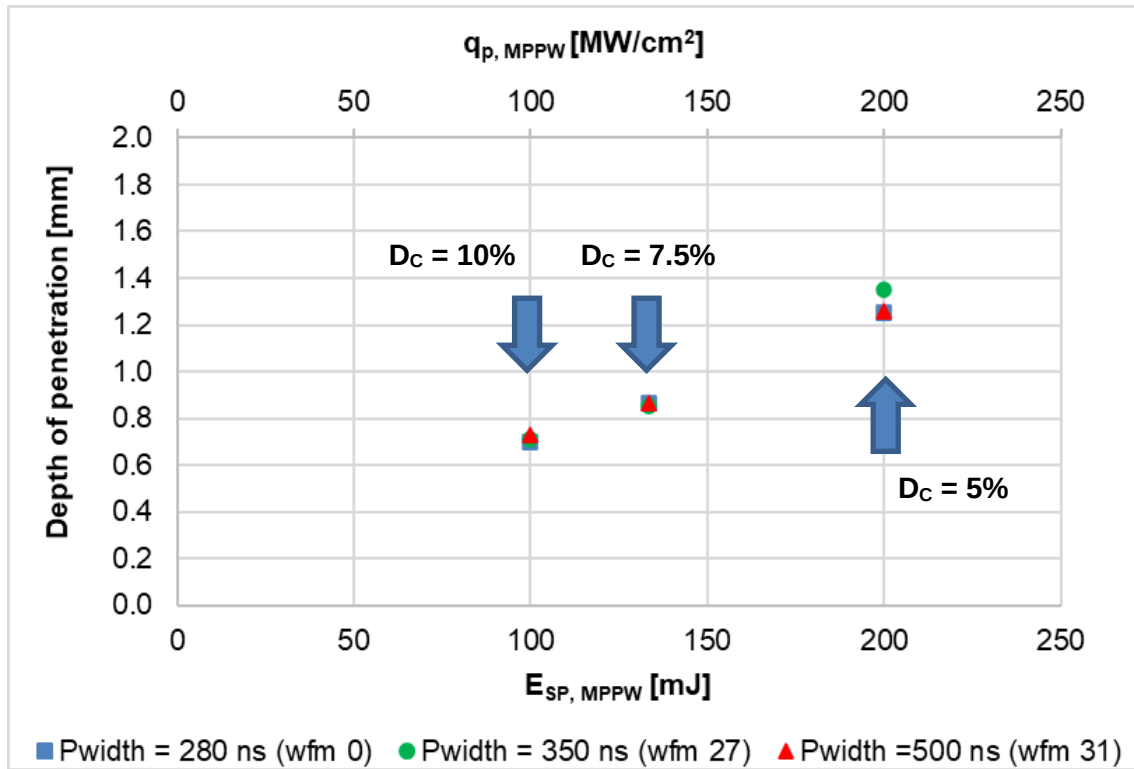


Figure 5-10 Effect of the fundamental laser-material interaction parameters (FLMIP) on penetration depth using different waveforms at a constant average power of 10.4 MW/cm² and interaction time of 0.1 ms.

In Figure 5-11, all micrographs were achieved at a constant average power density of 10.4 MW/cm², an average peak power density of 208 MW/cm², specific point energy of 200 mJ, an interaction time of 0.05 ms and a duty cycle of 5%. In micrograph 5-10, for a pulse width of 280 ns, travel speed of 17.5 mm/s and pulse repetition frequency of 179 kHz (Table 5-3), the laser emitted approximately 10229 pulses in a length of 1 mm. In micrograph 5-11 for a pulse width of 350 ns, pulse repetition frequency of 143 kHz and travel speed of 17.5 mm/s, 8171 pulses were emitted. Multiplying 10229 pulses by the pulse energy of 0.56 mJ, and 8171 pulses by 0.7 mJ, it is equal to 5.7 J. The same energy was delivered per unit length on the material in both cases, being the overall specific pulse energy of 200 mJ. Therefore, to replicate a weld profile in different waveforms at constant q_p , $E_{SP, MPPW}$, $q_{p, peak}$, $t_{i, MPPW}$, an identical duty cycle and travel speed are required to guarantee a similar thermal profile.

From Figure 5-11 to Figure 5-12, the duty cycle has been increased from 5% to 7.5%, the average power density and pulsed interaction time remained constant, and the average peak power density and specific point energy decreased to 139 MW/cm² and 67 mJ, respectively. As expected, the depth of penetration decreased, but it remained almost constant from micrographs 5-13 to 5-15.

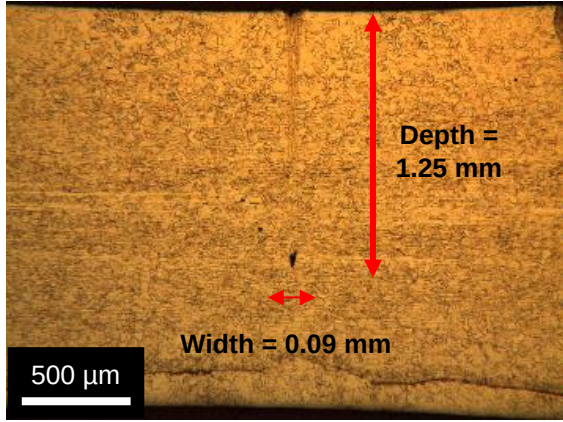
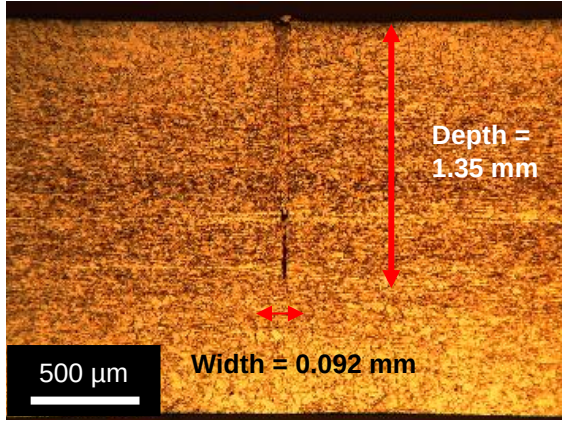
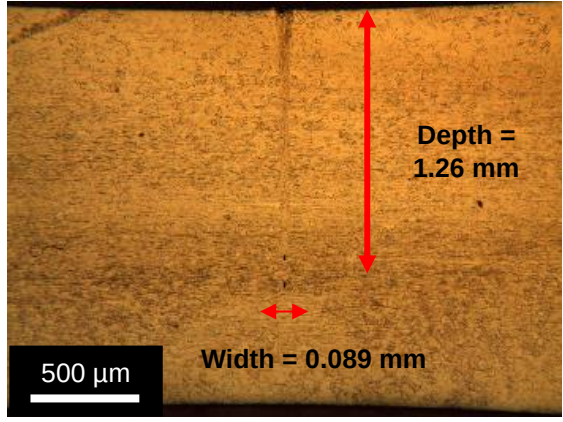
$D_c = 5\%$; $q_p = 10.4 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 208 \text{ MW/cm}^2$; $E_{SP, \text{MPPW}} = 200 \text{ mJ}$; $t_{i, \text{MPPW}} = 0.1 \text{ ms}$		
Micrograph 5-10	Micrograph 5-11	Micrograph 5-12
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 350 \text{ ns (Wfm 27)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$E_{\text{pulse}} = 0.56 \text{ mJ}$; $P_{\text{peak}} = 2.0 \text{ kW}$	$E_{\text{pulse}} = 0.70 \text{ mJ}$; $P_{\text{peak}} = 2.0 \text{ kW}$	$E_{\text{pulse}} = 1.0 \text{ mJ}$; $P_{\text{peak}} = 2.0 \text{ kW}$
		
Depth = 1.25 mm; Width = 0.091 mm	Depth = 1.35 mm; Width = 0.092 mm	Depth = 1.26 mm; Width = 0.089 mm
Weld metal area = 0.10 mm^2	Weld metal area = 0.11 mm^2	Weld metal area = 0.10 mm^2

Figure 5-11 Micrographs of bead-on-plate welds achieved at different pulse widths and constant D_c of 5%, q_p of 10.4 MW/cm^2 , $q_{p, \text{peak}}$ of 208 MW/cm^2 , $E_{SP, \text{MPPW}}$ of 200 mJ and $t_{i, \text{MPPW}}$ of 0.1 ms.

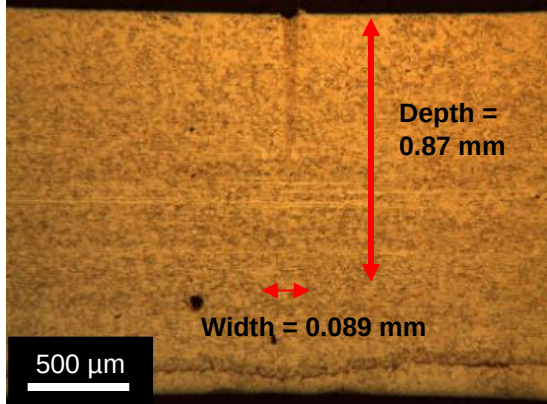
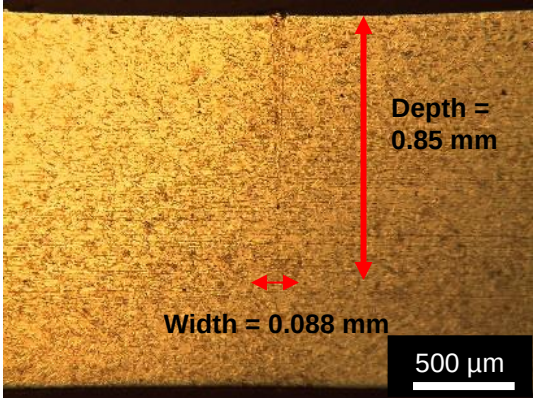
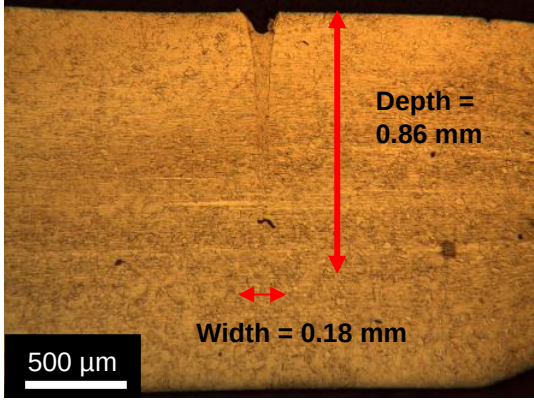
$D_c = 7.5\%$; $q_p = 10.4 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 139 \text{ MW/cm}^2$; $E_{\text{SP, MPPW}} = 133 \text{ mJ}$; $t_{i, \text{MPPW}} = 0.1 \text{ ms}$		
Micrograph 5-13	Micrograph 5-14	Micrograph 5-15
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 350 \text{ ns (Wfm 27)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$E_{\text{pulse}} = 0.37 \text{ mJ}$; $P_{\text{peak}} = 1.3 \text{ kW}$	$E_{\text{pulse}} = 0.47 \text{ mJ}$; $P_{\text{peak}} = 1.3 \text{ kW}$	$E_{\text{pulse}} = 0.67 \text{ mJ}$; $P_{\text{peak}} = 1.3 \text{ kW}$
		
Depth = 0.87 mm; Width = 0.089 mm	Depth = 0.85 mm; Width = 0.088 mm	Depth = 0.86 mm; Width = 0.18 mm
Weld metal area = 0.072 mm^2	Weld metal area = 0.071 mm^2	Weld metal area = 0.10 mm^2

Figure 5-12 Micrographs of bead-on-plate welds achieved at different pulse widths, constant D_c of 7.5%, q_p of 10.4 MW/cm^2 , $q_{p, \text{peak}}$ of 139 MW/cm^2 , $E_{\text{SP, MPPW}}$ of 133 mJ and $t_{i, \text{MPPW}}$ of 0.1 ms.

A visual representation of the previous explanation is shown in Figure 5-13. A constant duty cycle is possible through a trade-off between pulse duration and pulse repetition frequency. Within the same period, two pulses delivered in waveform 0 equate to the same energy as one pulse in waveform 31. Moreover, the time between pulses in waveform 0 is similar to the summation of the time between pulses in waveform 31. Therefore, the equal penetration depth achieved in the micrographs in Figure 5-11 and Figure 5-12 can be attributed to the equivalent energy of 200 mJ delivered to the material in all waveforms at a constant duty cycle, but also travel speed (Table 5-5), allowing similar overall thermal losses. It can be concluded that a constant duty cycle is critical in controlling the weld shape in different waveforms with different pulse energies and similar average peak powers.

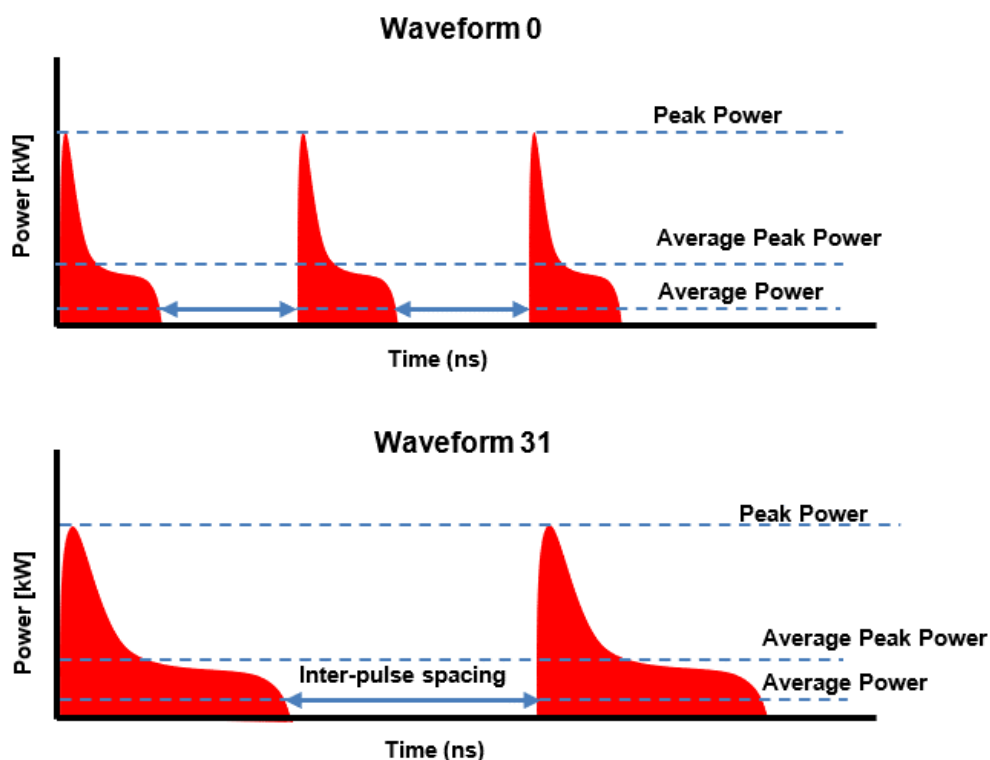


Figure 5-13 Temporal output of an MPPW laser at constant average peak power, average power and duty cycle applied in different waveforms: waveform 0) low pulse energy, short pulse duration and high pulse repetition frequency; waveform 31) high pulse energy, long pulse duration and low pulse repetition frequency.

5.4 Summary of discussions

Applying the fundamental laser-material interaction parameters with different waveforms with characteristic pulse duration, average peak power, and pulse energy revealed how the weld shape can be manipulated for a particular pulse shape.

The duty cycle is a critical parameter in controlling the penetration depth, regardless of the pulse shape obtained in different waveforms. It is even more important than the average peak power density, as it determines the inter-pulse thermal losses which are not yet captured by the current FLMIP formulae. Therefore, as long as the pulse energy, pulse width, and frequency are maximised, any pulse shape must be obtained with just one waveform. For this particular MPPW laser, waveform 31 is the most flexible for micro-welding.

At constant q_p , $E_{SP, MPPW}$, $q_{p, peak}$, $t_{i, MPPW}$, a constant duty cycle is required to guarantee an identical thermal profile, being possible to replicate the same weld shape in different waveforms.

6 Comparison of lasers with different temporal outputs

Part of this chapter is based on the following publication:

Coroado J.*, Williams S., Suder W., Ganguly S., Meco S., Pardal G. (2022) 'New phenomenological model for comparison of lasers with different temporal outputs' *The International Journal of Advanced Manufacturing Technology*, 120, pp. 6107–6123, <https://doi.org/https://doi.org/10.1007/s00170-022-09081-8>.

6.1 Introduction

The latest generation of multi-pulse pulsed wave (MPPW) fibre lasers allows flexibility in applying energy. Low pulse energy and high peak power delivered at high frequency (kHz) are enough to generate melting from a certain overlap between pulses, despite the low laser average power. On the other hand, CW lasers are characterised by a higher average power and lower peak power than MPPW.

It was concluded in chapters 4 and 5 that the definitions of the fundamental laser-material interaction parameters (FLMIP) initially developed to control the CW welding process can also be applied in MPPW mode. This section aims to use a new model that describes the energy received by the material to compare both lasers under like-to-like conditions to understand which one gives better weld shape control, melting and penetration efficiency, and productivity for a particular application. The objectives are as follows:

- Application of similar energy and travel speed in MPPW and CW laser processing of stainless steel using a constant overlapping factor between pulses in MPPW mode.
- Application of similar energy and different travel speeds in MPPW and CW laser processing of stainless steel using a constant pulse repetition frequency in MPPW mode.
- Analysis of the weld shape, penetration and welding efficiency in both welding modes.

- MPPW and CW laser welding of stainless steel and aluminium, and correlation of the welding parameters with the material properties to achieve similar penetration depth in both metals.

6.2 Experimental procedure

6.2.1 Materials

The materials used in the experiments were 2 mm thick plates of stainless steel (SS) 304L and aluminium (Al) 5251H22. The chemical compositions of each alloy are presented in Table 3-1 and Table 3-2 in section 3.1, and their physical properties are shown in Table 6-1.

Table 6-1 Physical properties of the base materials [121] [122][129].

Property	Symbol	Units	Al 5251H22	SS304 L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Vaporisation Temperature	T_v	W.(m.K) ⁻¹	2790	3023
Thermal conductivity	k	W m ⁻¹ K ⁻¹	134	16.2
Thermal diffusivity	α	m ² s ⁻¹	5.7×10^{-5}	5.5×10^{-6}
Thermal heat capacity	q	J/Kg	390×10^3	1495.3×10^3
Modulus of Elasticity	E	GPa	70	193

6.2.2 Methodology and experimental setup

The fibre lasers used to generate bead-on-plate welds were a 100 W average output power nanosecond MPPW laser and a 500 W average output power CW laser. The MPPW enabled the change of the processing parameters (average peak power, pulse energy and pulse duration).

In this study, one waveform only, with maximum pulse energy and most prolonged pulse duration, was used, as shown in Table 6-2. The pulse shape measurement of waveform 31 for different frequencies was previously shown in Figure 4-8 in section 4.3.1, and the actual pulse energy and average peak power were also presented in Figure 4-9 in the same section. The experimental setup and the welding configuration are shown in section 3.

Table 6-2 Properties of waveform 31 of MPPW laser [126].

Waveform	Pulse duration [ns]	Pulse repetition frequency [kHz]	Average power [W]	Pulse Energy [mJ]	Peak power [kW]
wfm	P_{width}	PRF_0	P_L	E_{pulse}	-
31	500	100	100	1	7

6.2.2.1 Constant overlap factor

This section aims to investigate the effect of the MPPW laser's inter-pulse thermal losses on the weld shape, i.e. penetration depth and width, penetration and melting efficiency, and to make a comparison with CW welds under similar processing conditions.

The energy used to penetrate 1 mm of metal (P_{Eff}) was calculated as the ratio between the total applied energy (E_{SP}) and penetration depth (P_{Depth}), as given by Equation (6-1) as the process efficiency (P_{Eff}). The melting efficiency (Z_m) was calculated as the ratio between the energy per unit length required to melt the weld bead (E_m) and the total energy available per unit length (E_{SP}), as given by Equation (6-2) [129].

$$P_{Eff} = E_{SP} / P_{Depth} \text{ [J/mm]} \quad (6-1)$$

$$Z_m = \frac{E_m}{E_{SP}} * 100 \text{ [%]} \quad (6-2)$$

The heat necessary to raise one gram of steel to the melting temperature (q) is 1495.3 J/g [129] and 390 J/g for aluminium [121]. Therefore, E_m can be calculated as the product between the weight of the weld bead, which corresponds to the area of the cross-section (A_{CS}) multiplied by the weld length as the beam diameter (d), multiplied by q , as given by Equation (6-3) [129].

$$E_m = \rho * A_{CS} * d * q \text{ [J]} \quad (6-3)$$

A constant overlap factor of 99% was used in MPPW mode, and a similar range of travel speeds from 32 to 140 mm/s, average power, and beam diameter were applied in both temporal modes. The average power density was kept similar in

both laser modes, and the average peak power density and energy were varied in MPPW mode through different pulse repetition frequencies. The set of parameters used is shown in Table 6-3.

Table 6-3 MPPW and CW welding parameters at a similar range of travel speeds, average power, beam diameter, and constant overlap factor of 99% in MPPW.

MPPW laser											
Fundamental laser material interaction parameters				System parameters						Calculated Parameters	
$q_{p, peak}$	q_p	$E_{SP, MPPW}$	$t_{i, MPPW}$	PRF	v	d	P_L	E_{pulse}	P_{peak}	O_F	D_C
[MW/cm ²]	[MW/cm ²]	[mJ]	[ms]	[kHz]	[mm/s]	[μm]	[W]	[mJ]	[kW]	[%]	[%]
208	10.4	100	0.05	100	35	35	100	1.0	2.0	99	5
104	10.4	50	0.05	200	70	35	100	0.50	1.0	99	10
52	10.4	25	0.05	400	140	35	100	0.25	0.5	99	20
CW laser											
Fundamental laser material interaction parameters				System Parameters							
q_p [MW/cm ²]	$E_{SP, CW}$ [mJ]	$t_{i, CW}$ [ms]	v [mm/s]	d [μm]	P_L [W]						
10.4	100	1.0	35	35	100						
10.4	50	0.5	70	35	100						
10.4	25	0.25	140	35	100						
Note: The bold shows the similar parameters used in both MPPW and CW lasers.											

6.2.2.2 Constant frequency

At constant frequency and lower travel speed, the delivered energy by the MPPW laser can equal that of the CW laser. This section investigates the effect of the MPPW laser's processing speed on bead-on-plate stainless steel weld shape, penetration and melting efficiency. CW welds are compared at similar energy levels.

A constant frequency of 400 kHz was used in MPPW mode, and equal average peak power and beam diameter were applied in both temporal modes. Both lasers kept the average peak power density and applied energies similar. The set of parameters used is shown in Table 6-4.

Table 6-4 MPPW and CW welding parameters at a similar average peak power, beam diameter, and constant frequency of 400 kHz in MPPW.

MPPW laser											
Fundamental laser material interaction parameters				System parameters						Calculated Parameters	
E _{SP, MPPW} [mJ]	t _{i, MPPW} [ms]	q _{p, peak} [MW/cm ²]	q _p [MW/cm ²]	v [mm/s]	d [μm]	P _L [W]	PRF [kHz]	E _{pulse} [mJ]	P _{peak} [W]	O _F [%]	D _C [%]
25	0.050	8.0	1.6	356	89	100	400	0.25	500	99.0	20
125	0.25	8.0	1.6	71	89	100	400	0.25	500	99.8	20
250	0.50	8.0	1.6	35	89	100	400	0.25	500	99.9	20
500	1.0	8.0	1.6	17	89	100	400	0.25	500	99.95	20
1000	2.0	8.0	1.6	9	89	100	400	0.25	500	99.97	20
CW laser											
Fundamental laser material interaction parameters					System parameters						
E _{SP, CW} [mJ]	t _{i, CW} [ms]	q _p [MW/cm ²]		v [mm/s]		d [μm]		P _L [W]			
25	0.050	8.0		1756		89		500			
125	0.25	8.0		356		89		500			
250	0.50	8.0		178		89		500			
500	1.0	8.0		89		89		500			
1000	2.0	8.0		45		89		500			
Note: The bold shows the similar parameters used in both MPPW and CW lasers.											

6.2.2.3 Comparison between stainless steel and aluminium

MPPW and CW laser welding was applied in SS and Al to correlate the welding parameters with material properties to achieve a similar penetration depth. The set of parameters used in MPPW and CW modes is shown in Table 6-5.

Table 6-5 MPPW and CW welding parameters used in SS 304 L and Al 5251.

MPPW laser											
Fundamental laser material interaction parameters				System parameters				Calculated Parameters			
$E_{SP, \text{MPPW}}$ [mJ]	$t_{i, \text{MPPW}}$ [ms]	$q_{p, \text{peak}}$ [MW/cm ²]	q_p [MW/cm ²]	v [mm/s]	d [μm]	P_L [W]	PRF [kHz]	E_{pulse} [mJ]	P_{peak} [kW]	O_F [%]	D_C [%]
33	0.05	59	10.4	105	35	100	300	0.33	0.67	99.0	15
250	0.50	62	10.4	14	35	100	400	0.25	0.50	99.9	20
CW laser											
Fundamental laser material interaction parameters				System parameters							
$E_{SP, \text{cw}}$ [mJ]	$t_{i, \text{cw}}$ [ms]	q_p [MW/cm ²]	v [mm/s]		d [μm]	P_L [W]					
20	0.05	41.6	700		35	500					
200	0.50	41.6	70		35	500					

6.2.3 Weld shape characterisation

The weld geometry analysis was based on optical microscopy to measure the fusion zone geometry, i.e. depth of penetration and weld width. More details are presented in section 3.3.

6.3 Results and discussion

6.3.1 Constant overlap factor

If we neglect the high peak power and frequency of the MPPW laser, then it can be treated almost as a CW laser, and a direct comparison can be made. In Figure 6-1 and Figure 6-2, both lasers were compared at the same average power, travel speed and spot size. The MPPW laser gives higher penetration, but the weld profiles in Figure 6-2 show that CW welds are much larger than in MPPW. As the travel speed increases at a constant overlap factor, the weld width remains relatively stable in MPPW, with a slight deviation at 140 mm/s. Still, it decreases in CW mode eventually to reach the same low weld width as in MPPW mode. Therefore, in theory, the weld width should not change as the travel speed increases and the pulse energy decreases. Nevertheless, from 35 mm/s to 140 mm/s, the weld width of the MPPW laser is almost constant compared to CW.

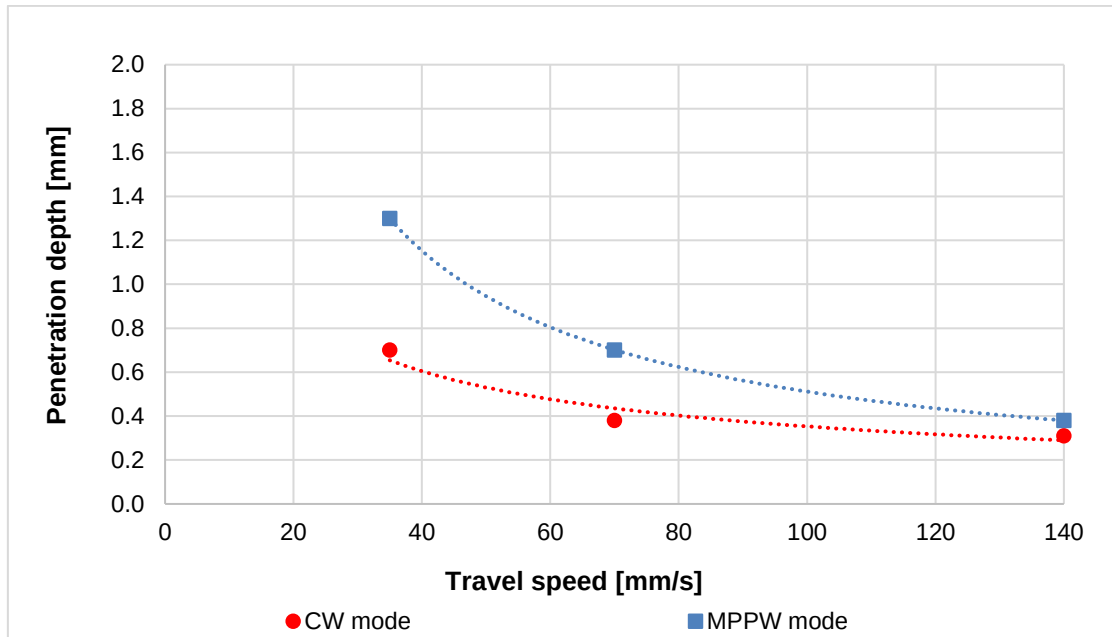


Figure 6-1 Depth of penetration in CW and MPPW laser welding at an average power of 100 W, beam diameter of 35 μm and overlap factor of 99% in MPPW.

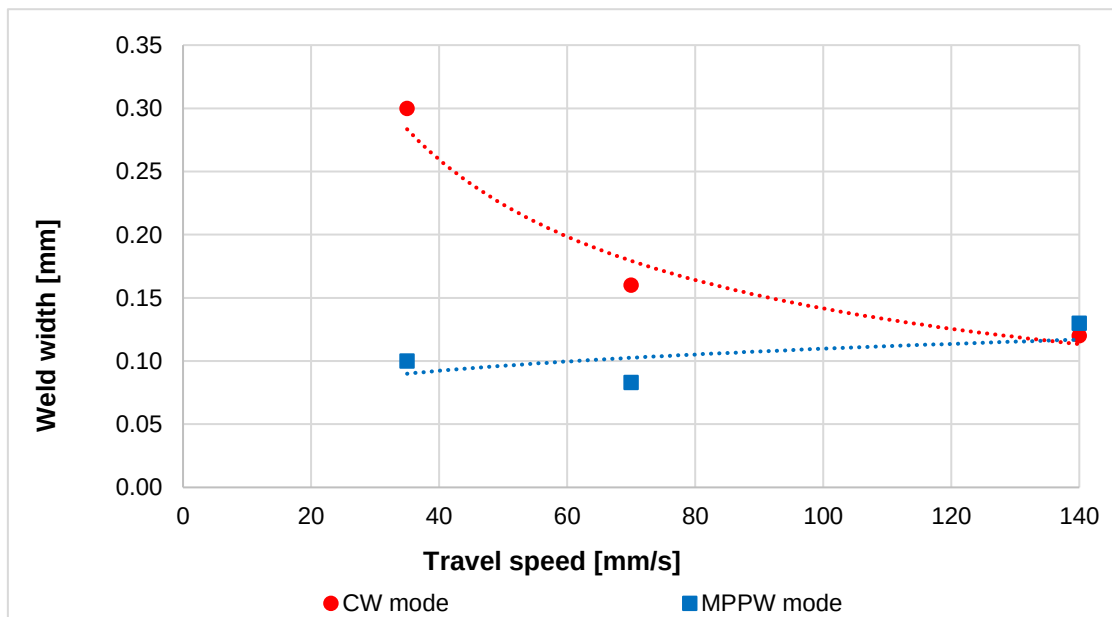


Figure 6-2 Weld width in CW and MPPW laser welding at an average power of 100W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

The micrographs of each temporal mode from Figure 6-1 and Figure 6-2 are shown in Figure 6-3 and Figure 6-4. In Figure 6-3, the thermal losses are the same in both laser modes since the travel speed is the same, but the duty cycle

of the MPPW laser is much less than the 100% in CW laser. Therefore, both definitions of interaction time capture this and explain the difference in weld width, being the wider CW weld in Figure 6-3A attributed to a higher interaction time than in MPPW mode in Figure 6-3B. This difference might also be related to the plasma plume formation, as previously explained in section 2.2.1.1. For moderate penetration achieved at a higher interaction time as shown in Figure 6-3a, the weld width is larger due to the lower keyhole angle in this regime, forming a larger and taller plasma plume erupted mainly from the top part of the weld. Therefore, the laser cannot reach the bottom of the melt pool, being most of the heat accumulated on the melt pool surface, enlarging it. On the other hand, for excessive penetration achieved at a lower interaction time in MPPW mode as shown in Figure 6-3a, a shorter plasma plume and higher keyhole angle allow a more efficient laser absorption, and consequently, a deeper and narrower weld.

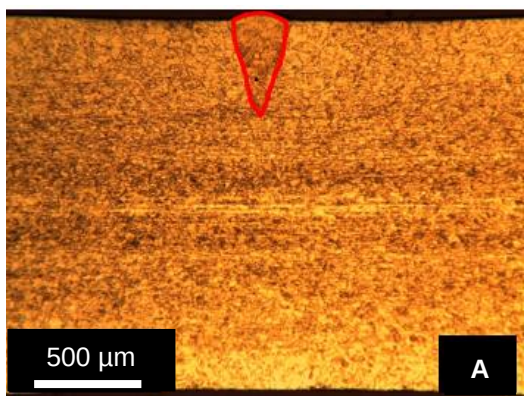
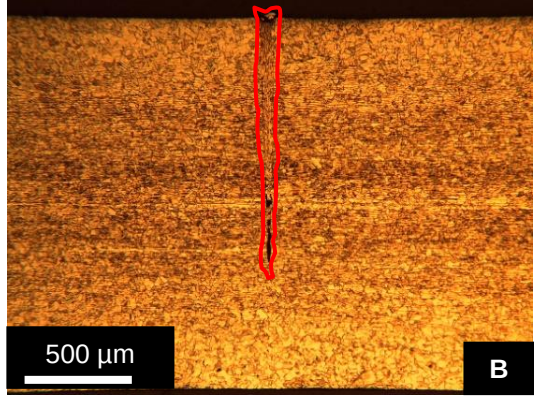
$v = 35 \text{ mm/s}$; $P_L = 100 \text{ W}$; $d = 35 \mu\text{m}$	
CW mode	MPPW mode
$q_p = 10.4 \text{ MW/cm}^2$ $E_{SP, CW} = 100 \text{ mJ}$ $t_{i, CW} = 1 \text{ ms}$	$q_{p, \text{peak}} = 208 \text{ MW/cm}^2$; $q_p = 10.4 \text{ MW/cm}^2$ $E_{SP, MPPW} = 100 \text{ mJ}$ $t_{i, MPPW} = 0.05 \text{ ms}$
	
Depth = 0.7 mm; Weld width = 0.3 mm Weld metal area = 0.12 mm ²	Depth = 1.3 mm; Weld width = 0.11 mm Weld metal area = 0.069 mm ²

Figure 6-3 CW and MPPW welds (weld boundaries delimited in red) at a travel speed of 35 mm/s, average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

From Figure 6-3 to Figure 6-4, the CW and MPPW lasers behave as normal, reducing the penetration depth with travel speed due to an energy reduction.

Despite the five times higher average peak power density in MPPW laser in Figure 6-4B, the penetration depth is almost the same as in CW laser in Figure 6-4A. This means that it is not the average peak power density but the frequency and hence the inter-pulse thermal losses that are important, as previously concluded in section 5, only for the MPPW laser. In the regime shown in Figure 6-4, the pulse energy of individual pulses is too low to generate melting, and more pulses are needed to initiate melting at a constant overlap factor. Hence the thermal losses are more important than the peak power density of individual pulses. On the other hand, fewer pulses are needed to melt in Figure 6-3B due to the higher energy per pulse, but the higher inter-pulse spacing and travel speed generated higher thermal losses than in Figure 6-4B, which explains the similar weld widths in both cases.

The weld width is similar for similar applied energy and average power in Figure 6-4A and B, despite the five-times difference in interaction time. This observation shows once again the limitation of the FLMIP as it would be expected to have a much narrower MPPW weld (Figure 6-4B) than in CW laser (Figure 6-4A). As also concluded in section 4, it is necessary to capture the inter-pulse thermal losses effect when comparing different laser temporal modes.

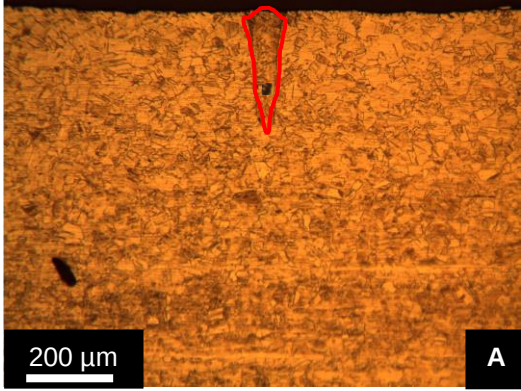
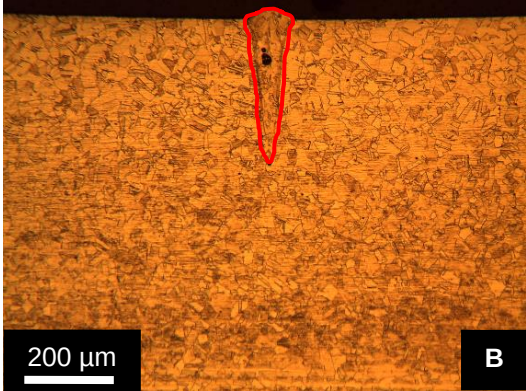
$v = 140 \text{ mm/s}$; $P_L = 100 \text{ W}$; $d = 35 \text{ }\mu\text{m}$	
CW mode	MPPW mode
$q_{p, \text{peak}} = 10.4 \text{ MW/cm}^2$ $E_{SP, \text{CW}} = 25 \text{ mJ}$ $t_{i, \text{CW}} = 0.25 \text{ ms}$	$q_{p, \text{peak}} = 52 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 10.4 \text{ MW/cm}^2$ $E_{SP, \text{MPPW}} = 25 \text{ mJ}$ $t_{i, \text{MPPW}} = 0.05 \text{ ms}$
	
Depth = 0.31 mm; Weld width = 0.13 mm Weld metal area = 0.024 mm ²	Depth = 0.38 mm; Weld width = 0.12 mm Weld metal area = 0.029 mm ²

Figure 6-4 CW and MPPW welds (weld boundaries delimited in red) at a travel speed of 140 mm/s, average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

The process and melting efficiencies from Figure 6-1 and Figure 6-2 are shown in Figure 6-5 and Figure 6-6, respectively. In MPPW mode, the higher peak power opens the keyhole more efficiently, allowing a higher process efficiency than in CW mode for similar travel speeds, as observed in Figure 6-5. However, as the frequency increases in the same proportion of travel speed to keep the overlap factor constant, the duty cycle increases in MPPW mode, decreasing the thermal losses between pulses. Thus, the process efficiency converges in both temporal modes.

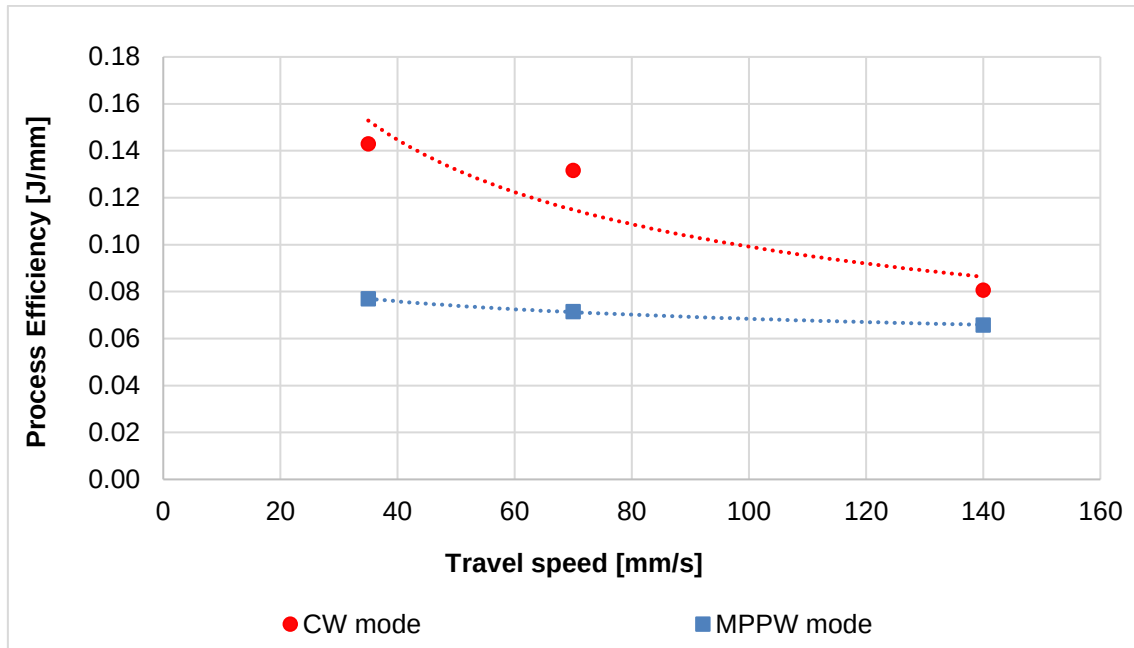


Figure 6-5 Energy to penetrate 1 mm of metal in CW and MPPW laser modes at an average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

The melting efficiency of both laser modes is shown in Figure 6-6. MPPW laser requires more energy than CW laser to melt 1 mm³ of metal at similar travel speed. As the travel speed increases, the energy needed by CW mode increases slightly since the welds become narrower and shallower. On the other hand, in MPPW mode, the weld width remains constant, but the penetration depth decreases, being the weld aspect ratio consistently higher than in CW mode. The melting and process efficiencies converge in both temporal modes as the duty cycle of MPPW mode increases and the inter-pulse thermal losses decrease, becoming similar for higher travel speeds. This observation clearly shows the need to reformulate the laser-material interaction time definition to account for the heat dissipation between pulses.

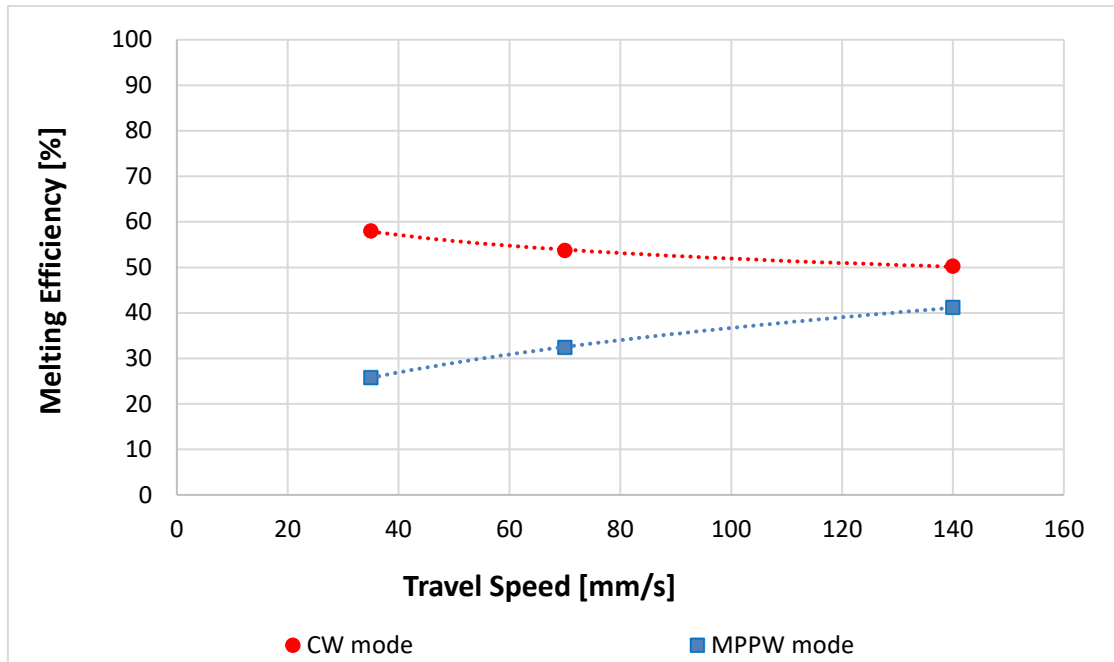


Figure 6-6 Melting efficiency of CW and MPPW laser modes at an average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

6.3.2 Constant frequency

A comparison between CW and MPPW seam welding is shown in Figure 6-7 and Figure 6-8 at different travel speeds and similar average peak power and beam diameter. The penetration depth and weld width decrease as the travel speed increases in both welding modes. Since the frequency is kept constant in MPPW mode, the duty cycle and the energy delivered per pulse remained constant, being the thermal losses constant as well.

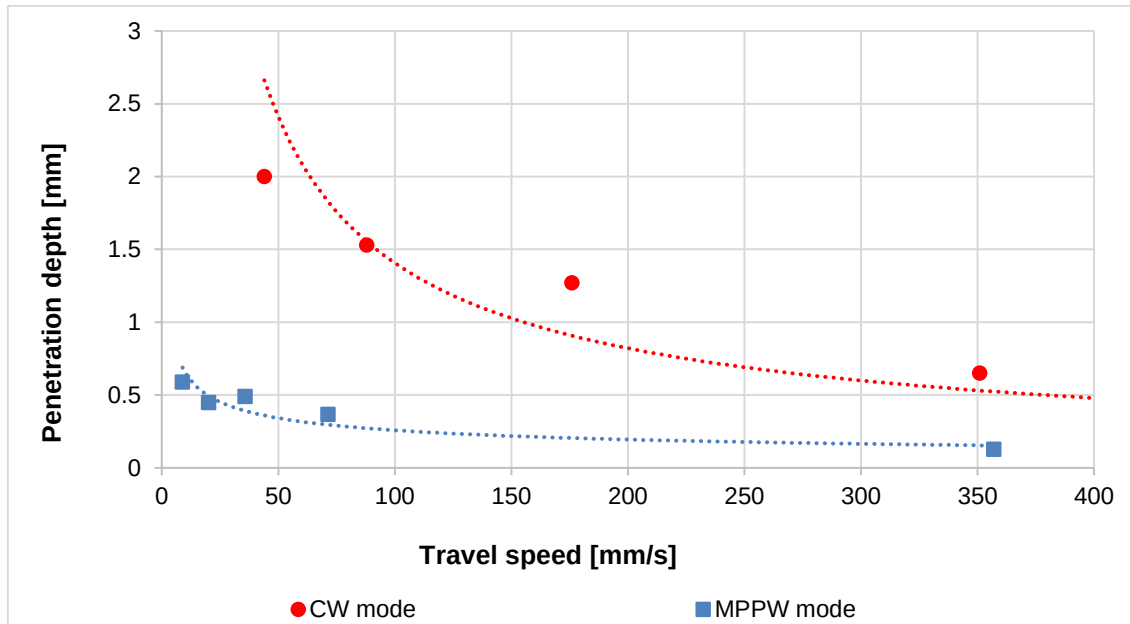


Figure 6-7 Depth of penetration in CW and MPPW laser welding at an average peak power of 500 W and a constant frequency of 400 kHz in MPPW.

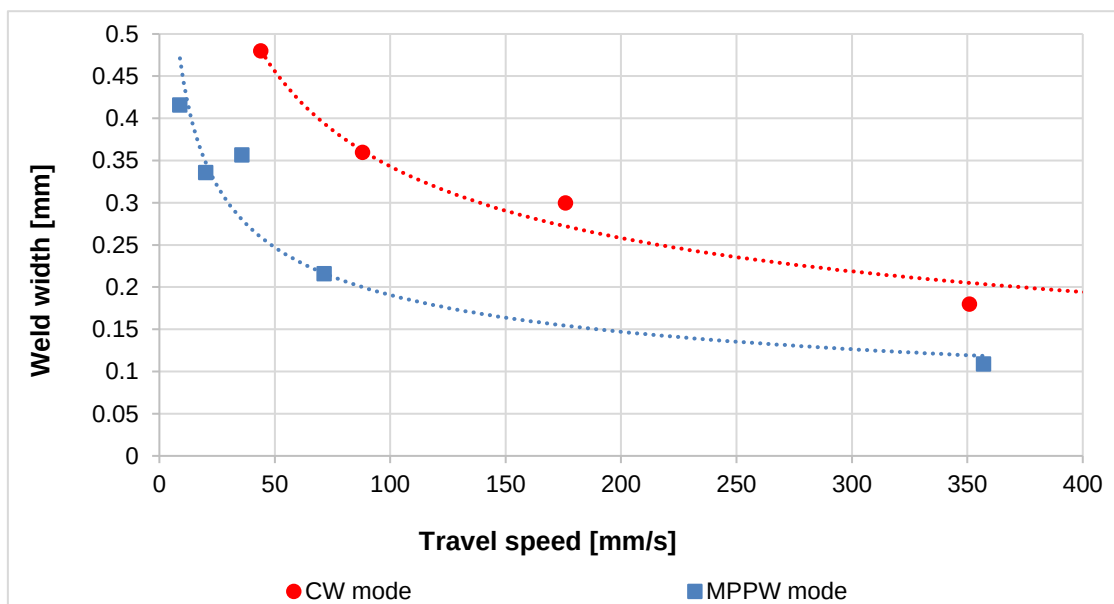


Figure 6-8 Weld width in CW and MPPW laser welding at an average peak power of 500 W and a constant frequency of 400 kHz in MPPW.

A micrograph of each temporal mode from Figure 6-7 and Figure 6-8 is shown in Figure 6-9. The reduction in travel speed at a constant frequency in MPPW mode allowed energy to build up to the same level as in CW mode. However, it is shown in Figure 6-9B for MPPW laser that the thermal losses are higher in this regime since the penetration depth is shallower and the weld width is larger than in CW

mode in Figure 6-9A. This is a limitation of the current definition of interaction time in MPPW mode, as it should be expected to have a similar weld width as in CW mode for an equal interaction time.

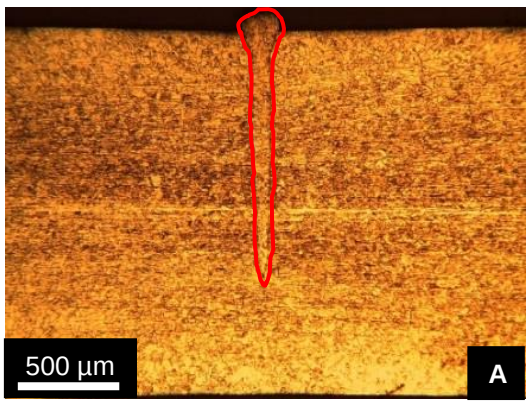
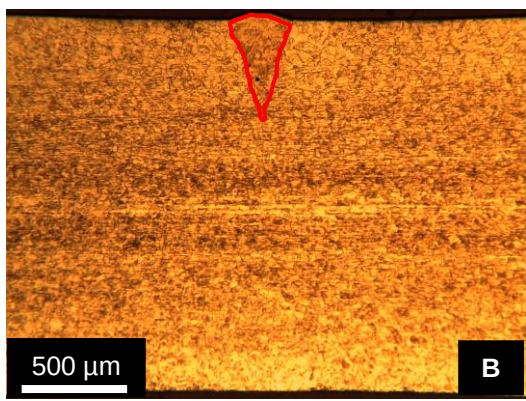
$P_{\text{peak}} = 500 \text{ W}$; $d = 89 \mu\text{m}$	
CW mode	MPPW mode
$v = 178 \text{ mm/s}$; $P_L = 500 \text{ W}$	$v = 35.6 \text{ mm/s}$; $\text{PRF} = 400 \text{ kHz}$; $P_L = 100 \text{ W}$
$q_p = 8 \text{ MW/cm}^2$ $E_{\text{SP, CW}} = 250 \text{ mJ}$	$q_p = 1.6 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 8 \text{ MW/cm}^2$ $E_{\text{SP, MPPW}} = 250 \text{ mJ}$
$t_{i, \text{CW}} = 0.5 \text{ ms}$	$t_{i, \text{MPPW}} = 0.5 \text{ ms}$
	
Depth = 1.3 mm; Weld width = 0.20 mm Weld metal area = 0.15 mm ²	Depth = 0.55 mm; Weld width = 0.29 mm Weld metal area = 0.082 mm ²

Figure 6-9 CW and MPPW (weld boundaries delimited in red) at an average peak power of 500 W, beam diameter of 89 μm and a frequency of 400 kHz in MPPW.

The process and melting efficiencies from Figure 6-7 and Figure 6-8 are presented in Figure 6-10 and Figure 6-11, respectively. The energy required in MPPW laser to melt 1 mm³ and penetrate 1 mm of metal is always higher than CW until a certain travel speed. Both temporal modes start converging, as observed in the previous section. Due to the lack of average power in MPPW laser compared to CW mode, reducing the travel speed to achieve similar interaction time and, consequently, equal applied energy, is inefficient. This conclusion agrees with the observations of Figure 4-13 shown previously in section 4.3.1, where the potential limitations of this MPPW laser in vaporising metal were highlighted.

The thermal losses are more intense in MPPW mode for low travel speeds, and the required energy to penetrate and melt the metal increases exponentially in comparison to CW mode. Assuncao and Williams [73] observed opposite results

to the ones shown in Figure 6-10. According to them, the penetration efficiency is higher in PW than in CW mode. However, they compared spot welds in SPPW with seam welds in CW mode, which may have had an impact on the results due to the different melt pool dynamics. The SPPW laser was stationary, and the interaction time was equal to the pulse width, being the total energy uniquely delivered in a single spot. On the other hand, the beam in CW mode was in movement, and part of the energy was also used to heat the substrate for a certain weld length, being consequently lost and the penetration depth lower.

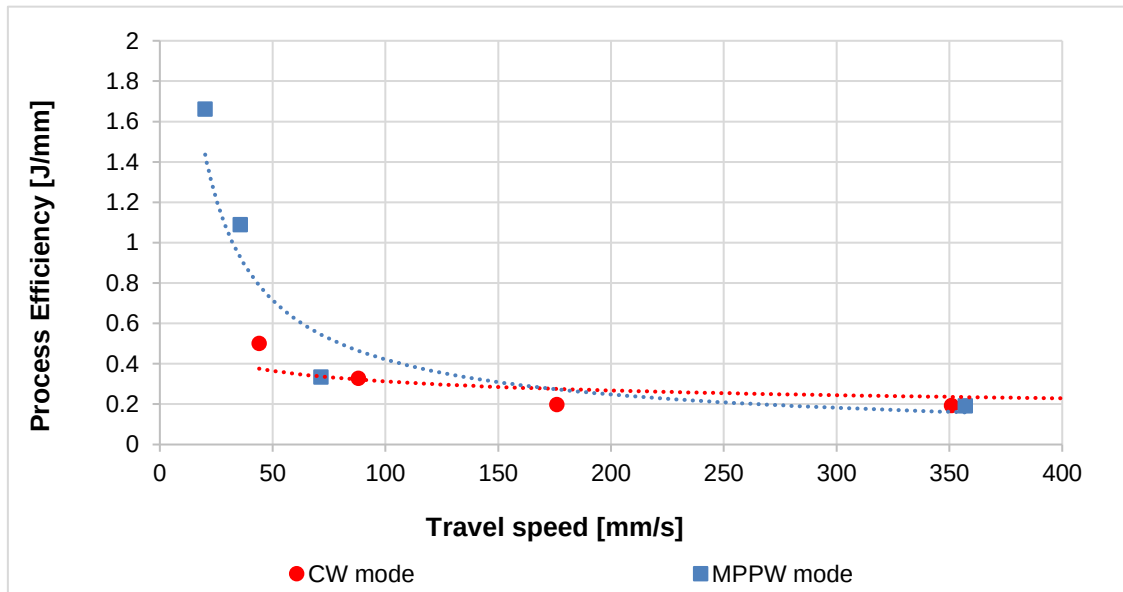


Figure 6-10 Process efficiency in CW and MPPW laser modes at an average peak power of 500 W, beam diameter of 89 μm and a constant frequency of 400 kHz in MPPW.

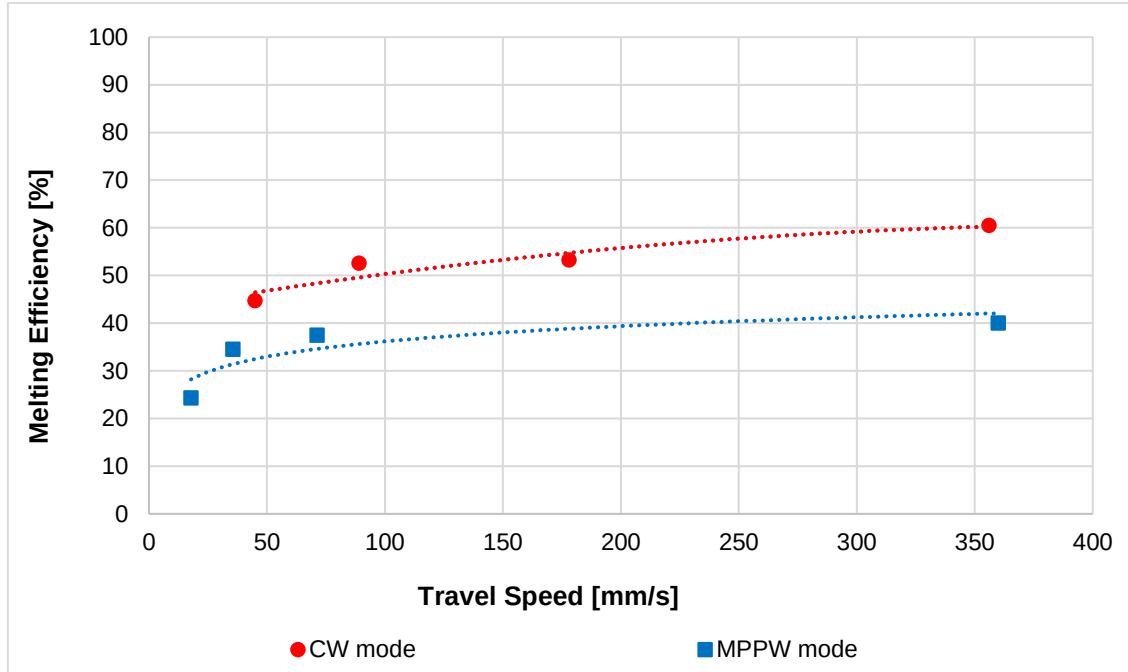


Figure 6-11 Melting efficiency in CW and MPPW laser modes at an average peak power of 500 W, beam diameter of 89 μm and a constant frequency of 400 kHz in MPPW.

6.3.3 Comparison between stainless steel and aluminium

The intrinsic differences in physical properties between SS and Al (Table 6-1) create some challenges in the process application [64]. This section compares both metals' melting and penetration efficiency in CW and MPPW laser processing for similar penetration depths.

Figure 6-12 shows two SS and Al MPPW welds for a similar penetration depth of 0.5 mm. Al requires more energy to melt the same volume of molten metal than SS, being the melting efficiency much lower. This phenomenon can be attributed to the heat dissipation between pulses associated with the material's thermal properties. The higher thermal conductivity of Al facilitates heat dissipation compared to SS. Most of it is dissipated between pulses, and more energy is required to achieve similar penetration depth. On the other hand, the lower thermal conductivity of SS allows it to store each pulse's energy more efficiently.

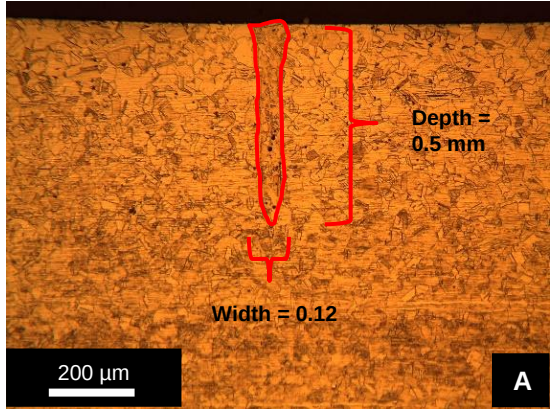
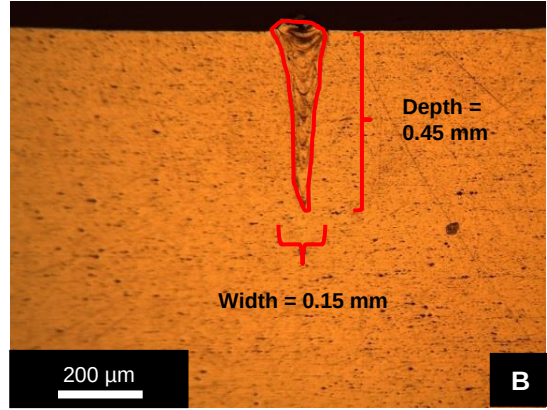
MPPW mode ($d = 35 \mu\text{m}$); $P = 100\text{W}$	
SS 304 L	Al 5251
$v = 105 \text{ mm/s}$; PRF = 300 kHz	$v = 14 \text{ mm/s}$; PRF = 400 kHz
$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 59 \text{ MW/cm}^2$ $E_{\text{SP, MPPW}} = 33 \text{ mJ}$	$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 62 \text{ MW/cm}^2$ $E_{\text{SP, MPPW}} = 250 \text{ mJ}$
$t_{i, \text{MPPW}} = 0.050 \text{ ms}$	$t_{i, \text{MPPW}} = 0.50 \text{ ms}$
	
Depth = 0.5 mm; Weld width = 0.12 mm Weld metal area = 0.028 mm^2	Depth = 0.45 mm; Weld width = 0.15 mm Weld metal area = 0.035 mm^2
Melting efficiency = 35 %	Melting efficiency = 5.1 %

Figure 6-12 Micrographs of MPPW welds (weld boundaries delimited in red) of SS 304 L and Al 5251 at a similar penetration depth of 0.5 mm.

In Figure 6-13, the melting efficiency of CW mode to achieve the same penetration depth of 0.5 mm as in MPPW mode in Figure 6-12 is much higher, which can be attributed to the lower thermal losses in CW mode caused by a duty cycle of 100%. However, similar weld shapes can be observed, which means that from the material perspective, the FLMIP should control the process in both laser temporal modes if the overall utilised energy is correctly quantified considering the thermal losses and material's properties. Nevertheless, with the current FLMIP definitions, it is impossible to predict the welding parameters of such weld shapes without trial and error.

In Figure 6-13A, SS needed more energy per unit of weld metal volume than Al in Figure 6-13B to reach similar penetration efficiency. The continuous heat dissipation was used to enlarge Al's melt pool, being larger than in SS. The fact that SS (i.e. iron) has a higher melting and vaporisation point, lower thermal conductivity and diffusivity than Al made it difficult for the keyhole to achieve a

similar size. In Figure 6-14, the penetration is higher in SS than in Al for a higher energy level, but the weld metal volume for the same applied energy is still lower. Similar observations have been found in a previous study [8]. The authors concluded that the material's thermal conductivity assumed less relevance for lower energy levels in CW laser welding of Al and steel. The melting temperature was the most important physical property to consider in this regime. On the other hand, Al's capacity to dissipate heat was much higher than steel for higher energy levels, and the thermal conductivity overtakes the melting temperature as the most critical property in controlling the process [8].

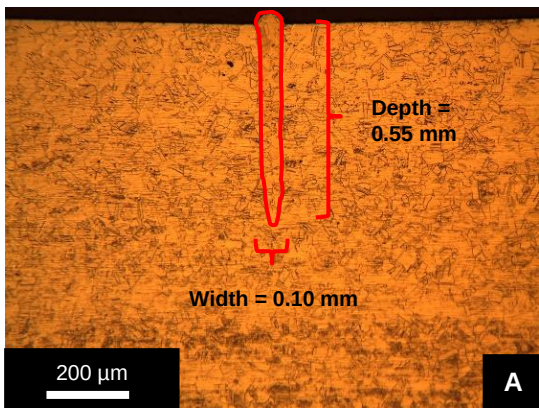
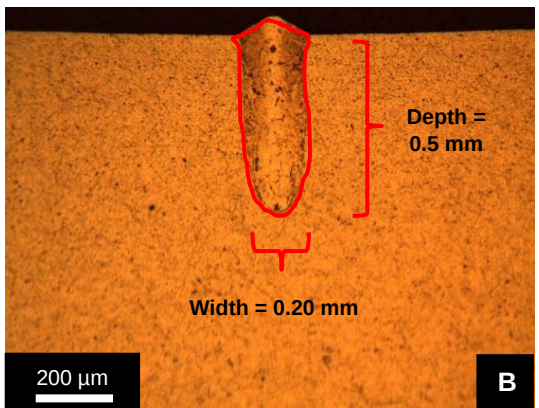
CW mode ($d = 35 \mu\text{m}$); $P_L = 400 \text{ W}$; $v = 700 \text{ mm/s}$	
$q_p = 41.6 \text{ MW/cm}^2$; $E_{SP, CW} = 20 \text{ mJ}$; $t_{i, CW} = 0.050 \text{ ms}$	
SS 304 L	Al 5251
	
Depth = 0.55 mm; Weld width = 0.1 mm Weld metal area = 0.028 mm^2	Depth = 0.5 mm; Weld width = 0.2 mm Weld metal area = 0.069 mm^2
Melting efficiency = 59 %	Melting efficiency = 13 %

Figure 6-13 Micrographs of CW welds of SS 304 L and Al 5251 at similar penetration depth of 0.5 mm.

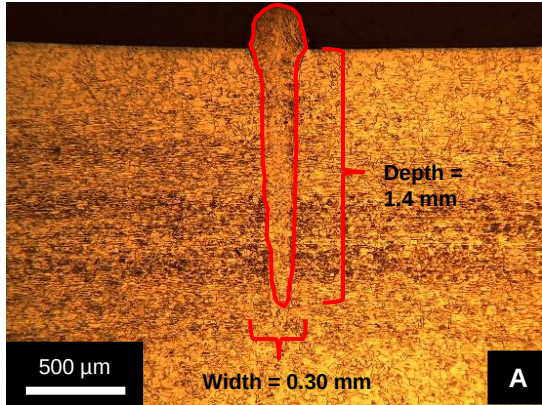
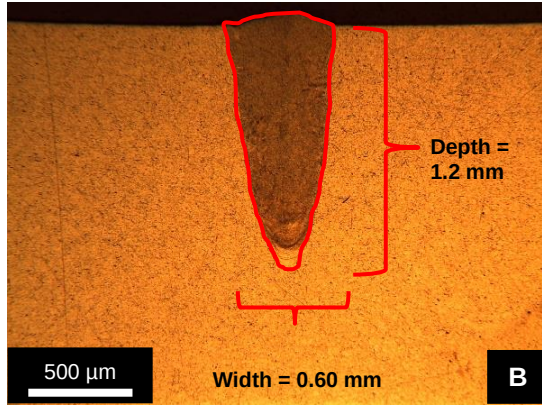
CW mode ($d = 35 \mu\text{m}$); $P_L = 400 \text{ W}$; $v = 70 \text{ mm/s}$	
$q_p = 41.6 \text{ MW/cm}^2$; $E_{SP, CW} = 200 \text{ mJ}$; $t_{i, CW} = 0.50 \text{ ms}$	
SS 304 L	Al 5251
	
Depth = 1.3 mm; Weld width = 0.3 mm Weld metal area = 0.25 mm^2	Depth = 1.2 mm; Weld width = 0.6 mm Weld metal area = 0.48 mm^2
Melting efficiency = 52 %	Melting efficiency = 8.8 %

Figure 6-14 Micrographs of CW welds (weld boundaries delimited in red) of SS 304 L and Al 5251 for a beam diameter of $35 \mu\text{m}$, average power of 400 W and travel speed of 70 mm/s.

6.4 Summary of discussions

There is a clear difference between laser temporal modes depending on what is being compared. The energy utilised for melting the material is higher for CW laser because it is operated at the optimum parameters range used in micro-welding (high travel speeds and high average power). Therefore, the CW laser allows low thermal losses, having higher melting efficiency than the MPPW laser.

The nanosecond MPPW works like ultra-short lasers, almost as in a drilling regime [33], generating low melting and high aspect ratio welds. The process efficiency is higher than in CW mode. Nevertheless, the new MPPW lasers don't provide the maximum energy for all ranges of frequencies because of the resonator's response above a particular critical frequency (PRF_0) and pulse duration. The pulse energy and peak power are higher for lower frequencies closer to PRF_0 . Still, the inter-pulse spacing is more prolonged, increasing the thermal losses between pulses and the required energy to achieve deeper and wider welds.

For high frequencies above PRF_0 , the pulse energy and peak power are decreased to avoid overheating the diodes [126]. The pulse shape becomes almost flat, as also previously observed in Figure 4-13 from section 4.3.1, reducing the energy available to penetrate and melt more of the base metal. Therefore, the lower average power of the MPPW laser in comparison to the CW laser is its most significant limitation, providing lower melting efficiency regardless of the frequency or travel speed used. The benefit of the much higher average peak power density of the MPPW laser is only relevant for very specific applications where high aspect ratio welds and low heat input are required to minimise the heat-affected zone, such as in the manufacturing of biomedical devices, orthopaedic and prosthetics [34]. However, if the application requires high productivity and good fit-up tolerance, such as welding of battery packs for electric vehicles [35], then the advantage of the higher average power available in the CW laser must be utilised, providing superior performance to the MPPW laser.

CW and MPPW laser processing modes showed different interactions with the material in micro seam welding. The following conclusions can be drawn:

- It is possible to compare both modes considering the energy applied to the material.
- The inter-pulse spacing is as essential as the overlap factor in MPPW mode.
- The average peak power density in MPWW mode can be neglected for similarly applied energies. Several pulses are needed to initiate melting at a constant overlap factor. Hence, thermal losses are more important than the high peak power of an individual pulse.
- The process efficiency of the MPPW laser is only higher than CW for low frequencies close to PRF_0 . However, the melting efficiency of the MPPW laser is lower.
- The melting and process efficiency of the MPPW laser converge with CW as the thermal losses become similar for high travel speeds and low inter-pulse spacing.

- For similar penetration depth, CW welding of Al requires less energy per unit of weld metal volume than SS, whereas the opposite was verified in MPPW mode.
- The formulae of the fundamental laser-material interaction parameters are limited as they don't consider the thermal losses between pulses and the material's properties.

7 Selection of processing parameters in CW micro-welding

This chapter is based on the following publication:

Coroado J.*, Ganguly S., Suder W., Williams S., Meco S., Pardal G. (2020) 'Selection of processing parameters in laser microwelding. Part 1: Continuous wave (CW) mode', *Lasers in Engineering*, 46(5-6), pp. 265–284.

7.1 Introduction

In laser welding applications, the weld profile is linked to the heat source's characteristics and the processing conditions. A phenomenological model that specifies the fusion zone's penetration depth and width can help achieve the desired welding parameters.

Usually, the parameters optimisation is based on the trial and error approach and can only be applied to a specific laser system characterised by a unique beam diameter. When transferred to another system with a different optical setup, this approach must be repeated until the suitable parameters are found again, which is very time consuming and expensive. In laser micro-welding, the laser spot size may influence the joint's melt pool dynamics. The ratio between the beam diameter and the material thickness is much smaller than in macro welding.

The power factor model, previously validated in CW macro seam welding of mild steel [76] and aluminium [8], has been tested in this section for micro-welding. using laser beam diameters 10x smaller than in previous studies. The interdependence between laser output power, travel speed and beam diameter was summarised in this model, optimising the system parameters for a specific application.

7.2 Experimental procedure

7.2.1 Materials

The materials used in the experiments were 2 mm thick plates of stainless steel (SS) 304 L and aluminium (Al) 5251H22. Their physical properties are shown in Table 7-1.

Table 7-1 Physical properties of the base materials [121][122].

Property	Symbol	Units	Al 5251 H22	SS 304 L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Vaporisation Temperature	T_v	K	2790	3023
Viscosity	η	m.Pas	1.3	8.0
Thermal conductivity	k	W m ⁻¹ K ⁻¹	134	16.2
Thermal diffusivity	α	m ² s ⁻¹	5.7×10^{-5}	5.5×10^{-6}
Modulus of Elasticity	E	GPa	70	193

7.2.2 Methodology and experimental setup

Bead-on-plate welds were produced using a 500 W average output power CW laser. The experimental setup and joint dimensions were already shown in section 3.1.3.

The interaction time and power factor's effect on the penetration depth were investigated with different beam diameters: 35 μm , 59 μm and 89 μm . Various combinations of laser power and travel speed were used for each beam diameter, producing a range of interaction times from 0.01 to 50 ms and power factors from 1.7 to 13.8 MW/m. The set of parameters used in both Al and SS is shown in Table 7-2. The weld shape, i.e. depth of penetration and weld width, was measured in all the experiments performed. Nevertheless, only some penetration depths were selected and presented to make a more straightforward results representation.

Table 7-2 Set of parameters applied in CW processing of SS 304 L and Al 5251 for different combinations of power factor and interaction time.

Beam diameter [μm]	Power Factor [MW/m]	Interaction time [ms]	Power [W]	Travel Speed [mm/s]	Average Power Density [MW/cm ²]	Specific Point Energy [mJ]
d	$P_{F, CW} = P_L/d$	$t_{i, CW} = d/v$	P_L	v	$q_p = P_L/A_S$	$E_{SP, CW} = q_p * t_{i, CW} * A_S$
35	1.7 - 13.8	0.01 – 13.8	58 - 472	2.0 - 3218	6.0 - 52	2.0 - 4000
59	3.1 - 7.8	0.05 - 50	195 - 439	6.0 - 1366	6.0 - 14	20 - 2771
89	4.5 - 5.6	0.05 – 8.0	396 - 494	11 – 1756	6.0 – 8.0	20 - 3950

7.2.3 Weld shape characterisation

The experimental error of the process was calculated based on two welds with similar conditions: one at the beginning (A) and another at the end (B) of the weld seam, which runs onto and off the sample, as shown in the Figure 7-1. The microstructural analysis was based on optical microscopy to measure the fusion zone geometry, i.e. depth of penetration and weld width. More details are presented in section 3.3.

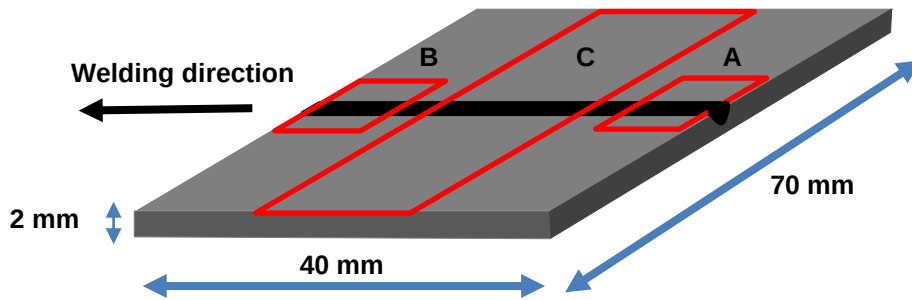


Figure 7-1 Schematic representation of the samples A and B extracted from the bead-on-plate welds for metallography analysis, and sample C for mechanical testing.

7.3 Results and discussion

7.3.1 Effect of interaction time and power factor on stainless steel

In Figure 7-2 and Figure 7-3, the penetration depth is shown as a function of power factor and interaction time using different focal spot diameter. Constant penetration is demonstrated in SS for constant interaction times but only for specific spot sizes, above which there is a discrepancy. For a beam diameter of 35 μm , at 0.25 ms, the penetration depth is lower than larger beams of 59 and 89 μm diameter. This difference is even more evident for a longer interaction time of 1 ms. However, there is almost no penetration depth variation for the shortest interaction time of 0.125 ms.

For the welding parameters tested, the energy losses rate went up with the reduction of beam diameter, which influenced the keyhole formation. It is known that the higher power densities achieved with smaller beam diameters attenuate the laser beam in the vapour plume [130] and create an intense closing force of the surface tension due to the narrow keyhole diameter [64]. This phenomenon can also be attributed to the laser energy absorption rate, which is affected by the beam diameter, low laser power and fast processing speeds, reducing the vapour pressure and consequently, the penetration depth [64].

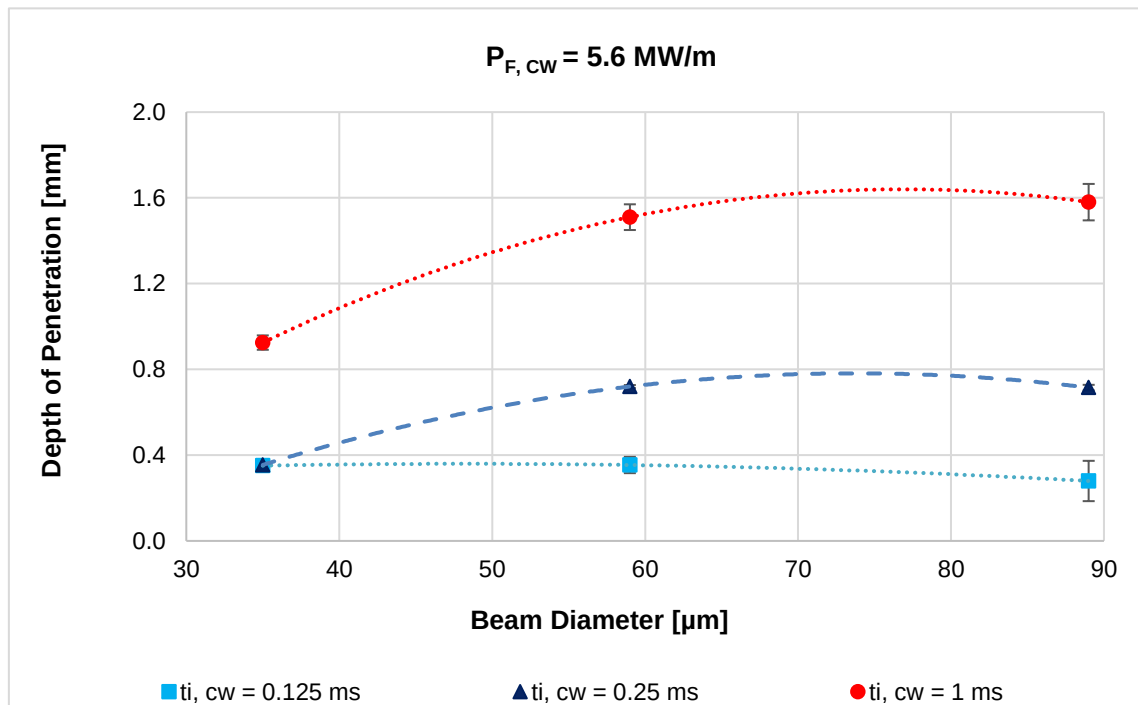


Figure 7-2 Effect of the beam diameter on the penetration depth of CW processing of SS at different interaction times and constant power factor of 5.6 MW/m.

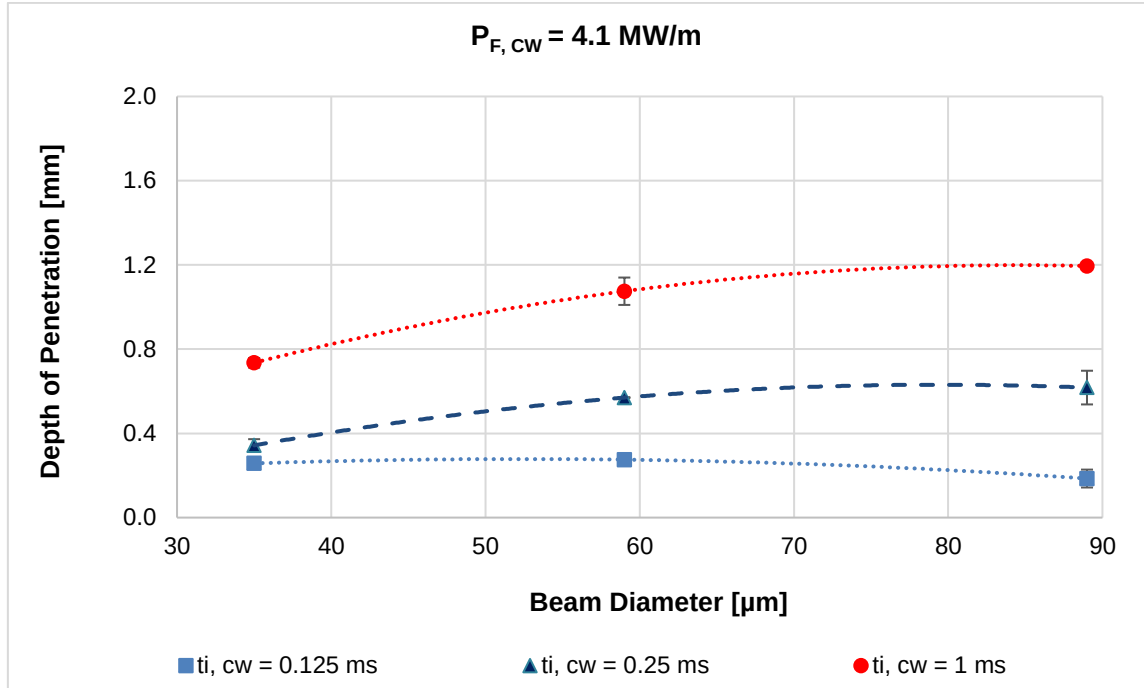


Figure 7-3 Effect of the beam diameter on the penetration depth of CW processing of SS at different interaction times and a constant power factor of 4.1 MW/m.

In CW laser welding, the penetration depth is controlled by the power density (q_p) and the specific point energy ($E_{SP, CW}$). The first parameter is dependent on the beam diameter as $1/d^2$, whilst the specific point energy is linearly proportional with the beam diameter [70]. Therefore, as a net result, the penetration depth is inversely proportional to the beam diameter. The power factor model works on this basis: a trade-off between the power density and the specific point energy maintains the penetration depth when the beam diameter is changed [70].

The specific point energies and power densities from Figure 7-2 have been calculated and plotted in Figure 7-4. As shown in Figure 7-4, decreasing the beam diameter at a constant power factor and interaction time increases power density and reduces specific point energy. For a power factor of 5.6 MW/m and an interaction time of 1.0 ms, a reduction of the beam diameter from 89 μm to 35 μm leads to a reduction in specific point energy from 500 J to 200 J (150%) and an increase in power density from 8.0 MW/cm² to 20 MW/cm² (150%). An increase in q_p equally compensates the reduction in $E_{SP, CW}$ and keeps the trade-off within

an optimum processing window. Nevertheless, there is a limit from where this trade-off doesn't work.

For a constant power factor of 5.6 MW/m and interaction times of 1.0 ms and 0.25 ms, penetration depth remains similar for beam diameters of 89 μm and 59 μm (Figure 7-2). In contrast, it decreases considerably when a spot size of 35 μm is used. The difference in penetration depth reached up to 110% for longer interaction times, which means the power factor model is not valid in this range. This observation can be explained by the higher thermal losses that a small beam diameter of 35 μm beam diameter is subjected to when a long interaction time of 1 ms is applied to the material. However, the difference in penetration is not visible in a beam diameter of 35 μm and an interaction time of 0.125ms (Figure 7-2 and Figure 7-3) as the travel speed is much higher, being the process more efficient in this regime with lower thermal losses.

In Figure 7-4, for a beam diameter of 35 μm , despite the high power density of 20 MW/cm², it is still not enough to compensate for the intense heat dissipation of the low applied energy, leading to a reduction of penetration depth when compared to larger beams. Similar results have been observed by Ayoola et al. They found that the ratio of energy for conduction losses to the energy for melting increases for small beam diameters [71]. The power factor model's limitations have also been observed in a previous study [70]. For constant power factor and high interaction time values, the higher specific point energy in larger beam diameter provided deeper welds compared to the higher power density in smaller beam diameter. The author attributed these observations to the significant fluctuation of penetration depth and weld width caused by the keyhole instabilities due to the large melt pool [70].

This study used a 5 mm copper backing bar underneath the substrate, as shown in Figure 3-3 from section 3, which might have influenced the results. As the laser's drilling force increases with the power density, the penetration depth gets closer to the copper heat sink, increasing the thermal losses. It may also explain why for lower interaction time and energy levels (Figure 7-4), the difference in penetration depth between beam diameters did not exceed the experimental

error of 10% (Figure 7-2). In Figure 7-4, despite reducing interaction time from 1.0 to 0.125 ms and the consequent decrease of specific point energy, the power density remained constant for each beam diameter. It shows that, for lower interaction times, the power density is high enough to compensate for the thermal losses caused by the variation of the applied energy and sufficient to achieve deep welds, avoiding the intense heat sinking effect caused by the copper backing bar.

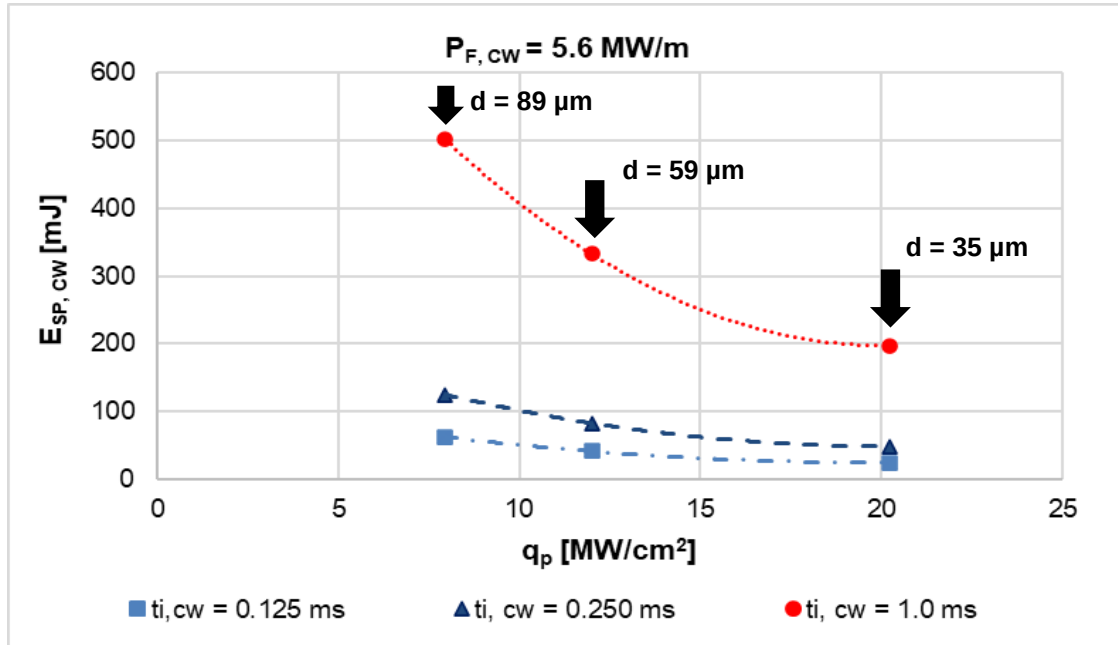


Figure 7-4 Specific point energy ($E_{SP, CW}$) versus power density (q_p) of CW welding of SS at different interaction times and constant power factor of 5.6 MW/m.

Figure 7-5 and Figure 7-6 show the weld profiles obtained using power factors of 5.6 and 4.1 MW/m from Figure 7-2 and Figure 7-3, respectively. The corresponding processing parameters are shown in Table 7-3.

Comparing micrographs 7-2 and 7-3 with micrographs 7-5 and 7-6 from Figure 7-5, the penetration depth and weld width increase as the interaction time increases at a constant power factor. According to Figure 7-4, $E_{SP, CW}$ is dependent on $t_{i, CW}$. Therefore, for longer $t_{i, CW}$, $E_{SP, CW}$ is also higher, and more penetration can be expected when q_p is kept constant. Decreasing the power factor from 5.6 MW/m to 4.1 MW/m for an interaction time of 1 ms, as shown in

micrographs 7-8, 7-9, 7-11 and 7-12 from Figure 7-6, the depth of penetration decreased from approximately 1.6 mm to 1.2 mm.

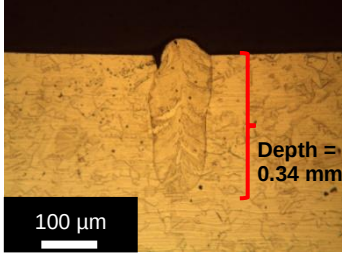
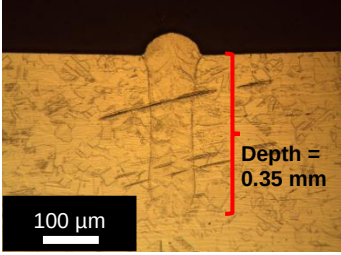
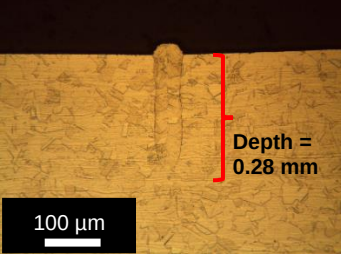
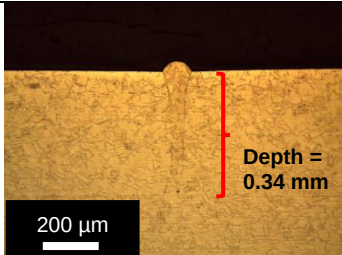
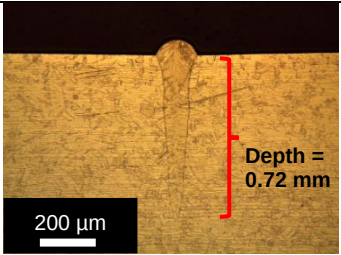
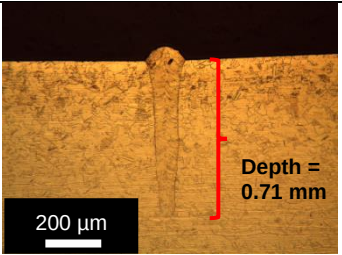
d = 35 μm	d = 59 μm	d = 89 μm
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 0.125 \text{ ms}$		
Micrograph 7-1	Micrograph 7-2	Micrograph 7-3
$P_L = 195 \text{ W}$, $v = 280 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 467 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 703 \text{ mm/s}$
		
Depth = 0.34 mm; Width = 0.13 mm	Depth = 0.35 mm; Width = 0.11 mm	Depth = 0.28 mm; Width = 0.11 mm
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 0.250 \text{ ms}$		
Micrograph 7-4	Micrograph 7-5	Micrograph 7-6
$P_L = 195 \text{ W}$, $v = 138 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 233 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 351 \text{ mm/s}$
		
Depth = 0.34 mm; Width = 0.14 mm	Depth = 0.72 mm; Width = 0.17 mm	Depth = 0.71 mm; Width = 0.16 mm

Figure 7-5 Constant combinations of power factor of 5.6 MW/m and interaction times of 0.125 ms and 0.250 ms for different weld depths in CW welding of stainless steel.

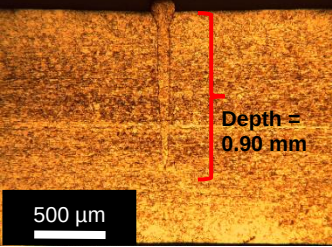
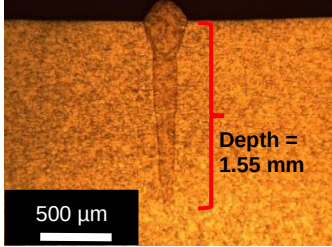
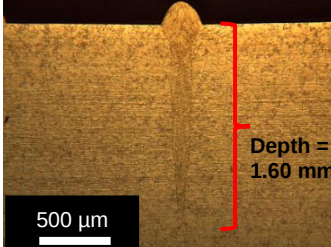
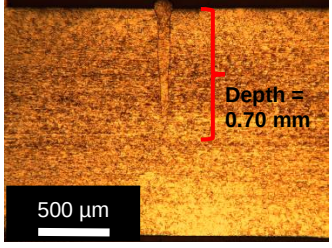
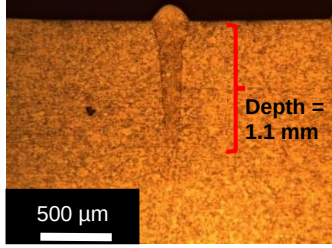
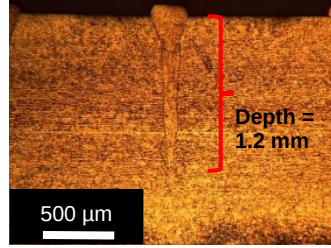
$d = 35 \mu\text{m}$	$d = 59 \mu\text{m}$	$d = 89 \mu\text{m}$
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 1.00 \text{ ms}$		
Micrograph 7-7	Micrograph 7-8	Micrograph 7-9
$P_L = 195 \text{ W}$, $v = 35 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 58 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 88 \text{ mm/s}$
		
Depth = 0.90 mm; Width = 0.35 mm	Depth = 1.55 mm; Width = 0.30 mm	Depth = 1.60 mm; Width = 0.30 mm
$P_{F, CW} = 4.1 \text{ MW/m}$; $t_{i, CW} = 1.00 \text{ ms}$		
Micrograph 7-10	Micrograph 7-11	Micrograph 7-12
$P_L = 144 \text{ W}$, $v = 35 \text{ mm/s}$	$P_L = 242 \text{ W}$, $v = 58 \text{ mm/s}$	$P_L = 364 \text{ W}$, $v = 88 \text{ mm/s}$
		
Depth = 0.70 mm; Width = 0.29 mm	Depth = 1.1 mm; Width = 0.30 mm	Depth = 1.2 mm; Width = 0.26 mm

Figure 7-6 Constant combinations of power factors of 5.6 and 4.1 MW/m and interaction time of 1.0 ms for different weld depths in CW welding of stainless steel.

Table 7-3 Set of power factors and interaction times for beam diameters of 35, 59 and 89 μm , and corresponding processing parameters applied in CW laser welding of SS 304 L.

Beam diameter [μm]	Power Factor [MW/m]	Interaction time [ms]	Power [W]	Travel speed [mm/s]	Specific point energy [mJ]	Power density [MW/cm ²]	Micrograph
d	$P_{F, CW}$	$t_{i, CW}$	P_L	v	$E_{SP, CW}$	q_p	
35	5.6	0.125	195	280	24	20	7-1
59	5.6	0.125	328	467	41	12	7-2
89	5.6	0.125	495	703	62	8	7-3
35	5.6	0.250	195	138	49	20	7-4
59	5.6	0.250	328	233	83	12	7-5
89	5.6	0.250	495	351	125	8	7-6
35	5.6	1	195	35	197	20	7-7
59	5.6	1	328	58	332	12	7-8
89	5.6	1	495	88	501	8	7-9
35	4.1	1	144	35	144	15	7-10
59	4.1	1	242	58	242	9	7-11
89	4.1	1	364	88	364	6	7-12

Different combinations of laser power, travel speed and beam diameters were tested to generate further power factor and interaction time combinations for several penetration depths. In Figure 7-7, constant penetration depth curves against interaction time and power factor can be seen. However, due to the variation in penetration depth for a spot size of 35 μm , as previously observed in Figure 7-2 and Figure 7-3, this beam diameter was not included in this graph for interaction times above 0.125 ms. A relationship between power factor and interaction time can be observed in micro-welding, as previously demonstrated in macro-welding using beam diameters 10x larger than those in this study [76][8]. Some micrographs from Figure 7-7 are shown in Figure 7-8. For a constant depth of penetration of 1.6 mm, the weld width is narrow for a high power factor and short interaction time (Figure 7-8A). It becomes wider for a higher interaction time and lower power factor (Figure 7-8C).

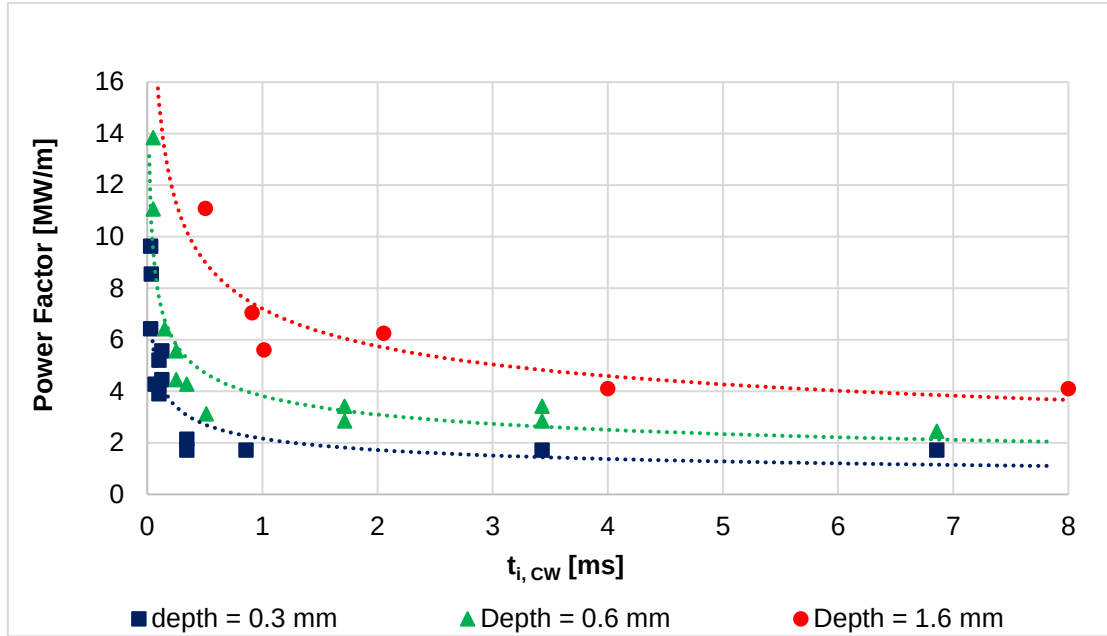


Figure 7-7 Power factor for penetration depths of 0.3 mm, 0.6 mm and 1.6 mm as function of interaction time for beam diameters of 35, 59 and 89 μm in CW welding of stainless steel.

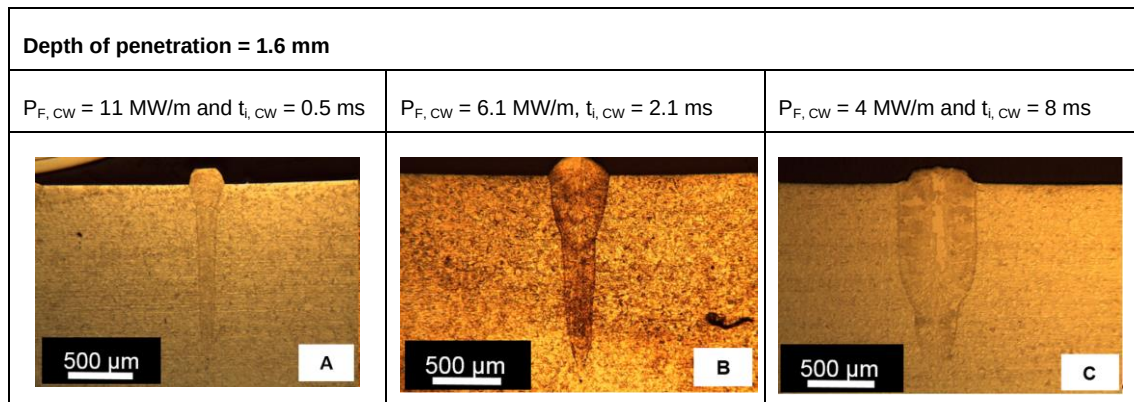


Figure 7-8 Micrographs of CW processing of stainless steel at constant depth of penetration of 1.6 mm achieved with different power factors and interaction times.

According to the power factor model's parameter selection chart shown in Figure 7-9, the interaction time is the first parameter selected based on quality requirements. The weld quality refers to the undercut and keyhole induced porosity, which are mainly controlled by the interaction time. Secondly, travel speed (v) is chosen based on the productivity required. The interaction time and travel speed combination will determine the only beam diameter (d) for the required application ($t_{i,CW} = d/v$). However, if the beam diameter is not suitable for

the optical system available, a different combination of interaction time and travel speed needs to be selected. Then, based on Figure 7-7, the power factor is chosen for a certain penetration depth which will accommodate a particular material thickness. Finally, the model will suggest the average power (P_L) to be used. Nevertheless, if the average power indicated is above the laser's capacity, according to Figure 7-7, a longer interaction time has to be used to accommodate the same penetration depth but for a lower power factor ($P_{F, cw} = P_L/d$).

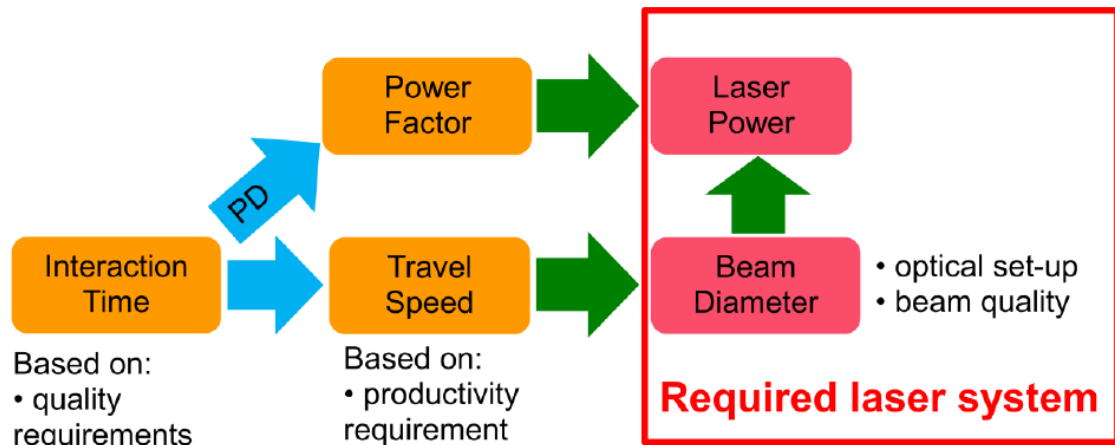


Figure 7-9 Parameters selection chart [70].

The chart presented in Figure 7-9 emphasises the power factor model as a completely different approach than the traditional method of a parametric study of the welding parameters selection. The model allows the user to obtain a specific weld shape for the desired application based on a power factor and interaction time. The process is more productive for shorter interaction times since a higher travel speed is required for a fixed beam diameter. However, shorter $t_{i, cw}$ means a narrower weld width profile, as observed in Figure 7-8A, which is not desired for applications where a high fit-up tolerance is necessary. Moreover, the weld quality is also worse in this regime, being possible to observe an undercut in micrographs 7-1 in Figure 7-5 for an interaction time of 0.125 ms and a beam diameter of 35 μm . For such a small spot size and low travel speed, a large melting pool is formed around the laser laser beam, closing the keyhole more easily, generating defects like this. Nevertheless, no porosity has been observed. On the other hand, a longer $t_{i, cw}$ gives high fit-up tolerance, as shown

in Figure 7-8C, but the productivity is less and the distortions higher. Hence, the necessary laser output power to penetrate a specific material thickness with particular productivity can be estimated independently of the optical setup used and transferable between different laser systems.

7.3.2 Effect of interaction time and power factor on aluminium

Similar studies, performed for SS, and described in the previous section, were conducted for Al. Figure 7-10 and Figure 7-11 show that the same three levels of interaction time are correlated with constant power factors of 5.6 and 4.1 MW/m, respectively, for different penetration depths. Constant trend lines of penetration depth were observed in Al when the spot size was varied between 35 and 89 μm . However, for an interaction time of 1 ms, the penetration is less deep for a beam diameter of 35 μm , remaining similar for 59 and 89 μm . In aluminium, like in stainless steel, there is also a threshold size of the beam where the model works.

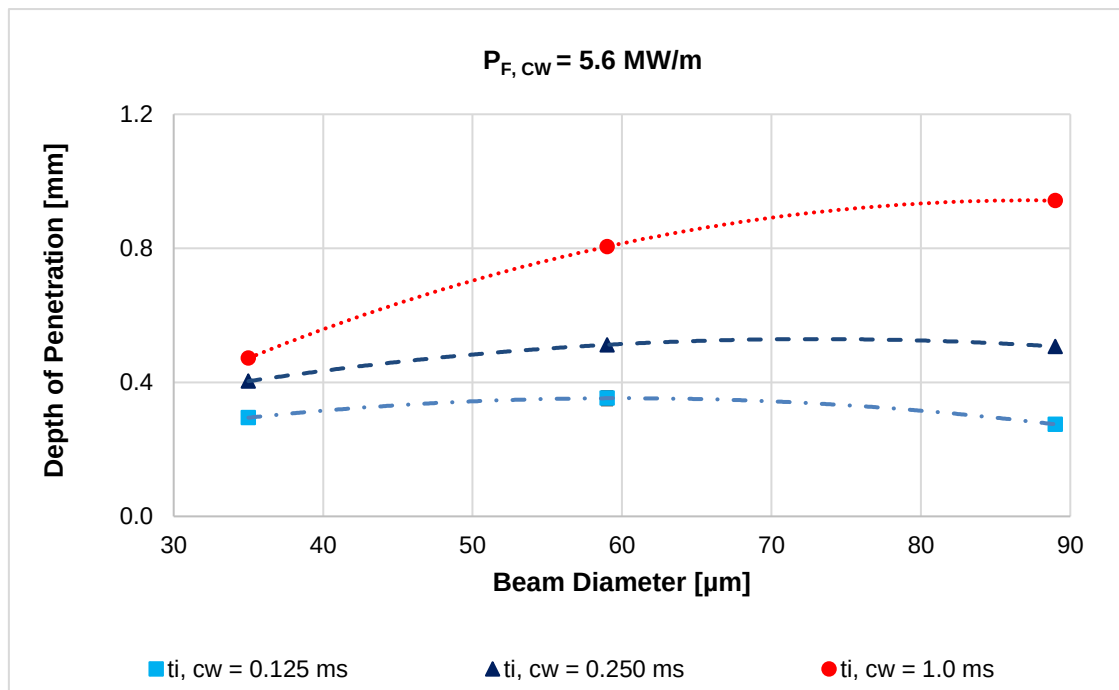


Figure 7-10 Effect of the beam diameter on the penetration depth of CW processing of Al at different interaction times and constant power factor of 5.6 MW/m.

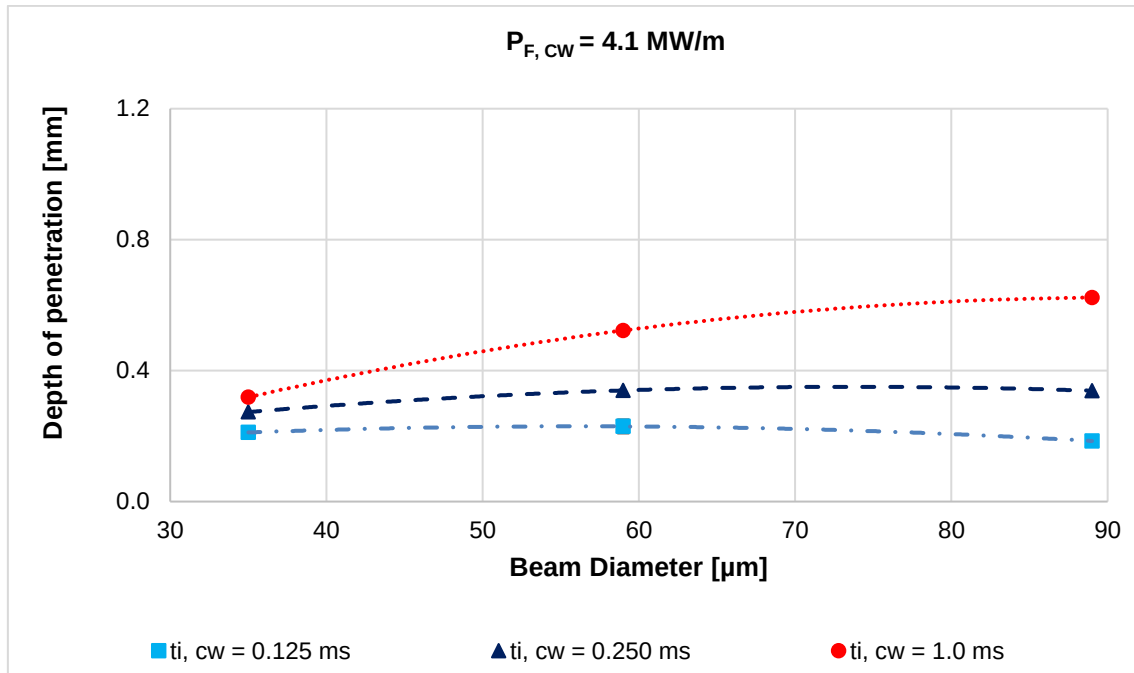


Figure 7-11 Effect of the beam diameter on the penetration depth of CW processing of Al at different interaction times and constant power factor of 4.1 MW/m.

The micrographs of the corresponding welding parameters from Figure 7-10 and Figure 7-11 are shown in Figure 7-12 and Figure 7-13. The related processing parameters are shown in Table 7-4. The conclusions are very similar to those for stainless steel in the previous section. For a constant power factor of 5.6 MW/m, increasing the interaction time from 0.125 ms to 0.250 ms, the depth of penetration depth increased on average from 0.3 mm to 0.5 mm. The weld width also increased from 0.27 to 0.30 mm, as demonstrated in micrographs 7-13 to 7-15 and micrographs 7-16 to 7-18 from Figure 7-12. Decreasing the power factor from 5.6 MW/m to 4.1 MW/m for a constant interaction time of 1 ms, the average penetration depth decreased from 0.9 to 0.6 mm, as shown in micrographs 7-20 and 7-21 and micrographs 7-23 and 7-24, respectively, from Figure 7-13. However, the average weld width was reduced from 0.57 mm to 0.47 mm, which means the power factor mainly influences the penetration depth but also affects the weld width in Al due to its high thermal conductivity. This creates greater model unpredictability compared to stainless steel.

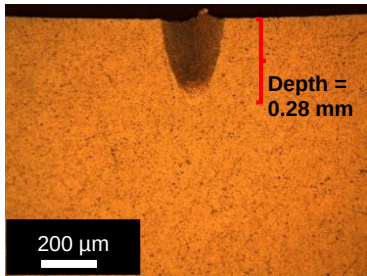
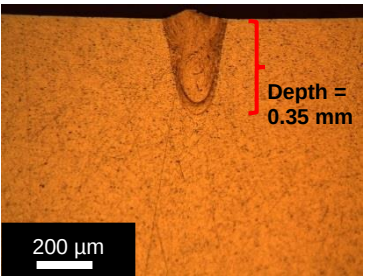
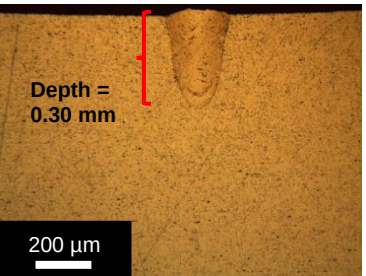
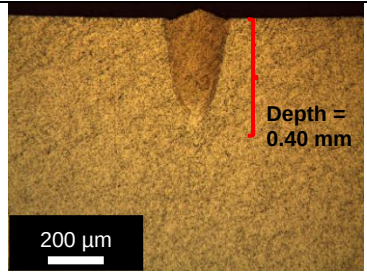
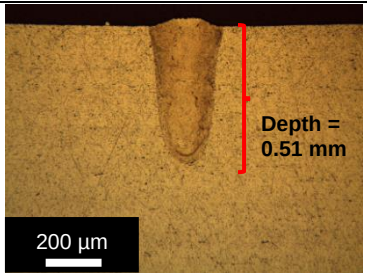
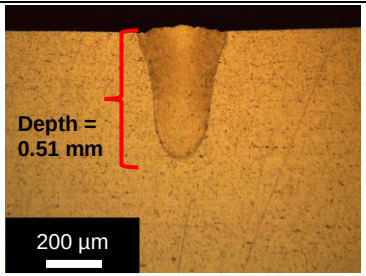
$d = 35 \mu\text{m}$	$d = 59 \mu\text{m}$	$d = 89 \mu\text{m}$
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 0.125 \text{ ms}$		
Micrograph 7-13	Micrograph 7-14	Micrograph 7-15
$P_L = 195 \text{ W}$, $v = 280 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 467 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 703 \text{ mm/s}$
		
Depth = 0.28 mm; Width = 0.21 mm	Depth = 0.35 mm; Width = 0.32 mm	Depth = 0.30 mm; Width = 0.27 mm
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 0.250 \text{ ms}$		
Micrograph 7-16	Micrograph 7-17	Micrograph 7-18
$P_L = 195 \text{ W}$, $v = 138 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 233 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 351 \text{ mm/s}$
		
Depth = 0.40 mm; Width = 0.26 mm	Depth = 0.51 mm; Width = 0.30 mm	Depth = 0.51 mm ; Width = 0.34 mm

Figure 7-12 Constant combinations of power factor of 5.6 MW/m and interaction times of 0.125 ms and 0.250 ms for different weld depths in CW welding of Al.

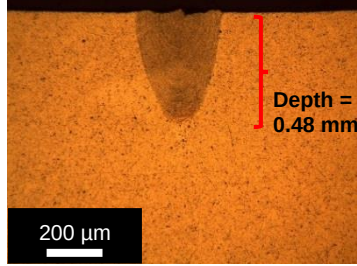
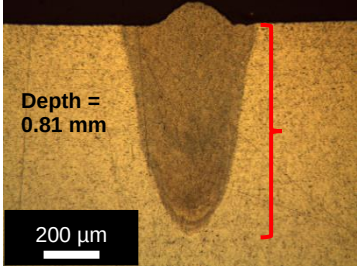
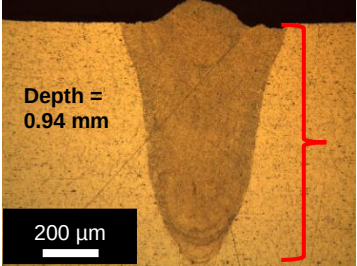
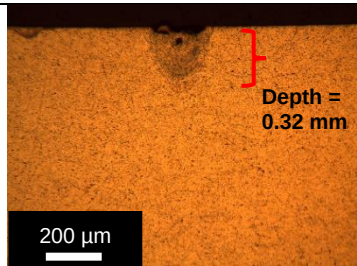
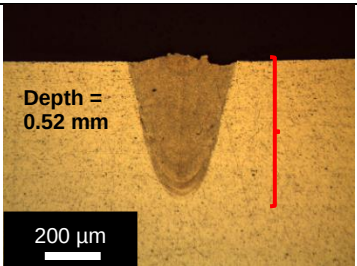
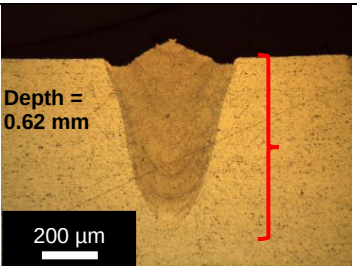
$d = 35 \mu\text{m}$	$d = 59 \mu\text{m}$	$d = 89 \mu\text{m}$
$P_{F, CW} = 5.6 \text{ MW/m}$; $t_{i, CW} = 1.00 \text{ ms}$		
Micrograph 7-19	Micrograph 7-20	Micrograph 7-21
$P_L = 195 \text{ W}$, $v = 35 \text{ mm/s}$	$P_L = 328 \text{ W}$, $v = 58 \text{ mm/s}$	$P_L = 495 \text{ W}$, $v = 88 \text{ mm/s}$
		
Depth = 0.48 mm; Width = 0.35 mm	Depth = 0.81 mm; Width = 0.51 mm	Depth = 0.94 mm; Width = 0.62 mm
$P_{F, CW} = 4.1 \text{ MW/m}$; $t_{i, CW} = 1.00 \text{ ms}$		
Micrograph 7-22	Micrograph 7-23	Micrograph 7-24
$P_L = 144 \text{ W}$, $v = 35 \text{ mm/s}$	$P_L = 242 \text{ W}$, $v = 58 \text{ mm/s}$	$P_L = 364 \text{ W}$, $v = 88 \text{ mm/s}$
		
Depth = 0.32 mm; Width = 0.24 mm	Depth = 0.52 mm; Width = 0.42 mm	Depth = 0.62 mm; Width = 0.51 mm

Figure 7-13 Constant combinations of power factor of 5.6 and 4.1 MW/m and interaction times of 1.0 ms for different weld depths in CW welding of Al.

Table 7-4 Set of power factors and interaction times for beam diameters of 35, 59 and 89 μm , and corresponding parameters applied in CW laser welding of Al5251.

Beam diameter [μm]	Power Factor [MW/m]	Interaction time [ms]	Power [W]	Travel speed [mm/s]	Specific point energy [mJ]	Power density [MW/cm ²]	Micrograph
d	$P_{F, CW}$	$t_{i, CW}$	P_L	v	$E_{SP, CW}$	q_p	
35	5.6	0.125	195	280	24	20	7-13
59	5.6	0.125	328	467	41	12	7-14
89	5.6	0.125	495	703	62	8	7-15
35	5.6	0.250	195	138	49	20	7-16
59	5.6	0.250	328	233	83	12	7-17
89	5.6	0.250	495	351	125	8	7-18
35	5.6	1	195	35	197	20	7-19
59	5.6	1	328	58	332	12	7-20
89	5.6	1	495	88	501	8	7-21
35	4.1	1	144	35	144	15	7-22
59	4.1	1	242	58	242	9	7-23
89	4.1	1	364	88	364	6	7-24

In Figure 7-14, the depths of penetration of 0.3 mm, 0.7 mm and 1 mm are plotted as a function of power factor and interaction time using beam diameters between 35 and 89 μm . However, due to the penetration depth variation for a beam diameter of 35 μm and interaction time of 1 ms, as previously observed in Figure 7-10 and Figure 7-11, this beam diameter was only used below 1 ms. As observed, the trend lines are generated independently of the beam diameter used, which means that the penetration depth can be determined only based on power factor and interaction time. Some micrographs from Figure 7-14 are shown in Figure 7-15. The effect of interaction time on the weld width is visible as the width increases with the interaction time for similar penetration depths, as previously observed in stainless steel.

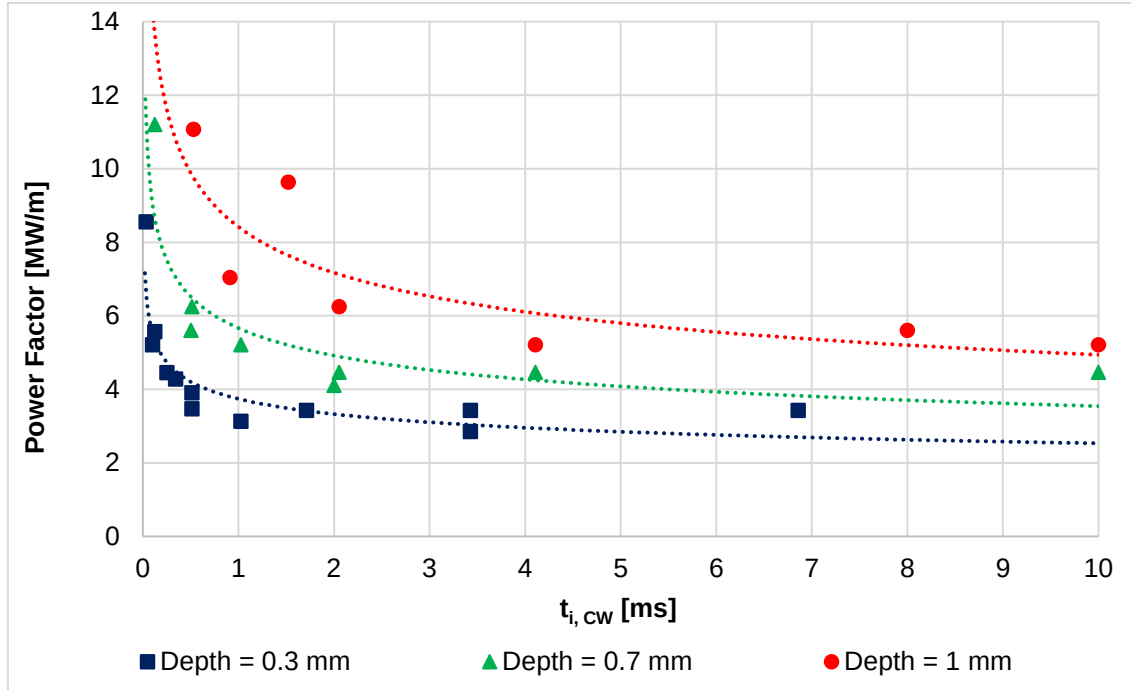


Figure 7-14 Power factor for penetration depths of 0.3 mm, 0.7 mm and 1 mm as a function of interaction time for beam diameters of 35, 59 and 89 μm in CW welding of Al.

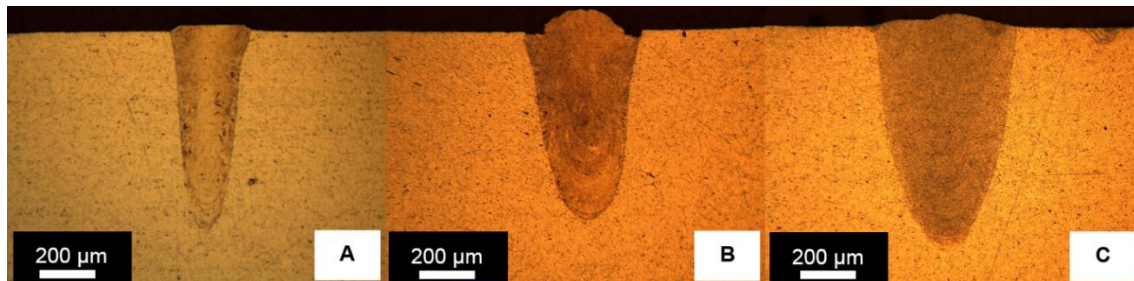


Figure 7-15 Micrographs of CW processing of Al at constant depth of penetration of 0.7 mm achieved with: A) $P_{F, CW} = 11.2 \text{ MW/m}$ and $t_{i, CW} = 0.2 \text{ ms}$; B) $P_{F, CW} = 4.0 \text{ MW/m}$, $t_{i, CW} = 2.0 \text{ ms}$; C) $P_{F, CW} = 4.5 \text{ MW/m}$ and $t_{i, CW} = 10 \text{ ms}$.

7.3.3 Comparison of the power factor model between aluminium and stainless steel

Aluminium and stainless steel were compared in this section for a constant penetration depth of 0.3 mm. The power factor curves were extracted from Figure 7-7 and Figure 7-14 and plotted in Figure 7-16. To achieve similar penetration in Al as in SS, a higher power factor is required for a constant interaction time, i.e.

the laser output power has to be higher for a fixed beam diameter. Alternatively, Al requires a higher interaction time than SS at a constant power factor, i.e. the necessary travel speed is less for a set beam diameter. One way to compare them is by the characteristic thermal time (t_0), which measures the time for heat to diffuse over a distance equal to the beam diameter [72], as previously explained in section 4.

Thermal diffusivity measures the transfer of energy of particular material from a hot to a cold point. For a beam diameter of 35 μm , thermal diffusivity of $6 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ and $6 \times 10^{-6} \text{ m}^2\text{s}^{-1}$ from Al and SS (Table 7-1, respectively), the characteristic thermal time of each metal is $1.35 \times 10^{-6} \text{ s}$ and $1.39 \times 10^{-5} \text{ s}$. Thus, the energy takes less time to reach the same distance in Al than in SS since it is more quickly transferred in all substrate directions. Therefore, the temperature rise will be less in Al, and a higher power factor is necessary to achieve similar penetration as in SS. Its trend line is above SS in Figure 7-16.

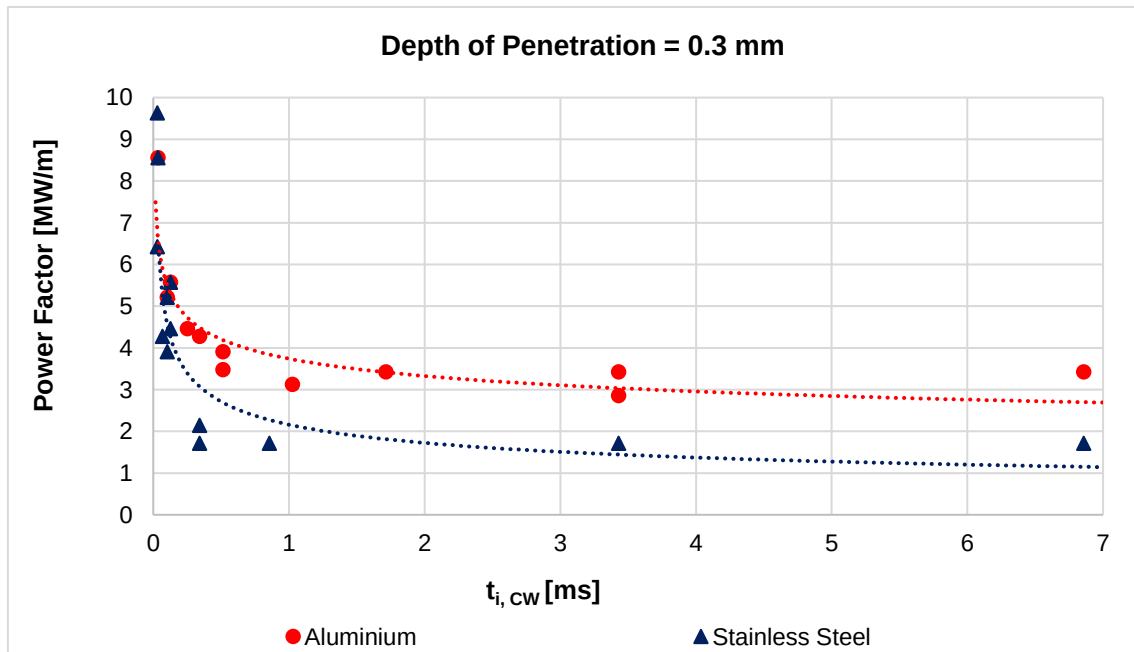


Figure 7-16 Comparison of the power factor model trend lines between Al and SS for a depth of penetration of 0.3 mm.

Some micrographs from Figure 7-16 are shown in Figure 7-17A-C and Figure 7-18D-F, for Al and SS, respectively. In Figure 7-17A and Figure 7-18A, it can be seen that the weld width in Al is wider than in SS for the same interaction time.

However, comparing Figure 7-17C and Figure 7-18C, the weld width is similar in both metals for an interaction time of 6.8 ms. For longer interaction time and consequently higher specific point energy, both metals achieve a plateau in the depth of penetration and weld width. This plateau is reached much sooner in Al since the thermal losses are higher. The energy is dissipated faster than in SS, and the vaporisation temperatures are similar for both metals (Table 7-1). Moreover, as the interaction times increases, the undercut visible in SS in 7-18A disappears in 7-18B-C. However, for Al Figure 7-17A-C, the undercut doesn't follow the same trend, being more evident in Figure 7-17C for higher interaction time. This phenomena may be related with the lower aluminium viscosity (Table 7-1) for higher temperatures, being the melt pool more unstable in this regime [70]. Nevertheless, no porosity has been observed in both metals in keyhole metals for the range of parameters tested, which shows that a relatively stable process is possible to achieve in CW mode.

The thermal losses should be captured by the definition of interaction time, which should incorporate the characteristic thermal time to allow direct comparison between different metals with different physical properties.

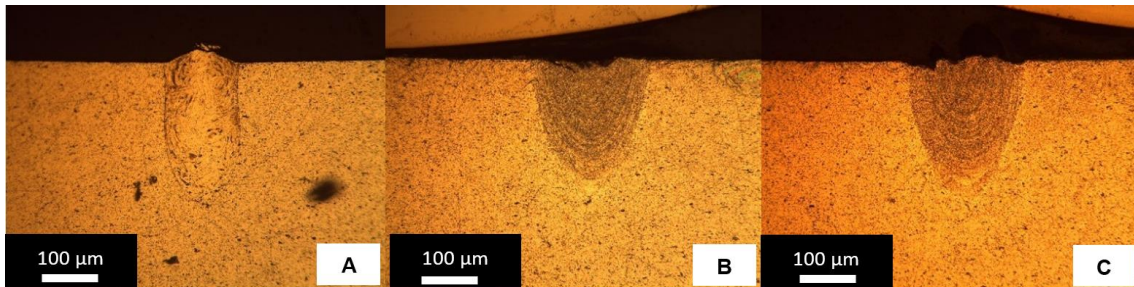


Figure 7-17 Aluminium micrographs for a constant depth of penetration of 0.3 mm achieved with: A) $P_{F, CW} = 8.5 \text{ MW/m}$ and $t_{i, CW} = 0.2 \text{ ms}$; B) $P_{F, CW} = 2.8 \text{ MW/m}$, $t_{i, CW} = 3.4 \text{ ms}$; C) $P_{F, CW} = 3.5 \text{ MW/m}$ and $t_{i, CW} = 6.8 \text{ ms}$.

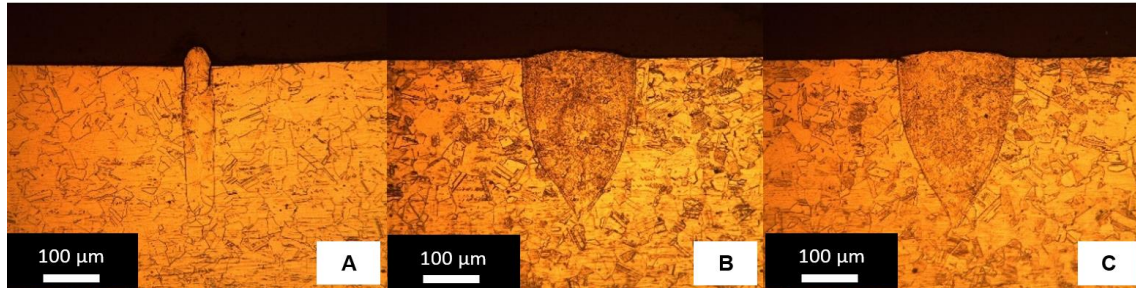


Figure 7-18 Stainless steel micrographs for a constant depth of penetration of 0.3 mm achieved with: A) $P_{F, CW} = 9.8 \text{ MW/m}$ and $t_{i, CW} = 0.2 \text{ ms}$; B) $P_{F, CW} = 1.8 \text{ MW/m}$, $t_{i, CW} = 3.4 \text{ ms}$; C) $P_{F, CW} = 1.8 \text{ MW/m}$ and $t_{i, CW} = 6.8 \text{ ms}$.

7.4 Summary of discussions

The power factor model has been used as a predictive algorithm to find the weld profile required for the desired application in CW micro-welding. The following conclusions can be drawn from this study:

- The power factor model's transferability between different optical setups is possible in micro-welding due to the beam diameter's independence.
- As previously observed in macro-welding for mild steel and Al, constant penetration depth curves against interaction time and power factor can also be obtained in micro-welding to select the parameters required for a certain weld width and depth of penetration.
- For a similar power factor, the thermal losses are higher for smaller beam diameters and higher interaction times, limiting the model applicability.
- The process is more efficient for low interaction times achieved with high travel speeds, being the thermal losses lower.
- The shorter characteristic thermal time of Al compared to SS justifies the gap in the characteristic curves of power factor vs interaction time in both metals.
- The characteristic thermal time should be incorporated into the definition of the interaction time to capture the thermal losses in different metals.

- The weld quality is better in SS for higher interaction times. Nevertheless, the opposite was observed in Al.

8 Selection of processing parameters in MPPW micro-welding

This chapter is based on the following publication:

Coroado J.*, Ganguly S., Suder W., Williams S., Meco S., Pardal G. (2021) 'Selection of parameters in nanosecond pulsed wave laser micro-welding', *The International Journal of Advanced Manufacturing Technology*, 115, pp. 2929–2944, <https://doi.org/10.1007/s00170-021-07251-8>.

8.1 Introduction

In the previous chapter, the power factor model was extended to CW micro-welding of stainless steel and aluminium. The model works based on the fundamental laser-material interaction parameters, which, along with this work, have proven to be comparable in CW and MPPW mode. Therefore, the power factor model may also apply to MPPW processing.

In CW mode, the power factor model correlates power factor ($P_{F, CW}$), defined by the ratio of average power and beam diameter ($P_{F, CW} = P_L/d$), and interaction time ($t_{i, CW}$), which represents the ratio between beam diameter and travel speed ($t_{i, CW} = d/v$). It was demonstrated with large beam diameters in macro-welding that similar penetration depths and weld widths are obtained for constant values of power factor and interaction time [70]. In the previous chapter, similar conclusions were observed in micro-welding. Nevertheless, there is a limitation in the spot size used for high interaction times in both welding regimes, which creates an optimum operating window.

The model might not be applicable in MPPW mode if the standard definition of power factor is used. As shown in Figure 8-1, for CW mode, the average power is similar to the average peak power. In MPPW mode, the average peak power is higher than the average power, which affects the final weld shape, as previously observed in sections 4 and 5. Hence, it is necessary to reformulate the definition of power factor in MPPW processing to consider the effect of average peak power in the weld shape when the average power is kept constant.

A new definition of power factor needs to be established, the $P_{F, MPPW}$, which can be defined as the ratio of average peak power by the beam diameter, as given by Equation (8-1):

$$P_{F, MPPW} = P_{peak}/d \text{ [MW/m]} \quad (8-1)$$

Since the interaction time (t_i) definition in MPPW mode ($t_{i, MPPW} = P_{width} * (1 - O_F/100)$) is different from CW ($t_{i, CW} = d/v$), it is also necessary to verify if this formula is applicable in the model.

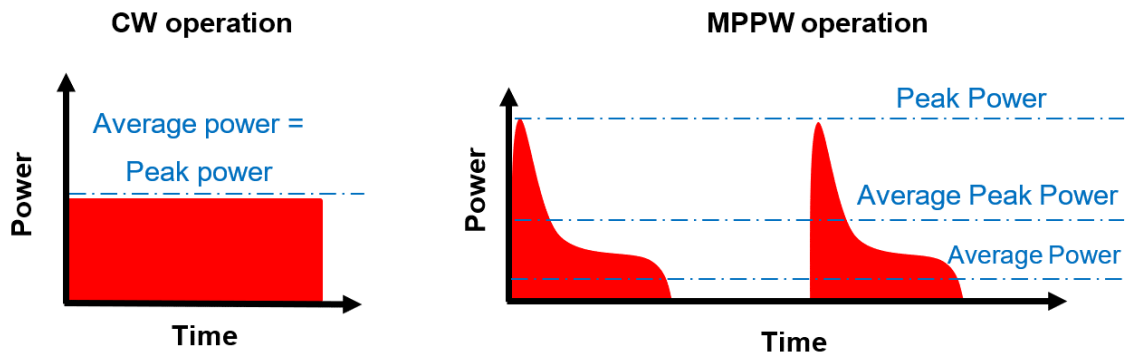


Figure 8-1 Temporal output of a CW and nanosecond MPPW lasers.

This chapter investigates if the depth of penetration and weld width can be predicted in MPPW mode through the power factor model for different beam diameters, average peak powers, pulse widths and pulse repetition frequencies. The objectives are as follows:

- Analysis of the trade-off between applied energy and average peak power density for different beam diameters in MPPW mode.
- Application of different combinations of power factor ($P_{F, MPPW} = P_{peak}/d$) and interaction time ($t_{i, MPPW} = P_{width} * (1 - O_F/100)$) in stainless steel for different beam diameters, constant average power and waveform.
- Analysis of the weld geometries in stainless steel and correlation of the results achieved with the different combinations of power factor and interaction time.
- Transfer of similar weld shapes in stainless steel between different temporal pulse shapes (waveforms) at constant average power and beam diameter.

- Model application in aluminium and comparison of the results with stainless steel.

8.2 Experimental procedure

8.2.1 Materials

The materials used in the experiments were 2 mm thick plates of stainless steel (SS) 304 L and aluminium (Al) 5251H22. Their physical properties are shown in Table 8-1.

Table 8-1 Physical properties of the base materials [121][122].

Property	Symbol	Units	Al 5251 H22	SS304L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Vaporisation Temperature	T_v	W.(m.K) ⁻¹	2790	3023
Thermal conductivity	k	W m ⁻¹ K ⁻¹	134	16.2
Thermal diffusivity	α	m ² s ⁻¹	5.7×10^{-5}	5.5×10^{-6}
Modulus of Elasticity	E	GPa	70	193

8.2.2 Methodology and experimental setup

The bead-on-plate welds were produced with a 100 W average output power nanosecond pulsed fibre laser. The experimental setup was already shown in section 3.

8.2.2.1 Experimental study rationale

It is known that in CW laser welding, the weld shape is controlled by both average power density and applied energy. High power density and applied energy guarantee a high vaporisation rate and, consequently, high aspect-ratio welds, whereas long laser-material interaction time creates large weld pools [44]. A specific penetration depth can be achieved through a trade-off between both parameters, which is the operational base of the power factor model in CW mode.

A similar approach used in CW mode has been tested in MPPW mode to control the weld shape. First, the average peak power density controls the transition from conduction to keyhole mode. High aspect-ratio welds will be achieved when high average peak power densities are applied through small beam diameters and

high average peak powers at low pulse repetition frequencies. Second, high applied energy will accumulate more heat to generate sufficient molten metal through large beam diameters and high energy per pulse. Third, large melt pools will characterise high interaction times achieved at low welding speeds and high pulse repetition frequencies. Combining these three might allow the applicability of the power factor model in MPPW mode.

The common variables of average peak power density, specific point energy and interaction time are the beam diameter and the pulse repetition frequency. Therefore, the foundation of the power factor model in MPPW mode is built on the relationship between both: the combination of small beam diameters and low pulse repetition frequencies will lead to high power factors and short interaction times. On the other hand, large beam diameters and high pulse repetition frequencies will lead to low power factors and long interaction times, creating enough heat accumulation to generate large welds, more suitable for applications with high fit-up tolerance required. In both cases, similar penetration depths may be reached for different trade-offs between power factor and interaction time, independently of the beam diameter and frequency selected.

The average laser output power was kept constant in this study. Therefore, the average power density can be disregarded from the analysis of the results. The selected laser temporal pulse shape dictates the maximum peak power and energy per pulse. Its effect on the material response was also investigated for different pulse repetition frequencies and correlated with the model.

8.2.2.2 Effect of beam diameter

To explore the applicability of the new parameters in different laser systems, a set of bead-on-plate stainless steel welds with different beam diameters of 0.35, 0.59 and 0.89 μm , constant average power and pulse width were studied in this chapter. Various combinations of P_{peak} , E_{pulse} , v and PRF were used for each beam diameter, resulting in a range of q_p from 1.60 to 10.4 MW/cm^2 , $q_{p, peak}$ from 32 to 81 MW/cm^2 and $E_{SP, MPPW}$ from 39 mJ to 1000 J. Since in CW mode it is possible to achieve the same penetration depth with high q_p and low $E_{SP, CW}$ or vice-versa [32], this section intends to prove that the same dependence is also

valid for MPPW mode when different beam diameters are applied. The set of parameters used is shown in Table 8-2.

Table 8-2 Set of parameters used for different beam diameters at a constant pulse width of 500 ns and average power of 100 W.

Beam diameter (μm)	Frequency (kHz)	Travel speed [mm/s]	Pulse energy [mJ]	Average peak power [kW]	Overlap factor [%]	Duty cycle [%]	Interaction time [ms]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]
d	PRF	v	E_{Pulse}	P_{peak}	O_F	D_C	$t_{i, \text{MPPW}}$	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$
35	255	89	0.39	0.78	99.0	12.75	0.05	10.4	81	39
59	151	89	0.66	1.3	99.0	7.6	0.05	3.70	48	66
89	100	89	1.0	2.0	99.0	5	0.05	1.60	32	100
35	255	18	0.39	0.78	99.8	12.75	0.25	10.4	81	195
59	151	18	0.66	1.3	99.8	7.6	0.25	3.70	48	330
89	100	18	1.0	2.0	99.8	5	0.25	1.60	32	500
35	255	9	0.39	0.78	99.9	12.75	0.5	10.4	81	390
59	151	9	0.66	1.3	99.9	7.6	0.5	3.70	48	660
89	100	9	1.0	2.0	99.9	5	0.5	1.60	32	1000

8.2.2.3 Effect of interaction time and power factor on stainless steel

This section has selected only one waveform with the maximum pulse energy and the longest pulse duration available in the laser. Its characteristics are shown in Table 8-3.

The power factor model was tested using a set of bead-on-plate stainless steel welds achieved with different beam diameters of 0.35, 0.59 and 0.89 μm , constant average power and constant pulse width. The effect on the penetration depth and weld width was investigated in two stages: First, for each beam diameter, different combinations of $P_{F, MPPW}$ and $t_{i, MPPW}$ were used by varying P_{peak} , E_{pulse} , v and PRF . These combinations of system parameters resulted in a range of $P_{F, MPPW}$ from 4.5 to 57 MW/m and $t_{i, MPPW}$ from 0.05 and 5 ms. The penetration depths and weld widths were analysed for each combination, and only four penetration depths (0.3, 0.7, 1.0 and 1.4 mm) were considered to simplify the representation of the results. In the second stage, to prove that similar weld shapes can be achieved independently of the beam diameter selected (35 to 89 μm), for each beam diameter, constant values of $P_{F, MPPW}$ of 22.4 and 11.2 MW/m were used for similar values of $t_{i, MPPW}$ ranging from 0.05 to 0.5 ms. The processing parameters are shown in Table 8-4 and Table 8-5.

Table 8-3 Characteristics of waveform 31 of MPPW laser [126].

Waveform	PRF ₀ [kHz]	Max pulse energy, E _{max} [mJ]	Pulse width [ns]	Peak Power at E _{max} [kW]
31	100	1	500	7

Table 8-4 Set of system parameters applied in MPPW laser welding of SS 304 L for different combinations of power factor and interaction time for beam diameters of 35, 59 and 89 μm .

Beam diameter [μm]	Power Factor [MW/m]	Interaction time	Overlap factor [%]	Duty cycle [%]	Average power [W]	Frequency [kHz]	Travel speed [mm/s]	Pulse energy [mJ]	Average Peak power [kW]
d	$P_{F, \text{MPPW}}$	$t_{i, \text{MPPW}}$	O_F	D_C	P_L	PRF	v	E_{Pulse}	P_{peak}
35	11.4 - 57	0.05 - 5	99 – 99.99	5-25	100	100 - 510	1.8 - 1755	0.2 - 1	0.4 - 2
59	6.8 – 33.6	0.05 - 5	99 – 99.99	5-25	100	100 – 510	1.8 - 2975	0.2 - 1	0.4 - 2
89	4.5 – 22.5	0.05 - 5	99 – 99.99	5-25	100	100 - 510	1.8 - 4450	0.2 - 1	0.4 - 2

Table 8-5 Set of fundamental parameters applied in MPPW laser welding of SS 304 L for different combinations of power factor and interaction time for beam diameters of 35, 59 and 89 μm .

Beam diameter [μm]	Power Factor [MW/m]	Interaction time [ms]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]
d	$P_{F, \text{MPPW}}$	$t_{i, \text{MPPW}}$	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$
35	11.4 - 57	0.05 - 5	10.4	41 - 208	2 - 2000
59	6.8 – 33.6	0.05 - 5	3.70	14 - 72	2 - 3500
89	4.5 – 22.5	0.05 - 5	1.60	6 - 32	2 - 10000

8.2.2.4 Effect of temporal pulse shape

This laser system allows the selection of thirty-one different waveforms. Each waveform is characterised by a specific P_{peak} , E_{pulse} and P_{width} and can be operated for a wide range of v and PRF . This section investigates the applicability of the power factor model in controlling the weld shape when different laser temporal pulse shapes are used. A set of bead-on-plate stainless steel welds with several combinations of $P_{F, MPPW}$ and $t_{i, MPPW}$ were studied in waveforms 0, 27 and 31 at constant beam diameter and average power. The intrinsic properties of each waveform are shown in Table 8-6, and the set of parameters used are shown in Table 8-7 and Table 8-8.

Table 8-6 Properties of waveforms 0, 27 and 31 at PRF_0 of 100 kHz and average power of 100 W [126].

Waveform	Pulse width [ns]	Pulse repetition frequency [kHz]	Max pulse energy, E_{max} [mJ]	Peak Power at E_{max} [kW]
wfm	P_{width}	PRF_0	E_{pulse}	-
0	280	100	1	10
27	350	100	1	7
31	500	100	1	7

Table 8-7 Set of power factors, interaction times and corresponding system parameters applied in MPPW laser welding of SS 304 L for waveforms 0, 27 and 31.

Waveform	Power Factor [MW/m]	Interaction time [ms]	Duty cycle [%]	Overlap factor [%]	Beam diameter [μm]	Pulse width [ns]	Average Power [W]	Travel speed [mm/s]	Frequency [kHz]	Pulse energy [mJ]	Average peak power [kW]
wfm	$P_{F, \text{MPPW}}$	$t_{i, \text{MPPW}}$	D_C	O_F	d	P_{width}	P_L	v	PRF	E_{pulse}	P_{peak}
0	102	0.056	2.8	99.5	35	280	100	17.5	100	1	3.6
27	81.6	0.070	3.5	99.5	35	350	100	17.5	100	1	2.9
31	57.1	0.10	5	99.5	35	500	100	17.5	100	1	2
0	57.1	0.10	5	99.72	35	280	100	17.5	179	0.56	2
27	57.1	0.10	5	99.65	35	350	100	17.5	143	0.7	2
31	57.1	0.10	5	99.5	35	500	100	17.5	100	1	2
0	28.6	0.10	0	99.72	35.0	280	100	35	357	0.28	1

Table 8-8 Set of power factors, interaction times and corresponding fundamental parameters applied in MPPW laser welding of SS 304 L for waveforms 0, 27 and 31.

Waveform	Power Factor [MW/m]	Interaction time [ms]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]
wfm	$P_{F, \text{MPPW}}$	$t_{i, \text{MPPW}}$	q_p	$q_{p, \text{peak}}$	$E_{\text{SP, MPPW}}$
0	102	0.056	10.4	371	200
27	81.6	0.070	10.4	297	200
31	57.1	0.10	10.4	208	200
0	57.1	0.10	10.4	208	200
27	57.1	0.10	10.4	208	200
31	57.1	0.10	10.4	208	200
0	26.6	0.10	10.4	104	100

8.2.3 Effect of interaction time and power factor on aluminium

Similar methodology and experimental setup applied for SS in section 8.2.2.3 have been replicated for Al in this section. Table 8-4 and Table 8-5 show the processing parameters used in Al for different combinations of power factor and interaction time for each beam diameter of 35, 59 and 89 μm .

8.2.4 Weld shape characterisation

The experimental error of the process was calculated based on two welds with similar conditions: one at the beginning and another at the end of the weld seam. The microstructural analysis was based on optical microscopy to measure the fusion zone geometry, i.e. depth of penetration and weld width. More details are presented in section 3.3.

8.3 Results and discussion

8.3.1 Effect of beam diameter

In section 4, it was showed that the penetration depth can be independently controlled by $q_{p, peak}$ and $E_{SP, MPPW}$ and q_p using constant beam diameter and average power. This section investigates the correlation between $q_{p, peak}$ and $E_{SP, MPPW}$ and its effect on the penetration depth when different beam diameters of 35, 59 and 89 μm and constant average power of 100 W are used.

From a wide range of experiments, a few different cases with the same penetration depth were selected and plotted as a function of $E_{SP, MPPW}$ and $q_{p, peak}$, as shown in Figure 8-2. The trend line corresponds to constant penetration depths from 0.5 to 1.7 mm. The $q_{p, peak}$ needed to achieve a particular penetration decreases quadratically with $E_{SP, MPPW}$. This means that, similarly to CW welding previously shown in section 7, there is also a trade-off between both parameters through a constant rate of material vaporisation [71] in MPPW micro-seam welding. Since both $t_{i, MPPW}$ and q_p have a direct influence on the maximum temperature of the thermal cycle [10], when $E_{SP, MPPW}$ increases through an

increase in $t_{i, MPPW}$ for a constant $q_{p, peak}$, the material experiences a peak in temperature for a longer period, increasing the penetration depth as well.

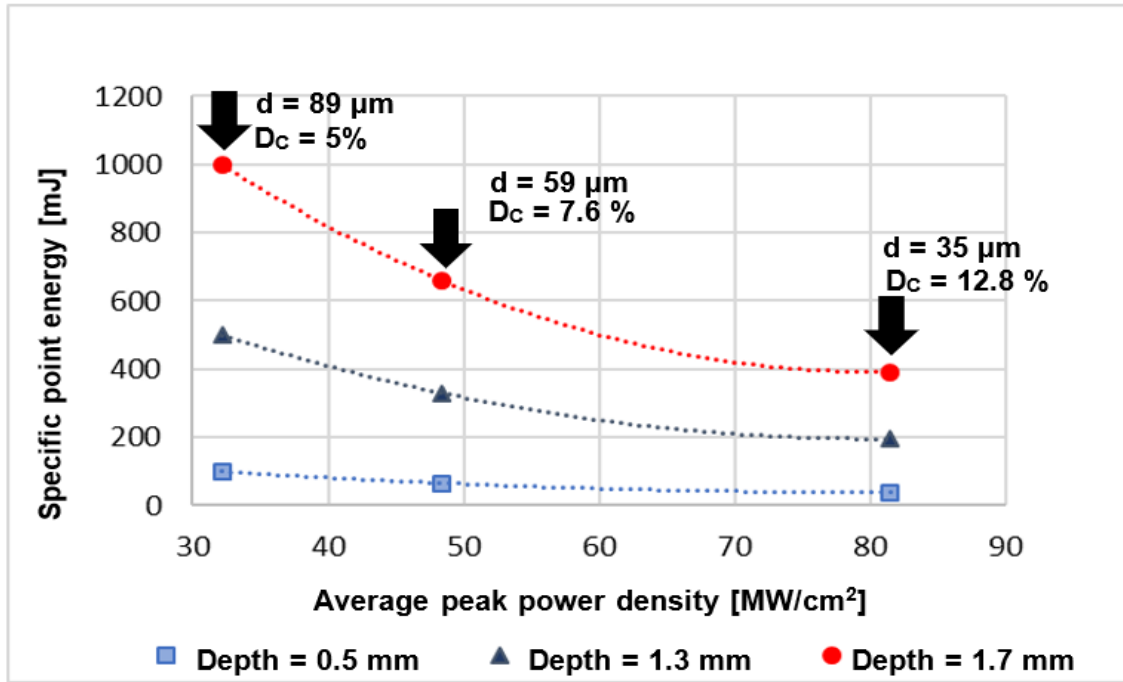


Figure 8-2 Specific point energy versus average peak power density for depths of penetration of 0.5, 1.3 and 1.7 mm at a constant average power of 100 W and pulse width of 500 ns

The corresponding micrographs from Figure 8-2 are shown in Figure 8-3 for a constant penetration depth of 0.5 mm. The duty cycle also needs to be considered in the trade-off between $E_{SP, MPPW}$ and $q_{p, peak}$ from Figure 8-3A-C. For the smallest beam diameter of 35µm (Figure 8-3A), the laser duty cycle is higher to balance the lower $E_{SP, MPPW}$ compared to Figure 8-3B-C. The substrate is subjected to a high thermal load for higher duty cycles since the period between pulses is shorter [131]. Consequently, there is a reduction of energy loss between pulses, and the process becomes more efficient, keeping the penetration depth constant with less applied energy. This is even more evident when the pulse overlapping is high, creating a cumulative energy effect of the laser radiation through several pulses [42]. A similar correlation of the laser duty cycle effect on the thermal losses and, consequently, weld shape, was observed in sections 4 to 6.

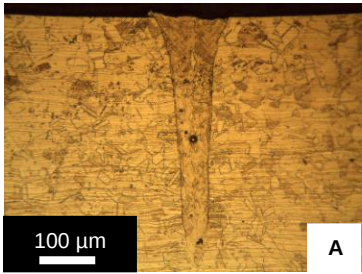
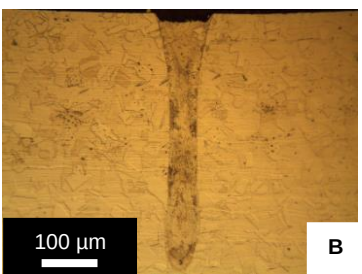
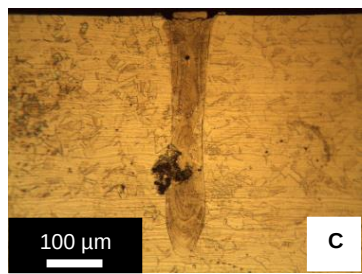
d = 35 μm; D_c = 12.8%	d = 59 μm; D_c = 7.6%	d = 89 μm; D_c = 5%
Depth of penetration = 0.5 mm; t_{i, MPPW} = 0.05 ms		
q _{p, peak} = 81 MW/cm ² E _{SP, MPPW} = 39 mJ	q _{p, peak} = 48 MW/cm ² E _{SP, MPPW} = 66 mJ	q _{p, peak} = 32 MW/cm ² E _{SP, MPPW} = 100 mJ
q _p = 10.4 MW/cm ²	q _p = 3.7 MW/cm ²	q _p = 1.6 MW/cm ²
		
PRF = 255 kHz; v = 89 mm/s	PRF = 151 kHz; v = 89 mm/s	PRF = 100 kHz; v = 89 mm/s
Epulse = 0.39 mJ; Ppeak = 0.78 kW	Epulse = 0.66 mJ; Ppeak = 1.3 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW

Figure 8-3 Different combinations of average power density, average peak power density and specific point energy for a constant weld depth of 0.5 mm.

8.3.2 Effect of interaction time and power factor on stainless steel

As shown in the previous section, it is possible to achieve constant penetration depth with different beam diameters by varying processing parameters in such a controlled way to reach a particular combination of $q_{p, peak}$ and $E_{SP, MPPW}$. The problem with such an approach is that both parameters are dependent on beam diameter and pulse repetition frequency. This can be simplified to a single parameter, the power factor. An example of random data plotted as a function of $P_{F, MPPW}$ is shown in Figure 8-4. Constant penetration depth curves can be obtained for different combinations of $t_{i, MPPW}$ and $P_{F, MPPW}$, being the weld width proportional to $t_{i, MPPW}$.

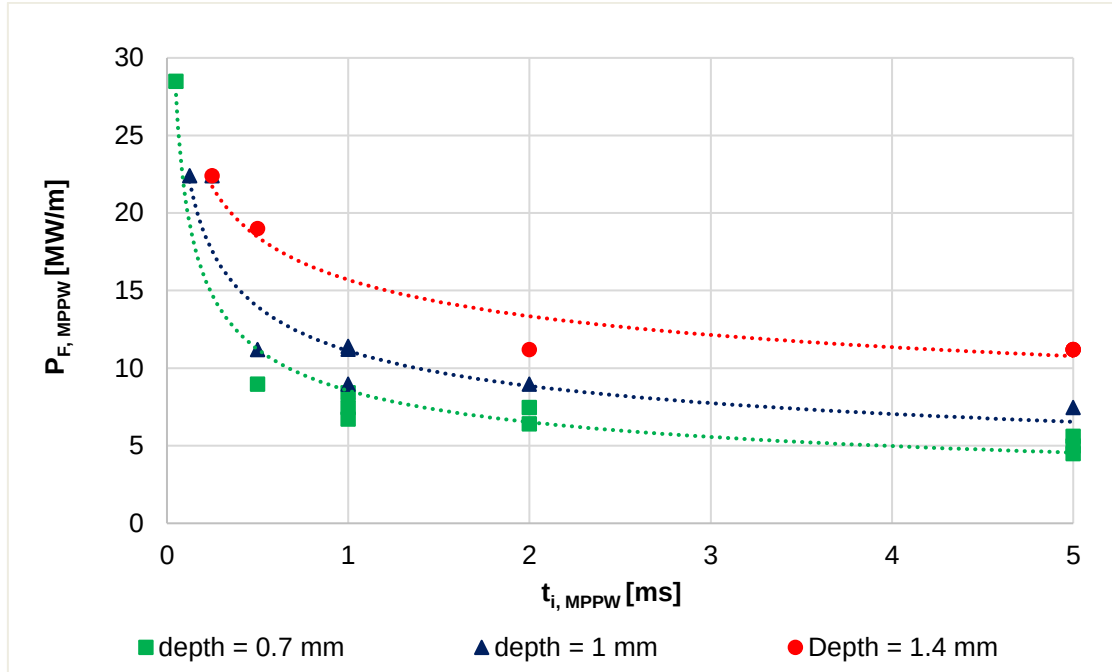


Figure 8-4 Power factor for penetration depths of 0.3, 0.7, 1 and 1.4 mm as a function of interaction time for beam diameters of 35, 59 and 89 μm .

Three micrographs were taken from the constant trend line of a penetration depth of 0.7 mm from Figure 8-4 and presented in Figure 8-5. At short $t_{i, MPPW}$ and high $P_{F, MPPW}$ (Figure 8-5A), spiky weld profiles are achieved, which is a characteristic of a short interaction between the laser and the material, leading to rapid keyhole development and solidification. Short $t_{i, MPPW}$ can either be achieved by fast welding speed, low overlapping factor or short pulse duration. Long $t_{i, MPPW}$ and low $P_{F, MPPW}$ (Figure 8-5C), on the other hand, resulted in a wide weld profile similar to CW welding. Note that long $t_{i, MPPW}$ can be achieved by a high overlapping factor. Eventually, the weld profile will approach a typical CW weld profile with a further increase of $t_{i, MPPW}$. However, this model is not necessarily a good theory, especially for the same penetration depth due to fit-up problems [110]. Similar trend lines observed in MPPW micro seam welding in Figure 8-4 using the new definition of power factor, have also been demonstrated in CW macro welding of low carbon steel [76] and aluminium [8] using the standard definition of the model, but also in CW micro-welding in section 7 of this work.

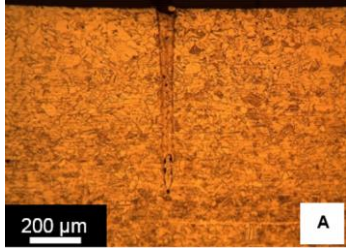
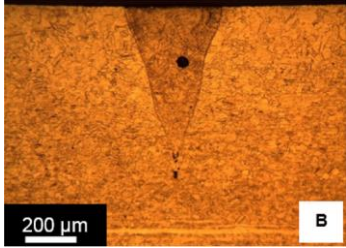
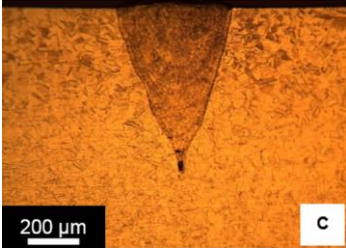
Depth of penetration = 0.7 mm		
d = 35 μm	d = 59 μm	d = 89 μm
$P_{F, \text{MPPW}} = 28.5 \text{ MW/m}$ $t_{i, \text{MPPW}} = 0.05 \text{ ms}$	$P_{F, \text{MPPW}} = 8.4 \text{ MW/m}$ $t_{i, \text{MPPW}} = 1 \text{ ms}$	$P_{F, \text{MPPW}} = 6.4 \text{ MW/m}$ $t_{i, \text{MPPW}} = 2 \text{ ms}$
		
Epulse = 0.50 mJ; Ppeak = 1.0 kW	Epulse = 0.66 mJ; Ppeak = 1.3 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW

Figure 8-5 Constant penetration depth of 0.7 mm achieved with different combinations of power factor and interaction time for beam diameters of 35 μm , 59 μm and 89 μm .

In Figure 8-6 and Figure 8-7, penetration depth is presented as a function of $P_{F, \text{MPPW}}$ and $t_{i, \text{MPPW}}$ using different beam diameters. Constant penetration is demonstrated for constant $t_{i, \text{MPPW}}$ but only for specific spot sizes. For a beam diameter of 35 μm at $t_{i, \text{MPPW}}$ of 0.5 ms, there is a higher variation in the depth of penetration when compared to larger beams of 59 and 89 μm .

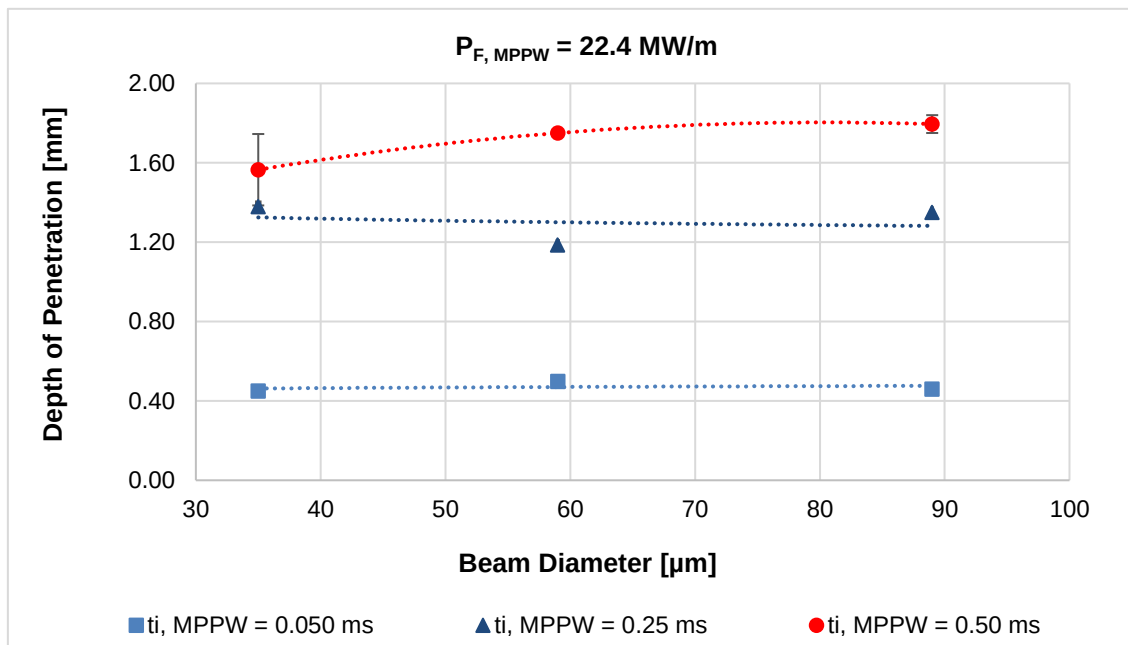


Figure 8-6 Effect of the beam diameter on the penetration depth of MPPW processing of SS at different interaction times and a constant power factor of 22.4 MW/m.

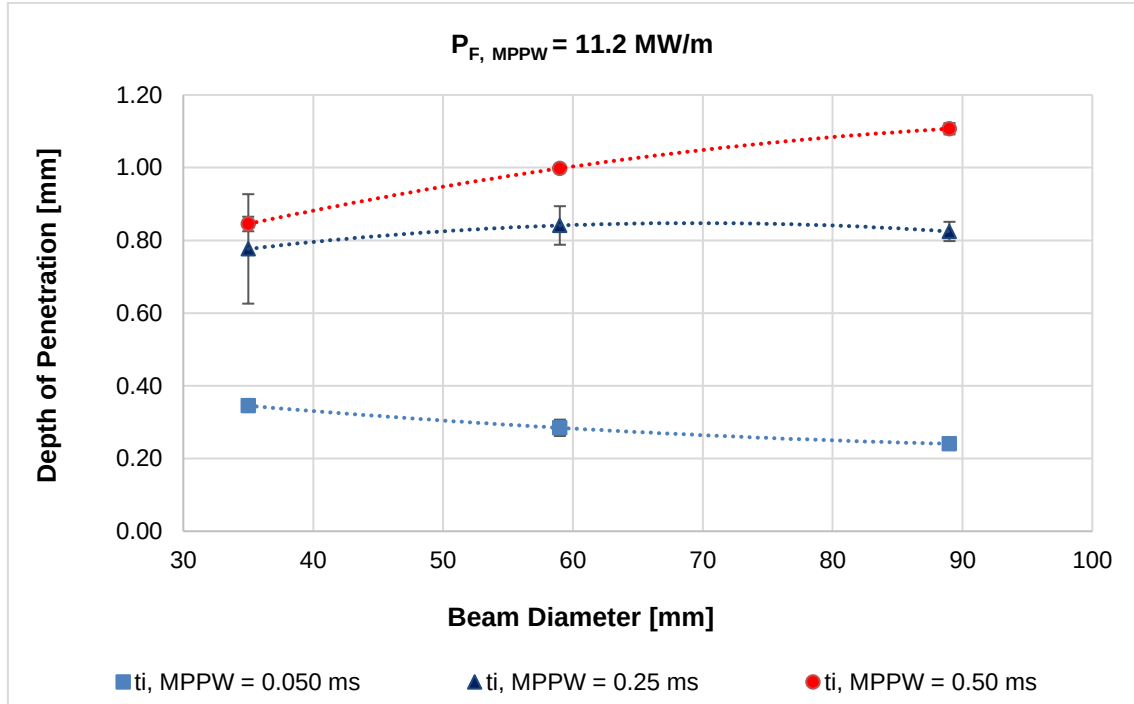


Figure 8-7 Effect of the beam diameter on the penetration depth of MPPW processing of SS at different interaction times and a constant power factor of 11.2 MW/m.

The weld profiles from Figure 8-6 and Figure 8-7 are shown in Figure 8-8 and Figure 8-9. Comparing Figure 8-8A-C with Figure 8-8D-F, the penetration depth increased at constant $P_{F, MPPW}$ since $t_{i, MPPW}$ increased from 0.05 ms to 0.25 ms. In Figure 8-9, on the other hand, the reduction of $P_{F, MPPW}$ from 22.4 to 11.2 MW/m at a constant $t_{i, MPPW}$ of 0.05 ms led to a reduction in the penetration depth. The variation of $P_{F, MPPW}$ at constant $t_{i, MPPW}$ and beam diameter influenced the penetration depth, since PRF increased to compensate for the thermal losses created by the E_{pulse} and P_{peak} reduction.

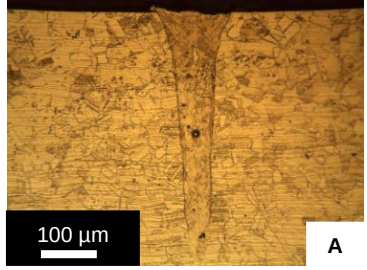
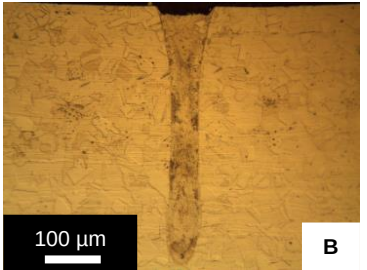
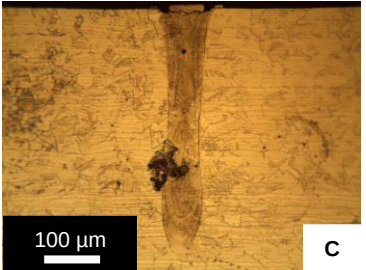
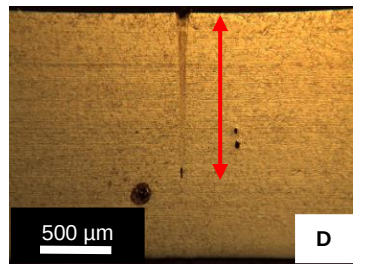
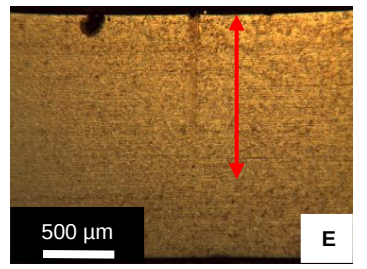
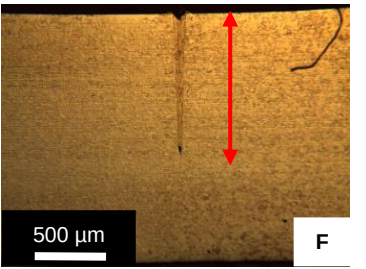
d = 35 μm	d = 59 μm	d = 89 μm
Depth of penetration = 0.5 mm; $P_{F, \text{MPPW}} = 22.4 \text{ MW/m}$; $t_{i, \text{MPPW}} = 0.05 \text{ ms}$		
PRF = 255 kHz; v = 89 mm/s	PRF = 151 kHz; v = 89 mm/s	PRF = 100 kHz; v = 89 mm/s
Epulse = 0.39 mJ; Ppeak = 0.78 kW	Epulse = 0.66 mJ; Ppeak = 1.3 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW
 A	 B	 C
Depth of penetration = 1.3 mm; $P_{F, \text{MPPW}} = 22.4 \text{ MW/m}$; $t_{i, \text{MPPW}} = 0.25 \text{ ms}$		
PRF = 255 kHz; v = 18 mm/s	PRF = 151 kHz; v = 18 mm/s	PRF = 100 kHz; v = 18 mm/s
Epulse = 0.39 mJ; Ppeak = 0.78 kW	Epulse = 0.66 mJ; Ppeak = 1.3 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW
 D	 E	 F

Figure 8-8 Constant combinations of power factor of 22.4 MW/m and interaction times of 0.05 ms and 0.25 ms for different beam diameters of 35, 59 and 89 μm in MPPW processing of SS at constant P_L of 100 W.

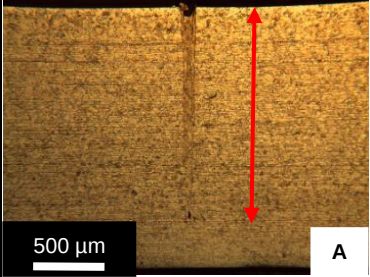
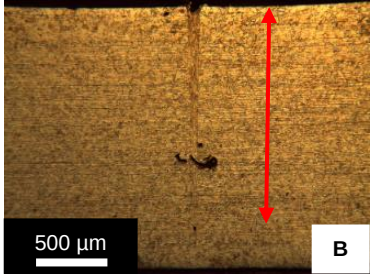
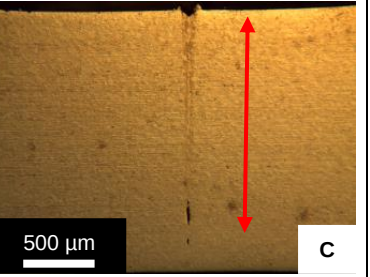
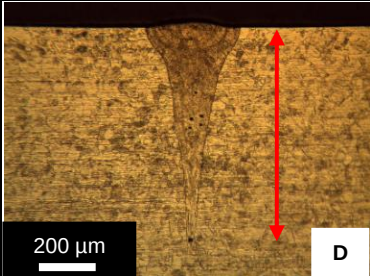
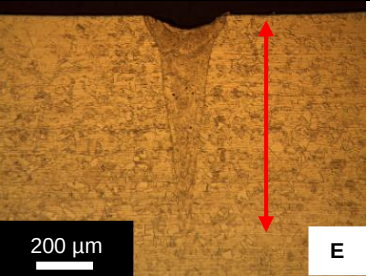
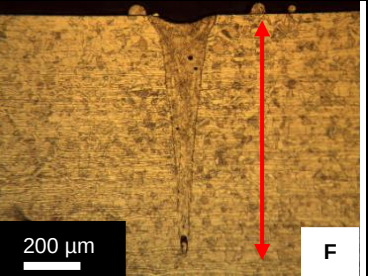
$d = 35 \mu\text{m}$	$d = 59 \mu\text{m}$	$d = 89 \mu\text{m}$
Depth of penetration = 1.7 mm; $P_{F, \text{MPPW}} = 22.4 \text{ MW/m}$; $t_{i, \text{MPPW}} = 0.5 \text{ ms}$		
PRF = 255 kHz; $v = 9 \text{ mm/s}$	PRF = 151 kHz; $v = 9 \text{ mm/s}$	PRF = 100 kHz; $v = 9 \text{ mm/s}$
Epulse = 0.39 mJ; Ppeak = 0.78 kW	Epulse = 0.66 mJ; Ppeak = 1.3 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW
		
Depth of penetration = 1.0 mm; $P_{F, \text{MPPW}} = 11.2 \text{ MW/m}$; $t_{i, \text{MPPW}} = 0.5 \text{ ms}$		
PRF = 510 kHz; $v = 18 \text{ mm/s}$	PRF = 303 kHz; $v = 18 \text{ mm/s}$	PRF = 200 kHz; $v = 18 \text{ mm/s}$
Epulse = 0.20 mJ; Ppeak = 0.41 kW	Epulse = 0.33 mJ; Ppeak = 0.7 kW	Epulse = 0.5 mJ; Ppeak = 1.0 kW
		

Figure 8-9 Constant combinations of power factors of 22.4 MW/m and 11.2 MW/ms and interaction time of 0.5 ms for different beam diameters of 35, 59 and 89 μm in MPPW processing of SS at constant P_L of 100 W.

In Figure 8-6 and Figure 8-7, despite the increase in interaction time from 0.25 ms to 0.5 ms at constant $P_{F, \text{MPPW}}$ and constant beam diameter of 35 μm , the penetration depth remained almost unchanged, which shows the limitation of the model in small beam diameters for high interaction times.

The model limitation is also visible for larger beam diameters from a certain $t_{i, \text{MPPW}}$ threshold, as shown in Figure 8-10, which was replicated from Figure 4-17 in section 4.3.2. For a beam diameter of 89 μm and constant $P_{F, \text{MPPW}}$ of 22.4 MW/m, the penetration depth increases until a $t_{i, \text{MPPW}}$ of 1 ms (Figure 8-10B) and then drops. The energy delivered in Figure 8-10C for a $t_{i, \text{MPPW}}$ of 5 ms is exceptionally high, being the thermal losses also higher for such a low travel speed, leading to a reduction in penetration depth. Thus, it can be concluded that, in MPPW welding, higher $t_{i, \text{MPPW}}$ and consequently, higher $E_{SP, \text{MPPW}}$, achieved

through larger spot sizes of (89 μm), are more efficient in providing the necessary cumulative heating to increase the penetration. However, there is a limit in the trade-off between $q_{p, peak}$ and $E_{SP, MPPW}$ to increase the penetration depth for a particular beam diameter, and this limit is reached sooner for smaller beam diameters. Similar results were observed in laser machining using a similar nanosecond MPPW laser. The ablation rate increased with the power density until a certain point and dropped from a specific limit [42]. The limitation of this trade-off can be translated in the combination of the maximum allowed $t_{i, MPPW}$ for a maximum $P_{F, MPPW}$. Therefore, in this study, for the range of beam diameters tested from 35 μm to 89 μm , similar penetration depths can only be guaranteed until the combination of a maximum t_i of 0.25 ms and a maximum $P_{F, MPPW}$ of 22.4 MW/m, as previously shown in Figure 8-4.

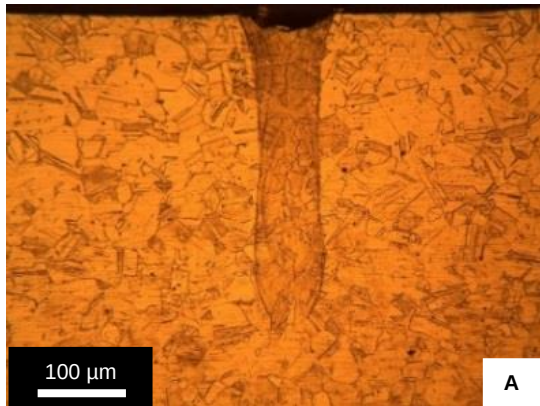
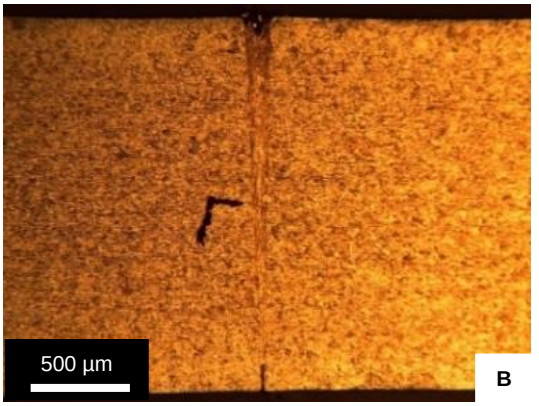
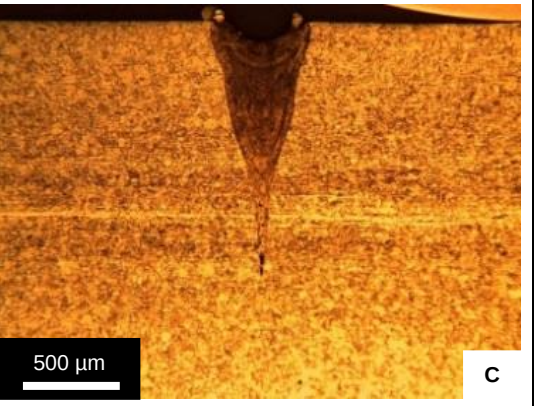
$P_{F, MPPW} = 22.4 \text{ MW/m}$; $P_{width} = 500 \text{ ns}$ (Wfm 31); $d = 89 \text{ }\mu\text{m}$; $P_L = 100 \text{ W}$; $D_c = 5\%$		
$E_{SP, MPPW} = 100 \text{ mJ}$; $t_{i, MPPW} = 0.05 \text{ ms}$	$E_{SP, MPPW} = 2000 \text{ mJ}$; $t_{i, MPPW} = 1 \text{ ms}$	$E_{SP, MPPW} = 10000 \text{ mJ}$; $t_{i, MPPW} = 5 \text{ ms}$
PRF = 100 kHz; $v = 89 \text{ mm/s}$	PRF = 100 kHz; $v = 4.5 \text{ mm/s}$	PRF = 100 kHz; $v = 0.9 \text{ mm/s}$
Epulse = 1.0 mJ; Ppeak = 2.0 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW	Epulse = 1.0 mJ; Ppeak = 2.0 kW
		
Depth = 0.39 mm; Width = 0.12 mm	Depth = 2.0 mm; Width = 0.15 mm	Depth = 1.31 mm; Width = 0.51
Weld metal area: 0.045 mm ²	Weld metal area: 0.14 mm ²	Weld metal area: 0.32 mm ²

Figure 8-10 Bead-on-plate welds at different interaction times, constant power factor of 22.4 MW/m, pulse duration of 500 ns, beam diameter of 89 μm , an average power of 100 W and duty cycle of 5%.

The parameter selection chart of the power factor model is shown in Figure 8-11. Similarly to the power factor model for CW mode presented in section 7, the $t_{i, MPPW}$ is also the first parameter to be selected based on quality requirements, which determines the weld shape. Then, the travel speed is chosen based on productivity. The laser user can choose which pulse repetition frequency and pulse width the laser will operate. The model will then suggest the beam diameter based on $t_{i, MPPW}$, travel speed, pulse repetition frequency, and pulse width. However, there is only one beam diameter for the combination of these four parameters. If the optical system's characteristics don't allow this selection, one of the four parameters must be changed. Then, from Figure 8-4, the $P_{F, MPPW}$ is selected to achieve a certain penetration depth in stainless steel. Finally, the model determines the laser peak power according to the $P_{F, MPPW}$ and beam diameter. According to Figure 8-5, a combination of low $t_{i, MPPW}$ and high power factors are used to achieve a penetration depth of 0.7 mm. Therefore, if the suggested average peak power is unrealistic, a longer $t_{i, MPPW}$ must be used to accommodate the same penetration depth. Nevertheless, as previously concluded for CW mode in section 7, shorter $t_{i, MPPW}$ gives narrower weld profiles, as observed in Figure 8-5A. In contrast, longer $t_{i, MPPW}$ provides high fit-up tolerance, as shown in Figure 8-5C, but less productivity.

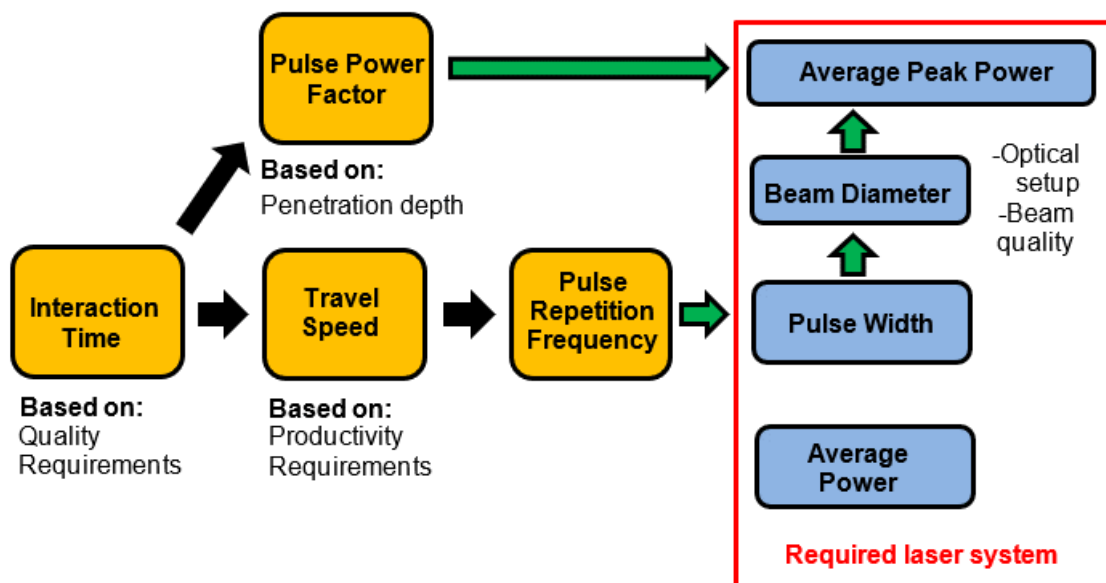


Figure 8-11 Parameter selection chart of the power factor model in MPPW mode.

8.3.3 Effect of temporal pulse shape

In the previous sections, the power factor model was applied for a single pulse duration of 500 ns. In this section, the model is used for different P_{Width} of 280, 350 and 500 ns at a constant beam diameter of 35 μm and average power of 100 W. The correspondent laser temporal response was measured in section 4, and is now shown in Figure 8-12 for a constant PRF of 100 kHz. The highest peak power of 10 kW is achieved for the shortest pulse duration (wfm 0), whereas for longer pulses of 280 ns (wfm 27) and 500 ns (wfm 31), similar peak powers of 7 kW are achieved. However, at similar PRF , all waveforms have the same pulse energy (Table 8-6), but the longer the pulse duration, the higher the laser duty cycle.

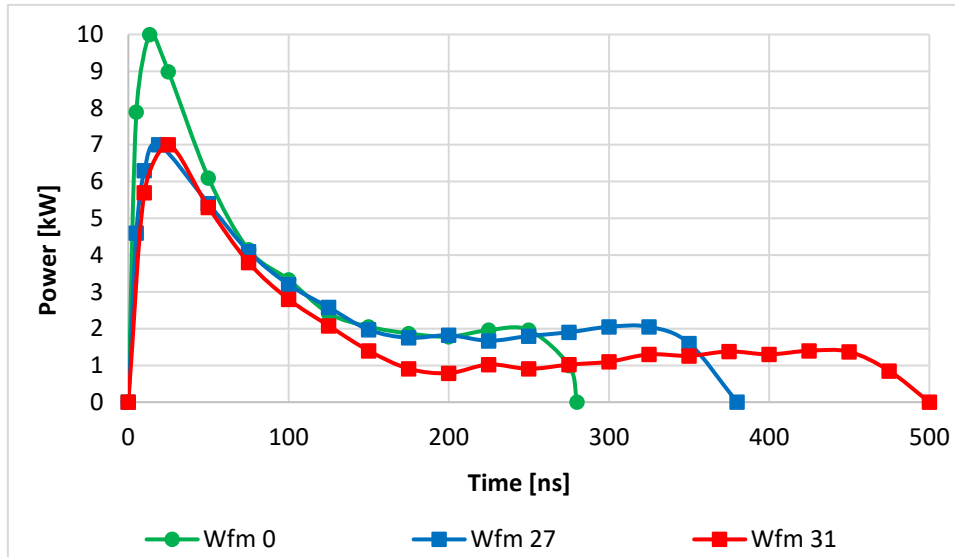


Figure 8-12 Pulse shapes of waveforms 0, 27 and 31 for a pulse repetition frequency of 100 kHz at an average power of 100W.

Figure 5-7 from section 5.3.1 was replicated and shown in Figure 8-13. A constant penetration depth of 1.3 mm was achieved independently of the waveform selected. For a short pulse duration, a high $P_{F, MPPW}$ is necessary to compensate for the low $t_{i, MPPW}$ (Figure 8-13A), whereas, for longer pulses, a low $P_{F, MPPW}$ is balanced by a high $t_{i, MPPW}$ (Figure 8-13C). From Figure 8-13A-B, the P_{Width} increased 1.25x, from 280ns to 350 ns. Consequently, the $P_{F, MPPW}$ was reduced 1.25x whereas, $t_{i, MPPW}$ was increased 1.25x. From Figure 8-13A-C, the P_{Width}

increased 1.8x, from 280ns to 500 ns, and $P_{F, MPPW}$ and $t_{i, MPPW}$ changed in the same proportion. In all cases, the penetration depth was kept constant since the duty cycle of the laser compensated for the difference in pulse duration and peak power verified in all waveforms in Figure 8-12, allowing constant thermal losses between pulses. These results follow the same trend lines of constant penetration depths previously shown in Figure 8-4.

As observed in Figure 8-14, the power factor model cannot be applied if the duty cycle is not adjusted in the same proportion as P_{Width} . From Figure 8-14A-B, P_{Width} increased 1.8x from 280 ns to 500 ns, but the duty cycle was reduced to half, which resulted in a constant $t_{i, MPPW}$, higher $P_{F, MPPW}$ and consequently, an increase in the penetration depth. Therefore, it can be concluded that the duty cycle is a critical parameter to consider in this model when different laser temporal modes are used.

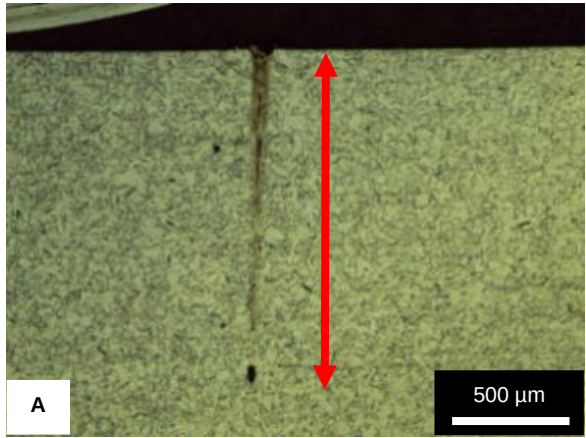
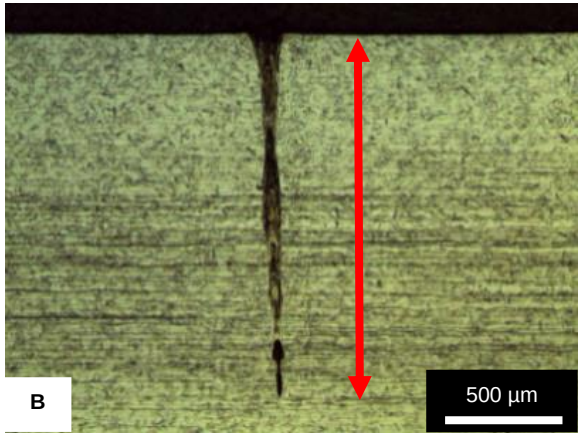
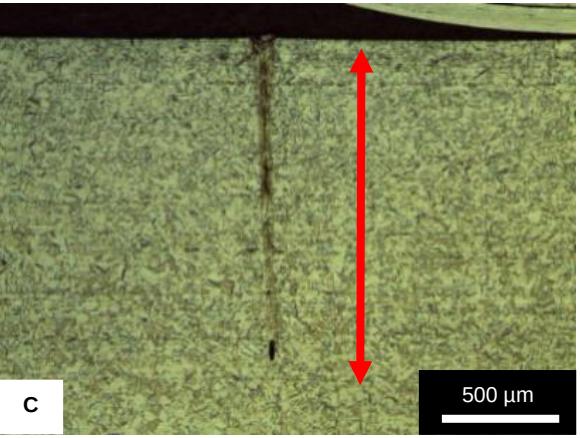
Depth of penetration = 1.3 mm; $P_L = 100\text{ W}$; $d = 35\text{ }\mu\text{m}$		
$P_{F, \text{MPPW}} = 102\text{ MW/m}^2$; $t_{i, \text{MPPW}} = 0.056\text{ ms}$	$P_{F, \text{MPPW}} = 81.6\text{ MW/m}^2$; $t_{i, \text{MPPW}} = 0.07\text{ ms}$	$P_{F, \text{MPPW}} = 57.1\text{ MW/m}^2$; $t_{i, \text{MPPW}} = 0.1\text{ ms}$
$P_{\text{width}} = 280\text{ ns}$ (Wfm 0)	$P_{\text{width}} = 350\text{ ns}$ (Wfm 27)	$P_{\text{width}} = 500\text{ ns}$ (Wfm 31)
$D_C = 2.8\%$	$D_C = 3.5\%$	$D_C = 5\%$
		

Figure 8-13 Constant penetration depth of 1.3 mm achieved with different combinations of power factors and interaction times in waveforms 0, 27 and 31 at a constant average power of 100 W and beam diameter of 35 μm .

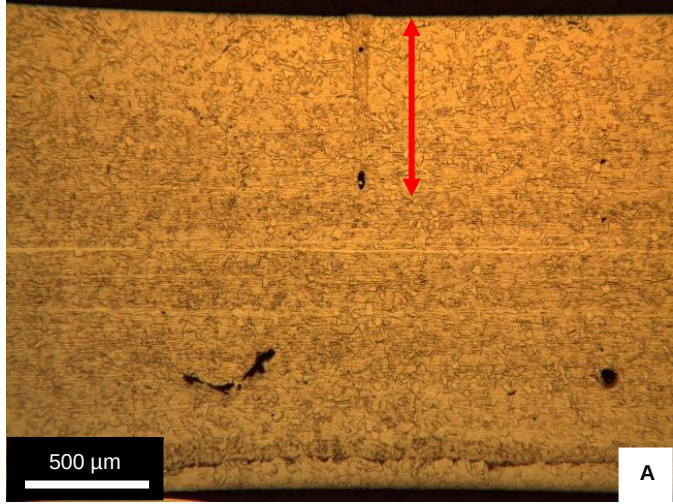
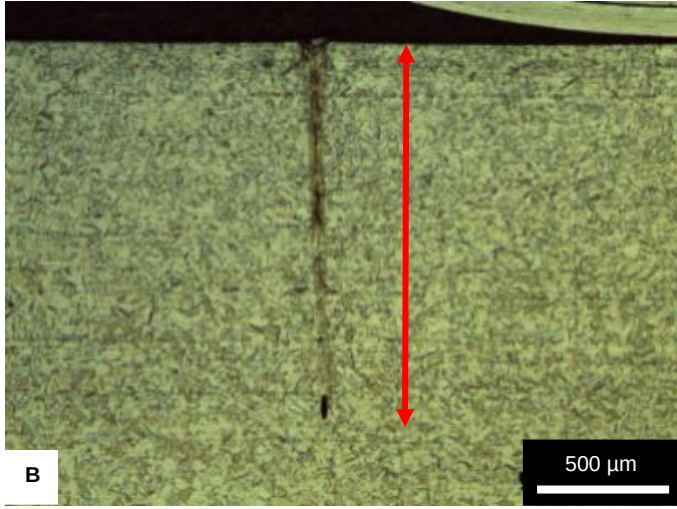
$P_{\text{width}} = 280 \text{ ns (Wfm 0)}$	$P_{\text{width}} = 500 \text{ ns (Wfm 31)}$
$P_{\text{F, MPPW}} = 28.6 \text{ MW/m; } t_{\text{i, MPPW}} = 0.1 \text{ ms}$	$P_{\text{F, MPPW}} = 57.1 \text{ MW/m; } t_{\text{i, MPPW}} = 0.1 \text{ ms}$
$D_{\text{C}} = 10\%$	$D_{\text{C}} = 5\%$
	
Depth = 0.70 mm	Depth = 1.3 mm

Figure 8-14 Different penetration depths achieved in waveforms 0 and 31 for various power factors and constant interaction time of 0.1 ms, average power of 100 W and beam diameter of 35 μm .

There is an alternative to applying the model in different temporal pulse shapes. Figure 5-11 from 5.3.1 was replicated and shown in Figure 8-15. In Figure 8-15, a constant penetration depth of 1.3 mm was achieved in different waveforms for a constant $P_{F, MPPW}$ and $t_{i, MPPW}$ due to a constant duty cycle of 5%. According to Table 8-7, this was possible by adjusting PRF to each P_{Width} . Hence, a constant combination of q_p , $q_{p, peak}$ and $E_{SP, MPPW}$ was possible for the three different waveforms (Table 8-8). Consequently, the substrate was subjected to a constant thermal cycle within the same period as a constant inter-pulse spacing and travel speed kept the surface temperature and the penetration depth constant [128]. As previously concluded in Figure 8-13, and confirmed in Figure 8-15, the duty cycle is a critical parameter to consider in the power factor model to achieve similar penetration depths in different waveforms. Similar results have been observed for laser scoring using a nanosecond MPPW laser [42], which means that the model might be extended to other applications rather than just micro-welding.

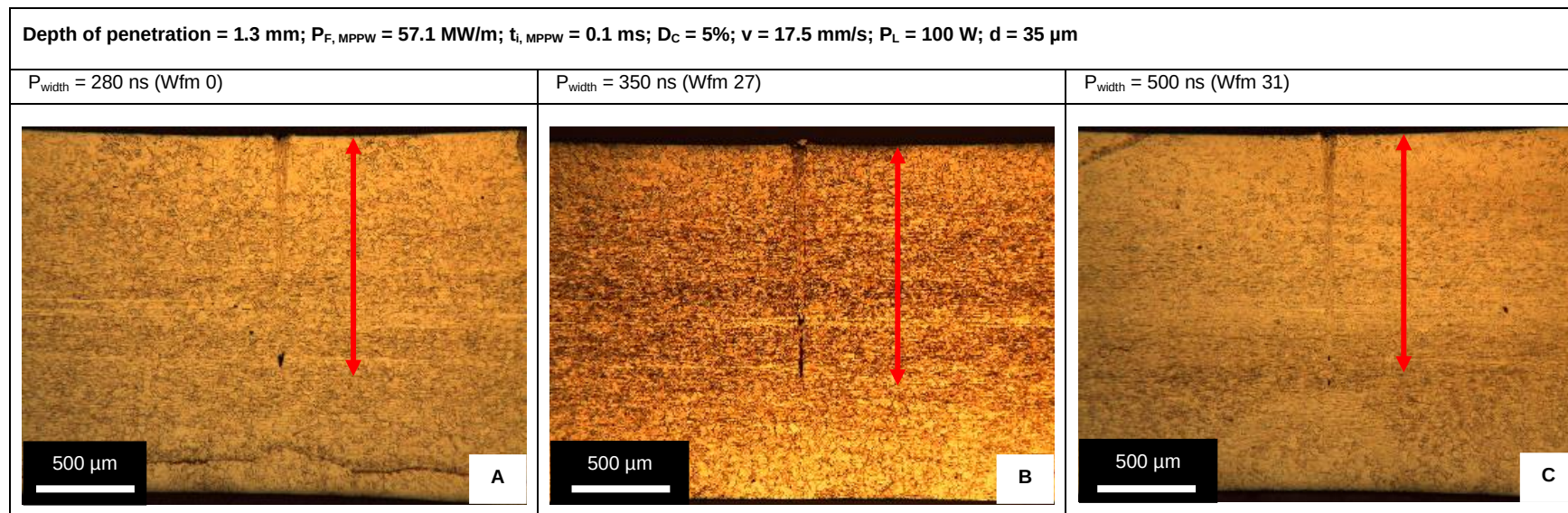


Figure 8-15 Constant penetration depth of 1.3 mm achieved in waveforms 0, 27 and 31 at a constant power factor of 57.1 MW/m, interaction time of 0.1 ms, a duty cycle of 5%, an average power of 100 W and beam diameter of 35 μm .

8.3.4 Effect of interaction time and power factor on aluminium

Identical parameters to those applied in SS were also used for Al in this section. The Power Factor model was validated for CW micro seam welding of Al in section 7.3.2, being possible to achieve constant penetration depth curves for different interaction times, independently of the beam diameter selected (Figure 7-10). However, the observations in MPPW mode are entirely different for the same alloy. In Figure 8-16 and Figure 8-17, the dispersion of the results is too high in order to have a model able to predict the penetration depth. It would be expectable lower penetration depths for lower interaction times for all beam diameters, as previously observed for SS in Figure 8-6 and Figure 8-7. However, for similar values of $P_{F, MPPW}$ and $t_{i, MPPW}$ applied for Al in Figure 8-16 and Figure 8-17, for beam diameters of 59 and 89 μm , the penetration depth is higher for an interaction time of 0.05 ms than for 0.5 ms. From the literature review, it was already known that the nanosecond pulsed laser creates spike-like welds due to the high-power density applied in the substrate at a rapid rate. Moreover, the presence of Mg and Zn in this alloy (Table 3-1 from section 3.1) increases the porosity in the weld pool [89], as observed in the micrographs from Figure 8-18, causing instability in the keyhole during the process. Consequently, it is difficult to predict the penetration depth based on this model.

In the opposite to what was observed in section 7 for stainless steel welds in CW mode, the weld quality cannot be controlled in MPPW mode as it was observed undercut and similar porosity in all welds independently of the interaction time and material used. The higher peak power density applied in MPPW in comparison to CW mode, opens the keyhole very easily, and vaporises the low melting point elements. On the other hand, the high pulse repetition frequency and low pulse energy are responsible for a fast freezing of the melt pool, entrapping some air at the bottom of the weld, which is shown as porosity. For the range of parameters studied in this section, the difference in peak power from waveform 0 (10kW) to waveform 31 (7 kW) (Table 8-6), is not reflected by a decrease in porosity, being it similar in all welds achieved in Figure 8-13 and Figure 8-14.

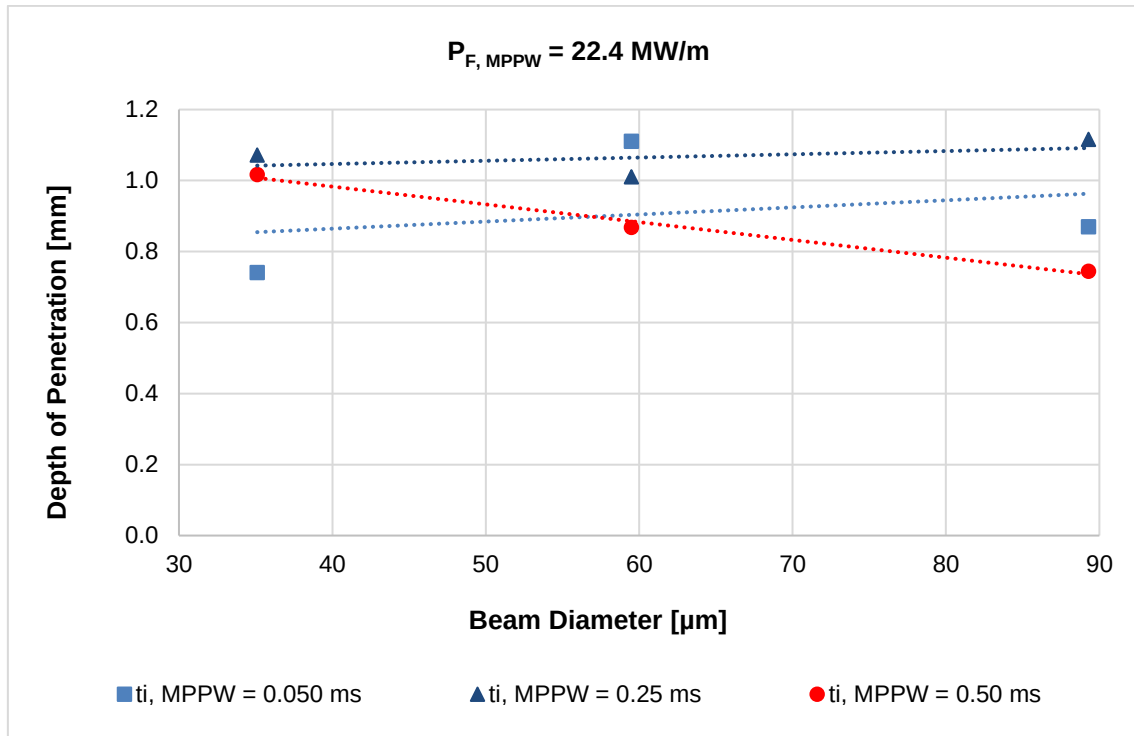


Figure 8-16 Effect of the beam diameter on the depth of penetration of MPPW processing of aluminium at different interaction times and a constant power factor of 22.4 MW/m.

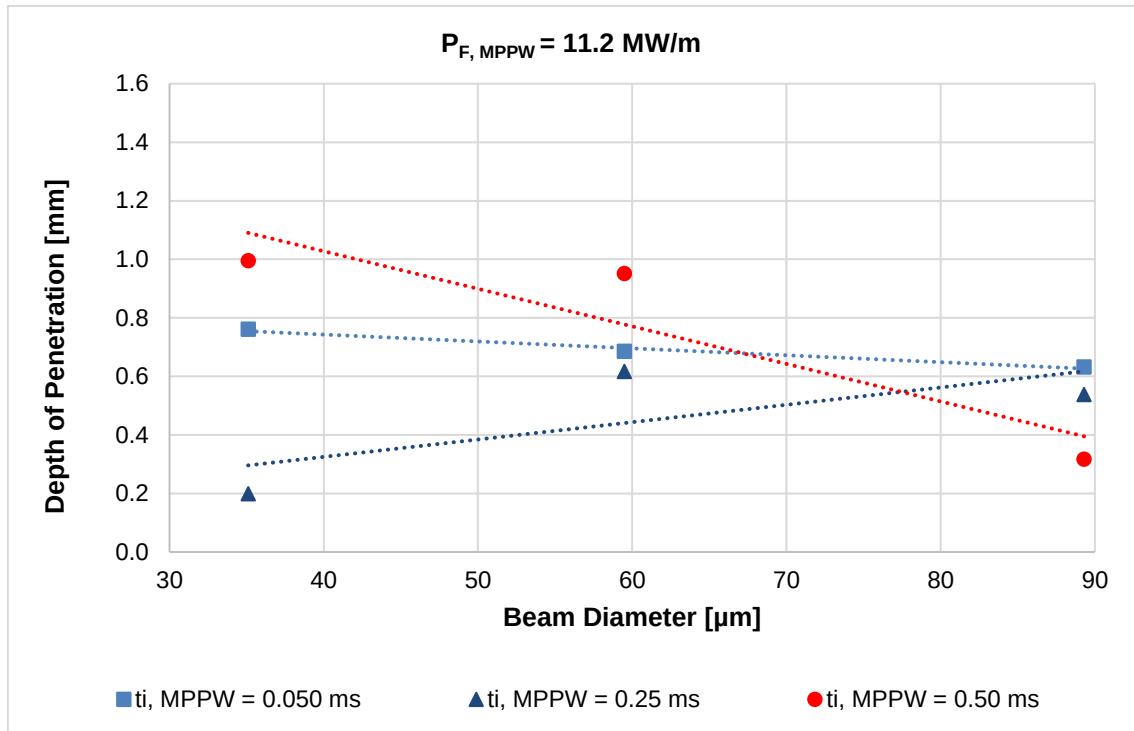


Figure 8-17 Effect of the beam diameter on the depth of penetration of MPPW processing of aluminium at different interaction times and a constant power factor of 11.2 MW/m.

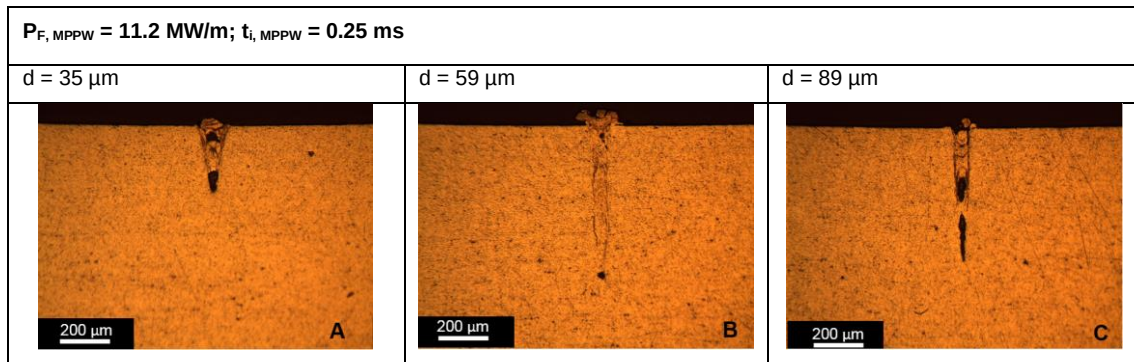


Figure 8-18 MPPW aluminium welds at a constant power factor of 11.2 MW/m and interaction time of 0.25 ms for beam diameters of 35 μm , 59 μm and 89 μm .

8.4 Summary of discussions

The standard formulation of the power factor model in CW processing was redesigned and exploited in MPPW seam welding. The power factor's new definition correlates the average peak power rather than the average power with the beam diameter. The following conclusions can be drawn:

- The power factor model allows the MPPW laser user to select a weld profile in stainless steel which meets certain productivity requirements independent of the laser system. Nevertheless, it cannot be used to select welds based on their quality.
- High aspect-ratio and productive welds can be achieved for high values of power factor and short interaction times, whereas wider melt pools suitable for higher fit-up tolerance and less productive applications can be achieved for lower power factors and longer interaction times.
- Constant penetration depth curves against interaction time and power factor were achieved in stainless steel: A certain combination between high power factor and short interaction time or vice versa will lead to similar penetration depths but different weld widths. The higher the penetration depth required, the higher the power factor needed for equal interaction time.
- For each beam diameter, there is a threshold in the maximum interaction time for a specific power factor, creating limitations on the model's applicability due to unpredictable variations of the penetration depth. This limit is reached sooner for smaller beams than larger beams due to the difference in high energy losses caused by the ratio of the heat source to the bulk material.
- For a constant average power and beam diameter, the duty cycle is a critical parameter to calculate the power factor and interaction time values needed to achieve similar weld shapes in different waveforms: For shorter pulse durations, the laser duty cycle is reduced to compensate in the same proportion the increase in peak power, keeping constant the trade-off between power factor and interaction time.

9 Application of MPPW and CW fibre lasers in dissimilar micro-welding

This chapter is based on the following publication:

Coroado J.*, Ganguly S., Suder W., Williams S., Meco S., Pardal G. (2021) 'Comparison of continuous and pulsed wave lasers in keyhole welding of stainless-steel to aluminium', *The International Journal of Advanced Manufacturing Technology*, 119, pp. 367–387, <https://doi.org/10.1007/s00170-021-08226-5>.

9.1 Introduction

This research aims to compare continuous wave and multi-pulse pulsed-wave to understand how the bond area, weld shape, IMCs distribution and lap-joint configuration affect the mechanical strength of welds achieved at similar applied energy per unit length. The objectives are as follows:

- Optimisation of the CW and MPPW laser welding parameters to achieve successful bonding between SS and Al.
- Metallurgical analysis of SS-Al and Al-SS lap-joints.
- Mechanical strength characterisation of the successful lap joints.

9.2 Experimental procedure

9.2.1 Materials

The welds were carried out in 5251 Al alloy and 304L austenitic SS. The chemical composition of each alloy is shown in Table 9-1 and Table 9-2, and the mechanical and physical properties are shown in Table 9-3 and Table 9-4, respectively.

Table 9-1 Chemical composition in %wt of Al 5251 H22 [121].

Si	Fe	Cu	Mn	Mg	Zn	Ti	Cr	Al
Max 0.4	Max 0.5	Max 0.15	0.1 – 0.5	1.7 – 2.4	Max 0.15	Max 0.15	Max 0.15	Bal.

Table 9-2 Chemical composition in %wt of SS 304 L [122].

Si	S	C	P	Mn	Ni	N	Cr	Fe
Max 1.00	Max 0.02	Max 0.03	Max 0.05	Max 2.00	8.00 – 10.50	Max 0.11	17.50 – 19.50	Bal.

Table 9-3 Mechanical properties of the base materials [121][122].

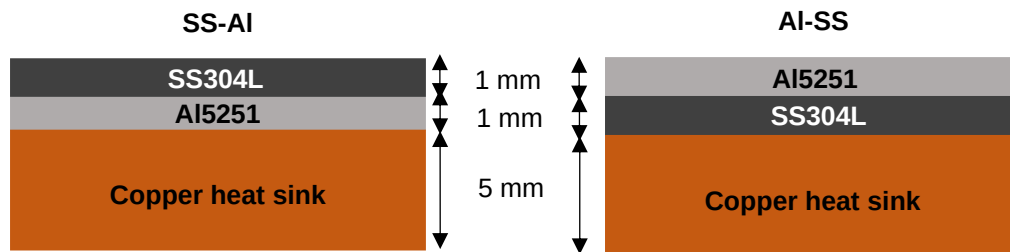
Material	Proof Stress, MPa	Tensile Strength, MPa	Elongation at failure, %
Al 5251 H22	120 min	190 - 230	15 - 20
SS 304 L	220 min	520 - 700	45 min

Table 9-4 Physical properties of the base materials [121][122].

Property	Symbol	Units	Al 5251 H22	SS 304L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Specific heat of solid phase	c_{ps}	J.kg ⁻¹ .K ⁻¹	850	477
Vaporisation Temperature	T_v	K	2790	3023
Viscosity	η	m.Pas	1.3	8.0
Thermal conductivity	k	W.m ⁻¹ .K ⁻¹	134	16.2
Thermal diffusivity	α	m ² .s ⁻¹	5.7×10^{-5}	5.5×10^{-6}
Modulus of Elasticity	E	GPa	70	193

9.2.2 Methodology and experimental setup

The lap-joints were produced as depicted in Figure 9-1, and the corresponding dimensions are shown in Figure 9-2. Two different fibre lasers were independently used: a 500 W average power CW laser and a 100 W average power nanosecond MPPW laser. More details of the experimental setup are described in section 3.

**Figure 9-1 Lap-joints of SS-Al and Al-SS.**

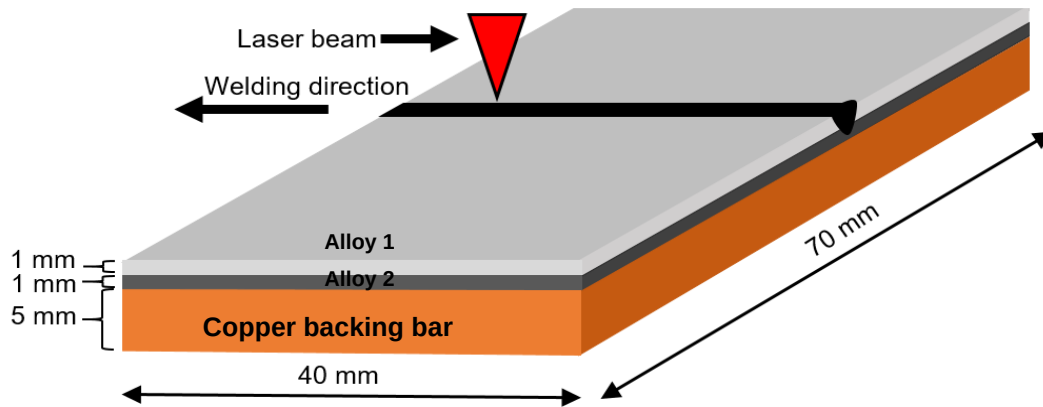


Figure 9-2 Lap-joints dimensions of SS-Al and Al-SS.

This study selected only one waveform with the maximum pulse energy and the longest pulse duration available in the laser. Its characteristics are shown in Table 9-5.

Table 9-5 Characteristics of waveform 31 of MPPW laser [126].

Waveform	PRF ₀ [kHz]	Max pulse energy, E _{max} [mJ]	Pulse width [ns]	Peak Power at E _{max} [kW]
31	100	1	500	7

9.2.2.1 CW laser welding of SS-Al and Al-SS

This section investigates the influence of power density (q_p) and specific point energy ($E_{SP, CW}$) on the bonding quality of lap welded joints of SS-Al and Al-SS, using a CW laser. For a constant beam diameter of 35 μm , different combinations of average power and travel speed were used, resulting in a range of q_p from 26 to 49 MW/cm^2 and $E_{SP, CW}$ from 137 to 1000 mJ. The set of parameters used is shown in Table 9-6. The values presented result from several experiments produced to identify the necessary laser parameters to ensure successful bonding between the base materials.

Table 9-6 CW laser welding parameters for a beam diameter of 35 μm .

System Parameters			Fundamental Laser Material Interaction Parameters		
Beam diameter [μm]	Average Power [W]	Travel Speed [mm/s]	Interaction time [ms]	Average Power Density [MW/cm ²]	Specific Point Energy [mJ]
d	P_L	v	$t_{i, \text{CW}}$	q_p	$E_{SP, \text{CW}}$
35	250-472	11-94	0.40-3.2	26-49	137-1000

9.2.2.2 MPPW laser welding of SS-Al and Al-SS

A nanosecond MPPW laser was used to join SS-Al and Al-SS. The aim is to study the influence of average peak power density ($q_{p, \text{peak}}$) and specific point energy ($E_{SP, \text{MPPW}}$) on the bonding quality of lap joints and compare the processing parameters to achieve similar MPPW and CW welds. Only one waveform with the maximum pulse energy and the longest pulse duration available in the laser has been selected. Its characteristics are shown in Table 9-7. For a constant beam diameter of 35 μm , an average power of 100 W and a pulse width of 500 ns, different combinations of peak power, pulse energy, travel speed and pulse repetition frequency were used, resulting in a constant q_p of 10.4 MW/cm² and a range of $q_{p, \text{peak}}$ from 33 to 208 MW/cm² and $E_{SP, \text{MPPW}}$ from 250 to 1000 mJ. The set of parameters used and the respective results are shown in Table 9-8.

Table 9-7 Characteristics of waveform 31 of MPPW laser [126].

Waveform	PRF ₀ [kHz]	Max pulse energy, E _{max} [mJ]	Pulse width [ns]	Peak Power at E _{max} [kW]
31	100	1	500	7

Table 9-8 MPPW laser welding parameters for a beam diameter of 35 μm , average power of 100 W and pulse width of 500 ns.

System parameters						Calculated parameters		Fundamental laser material interaction parameters			
Beam diameter [μm]	Average power [W]	Frequency [kHz]	Travel speed [mm/s]	Pulse energy [mJ]	Average peak power [kW]	Overlap factor [%]	Duty cycle [%]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]	Interaction time [ms]
d	P _L	PRF	v	E _{Pulse}	P _{peak}	O _F	D _C	q _p	q _{p, peak}	E _{SP, MPPW}	t _{i, MPPW}
35	100	100 - 807	3.5 - 14	0.12 - 1.0	0.25 - 2.0	99.9-99.98	5 - 40.4	10.4	26-208	250-1000	0.5-3.2

9.2.3 Metallographic and mechanical strength characterisation

The microstructural analysis was based on an optical microscope. The IMCs distribution and welding defects were analysed through SEM/EDS, as previously outlined in section 3.3. Tensile-shear tests have measured the mechanical strength of the joints according to the procedure described in section 3.4. Tensile shear tests were carried out to analyse the mechanical strength of selected successful joints from Table 9-6 and Table 9-8 for CW and MPPW modes, respectively. The maximum load and maximum load per unit of length of the welds were compared between both laser processing modes for similarly applied energies. The ultimate tensile strength (UTS) was also calculated for the strongest joint achieved in each mode by dividing the maximum load by the area of the weld cross-section.

9.3 Results and discussion

9.3.1 CW laser welding of SS-Al and Al-SS

Table 9-9 summarises the laser welding parameters used to join SS on Al. For each set of parameters, it is also indicated if the bonding was successful or not. Several micrographs of the welds' cross-sections have been analysed to verify defects such as porosity and cracking along the joint.

Table 9-9 CW laser welding parameters and results for a beam diameter of 35 μm .

System Parameters			FLMIP			Successful bonding?	
Beam diameter [μm]	Average Power [W]	Travel Speed [mm/s]	Interaction time [ms]	Average Power Density [MW/cm ²]	Specific Point Energy [mJ]	SS-Al lap-joint	Al-SS lap-joint
d	P _L	v	t _{i, CW}	q _p	E _{SP, CW}	-	-
35	250	64	0.55	26	137	NO	NO
35	250	32	1.1	26	273	YES	NO
35	250	16	2.2	26	545	YES	NO
35	304	64	0.55	32	166	NO	NO
35	304	32	1.1	32	333	YES	NO
35	304	16	2.2	32	665	YES	NO
35	320	64	0.50	33	176	YES	NO
35	320	41	0.90	33	273	YES	NO
35	320	34	1.0	33	333	YES	NO
35	320	22	1.6	33	516	YES	NO
35	320	11	3.2	33	1000	YES	NO
35	472	94	0.40	49	176	YES	NO
35	472	64	0.50	49	258	YES	NO
35	472	32	1.1	49	516	NO	NO

It is shown in Figure 9-3A-C the fusion zone of the lap-joints of SS-Al for different levels of specific point energy and constant power density. Figure 9-3D-F shows in more detail the respective joints magnification from Figure 9-3A-C. Due to the lower vaporisation temperature of Al in comparison to SS (Table 9-4), in Figure 9-3A occurred a violent ejection of metal for the highest $E_{SP, CW}$ and q_p applied. As $E_{SP, CW}$ decreased from Figure 9-3D-F at constant q_p through a reduction in $t_{i, CW}$ (Table 9-9), the penetration depth decreased as well, and weld quality was improved, i.e. cracks were reduced. This improvement is related to the IMC formation since they are dependent on the time and temperature of the process, decreasing with a reduction in energy input [34]. It is essential to highlight the difficulty in achieving low energy levels with CW lasers since high travel speeds are required to achieve rapid melting and solidification and, consequently, low IMC formation.

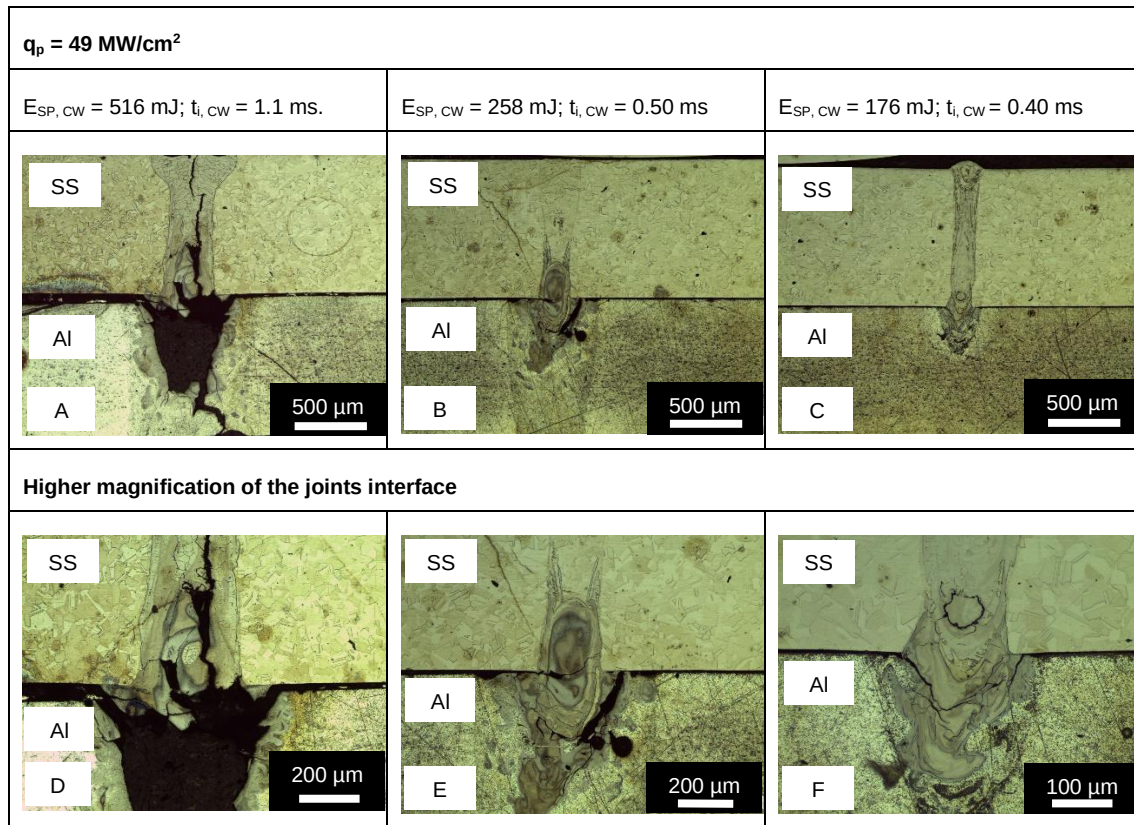


Figure 9-3 CW lap-joints of SS-Al for constant q_p of 49 MW/cm^2 and different E_{SP} , c_w and $t_{i, CW}$.

In Figure 9-3, the IMC were mixed and not distributed in a thin layer as a needle shape along with the interface, as observed in previous studies for laser conduction mode [105]. Since this study has been performed in keyhole mode, the mixing of both alloys was enhanced, and the IMCs distributed around the fusion zone, as observed in the EDS mapping in Figure 9-4. A several times lower viscosity of Al as compared to SS (Table 9-4) must be considered as an essential factor to explain how easy Fe diffuses in Al, enhancing their mixing. Moreover, the higher density of SS in comparison to Al (Table 9-4) may also have facilitated the mixing of both alloys. A similar explanation was given by Lee et al. when they tried to join Al to copper [132].

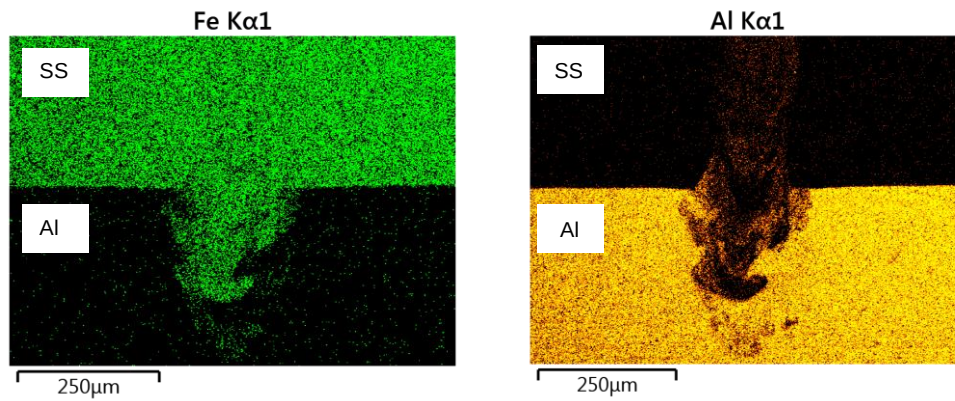


Figure 9-4 EDS mapping of Fe and Al elements from a CW lap-joint of SS-Al for q_p of 49 MW/cm², $E_{SP, CW}$ of 176 mJ and $t_{i, CW}$ of 0.4 ms.

It is known that lower power density decreases the reaction rate between Al and Fe, enabling better control of the IMCs formation [34]. Therefore, in this work, the power density has been decreased from 49 MW/cm² in Figure 9-3 to 33 MW/cm² in Figure 9-5 at constant $E_{SP, CW}$ through a reduction in average power and travel speed (Table 9-9). As expected, the weld quality has been improved, despite the small cracks caused by the remaining IMCs. Some solute bands of Fe-Al phases are visible on the edge of the weld. These bands have also been observed by Sierra et al. when joining steel to Al using a high-power CW laser [9]. They attributed their origin to the upward convection movements occurring at high temperatures, entrapping Al in steel. A rise in the volume of liquid Al due to the increase of steel penetration led to a greater Al–Fe dilution, which resulted in thicker bands, as observed in Figure 9-5D. These bands could form: (1) locally richer aluminium Fe–Al alloys, (2) Fe_xAl_y intermetallic phases if the formation threshold had been reached, or (3) could solidify as pure Al [9].

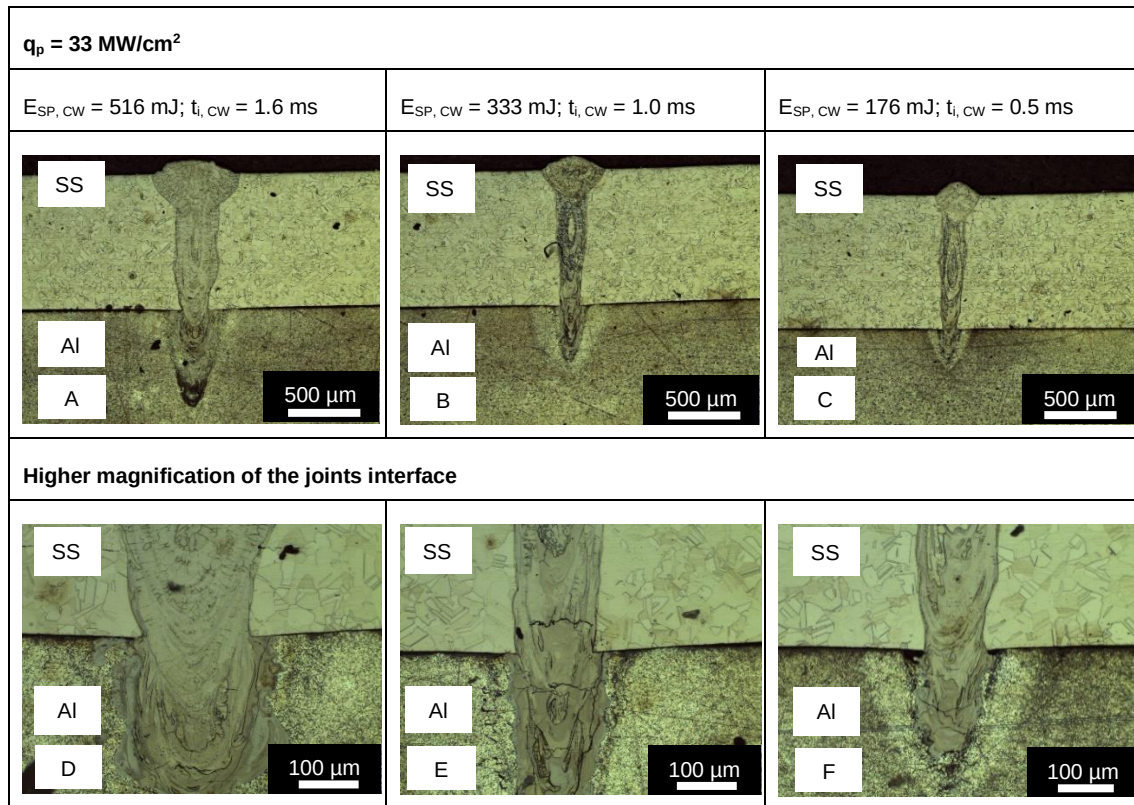


Figure 9-5 CW lap-joints of SS-Al for constant q_p of 33 MW/cm^2 and different $E_{SP, CW}$ and $t_{i, CW}$.

The IMCs distribution from Figure 9-5F was analysed in EDS spectrums in Figure 9-6. Spectrum number 34 shows that, in the stainless-steel sheet, there is a small concentration of Al and no cracks are visible in this region. At spectrum number 37, the concentration of Al increased slightly, and the formation of the cracks was more evident. Moving further into Al to spectrum number 38, the atomic percentage of Al is even higher and very similar to Fe, which coincides with the increase in the size of the cracks. However, due to the scattered intermetallic compounds close to the edge of the joint interface on spectrum number 43, the atomic percentage of Al is also high, and a small crack is visible. This is due to the high peak temperature generated by the high-power density applied in a small beam, resulting in a rise in the recoil pressure, causing the convection of Al upwards [80].

The IMCs are organised into two groups, the Fe-rich and the Al-rich IMCs. The hardest and thus more brittle IMCs are found in the Al-rich group [101][105] for an atomic concentration (at) of Al above 58%. Sierra et al. [9] observed that the

hardness and, consequently, the formation of the cracks increased in steel-on-aluminium laser welds for deeper penetrations, mainly attributed to an increase in the Al ratio in the weld. These conclusions are in agreement with spectrum 34 from Figure 9-6B, where the at.% of Al is below 10% and no cracks are visible, being all the Al dissolved in Fe [101], and also with spectrum 38, where the at.% of Al is close to 40% and larger cracks can be observed. However, due to the severe Al gradients across the weld metal area, different IMCs could have been formed at specific locations.

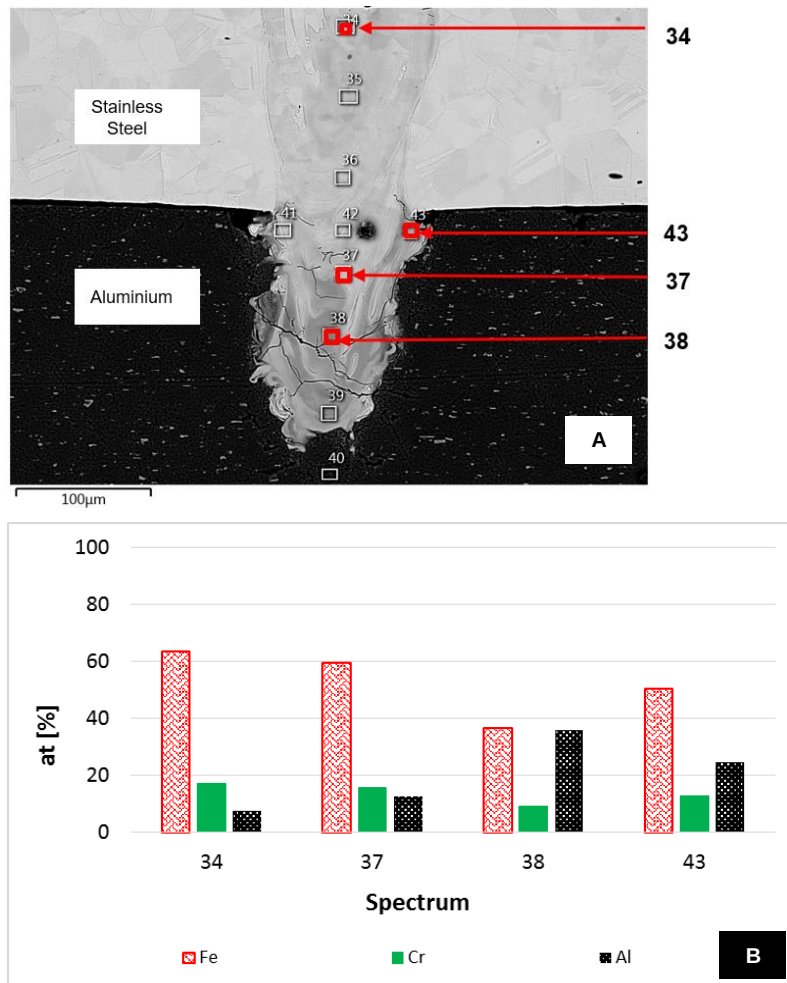


Figure 9-6 SEM micrograph (A) and respective EDS spectrum analysis (B) from a CW lap-joint of SS-Al for q_p of 33 MW/cm², $E_{SP, CW}$ of 176 mJ and $t_{i, CW}$ of 0.5 ms.

The welding parameters from Figure 9-5 were replicated for an Al-SS lap-joint configuration and presented in Figure 9-7. Despite the reduction of $E_{SP, CW}$ at constant q_p from Figure 9-7A-C, no successful lap-joints were possible to

achieve, breaking at the interface. In Figure 9-7A (Al-SS), for specific point energy of 516 mJ and power density of 33 MW/cm², the weld width of the upper sheet of Al was larger in comparison to Figure 9-5A (SS-Al). The higher thermal conductivity by a factor of eight and lower melting temperature by a factor of two of Al (Table 9-4) allowed a larger fusion zone in Figure 9-7A, conducting the heat faster to SS. On the other hand, for SS-Al in Figure 9-5A, similar energy of 516 mJ took longer to reach the Al sheet for an equal interaction time of 0.5 ms, since the specific heat capacity of SS is 1.8x lower than Al. Thus, the peak temperature reached on the joint interface was lower, decreasing the penetration depth and the IMCs concentration compared to the Al-SS lap-joint in Figure 9-7A. This may explain the difference in bonding for both joint configurations. Similar results were observed by Sierra et al. when joining aluminium-on-steel [9]. All welds performed were cracked at the joint interface. The steel interface exhibited large IMCs, more than 50 µm thick, because the liquid was richer in steel. They concluded that the cracks were probably related to the sensitivity to hot cracking of the Al alloys used in their study.

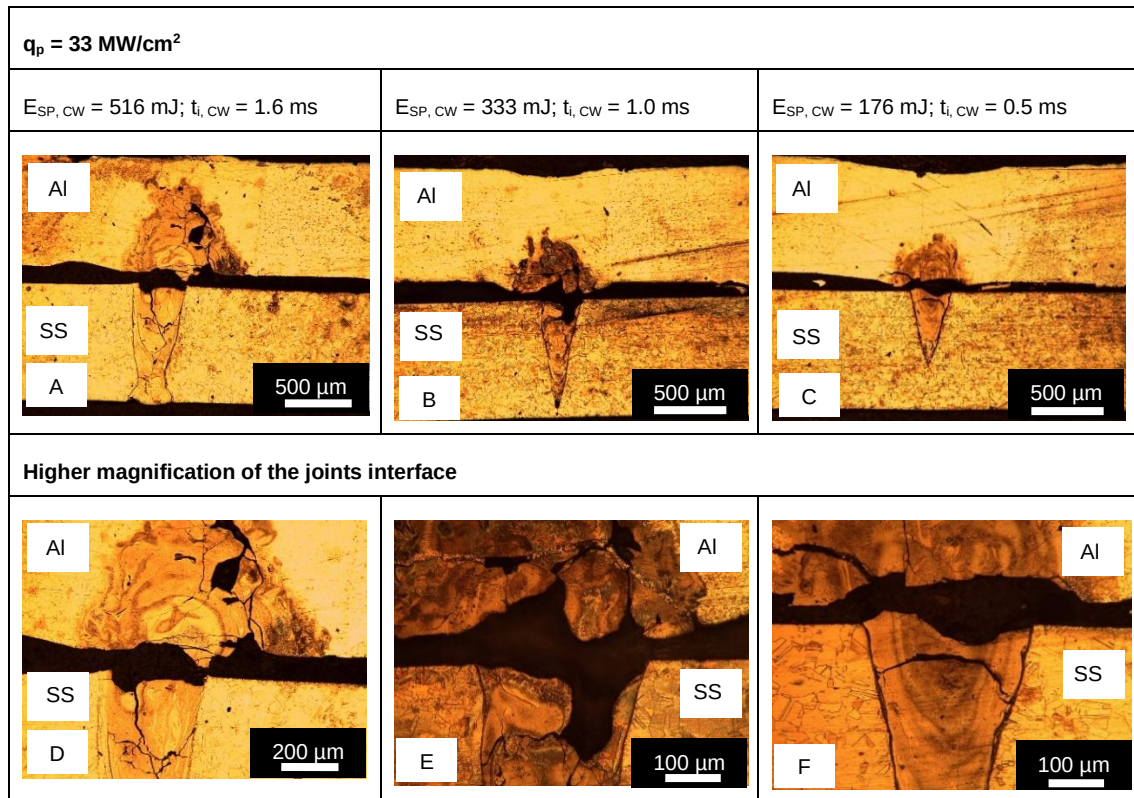


Figure 9-7 CW lap-joints of Al-SS for constant q_p of 33 MW/cm^2 and different $E_{SP, CW}$ and $t_{i, CW}$.

9.3.2 MPPW laser welding of SS-Al and Al-SS

This section used an MPPW laser to join SS-Al in the first stage and then Al-SS in the second stage. The welding parameters used are shown in Table 9-10.

Table 9-10 MPPW laser welding parameters and results for a beam diameter of 35 μm , average power of 100 W and pulse width of 500 ns.

System parameters				Calculated parameters		FLMIP		Successful bonding?			
Frequency [kHz]	Travel speed [mm/s]	Pulse energy [mJ]	Peak power [kW]	Overlap factor [%]	Duty cycle [%]	Average power density [MW/cm ²]	Average peak power density [MW/cm ²]	Specific point energy [mJ]	Interaction time [ms]	SS-Al lap-joint	Al-SS lap-joint
PRF	v	E _{pulse}	P _{peak}	O _F	D _C	q _p	q _{p, peak}	E _{SP, MPPW}	t _{i, MPPW}	-	
100	3.5	1.0	2.0	99.9	5	10.4	208	1000	0.5	NO	YES
150	5.2	0.67	1.3	99.9	7.5	10.4	139	667	0.5	NO	YES
300	10.5	0.33	0.67	99.9	15	10.4	69	333	0.5	NO	YES
400	14	0.25	0.50	99.9	20	10.4	52	250	0.5	NO	NO
807	6.4	0.12	0.25	99.98	40.4	10.4	26	545	2.2	NO	NO
640	3.5	0.16	0.31	99.98	32	10.4	33	1000	3.2	NO	NO
426	6.8	0.23	0.47	99.96	21.3	10.4	49	516	1.1	NO	NO

Figure 9-8A shows an MPPW lap-joint of SS-Al for $q_{p, peak}$ of 208 MW/cm² and $E_{SP, MPPW}$ of 1000 mJ. The respective EDS spectrum analysis is shown in Figure 9-8B. Several voids can be observed along the fusion zone in Figure 9-8A. Magnesium is one of the main alloying elements of the Al alloy used in this study (Table 3-1). Since the vaporisation temperature of magnesium (1363 K) is much lower than SS (3023 K) and Al (2790 K), its vaporisation may have a strong contribution to the keyhole instability, increasing the capillary forces generated and the likelihood of defect formation in the weld pool [81][89]. The lower viscosity of Al as compared to SS also enables more efficient melt removal from the bottom of the keyhole [70].

The EDS spectrum analysis from Figure 9-8B indicates a high concentration of Fe in the centre of the SS sheet, being residual the atomic percentage of Al. However, on the edge of the same horizontal line, the atomic percentage of Al is 49%. On the Al sheet, in the middle of the fusion zone, the atomic percentage of Al is almost 100%. The presence of voids caused by the entrapment of the vaporised alloys after solidification enhanced the mixing of both metals at the interface [133] where the atomic percentage of Al is above 70%. For these Al percentages, F_2Al_5 and $FeAl_3$ phases were formed [101][105]. The low fracture toughness of each phase may explain the lack of bonding between these alloys for the parameters tested due to crack formation [133].

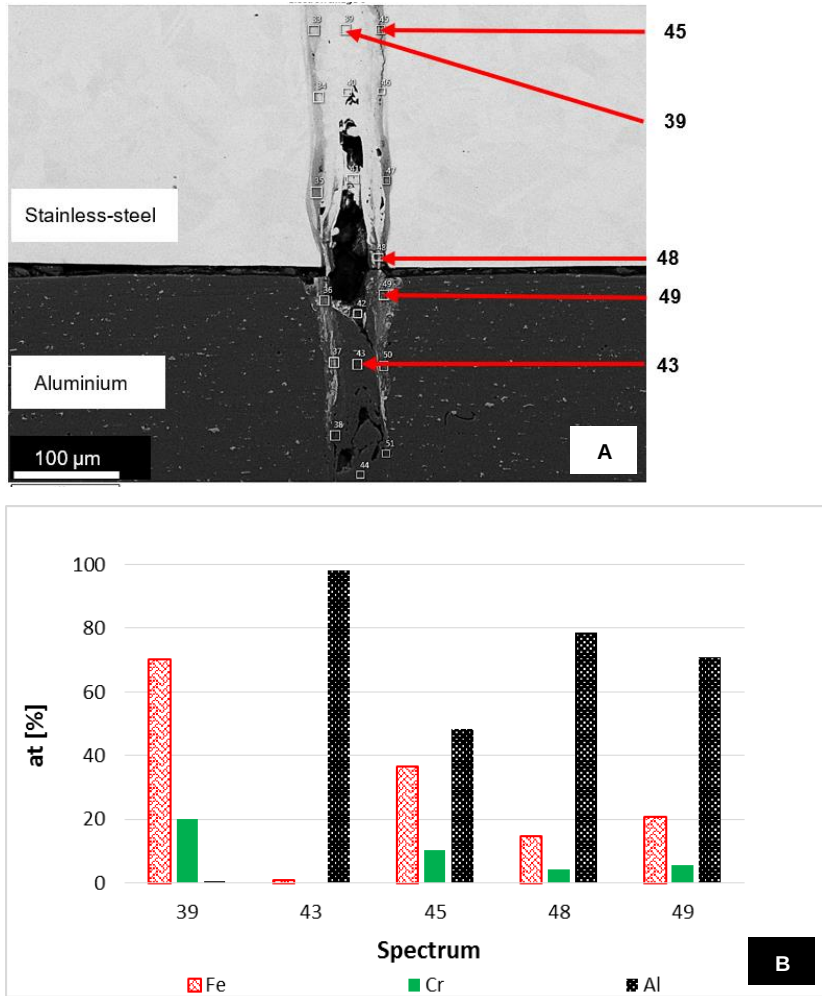


Figure 9-8 SEM micrograph (A) and respective EDS spectrum analysis (B) from a MPPW lap-joint of SS-Al for q_p of 10.4 MW/cm², $q_{p, peak}$ of 208 MW/cm², $E_{SP, MPPW}$ of 1000 mJ and $t_{i, MPPW}$ of 0.5 ms.

The SS-Al lap-joints were unsuccessful using an MPPW laser but successful in CW mode, as demonstrated in the previous section. A comparison between both temporal modes is shown in Figure 9-9 for a similar penetration depth of 1.2 mm. Despite the lower average power of the MPPW laser in comparison to the CW laser, its higher peak power generated a higher average peak power density applied in Figure 9-9B, increasing the vaporisation of Al and its alloying elements. This is likely to cause the escape of the vaporised elements towards the top of the narrow weld, causing a high pressure at the joint interface by a descending stream of molten steel and an ascending stream of molten Al, enhancing the mixing between the base metals and the formation of brittle IMCs. Moreover, the

difference in the thermal expansion coefficient of both alloys [134] will force a gap between both sheets, cracking the narrow joint and avoiding bonding. However, this phenomenon is not so evident in CW mode in Figure 9-9A.

For a similar interaction time of 0.5 ms, CW laser utilises a duty cycle of 100% at a travel speed of 64 mm/s (Table 9-9), whereas with MPPW laser, a duty cycle of 15% and a travel speed of 10.5 mm/s are applied. Thus, the thermal losses are lower in CW mode than in MPPW mode, being possible to achieve similar penetration depth at lower applied energy, as previously observed in section 6. A greater volume of SS was mixed in Al in CW mode (Figure 9-9A), breaking the balance between recoil pressure and surface tension, and enhancing the mixing between both alloys at the bottom of the weld, as previously shown in the EDS mapping from Figure 9-6. Hence, in CW mode, most of the brittle IMCs concentrations are shifted away from the joint interface, improving the bonding between both alloys.

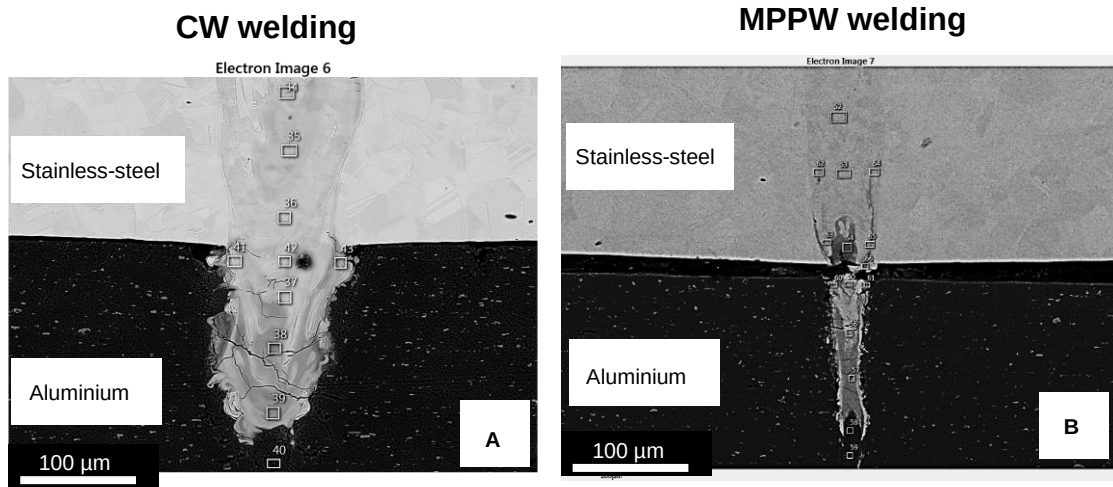


Figure 9-9 SS-Al lap-joints for a penetration depth of 1.2 mm: (A) CW welding at q_p of 33 MW/cm², $E_{SP, CW}$ of 176 mJ and $t_{i, CW}$ of 0.5 ms; (B) MPPW welding at q_p of 10.4 MW/cm², $q_{p, peak}$ of 69 MW/cm², $E_{SP, MPPW}$ of 333 mJ and $t_{i, MPPW}$ of 0.5 ms.

The welding parameters from Table 9-10 have been replicated for Al-SS lap-joint configuration and presented in Figure 9-10. Decreasing $E_{SP, MPPW}$ and $q_{p, peak}$ at constant q_p and $t_{i, MPPW}$ through an increase in travel speed and PRF , the

penetration depth decreased from Figure 9-10A-C, and the weld quality was decreased as well, with some cracks being visible at the joint interface in Figure 9-10F. Due to Al being positioned on top, its alloying elements are more likely to vaporise and escape from the top of the weld pool, generating capillary forces which drag SS (Fe) into Al, as observed in the EDS mapping from Figure 9-11, corresponding to Figure 9-10D. Similar results were observed in Figure 9-7 for CW mode.

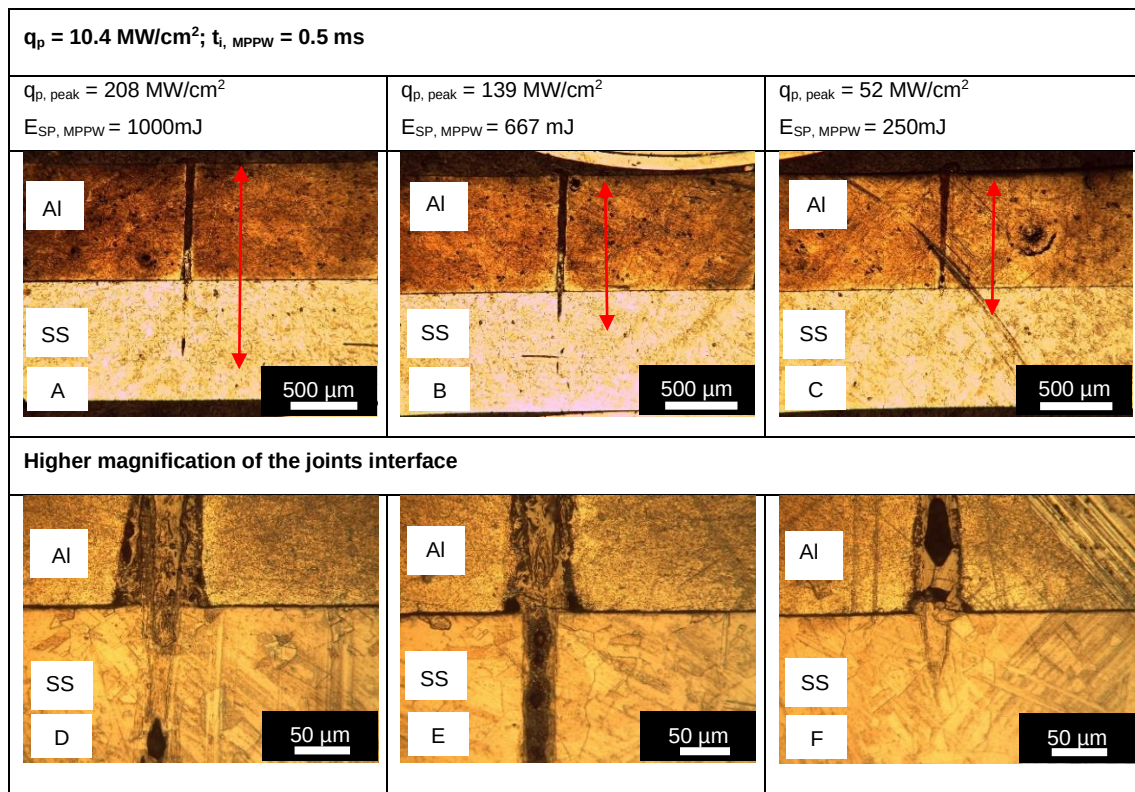


Figure 9-10 MPPW lap-joints of Al-SS for constant q_p of 10.4, $t_{i, \text{MPPW}}$ of 0.5 ms and different $q_{p, \text{peak}}$ and $E_{\text{SP, MPPW}}$.

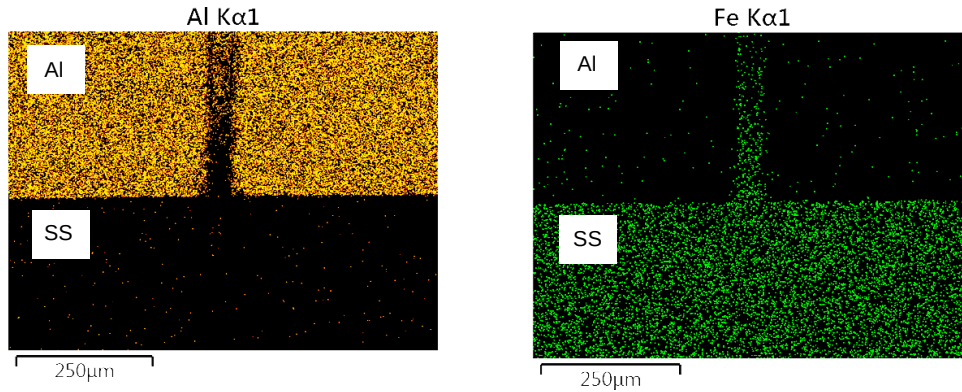


Figure 9-11 EDS mapping of Fe and Al elements from a MPPW lap-joint of Al-SS for q_p of 10.4 MW/cm², $q_{p, peak}$ of 208 MW/cm², $E_{SP, MPPW}$ of 1000 mJ and $t_{i, MPPW}$ of 0.5 ms.

Several sections from Figure 9-10D were analysed in Figure 9-12 at the top (Figure 9-12A), middle (Figure 9-12B), and at the joint interface (Figure 9-12C). The corresponding SEM analysis is shown in Figure 9-13. In spectrum 67 from Figure 9-13, there is a high atomic concentration of Al compared to Fe, whereas, in spectrum 64, the atomic percentage of iron increased. This is likely caused by the high peak power density applied in MPPW mode at a high pulse repetition frequency, which forced the stirring and mixing of Al in SS, despite the difference in density and viscosity. Consequently, the higher peak temperature in the centre of the beam increased the concentration of FeAl₃ in this area, being visible a large crack along the fusion zone.

In spectrum 52 from Figure 9-13, the concentration of Al in the fusion zone decreased in comparison to spectrum 64, increasing the concentration of Fe, being formed FeAl phase (Iron-rich IMC), which has higher ductility [101][105]. Thus, the cracks' size was reduced. At the joint interface, the atomic concentration of Al is almost non-existent, being dominated by iron, as shown in spectrum 39. Therefore, most of the Al is dissolved into Fe [101][105] and most of the IMCs were shifted away from this region, which is why no cracks are visible.

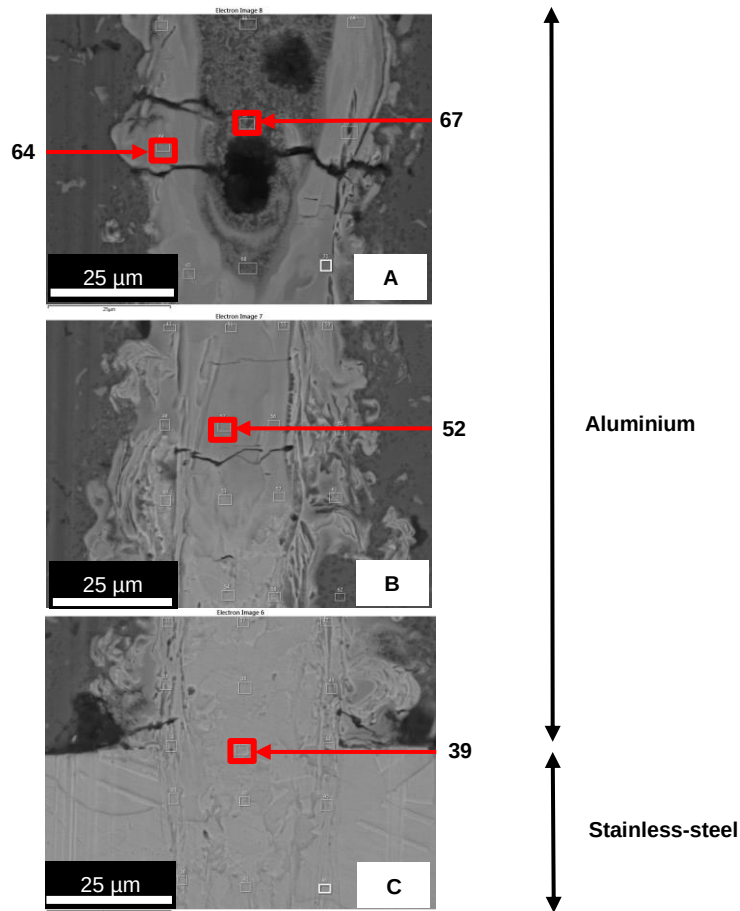


Figure 9-12 SEM micrographs from a MPPW lap-joint of Al-SS for q_p of 10.4 MW/cm², $q_{p, peak}$ of 208 MW/cm², $E_{SP, MPPW}$ of 1000 mJ and $t_{i, MPPW}$ of 0.5 ms.

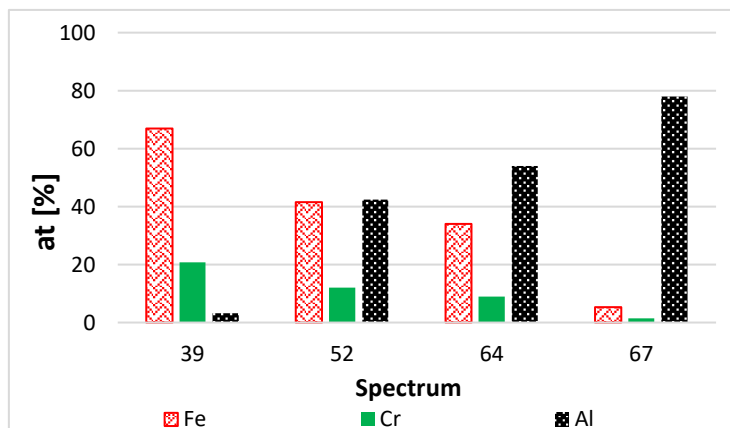


Figure 9-13 EDS spectrum analysis from a MPPW weld of Al-SS for q_p of 10.4 MW/cm², $q_{p, peak}$ of 208 MW/cm², $E_{SP, MPPW}$ 1000 mJ and $t_{i, MPPW}$ of 0.5 ms.

The EDS spectrum analysis from Figure 9-10F is shown in Figure 9-14. When the peak power density and specific pulse energy were reduced, the penetration depth and the weld quality were reduced, making more cracks on the aluminium side visible. The mixing between both alloys was shifted closer to the joint interface, being formed Al-rich brittle IMCs (Fe_2Al_3) [101][105], which avoided a successful bonding. It may be possible that the reduction in the applied energy led to a decrease in peak temperature in the molten metal. Since the temperature reduction increases the viscosity of both alloys [70], the capillary forces are reduced, being more difficult for SS to push Al towards the top of the weld pool. Hence, this may explain the higher IMC concentration and cracks at the interface.

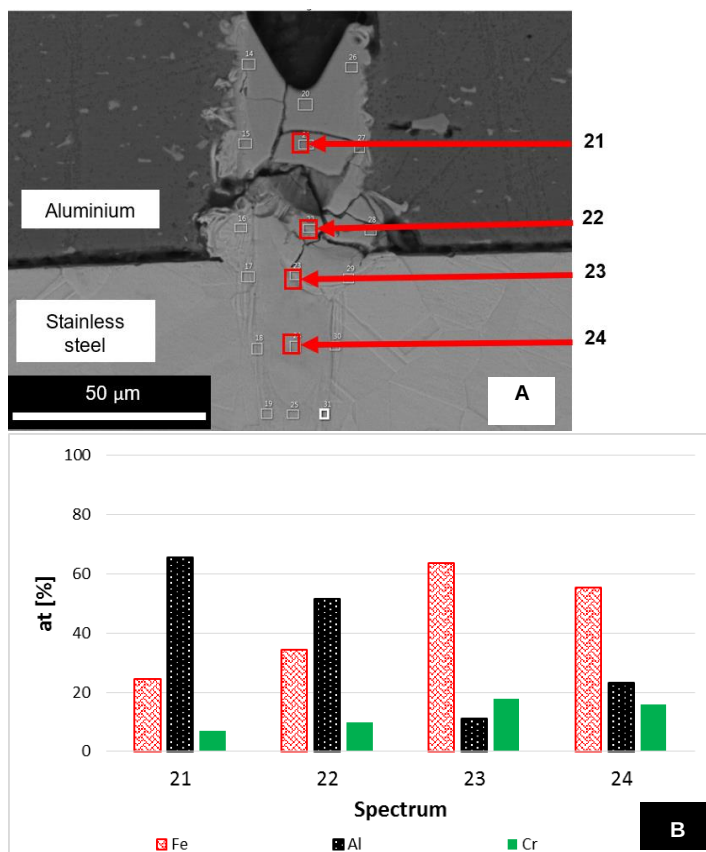


Figure 9-14 SEM micrograph (A) and respective EDS spectrum analysis (B) from a MPPW lap-joint of Al-SS for q_p of 10.4 MW/cm^2 , $q_{p, \text{peak}}$ of 52 MW/cm^2 , $E_{\text{SP, MPPW}}$ of 250 mJ and $t_{i, \text{MPPW}}$ of 0.5 ms .

The MPPW Al-SS lap-joints were successful but unsuccessful in CW mode, as demonstrated in section 9.3.1. A comparison between both temporal modes is

shown in Figure 9-15 for a similar penetration depth of 1.6 mm. The CW weld shown in Figure 9-15B needed a higher average power density and lower peak power density than the MPPW laser to open the keyhole in Al, leading to a wide melt pool and, consequently, high distortion of the top sheet. Thus, the mix of Fe and Al has increased, being the IMCs scattered across a large area. However, in Figure 9-15A, the weld width of Al in MPPW mode is 10x smaller than in CW mode, forcing Fe to displace Al from the joint interface, as previously observed in the EDS mapping from Figure 9-11. This phenomenon was created by the high peak power and low pulse energy applied in short pulses at high frequency. The keyhole formed was able to transfer the heat more efficiently from the Al sheet to SS, being the copper backing bar fundamental to drive the laser energy downwards, providing a narrow melt pool, low distortion, and low diffusion of Al into Fe. Consequently, the mixing between both alloys in MPPW mode is shifted away from the joint interface, as shown in Figure 9-12, allowing successful joints.

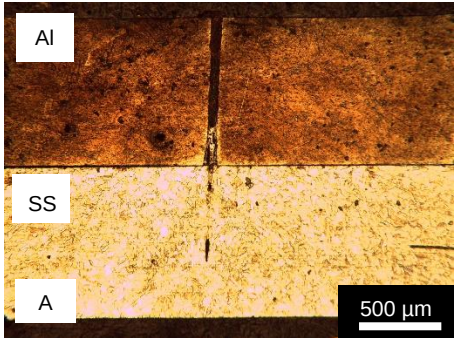
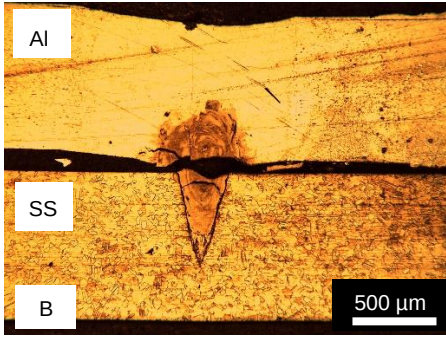
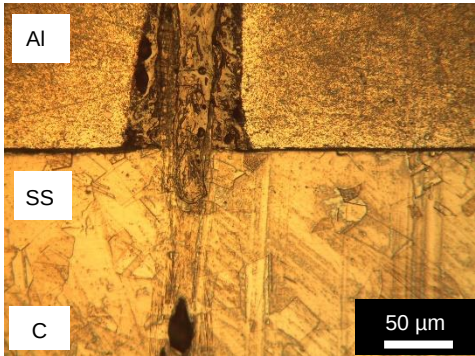
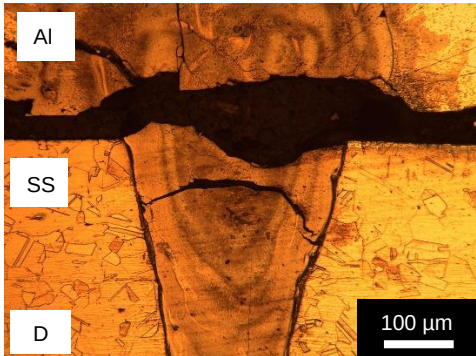
Depth of Penetration = 1.6 mm; $t_{i, \text{MPPW}} = t_{i, \text{CW}} = 0.5 \text{ ms}$	
MPPW welding	CW welding
$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 208 \text{ MW/cm}^2$ $E_{SP, \text{MPPW}} = 1000 \text{ mJ}$	$q_p = 33 \text{ MW/cm}^2 = q_{p, \text{peak}}$ $E_{SP, \text{CW}} = 176 \text{ mJ}$
	
Higher magnification of the joints interface	
	

Figure 9-15 MPPW and CW lap-joints of Al-SS for a penetration depth of 1.6 mm and interaction time of 0.5 ms.

9.3.3 Mechanical testing

9.3.3.1 Tensile shear load of CW and MPPW joints

A subsection of the successful set of parameters from Table 9-9 and Table 9-10 was chosen to conduct mechanical tests to evaluate the tensile shear load of CW and MPPW joints, respectively. It is shown in Figure 9-16 that, for constant E_{SP} , c_w and q_p , the breaking load of CW welds increases with an increase in the number of weld lines. There is also a trend in the rise of the tensile shear load with the rise of the specific point energy from 333 mJ to 1000 mJ, being possible to reach 1700 N using four weld lines. This observation may be related to the larger bonding area achieved for a longer thermal cycle, as also reported by Meco

et al. [10], creating a better anchoring effect of the weld-aluminium interface due to higher penetration. On the other hand, since the penetration is deeper for higher energy levels, most of the brittle IMCs are concentrated at the bottom of the weld-aluminium interface, being most of the cracks shifted away from the joint interface, reducing their propagation, as previously explained in section 9.3.1. Thus, the remaining cracks will avoid increasing tensile shear load in the same proportion as the increase in weld lines number.

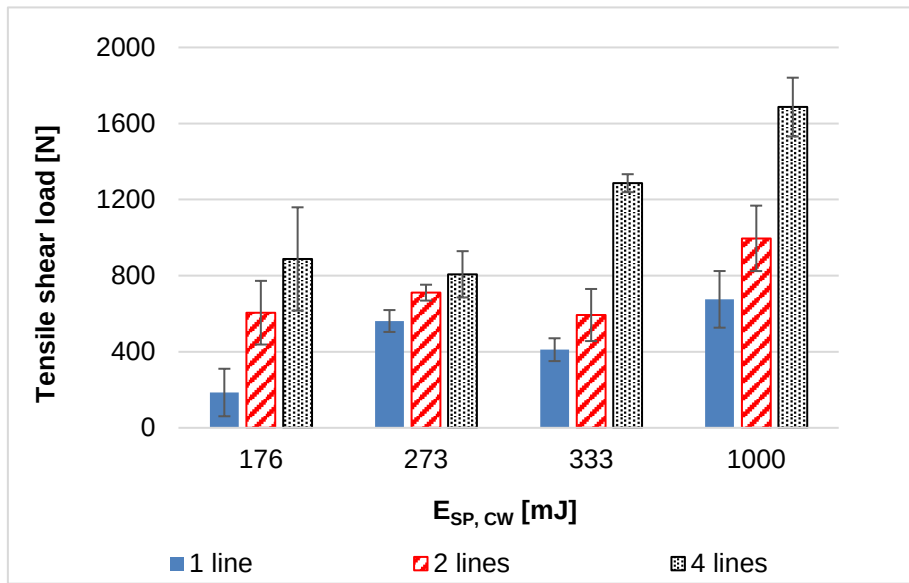


Figure 9-16 Tensile shear load versus $E_{SP, CW}$ of CW lap-joints of SS-Al for q_p of 33 MW/cm².

The tensile shear load versus strain of the strongest and weakest CW welds achieved at 1000 mJ is shown in Figure 9-17 and Figure 9-18, respectively. Some loading irregularity is visible due to the variable weld thickness caused by the uneven IMCs distribution along the weld. Despite the shear failure at the metal interface in both figures, higher plastic deformation was achieved with four welds lines, which means the load was distributed evenly to all welds in shear failure mode.

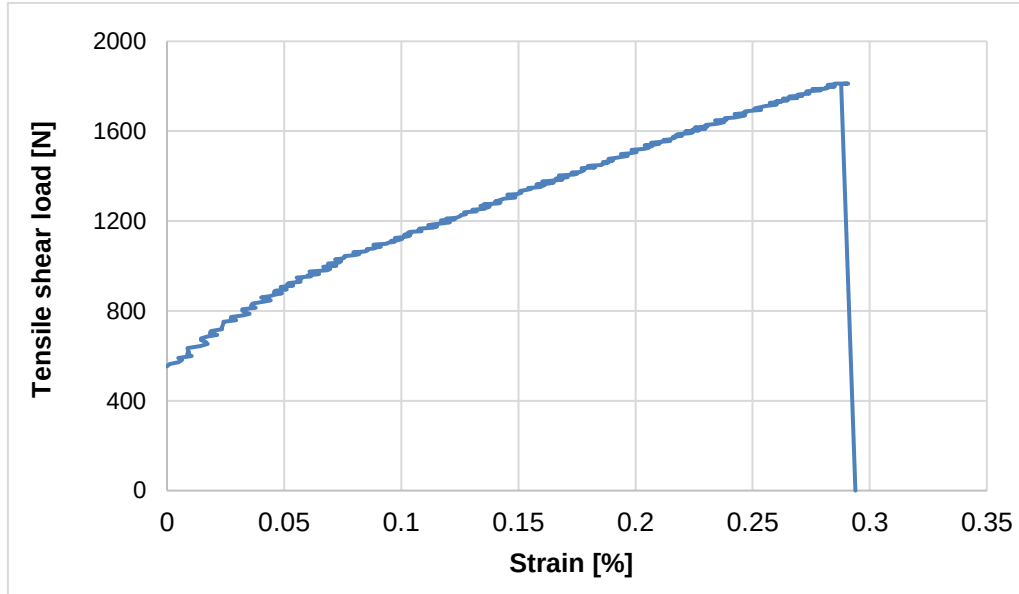


Figure 9-17 Tensile shear load versus strain of CW lap-joints of SS-Al for q_p of 33 MW/cm² and $E_{SP, CW}$ of 1000 mJ (4 weld lines).

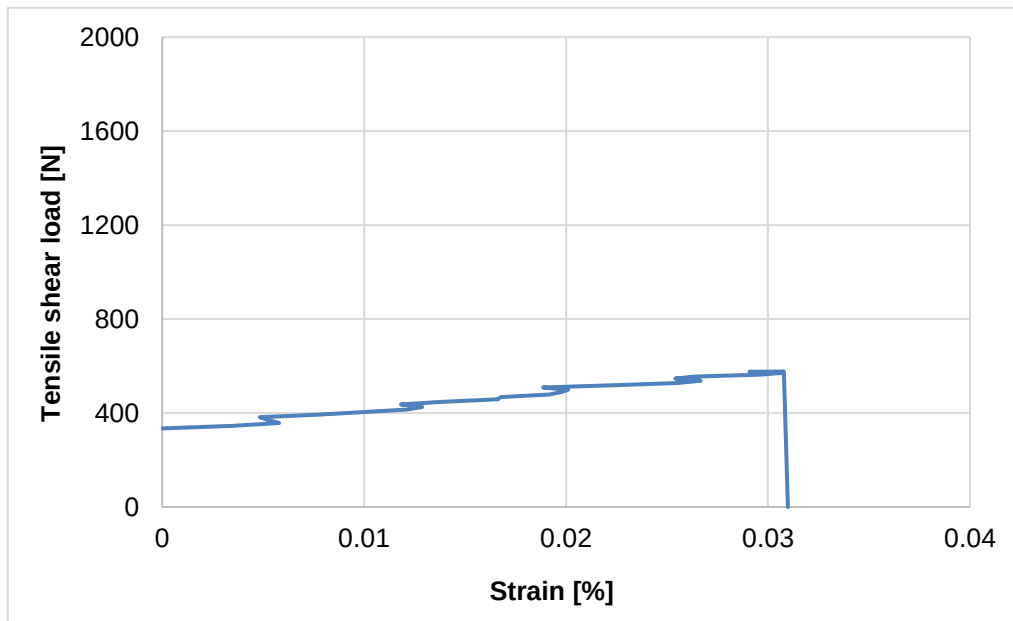


Figure 9-18 Tensile shear load versus strain of CW lap-joints of SS-Al for q_p of 33 MW/cm² and $E_{SP, CW}$ of 1000 mJ (1 weld line).

As shown in Figure 9-19 for MPPW mode, the maximum tensile shear load increases with the increase in the number of weld lines and with the $E_{SP, MPPW}$. A maximum load of 1330 N was achieved using four weld lines for the energy of 1000 mJ and an interaction time of 0.5 ms. Contrary to what was observed in CW

mode, the increase in tensile shear load with the applied energy is not related to the increase of the bonding area since the MPPW weld width remained almost constant for different energy levels, as previously shown in Figure 9-10. For a constant weld width, a higher applied energy will force a larger volume of SS to push Al through a narrow channel, preventing the defects caused by the brittle IMCs at the joint interface. Consequently, this mechanism allows an increase in the load-bearing capacity of MPPW welds.

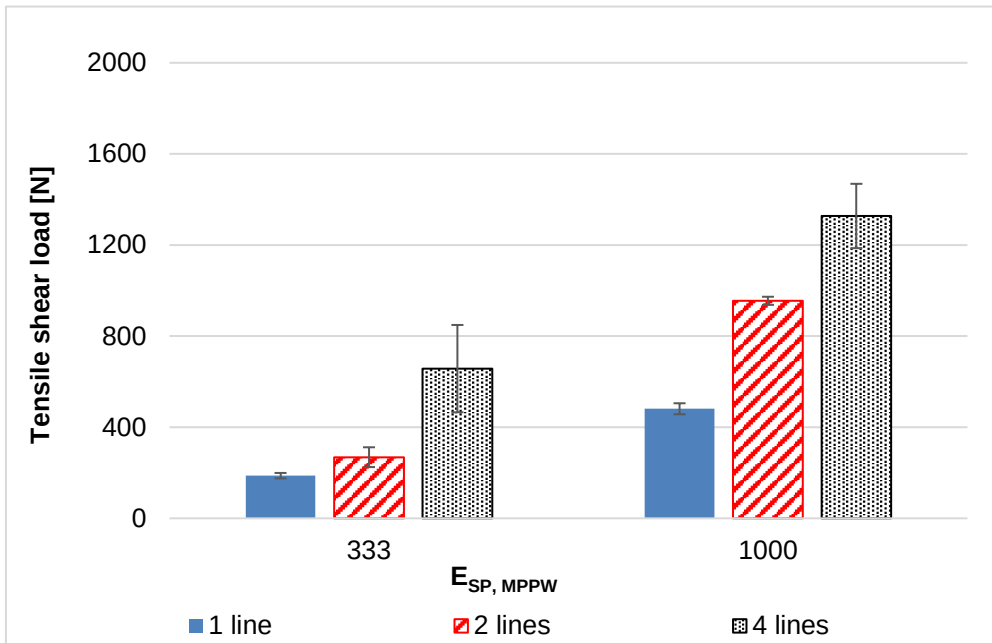


Figure 9-19 Tensile shear load versus $E_{SP, MPPW}$ of MPPW lap-joints of Al-SS.

The tensile shear load versus strain of the strongest and weakest MPPW welds achieved at 1000 mJ are shown in Figure 9-20 and Figure 9-21, respectively. Like the observations in CW mode, the MPPW welds failed at the metal interface in both cases, and more plastic deformation was achieved with four weld lines in Figure 9-20. However, the plastic deformation was higher than in CW mode due to the absence of IMCs at the weld joint, which correlates well with the observations in Figure 9-12 and Figure 9-13.

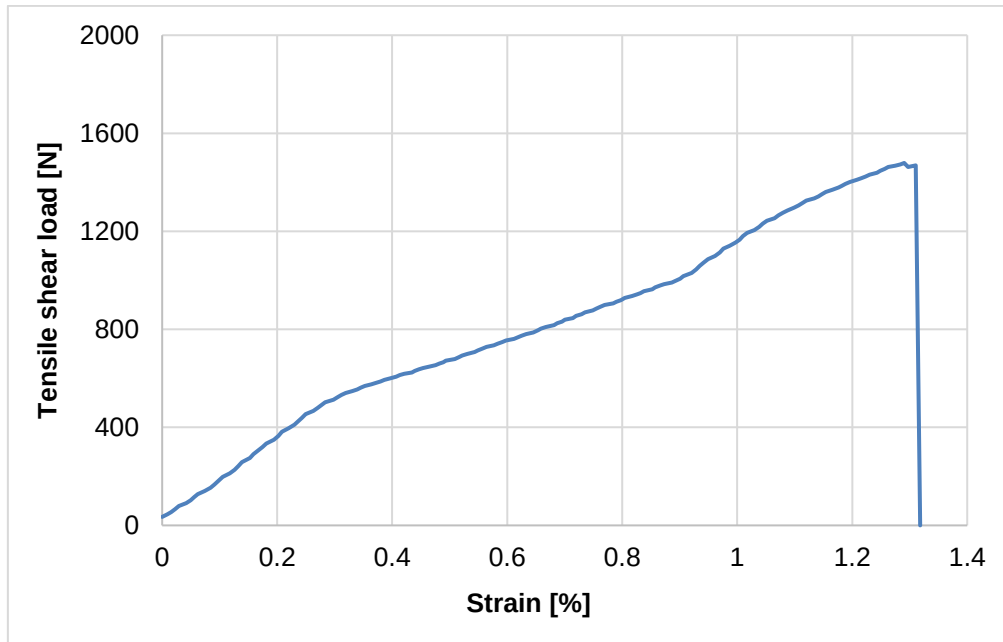


Figure 9-20 Tensile shear load versus strain of MPPW lap-joints of Al-SS for E_{SP} , MPPW of 1000 mJ (4 weld lines).

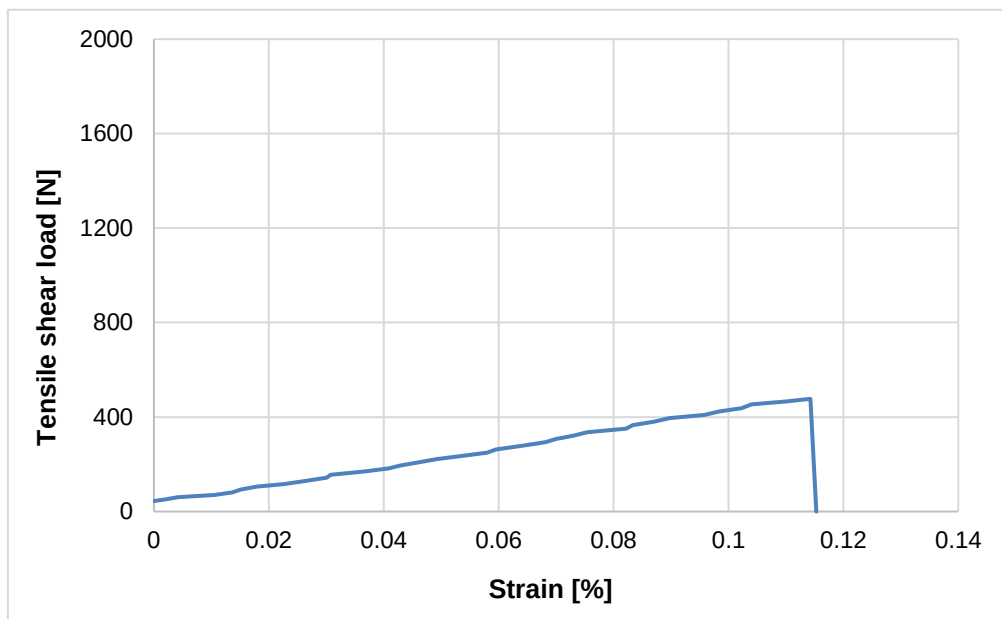


Figure 9-21 Tensile shear load versus strain of MPPW lap-joints of Al-SS for E_{SP} , MPPW of 1000 mJ (1 weld line).

9.3.3.2 Tensile shear strength of CW and MPPW joints

In Figure 9-22, the tensile shear strength of CW welds was calculated by dividing the maximum tensile shear load by the bonding area (weld width multiplied by

the total weld length). Increasing $E_{SP, CW}$ from 333 mJ to 1000 mJ at a constant q_p of 33 MW/cm², the load per unit of weld metal area remained similar for each weld pattern. Thus, the advantage of a larger bonding area for higher values of specific pulse energy may have a threshold to improve the load-bearing capacity, as further IMCs growth would outweigh the advantage of the higher wetting area, decreasing the linear strength from a certain threshold, as shown by Sierra et al. [9]. These results suggest that it is difficult to further improve the mechanical strength of the joints by solely controlling the energy of the process, as also observed by Mecó et al. [10]. Still, a definite answer would need more experiments. They concluded that the bonding area is one of the key factors for the integrity of the Fe-Al joints, and the mechanical strength of the joints couldn't be improved by increasing the bonding through power density since it is the parameter that most controls the temperature and consequently, the IMC growth would be enhanced. However, the authors suggested that by producing parallel weld seams, the bonding area could be increased, avoiding the negative effect of the IMCs. That strategy was used in this work in Figure 9-19 and has revealed to be successful.

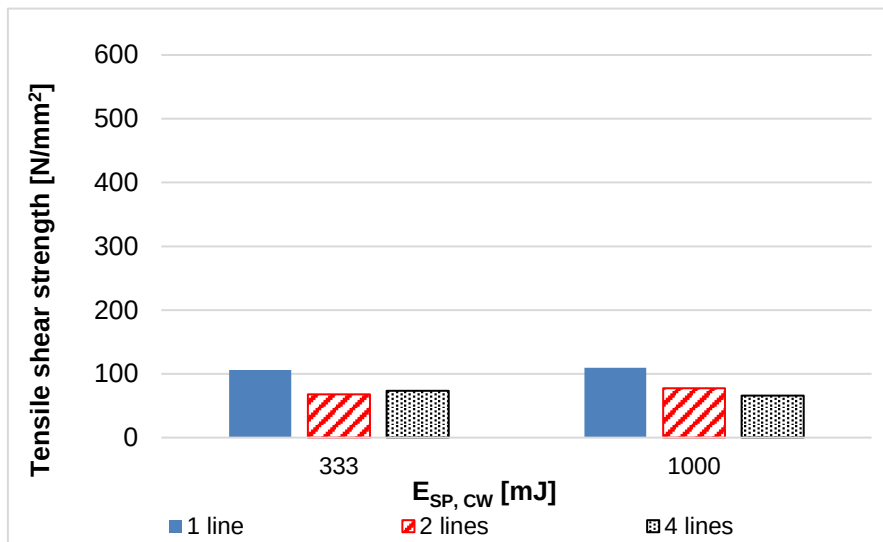


Figure 9-22 Tensile shear strength versus $E_{SP, CW}$ of CW lap-joints of SS-Al for q_p of 33 MW/cm².

In Figure 9-23, the tensile shear strength of MPPW welds increases with $E_{SP, MPPW}$ but not with the number of weld lines. The advantage of a larger bonding

area achieved through a longer weld length may have a threshold to improve the load-bearing capacity. This observation may be explained by the variation of IMCs agglomeration along the joint interface, creating weaker points that decrease the linear strength from a certain weld length threshold. Due to the narrower MPPW welds, the tensile shear strength can be almost 5x higher than CW welds. This highlights once again the importance of the pulse shape in controlling the temperature distribution in the processed metal [76]. For high peak power, the heat is quickly transferred to the material, and a keyhole is formed, increasing the laser absorptivity [43]. On the other hand, the short pulse duration provides fast freezing of the melt pool, which avoids the heat diffusion by conduction, leading to higher aspect ratio welds, low heat affected zone, precise control of the heat input and limited growth of the IMCs in comparison to CW mode. Therefore, if the welding application requires a higher fit-up tolerance and productivity, CW laser is more indicated. The higher average power and the constant and lower peak power provide a stable heat conduction mechanism, which results in larger welds [92].

The addition of many narrower welds using low power density and energy levels above 333 mJ allowed equivalent bonding areas to CW and localised diffusion of Fe into Al, pushing the IMCs out to the fusion zone in Al-SS joints. Thus, for similar applied energy of 1000 mJ and using four weld lines, an ultimate tensile strength (UTS) of 332 MPa was possible in Al-SS joints for MPPW mode, whereas in SS-Al CW welds, it was only possible 65 MPa for the same conditions. This reveals that MPPW welds can be nearly 5x stronger than the weakest parent metal (Al) shown in Table 3-3.

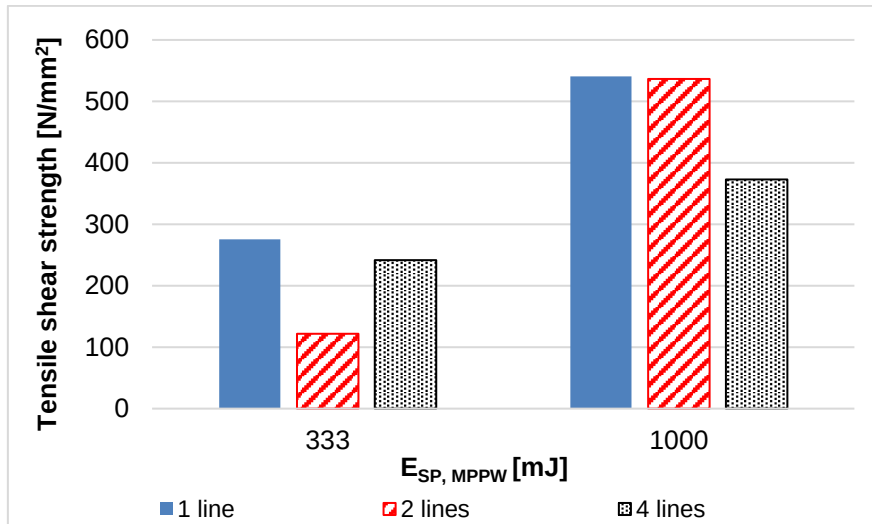


Figure 9-23 Tensile shear strength versus $E_{SP, MPPW}$ of MPPW lap-joints of Al-SS.

It was impossible to control the brittle IMCs formation for the range of parameters tested in both laser temporal modes. In CW laser it was harder to decouple temperature from the melt area, which created a high concentration and more scattered IMCs in the fusion zone, especially for Al-SS joints where there was a high diffusion of Fe to the wider Al weld. On the other hand, for MPPW laser, there was more flexibility in reducing the alloys mixing and increasing the weld strength by minimising the IMC formation through the faster freezing of the weld pool. The thermal cycle was so short and the energy application so fast that no intermetallic pattern was observed using a standard optical microscope. However, in previous studies [10][134], evident IMCs patterns have been observed in CW mode even with low magnifications due to the higher energy application and longer thermal cycle by defocusing the laser beam. In both situations, a sparse solid solubility has also been observed, resulting in a brittle intermetallic formation, but in different scales/dimensions compared to the results observed in this work.

The limitation imposed by the melting temperature of these alloys, maximum weld width and penetration depth on the IMCs growth and distribution in the weld fusion zone creates a limit on the laser parameters selection to maximise the tensile shear load. Thus, several combinations of energy and power density can be used to achieve similar welds, but the maximum tensile shear strength can

only be achieved for a particular weld shape for these alloys and thicknesses. Larger beam diameters and different weld patterns could increase the bonding area and, consequently, the weld strength even more. In MPPW mode, shorter pulse durations could also be explored to provide higher peak power density to push the IMCs out of the welding zone.

9.4 Summary of discussions

The lap-joints of SS-Al were unsuccessful using an MPPW laser but successful in CW mode. The higher average peak power density applied in MPPW mode enhanced Al and its alloying elements' vaporisation. However, due to the keyhole pressure, a descending stream of molten SS and an ascending stream of molten Al enhanced the mixing between both alloys at the joint interface. Consequently, several brittle IMCs have been formed, associated with a lack of bonding. In CW mode, SS was plunged into Al through a larger molten metal volume, and the mixing between both alloys was enhanced at the bottom of the weld. Thus, the brittle IMCs concentration was shifted away from the joint interface, improving the bonding between both alloys.

The lap-joints of Al-SS were successful using an MPPW laser but unsuccessful in CW mode. Due to the larger weld width of Al in CW mode, iron was diffused over a larger area and the brittle IMCs were scattered along with the joint interface, increasing the cracking likelihood, and avoiding the bonding between the joining partners. However, the weld width of Al in MPPW mode was 10x narrower than in CW mode, which forced iron to diffuse into Al through a narrower channel, pushing Al towards the top of the upper sheet. Hence, for high energy and average peak power density in MPPW mode, the porosity was entrapped at the bottom of the weld, and the mixing between both alloys was shifted away from the joint interface, being the brittle IMCs concentrated at the top of the weld, which allowed a strong bonding between both alloys. Therefore, the welding defects didn't affect the joint strength.

For similar applied energy, the welds' maximum tensile shear load was higher in CW than in MPPW laser welding. Nevertheless, the maximum load per unit length

of weld was higher in MPPW mode. If the welding application requires a higher fit-up tolerance, productivity, and SS on top of Al, CW laser is more indicated, providing a flexible weld shape and larger bonding areas. On the other hand, if the requirements are low heat affected zone, precise control of the heat input, narrow joints, and Al on top of SS, MPPW is the most suitable laser mode.

The following conclusions can be drawn from this chapter:

- The SS-Al lap-joints were successful in CW mode but unsuccessful in MPPW.
- The Al-SS lap-joints were successful in MPPW mode but unsuccessful in CW.
- For similar applied energy and the number of weld lines, the maximum tensile shear loads were higher in CW than in MPPW laser welding. However, the UTS was five times higher in MPPW mode for the strongest weld.
- CW laser provides better higher fit-up tolerance and productivity. On the other hand, lower heat-affected zone, more precise control of the heat input, higher aspect ratio welds, and Al-SS joints can only be achieved in MPPW laser mode.
- Further investigation using larger beam diameters and different weld patterns is recommended to increase the bonding area and consequently, the weld strength. In MPPW mode, different pulse durations could also be explored.

10 New phenomenological model for comparison of lasers with different temporal outputs

Part of this chapter is based on the following publication:

Coroado J.*, Williams S., Suder W., Ganguly S., Meco S., Pardal G. (2022) ‘New phenomenological model for comparison of lasers with different temporal outputs’ *The International Journal of Advanced Manufacturing Technology*, 120, pp. 6107–6123, <https://doi.org/https://doi.org/10.1007/s00170-022-09081-8>.

10.1 Introduction

From sections 4 to 9, it was observed that the current processing parameters do not capture the thermal losses and the material’s physical properties. Hence, similar weld shapes cannot be achieved in MPPW and CW modes for a similar set of fundamental laser-material parameters. This research aims to find a new approach to compare both temporal modes and establish a new definition of interaction time that captures global losses due to processing speed and thermal losses due to the absence of power in between the pulses for different materials.

10.2 Experimental procedure

10.2.1 Materials

The materials used in the experiments were 2 mm thick plates of stainless steel (SS) 304 L and aluminium (Al) 5251H22. Their physical properties are shown in Table 10-1.

Table 10-1 Physical properties of the base materials [121][122].

Property	Symbol	Units	Al 5251 H22	SS304L
Density	ρ	Kg/m ³	2690	8000
Melting Temperature	T_m	K	898	1723
Vaporisation Temperature	T_v	W.(m.K) ⁻¹	2790	3023
Thermal conductivity	k	W m ⁻¹ K ⁻¹	134	16.2
Thermal diffusivity	α	m ² s ⁻¹	5.7 x 10 ⁻⁵	5.5 x 10 ⁻⁶
Modulus of Elasticity	E	GPa	70	193

10.2.2 Methodology and experimental setup

The fibre lasers used to generate bead-on-plate welds were a 100 W average output power nanosecond MPPW laser and a 500 W average output power CW laser. The experimental setup and the welding configuration are shown in section 3.

Usually, the MPPW process would have specified pulse duration and overlap factor when using system parameters, whilst the processing speed would be selected in CW. From the material perspective, it should be able to describe how much energy is applied per unit length for both processes to achieve similar weld shapes. The current laser welding definitions are limited and do not allow accurate comparison between MPPW and CW modes.

MPPW welding is more complex than single-pulse pulsed-wave (SPPW) and CW due to energy build up and transient thermal cycle between the pulses. Several factors affect the overlap between pulses in MPPW welding and, consequently, the thermal losses. First, the inter-pulse spacing increases as the frequency and the laser duty cycle decrease, as shown by Equation (10-1), with more significant thermal losses in this regime.

$$I_s = (1 - DC)/PRF [s] \quad (10-1)$$

Second, the higher the energy delivered in several consecutive pulses, the longer it takes for the material to cool back to room temperature, even if the overlap between pulses is close to zero. Third, the thermal losses will be lower if the same energy is delivered faster to the material. And fourth, the physical properties of the processed material will affect the thermal losses since the time for the heat to diffuse over a unit distance, referred to as characteristic length, depends on the material's thermal diffusivity (α) and is quantified by the characteristic thermal time t_0 [74], as given by Equation (10-2) [72].

$$t_0 = d^2/16\alpha [s] \quad (10-2)$$

To compare CW and PW processes, we need to have a way of converting travel speed from CW to the time-domain of pulse duration from PW. Interaction time,

a discrete unit time, can be used for this purpose. For CW mode, the laser-material interaction time ($t_{i, CW}$) is represented by the ratio of the beam diameter (d) in the welding direction to the travel speed (v), as given by Equation (10-3).

$$t_{i, CW} = d/v [ms] \quad (10-3)$$

The laser-material interaction time in SPPW mode ($t_{i, SPPW}$) is equal to the pulse duration, as given by Equation (10-4).

$$t_{i, SPPW} = P_{Width} [ms] \quad (10-4)$$

However, in MPPW processing, the pulse duration needs to be converted back into the space domain, where the cumulative exposure time of multiple spots over a unit length can be calculated. This should consider the overlap factor and the gap between individual pulses. In the old definition previously presented in section 4, interaction time in MPPW mode ($t_{i, MPPW (old)}$) represents the summation of the duration of each emitted pulse with a particular overlap factor (O_F), as given by Equations (10-5) and (10-6), respectively. At 0% overlap factor, the interaction time equals pulse width, and at 100%, the equation is not applicable since the beam is stationary.

$$t_{i, MPPW (old)} = P_{Width}/(1 - O_F/100) [ms] \quad (10-5)$$

$$O_F = (1 - v/d * PRF)100 [\%] \quad (10-6)$$

In Equation (10-6), it is possible to have the same overlap factor achieved at different processing speeds, hence different frequencies. In such a case, the inter-pulse spacing will be different. The laser-material interaction time in Equation (10-5) doesn't capture the thermal losses created by the inter-pulse spacing and material properties. A new definition that captures global losses due to processing speed and thermal losses due to the absence of power in between the pulses is proposed in Equation (10-7), the new MPPW interaction time ($t_{i, MPPW (new)}$). If there is no inter-pulse spacing, $t_{i, MPPW (new)}$ is equal to the ratio between beam diameter and travel speed, like in Equation (10-3) for CW mode. The larger the beam diameter used, the longer the characteristic thermal time, being smaller the ratio between I_s and t_0 . This ratio also gets smaller for short

inter-pulse spacing, and in both cases, $t_{i, MPPW (new)}$ approximates the standard definition of $t_{i, CW}$ in Equation (10-3) for CW mode. The overall effective applied energy in MPPW welding delivered for a particular interaction time is given by Equation (10-8).

$$t_{i, MPPW (new)} = (d/v)/(1 + I_s/t_0) [ms] \quad (10-7)$$

$$E_{SP, MPPW (new)} = q_p * t_{i, MPPW (new)} * As = P_L * t_{i, MPPW (new)} [J] \quad (10-8)$$

10.2.3 Results and discussion

From Figure 10-1 to Figure 10-3 is shown how the new definition of interaction time ($t_{i, MPPW (new)}$) proposed in Eq.(10-7) evolves with travel speed (v) at different beam diameters (d). This analysis was done for SS304L and its thermal diffusivity is shown (10-3), being the characteristic thermal time (t_0) only dependent from d , as per Equation (10-2). In , as v increases at a constant overlap factor of 99%, the frequency increases in the same proportion of v , increasing the duty cycle as well. Hence, according to Equation (10-1), the interpulse spacing (I_s) remains constant, and the ratio I_s/t_0 is kept constant. Consequently, the ratio d/v decreases, and the interaction time decreases proportionally. Therefore, for larger beam diameters, the ratio d/v is higher, being higher the interaction time.

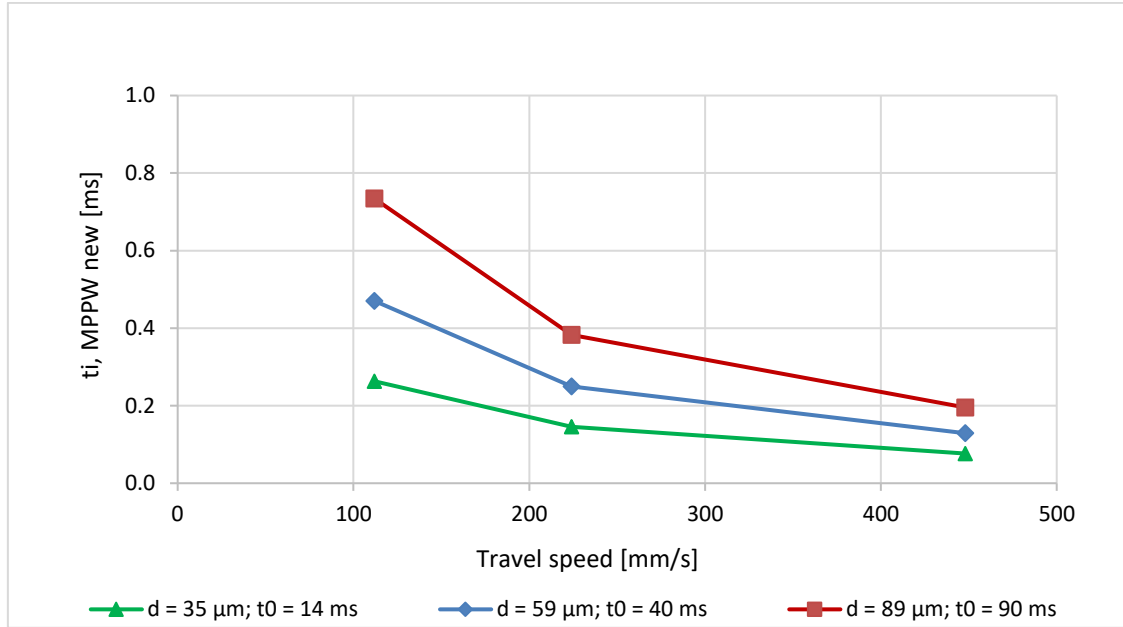


Figure 10-1 Interaction times versus travel speed for a constant overlap factor of 99%, pulse width of 500 ns and different beam diameters.

In Figure 10-2, $t_i, MPPW (new)$ decreases as the travel speed increases at constant pulse width, frequency and beam diameter. For constant d and frequency, the ratio I_s/t_0 does not change, being $t_i, MPPW (new)$ only dependent on the ratio d/v . Therefore, higher interaction times are possible to achieve with larger beam diameters.

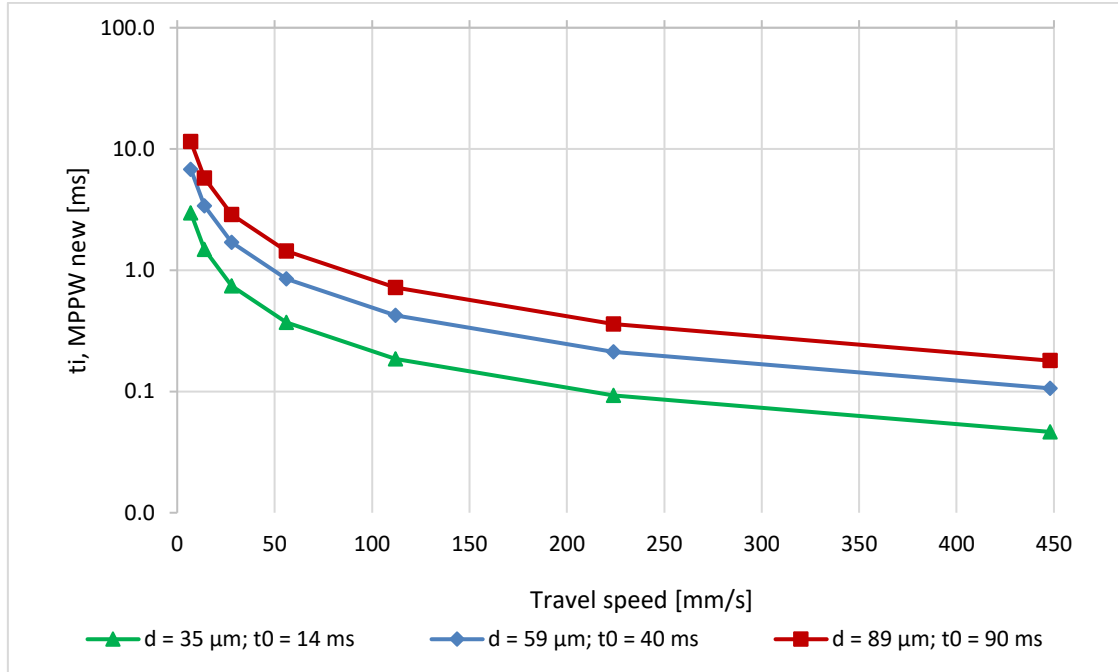


Figure 10-2 Interaction times versus travel speed for a constant frequency of 100 kHz, pulse width of 500 ns and different beam diameters.

As the frequency increases at constant travel speed and beam diameter, the interpulse spacing decreases and the ratio I_s/t_0 decreases, increasing the interaction time, as shown in Figure 10-3. Thus, according to Equation (10-7), t_i , $MPPW (new)$ is higher when the ratio d/v increase for larger beam diameters.

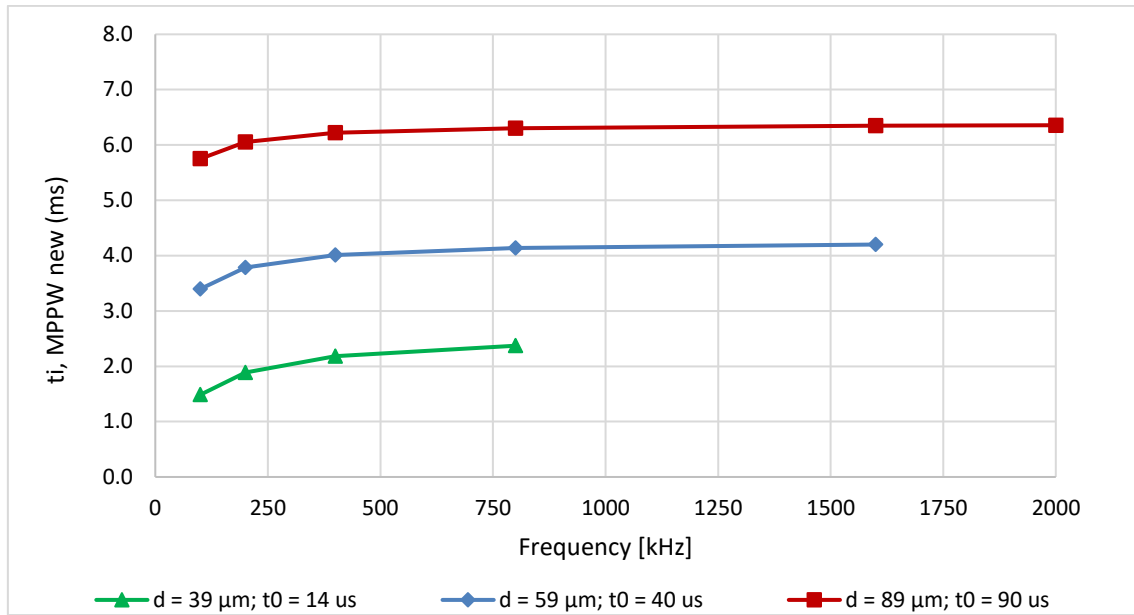


Figure 10-3 Interaction times versus frequency for a constant travel speed of 14 mm/s, pulse width of 500 ns and different beam diameters.

Figure 10-4 to Figure 10-6 compares the two different definitions of interaction time for MPPW mode for SS304L, the old definition presented in section 4, the new definition proposed in this section, and a standard definition from CW mode. Figure 10-4 shows the effect of different travel speeds on $t_{i, CW}$ at a constant beam diameter, and on $t_{i, MPPW \text{ (new)}}$ and $t_{i, MPPW \text{ (old)}}$ at a constant overlap factor, beam diameter and pulse width. As the travel speed increases, $t_{i, MPPW \text{ (new)}}$ and $t_{i, CW}$ decrease. The overlap between pulses is kept constant as $t_{i, MPPW \text{ (new)}}$ decreases since the frequency increases in the same proportion of travel speed. However, for similar travel speed, $t_{i, MPPW \text{ (new)}}$ begins at a higher value than $t_{i, MPPW \text{ (old)}}$ as it allows for energy accumulation between pulses and, consequently, a reduction of thermal losses. Thus, the new definition $t_{i, MPPW \text{ (new)}}$ approaches that of $t_{i, CW}$ much more quickly since the gap between pulses decreases. As the travel speed increases, the difference between $t_{i, MPPW \text{ (new)}}$, $t_{i, MPPW \text{ (old)}}$ and $t_{i, CW}$ becomes much smaller. The $t_{i, MPPW \text{ (old)}}$ remains constant and below the other two definitions. It only considers the summation of pulses delivered in a specific spatial domain without capturing neither the inter-pulse spacing nor the material properties effects on the heat accumulation. Therefore, the ratio between inter-pulse

spacing and the characteristic thermal time from $t_{i, \text{MPPW (new)}}$ in Eq. (10-7) represents the local thermal losses characteristic of MPPW operation lasers.

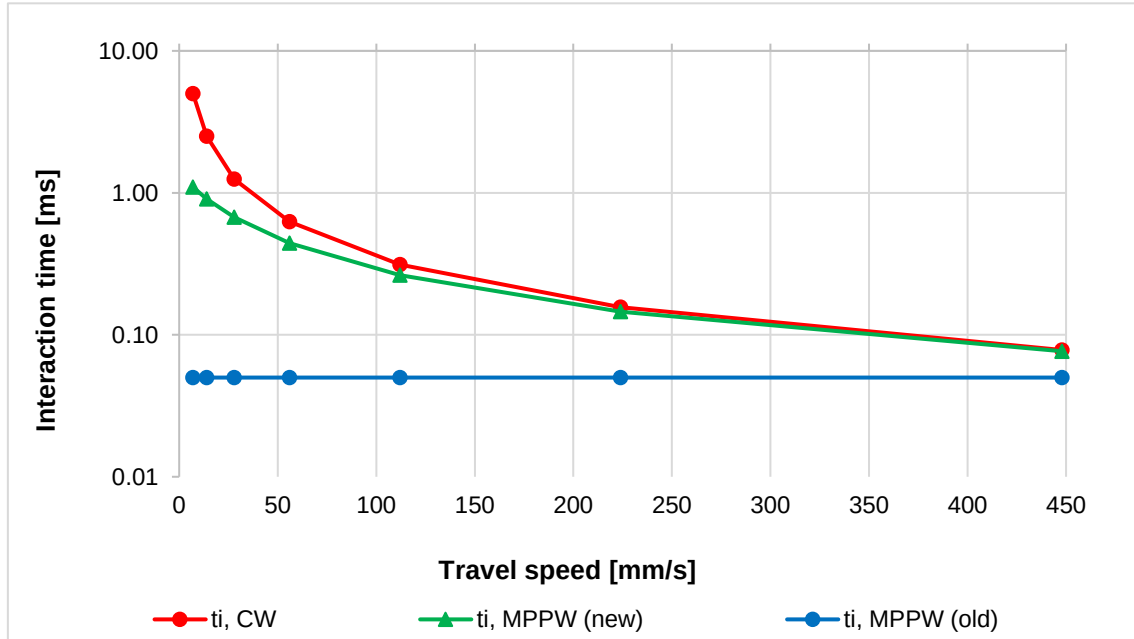


Figure 10-4 Interaction times versus travel speed for a constant overlap factor of 99%, beam diameter of 35 μm , and pulse width of 500 ns.

Figure 10-5 shows the effect of different travel speeds on $t_{i, \text{CW}}$ at a constant beam diameter, and on $t_{i, \text{MPPW (new)}}$ and $t_{i, \text{MPPW (old)}}$ at a constant frequency, beam diameter and pulse width. All interaction times decrease as the travel speed increases, being the global thermal losses similar in CW and MPPW modes for similar speeds. As the pulse width and frequency are constant, the inter-pulse spacing does not change. Therefore, the gap between $t_{i, \text{MPPW (new)}}$, $t_{i, \text{MPPW (old)}}$, $t_{i, \text{CW}}$ is constant since the local thermal losses caused by the constant inter-pulse spacing are similar.

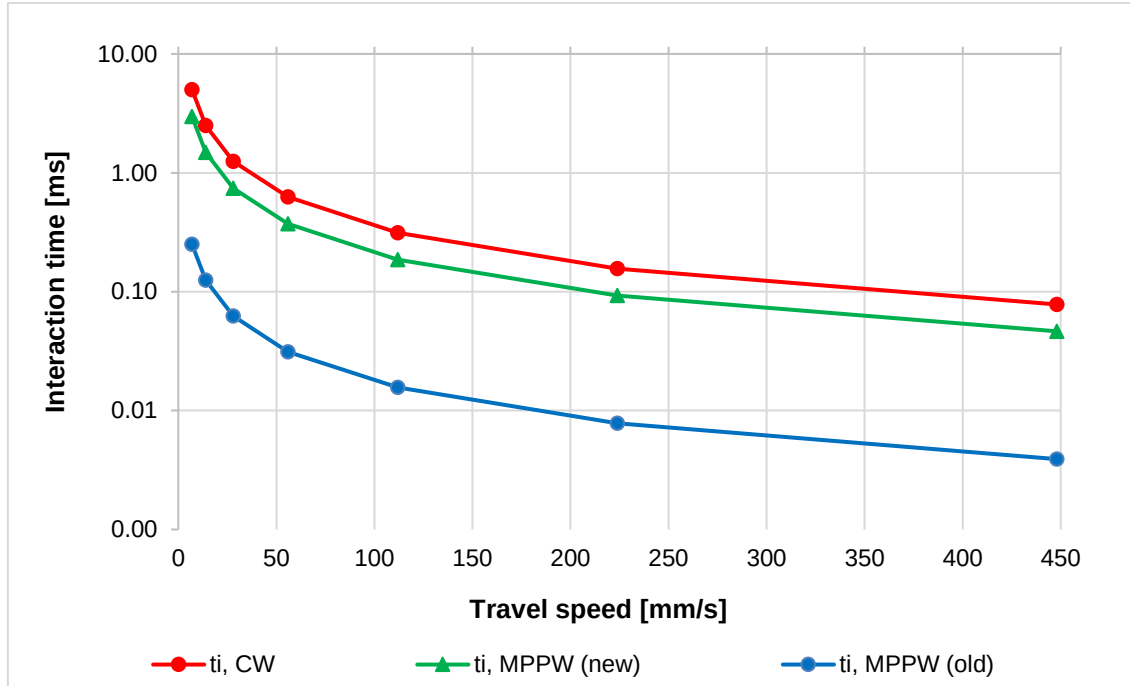


Figure 10-5 Interaction times versus travel speed for a constant frequency of 100 kHz, beam diameter of 35 μm and pulse width of 500 ns.

In Figure 10-6, $t_{i, CW}$ is insensitive to the pulsing frequency, being constant for constant processing speed. It considers global thermal losses dependent on travel speed and material thermal properties. The $t_{i, MPPW (old)}$ and $t_{i, MPPW (new)}$ increase as the frequency increases at a constant travel speed, increasing the overlap factor in the same proportion. However, for similar frequency $t_{i, MPPW (new)}$ begins at a higher value than $t_{i, MPPW (old)}$ as it allows for energy accumulation between pulses and, consequently, a reduction of thermal losses. Therefore, as previously observed in Figure 10-4, the new definition $t_{i, MPPW (new)}$ approaches that of $t_{i, CW}$ much more quickly in Figure 10-6 since it considers the reduction of inter-pulse spacing for higher frequencies.

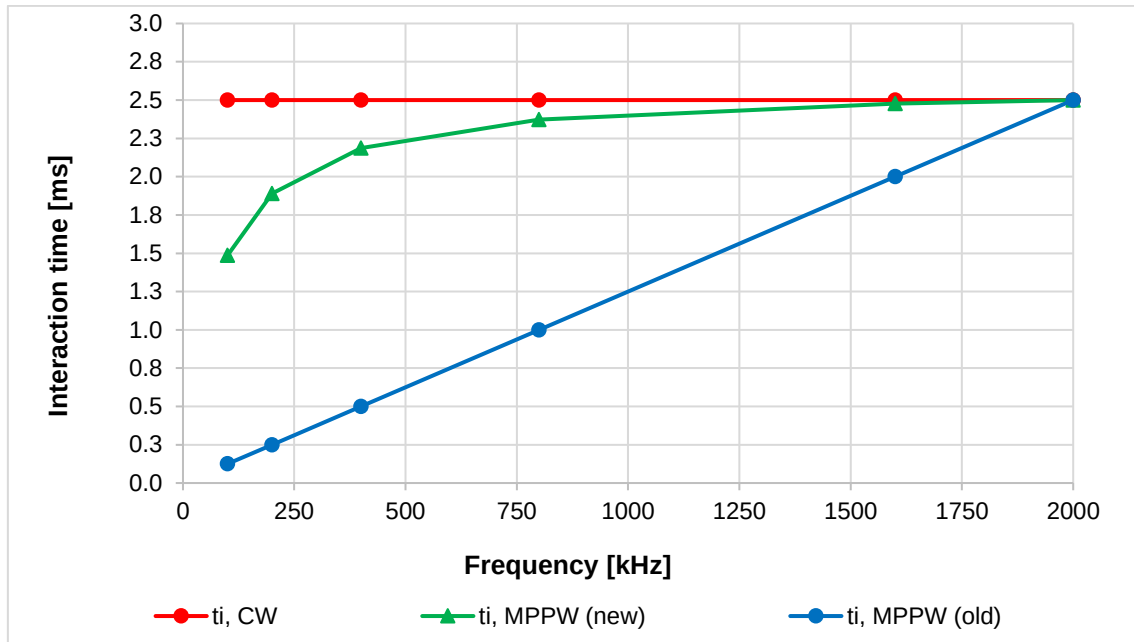


Figure 10-6 Interaction times versus frequency for a constant travel speed of 14 mm/s, beam diameter of 35 μm , and pulse width of 500 ns.

The new and old definitions of interaction time and applied energy can now be compared in CW and MPPW laser modes. Figure 6-3 and Figure 6-4 from section 6.3.1 were replicated in Figure 10-7 and Figure 10-8, respectively. The lower $t_{i, \text{MPPW (old)}}$ and $t_{i, \text{MPPW (new)}}$ (Figure 10-7B) compared to $t_{i, \text{CW}}$ (Figure 10-7A), are responsible for a narrower weld width, as the thermal losses captured in both the new and old definitions. However, the penetration depth is still higher in MPPW mode (Figure 10-7B) due to the 20x higher average peak power density.

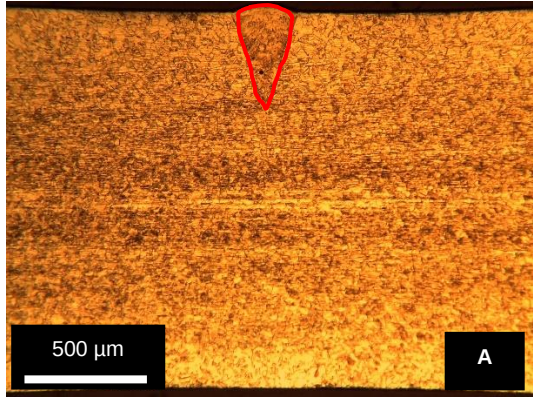
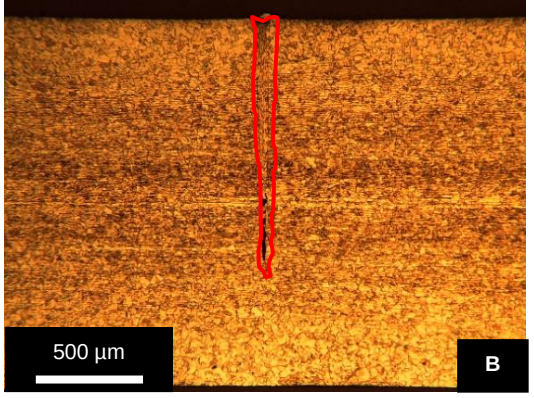
$v = 35 \text{ mm/s}$; $P_L = 100 \text{ W}$; $d = 35 \mu\text{m}$	
CW mode	MPPW mode
$q_p = 10.4 \text{ MW/cm}^2$ $E_{SP, CW} = 100 \text{ mJ}$ $t_{i, CW} = 1 \text{ ms}$	$q_{p, peak} = 208 \text{ MW/cm}^2$; $q_p = 10.4 \text{ MW/cm}^2$ $E_{SP, MPPW (new)} = 59 \text{ mJ}$; $E_{SP, MPPW (old)} = 100 \text{ mJ}$ $t_{i, MPPW (new)} = 0.59 \text{ ms}$; $t_{i, MPPW (old)} = 0.05 \text{ ms}$
	
Depth = 0.7 mm; Weld width = 0.3 mm	Depth = 1.3 mm; Weld width = 0.11 mm

Figure 10-7 CW and MPPW welds (weld boundaries delimited in red) at a travel speed of 35 mm/s, average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

From Figure 10-7 to Figure 10-8, $t_{i, MPPW (new)}$ is much closer to $t_{i, CW}$, being the thermal losses similar. On the other hand, $t_{i, MPPW (old)}$ remained unchanged and below $t_{i, MPPW (new)}$ and $t_{i, CW}$, being unable to capture the effect of pulse spacing reduction on the weld shape. Despite the 5x higher average peak power density in MPPW in Figure 10-8B, the penetration depth is similar to CW mode in Figure 10-8A. Thus, the inter-pulse thermal losses are more relevant and are captured by the proposed new definitions of interaction time and applied energy.

The melting and penetration efficiencies converge in both laser temporal modes from Figure 10-7 to Figure 10-8 as the inter-pulse thermal losses decrease and become similar for higher travel speeds and frequencies. This observation agrees with the rationale behind the formulation of the new definition of interaction time previously explained in Figure 10-4. Therefore, ideally, the penetration depth and weld width should be the same in MPPW and CW laser if constantly applied energies, average powers and interaction times are used.

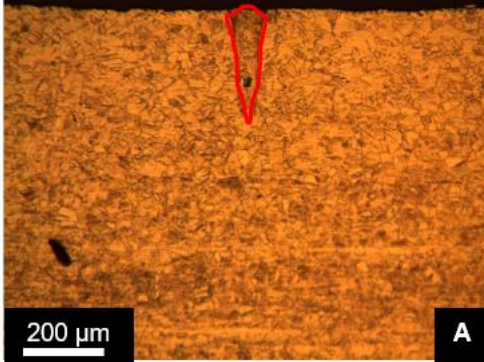
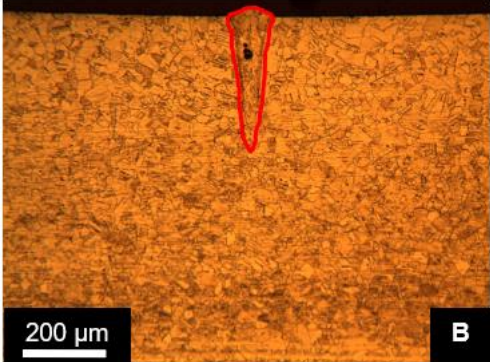
$v = 140 \text{ mm/s}$; $P_L = 100 \text{ W}$; $d = 35 \mu\text{m}$	
CW mode	MPPW mode
$q_{p, \text{peak}} = 10.4 \text{ MW/cm}^2$ $E_{SP, CW} = 25 \text{ mJ}$ $t_{i, CW} = 0.25 \text{ ms}$	$q_{p, \text{peak}} = 52 \text{ MW/cm}^2$; $q_{p, \text{peak}} = 10.4 \text{ MW/cm}^2$ $E_{SP, MPPW} = 25 \text{ mJ}$ $t_{i, MPPW} = 0.05 \text{ ms}$
	
Depth = 0.31 mm; Weld width = 0.13 mm Weld metal area = 0.024 mm ²	Depth = 0.38 mm; Weld width = 0.12 mm Weld metal area = 0.029 mm ²

Figure 10-8 CW and MPPW welds (weld boundaries delimited in red) at a travel speed of 140 mm/s, average power of 100 W, beam diameter of 35 μm and constant overlap factor of 99% in MPPW.

Figure 6-9 from section 6.3.2 was replicated in Figure 10-9. The reduction in travel speed at a constant frequency in MPPW mode allowed energy to build up to the same level as in CW mode. However, it is shown in Figure 10-9B for MPPW laser that the global thermal losses are higher in this regime since the penetration depth is shallower and the weld width is larger than in CW mode in Figure 10-9A. This is captured by $t_{i, MPPW (new)}$, which is much higher than $t_{i, CW}$, but not by $t_{i, MPPW (old)}$, which is equal to $t_{i, CW}$.

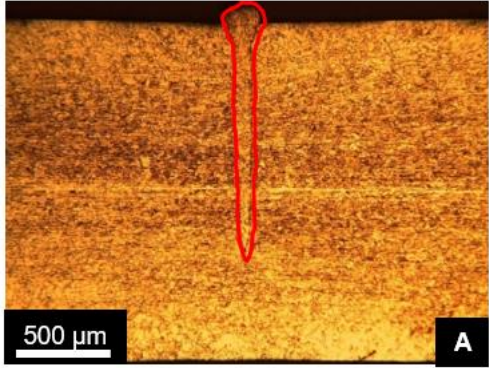
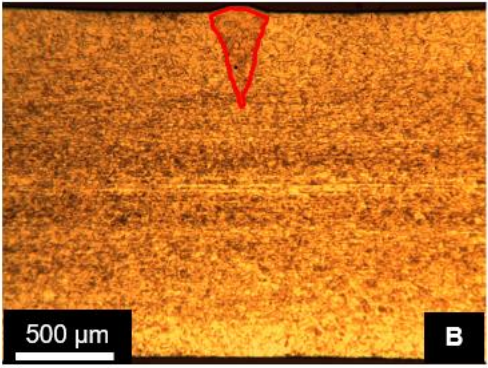
$P_{peak} = 500 \text{ W}; d = 89 \mu\text{m}$	
CW mode	MPPW mode
$v = 178 \text{ mm/s}; P_L = 500 \text{ W}$	$v = 35.6 \text{ mm/s}; \text{PRF} = 400 \text{ kHz}; P_L = 100 \text{ W}$
$q_p = 8 \text{ MW/cm}^2$ $E_{SP, CW} = 250 \text{ mJ}$	$q_p = 1.6 \text{ MW/cm}^2; q_{p, peak} = 8 \text{ MW/cm}^2$ $E_{SP, MPPW} = 250 \text{ mJ}$
$t_{i, CW} = 0.5 \text{ ms}$	$t_{i, MPPW} = 0.5 \text{ ms}$
	
Depth = 1.3 mm; Weld width = 0.20 mm Weld metal area = 0.15 mm ²	Depth = 0.55 mm; Weld width = 0.29 mm Weld metal area = 0.082 mm ²

Figure 10-9 CW and MPPW welds (weld boundaries delimited in red) at an average peak power of 500 W, beam diameter of 89 μm and a frequency of 400 kHz in MPPW.

The new proposed interaction time captures the thermal losses in MPPW mode, being the applied energy dependent on average power as in CW mode. Therefore, following the same principle, the power factor definition in CW mode ($P_{F, CW} = P_L/d$) might also apply in MPPW, changing not the power factor formula to cover the peak power effect ($P_{F, MPPW} = P_{peak}/d$), but the interaction time instead ($t_{i, MPPW (new)}$). A MPPW weld from Figure 6-12A and a CW weld from Figure 6-13A, previously shown in section 6.3.3, are replicated in Figure 10-10. A similar penetration depth was achieved in both laser modes for different combinations of $P_{F, CW}$ and interaction time, as previously observed in CW mode (Figure 7-8 in section 7.3.1) and MPPW mode (Figure 8-5 in section 8.3.2). This observation shows that the new definition of interaction time ($t_{i, MPPW (new)}$) allows the transferability of the model independently of the temporal laser mode and average power used by capturing the inter-pulse thermal losses effect.

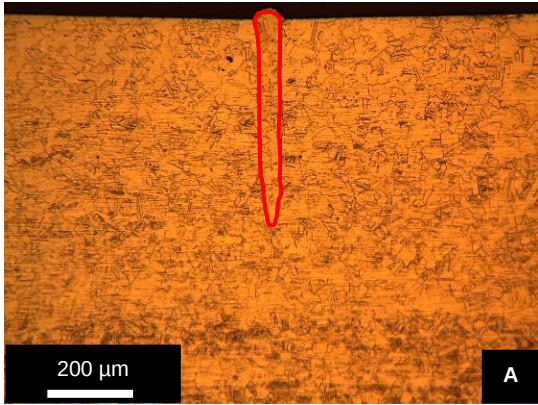
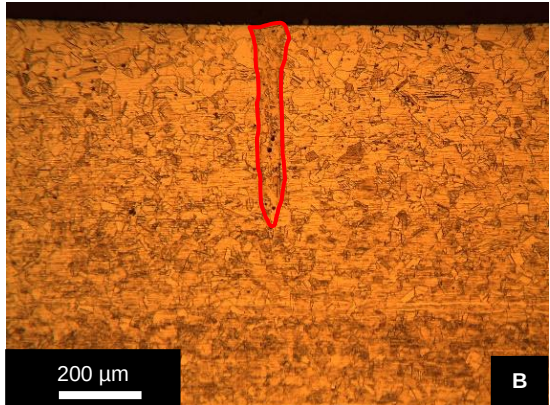
Penetration depth = 0.5 mm	
CW mode	MPPW mode
$P_{F, CW} = 11.4 \text{ MW/m}; t_{i, CW} = 0.050 \text{ ms}$	$P_{F, CW} = 2.9 \text{ MW/m}; t_{i, MPPW (new)} = 0.28 \text{ ms}$
$q_p = 42 \text{ MW/cm}^2$ $E_{SP, CW} = 20 \text{ mJ}$	$q_p = 10.4 \text{ MW/cm}^2; q_{p, peak} = 59 \text{ MW/cm}^2$ $E_{SP, MPPW (new)} = 28 \text{ mJ}$
	
Weld width = 0.10 mm	Weld width = 0.12 mm

Figure 10-10 Constant penetration depth of 0.5 mm (weld boundaries delimited in red) achieved with different combinations of power factors and interaction times for a constant beam diameter of 35 μm in (A) CW and (B) MPPW lasers.

In Figure 10-11, similar weld shapes were achieved for a constant power factor and equal interaction time. Thus, as long as these two values are the same, the thermal losses remain unchanged, and the weld shape can be replicated independently of the temporal laser mode. This is equivalent to having a constant set of average power density, specific point energy and interaction time, as observed in (replicated from Figure 5-7 in 5.3.1), despite the different waveforms with different average peak power densities. It can be concluded that the new definitions of $t_{i, MPPW (new)}$ and $E_{SP, MPPW (new)}$ can capture the effect of the thermal losses on the weld shape, allowing a direct comparison between different laser temporal modes.

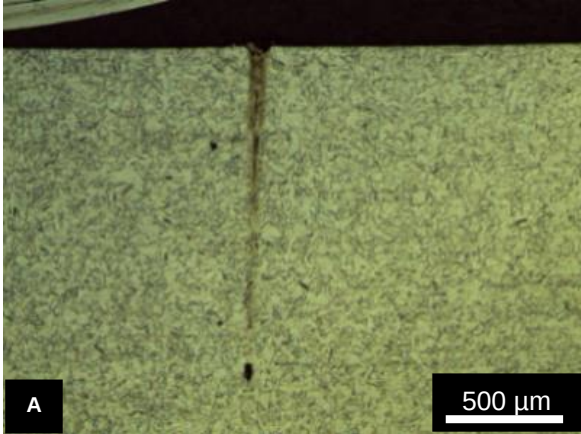
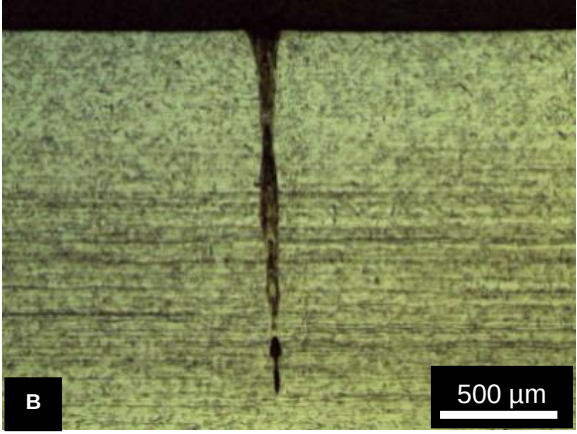
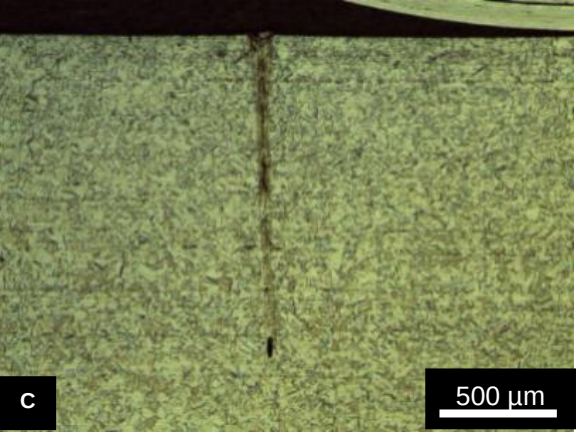
Penetration depth = 1.3 mm		
$P_{F, CW} = 2.9 \text{ MW/m}$; $t_{i, MPPW (new)} = 1.2 \text{ ms}$		
$P_{width} = 280 \text{ ns (Wfm 0)}$	$P_{width} = 350 \text{ ns (Wfm 27)}$	$P_{width} = 500 \text{ ns (Wfm 31)}$
$D_C = 2.8\%$; $t_{i, MPPW (old)} = 0.057 \text{ ms}$	$D_C = 3.5\%$; $t_{i, MPPW (old)} = 0.07 \text{ ms}$	$D_C = 5\%$; $t_{i, MPPW (old)} = 0.1 \text{ ms}$
$E_{SP, MPPW (old)} = 200 \text{ mJ}$; $E_{SP, MPPW (new)} = 120 \text{ mJ}$	$E_{SP, MPPW (old)} = 200 \text{ mJ}$; $E_{SP, MPPW (new)} = 120 \text{ mJ}$	$E_{SP, MPPW (old)} = 200 \text{ mJ}$; $E_{SP, MPPW (new)} = 120 \text{ mJ}$
$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, peak} = 371 \text{ MW/cm}^2$	$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, peak} = 297 \text{ MW/cm}^2$	$q_p = 10.4 \text{ MW/cm}^2$; $q_{p, peak} = 208 \text{ MW/cm}^2$
		

Figure 10-11 MPPW welds at constant penetration depth of 1.3 mm achieved with a power factor of 2.9 MW/m and $t_{i, MPPW (new)}$ of 1.2 ms in waveforms 0, 27 and 31

10.3 Summary of discussions

CW and MPPW laser processing modes showed different interactions with the material in micro-seam welding. Comparing both processes, the following conclusions can be drawn:

- A new definition of interaction time has been proposed, tested and validated to enable like-for-like comparison with CW mode by capturing the thermal losses effect on the weld shape.
- For similarly applied energies, the average peak power density in MPWW mode can be neglected. Several pulses are needed to initiate melting at a constant overlap factor; hence, the thermal losses are more important than the high peak power of an individual pulse.
- The new definition of interaction time allows the transferability of the power factor model independently of the temporal laser mode by capturing the inter-pulse thermal losses effect.
- The definition of power factor model for CW mode can be used in MPPW mode with the new definition of interaction time, allowing similar weld shapes for similar values of PF_{CW} and $t_{i, MPPW (new)}$, independently of the waveform selected.

11 Summary

11.1 Overall discussion

Laser welding was the joining process used in this work. Its precise and low heat input, high energy density and weld shape flexibility made it the best choice compared to other methods to join both similar and dissimilar alloys. Micro seam welding was investigated in continuous-wave and multi-pulse pulsed-wave processing despite all the welding techniques available. It allowed an equal and straightforward comparison between both laser temporal modes under the same welding conditions.

11.1.1 Characterisation of the nanosecond MPPW laser

The nanosecond multi-pulse pulsed wave laser has been fully characterised. The actual pulse energy and average peak power of different waveforms with different pulse durations, pulse repetition frequencies and average powers match the theoretical values defined for single-pulse pulsed-wave lasers. New definitions of the fundamental laser-material interaction parameters have been established to control the process: the average power density, average peak power density, and specific point energy independently control the penetration depth, whereas the interaction time controls the weld width for a particular range of applied energies.

The characterisation of the MPPW laser showed that the average power and pulse repetition frequency create significant processing limitations. As the frequency increases above PRF_0 or the average power decreases below 100 W, the ratio between peak power and average peak power drops as the pulse shape becomes almost square. Thus, the impact of the peak power on the material vaporisation rate can only be maximised within a narrow range of frequencies close to PRF_0 at maximum average power. This regime is characterised by high aspect ratio welds achieved at high average peak power density and low laser-material interaction time. On the other hand, as the frequency increases and the travel speed decreases, the laser-material interaction time increases. The high thermal losses characterise this regime, and low aspect ratio welds can be achieved at high energies and low average peak power densities. Thus, a trade-

off between applied energy and average peak power density is necessary to control the thermal losses, create enough material vaporisation and guarantee a certain penetration depth and weld width.

The laser duty cycle plays an essential role in controlling the thermal losses, as it dictates the time between pulses, i.e. the inter-pulse spacing. For constant applied energy, the heat losses created by the reduction in average peak power density can be compensated by increasing the duty cycle. However, increasing the duty cycle at constant applied energy, average peak power density and interaction time reduces the inter-pulse spacing. Consequently, the thermal losses between pulses decrease, and the penetration depth and overall melting efficiency of the process increase.

The time for the heat to diffuse over a unit distance depends on the metal's thermal diffusivity (α) and is quantified by the characteristic thermal time. The required inter-pulse spacing to generate material melting should be below the characteristic thermal time of the process, preventing the heat dissipation before the next pulse arrives. It allows a higher and faster heat accumulation between pulses to reach the melting temperature of the metal much quicker. A simplistic thermal model is able to demonstrate how the application of each pulse and the material's properties influence the temperature profile to generate a specific weld profile. Since the current definitions of the fundamental laser-material interaction parameters are independent of the material's properties and cannot predict energy accumulation and dissipation between pulses, it creates limitations. For similar laser-material interaction times, the laser can deliver the same energy per unit length with a certain number of pulses. Nevertheless, different weld profiles will be achieved for different pulse repetition frequencies and material's thermal diffusivities. Higher frequencies and lower thermal diffusivity allow a lower heat dissipation between pulses and higher penetration depth. Thus, the definition of interaction time should be redesigned to consider the thermal losses between pulses and in different metals. It will allow an accurate comparison between pulsed and continuous-wave lasers for similar applied energies at different duty cycles.

11.1.2 Selection of waveforms in multi-pulse pulsed-wave welding

The nanosecond MPPW laser used in this study provides different pulse shapes, also referred to as pre-programmed waveforms. More precisely, 31 different waveforms with different pulse duration, pulse energy and peak power can be used, making it challenging to select the most suitable for micro-welding or any other application, such as scoring. The process is even more complex if we consider other variables such as travel speed, pulse repetition frequency, average power, and beam diameter. Nevertheless, the fundamental laser-material interaction parameters established for MPPW laser revealed how the weld shape, i.e., depth of penetration and weld width, can be manipulated independently of the waveform selected.

The laser duty cycle is more important than the peak power in controlling the weld shape, as it dictates the thermal losses between pulses. It is possible to achieve similar weld shapes in different waveforms if the duty cycle compensates for the thermal losses between pulses at constant average power and applied energy. A low duty cycle will generate higher losses for waveforms with short pulse duration but high peak power. Therefore, the laser user can select any waveform as long as the difference in duty cycle compensates for the difference in peak power. On the other hand, when a constant duty cycle and travel speed are used, a constant set of FLMIP can be transferred between waveforms. Thus, the overall thermal losses remain unchanged, and the weld profile can be replicated.

The existence of 31 waveforms only complicates the parameters selection in the nanosecond MPPW studied, as the same weld shape can be easily replicated with a different set of parameters. The waveform with the longest pulse duration, highest pulse energy, and lowest peak power is desired to maximise the variety of weld shapes. Hence, the material will have more time to absorb the laser energy and melt the metal instead of vaporising it quickly, enhancing the weld quality. For this laser, waveform 31 is the one recommended for micro joining.

Determining the trade-off between FLMIP to predict penetration depth and weld width in different waveforms is challenging if the thermal losses are not

considered. Once again, the characteristic thermal time should be incorporated into the definition of laser-material interaction time to account for these losses created by the different duty cycles in different waveforms.

11.1.3 Comparison of lasers with different temporal outputs

The comparison between MPPW and CW laser modes showed that the fundamental laser material-interaction parameters are comparable to a certain extent. The MPPW needs fewer pulses to generate melting at lower operating frequencies due to the higher energy per pulse. However, the low laser duty cycle close to PRF_0 causes high thermal losses and creates similar weld widths regardless of the energy applied. It is also near PRF_0 that the higher peak power of the MPPW laser allows a higher penetration efficiency than in CW. Still, as the duty cycle increases, the penetration efficiency converges in both temporal modes, suggesting that the thermal losses between pulses decrease, becoming similar to CW mode at high frequencies and travel speeds. Therefore, as the frequency increases beyond PRF_0 , similar weld shapes, i.e., penetration depth and weld width, can be achieved in both lasers, despite the higher average peak power density in MPPW mode. Thus, the benefit of the higher peak power compared to CW mode is limited to a short range of frequencies and is not relevant anymore as the pulse shape becomes flat.

Matching the applied energy and interaction time in MPPW as in CW laser is inefficient. Increasing the number of pulses emitted per unit of weld length through a reduction in travel speed creates high thermal losses reflected by larger weld widths and shallower penetration depths compared to CW mode. Thus, the melting efficiency is consistently lower in MPPW mode. This is a limitation of the current definition of interaction time, as it doesn't capture the inter-pulse thermal losses, being impossible to achieve similar weld shapes in both lasers for a similar set of FLMP.

The CW laser is the preferred option for micro-seam welding as its higher average power allows higher weld shape flexibility, higher productivity and melting efficiency than MPPW.

11.1.4 Selection of processing parameters in CW micro seam welding

In CW micro seam welding of Al and SS, it is possible to use a predictive algorithm to find the weld profile required for a specific application. The joint's shape can be selected based on quality and productivity requirements, which are determined by the interaction time. The process is more productive for shorter interaction times, but narrower weld profiles will be obtained. On the other hand, longer interaction times provide higher fit-up tolerance but limited productivity. The power factor allows the selection of required penetration depths to accommodate a particular material thickness. The model will suggest the respective laser system parameters, i.e. beam diameter, average power, and travel speed. This allows the transferability of the parameters between different optical setups without a trial and error approach.

The power factor model works based on a trade-off between power density and the specific point energy, being possible to maintain the same penetration depth for different weld widths with a random set of processing parameters. Nevertheless, in stainless steel and aluminium, this trade-off doesn't work for small spot sizes and low travel speeds due to the high thermal losses, which defines the limits of the model applicability. High power density and low energy applied in small spots for an extended period are inefficient in micro-welding. The intense energy dissipation leads to a reduction in penetration depth, which the model does not predict.

Another limitation of the model is the impossibility of being transferred among different metals as it does not consider the material's physical properties. Comparing Al and SS, different weld shapes are achieved for similar power factors and interaction times. Due to the shorter characteristic thermal time, the energy is dissipated more quickly in Al, requiring a higher power factor to reach a similar penetration depth as in SS. Therefore, the current model definition is not perfect, and it is necessary to create a new study every time a new metal is studied, which is time-consuming and expensive.

11.1.5 Selection of processing parameters in MPPW micro seam welding

The selection of parameters in MPPW micro seam welding is a complex process. Combining beam diameter, average power, peak power, pulse energy, pulse width, pulse repetition frequency, and travel speed are necessary to achieve a particular weld shape. The new definition of the power factor model for MPPW laser mode facilitates this selection. It allows a more effortless transfer of parameters between different optical systems based on only two parameters: power factor and interaction time.

High aspect-ratio welds are achievable for high power factors and low interaction times through larger beam diameters (59 to 89 μm), high travel speeds, and low peak power and pulse energy at high pulse repetition frequencies. In this regime, the process is highly productive. The weld shapes are indicated for ultra-precision joining, such as medical applications, as the fit-up tolerance and the heat-affected zone are very low. On the other hand, lower aspect ratio welds with similar penetration depths can also be achieved for lower power factors and higher interaction times. The welds will be much larger through smaller beam diameters (35 to 59 μm), lower travel speeds, and higher peak power and pulse energies at low frequencies. Therefore, this regime is characterised by higher thermal losses and is suitable for applications requiring high fit-up tolerance but not high productivity or small heat-affected zones.

In MPPW mode, the new model works based on a trade-off between the applied energy and the average peak power density for different beam diameters. The duty cycle plays a fundamental role in balancing the thermal losses between pulses. It enables the transfer of similar power factors and interaction times across different waveforms to replicate similar weld shapes. Nevertheless, this balance cannot be reached for high interaction times and is broken sooner for smaller beam diameters as the thermal losses are more intense due to the lower ratio of the heat source to the bulk material. Therefore, the model shows some limitations in this regime where the available average power (100 W) is insufficient.

The power factor model is unsuitable for aluminium in MPPW mode as the high laser peak power creates intense vaporisation of the elements with a lower melting point. Thus, it needs to be optimised to guarantee a stable weld pool and a working envelope where the drilling regime is avoided. It should be possible at higher frequencies, but it would behave almost like a CW laser in that regime.

11.1.6 Performance of different laser temporal modes in dissimilar metal joining

The advancements of the latest generation of fibre pulsed lasers in pulse shape modulation minimise the formation of brittle intermetallic compounds (IMCs) through fast freezing of the melt pool. Nevertheless, their lower average power compared to CW lasers create a significant drawback for the application in thicker material sheets. Joining aluminium and stainless steel was challenging due to the alloys' different physical properties and chemical incompatibility, having been necessary to optimise the weld configuration and processing parameters for each temporal laser mode.

Al-SS joints are possible with the MPPW laser for high energy and average peak power density achieved at low frequencies. In this regime, the narrow weld profile limits the brittle IMCs formation and concentration at the joint interface. Higher loads per unit weld length can be achieved in MPPW than CW for similar applied energy. However, this is possible only for a low range of frequencies close to PRF_0 due to the limited average power of the MPPW laser and low travel speeds to increase the heat accumulation between pulses, becoming the process very inefficient for this application. On the other hand, the higher average power of the CW laser allows successful SS-Al joints with higher weld shape flexibility, higher productivity and higher tensile shear loads than MPPW. Still, it is unsuitable for providing successful Al-SS joints as it creates large aluminium melt pools, enhancing the mixing of both alloys at the interface where more IMCs are created. This is a clear disadvantage compared to MPPW laser, which must be considered before manufacturing dissimilar welds.

11.1.7 New phenomenological model for comparison of lasers with different temporal outputs

Traditional high-power single pulse pulsed wave (SPPW) lasers are being replaced by high-frequency, and low energy multi-pulse pulsed wave (MPPW) fibre lasers. However, as these lasers operate at very high frequencies, near continuous wave (CW) operation, it was not clear the benefit of such frequencies in comparison to CW lasers for micro-welding. The weld thermal cycle varies thermal losses which are affected by the time between pulses, pulse energy, welding time, and physical properties of the processed material. To compare different laser temporal modes, it was necessary to find a discrete unit common CW and PW processing, and interaction time was the only one able to relate travel speed and pulse duration for each case. A new definition of interaction time ($t_i, \text{MPPW (new)}$) and applied energy ($E_{SP, \text{MPPW (new)}}$) have been proposed and able to capture conduction losses by travel speed and heat inter-pulse losses due to periodic lack of laser power, allowing a direct comparison between different laser temporal modes. This new approach simplifies the selection of parameters by the laser user, and is well correlated to the fundamental laser material interaction parameters. A constant set of average power density, specific point energy and interaction time can be replicated in different waveforms, being possible to achieve similar weld shapes in MPPW mode. Alternatively, the power factor model has proven to be capable of simplifying the selection process independently of the laser temporal mode.

11.2 Conclusions

- The low average power is the most significant limitation of the MPPW laser used in this study.
- The benefit of the high peak power is only possible for a narrow range of frequencies close to PRF_0 , providing high aspect-ratio welds.
- Similar weld shapes can be achieved in different waveforms in MPPW laser welding.

- Waveform 31 provides the best weld shape flexibility and low vaporisation rate, being the one recommended for MPPW micro-welding.
- The inter-pulse thermal losses and materials' properties can be captured by the new definition of interaction time in MPPW laser, allowing a like-for-like comparison in different temporal modes.
- The higher average power of the CW laser provides higher weld shape flexibility, productivity and melting efficiency and stronger joints than the MPPW laser.
- MPPW laser is preferred for dissimilar aluminium welding on stainless steel, whereas CW laser is preferred for stainless steel on aluminium.
- The weld shape can be replicated independently of the temporal laser mode for constant values of power factor and interaction time. This is equivalent to having a constant average power density, specific point energy and interaction time.

11.3 Future work

11.3.1 Development of the thermal model to predict the weld shape in MPPW seam welding

In section 4, a simple thermal model showed each pulse's influence on the temperature profile of the base material. It would be helpful to have computer simulations to predict the necessary energy per unit length to achieve a certain depth of penetration and weld width. Hence, the welding parameters, i.e. pulse energy, average peak power and pulse duration, can be derived.

11.3.2 Comparison between different laser temporal modes and materials

The comparison between the two temporal laser modes, continuous-wave and nanosecond multi-pulse pulsed-wave laser, was made in chapter 6. This study should be extended to different laser temporal regimes, such as the millisecond, to understand if there is any limit on the new definitions of interaction time ($t_{i, MPPW (new)}$) and energy ($E_{SP, MPPW (new)}$) in controlling the process. The new definitions

must be tested on a wider variety of parameters and materials to understand their limitations.

The definition of $t_{i, CW}$ should be revised to reflect the materials' physical properties' effect on the weld shape. After that, a like-for-like comparison between different lasers and metals can be made. The power factor model should also be used to facilitate this comparison.

11.3.3 Material thickness

The bead-on-plate welds produced from sections 4 to 8 to were conducted in 2 mm thick plates to explore the laser systems' full capabilities without having the material thickness as a constrain. However, this study's primary focus is micro-welding since the beams used were between 35 and 89 μm . Further research should be done in ultra-thin sheets and investigate if this work's findings are independent of the material thickness for similar and dissimilar metal joining.

11.3.4 Laser wobbling

The advantages of wobbling are well known in CW and MPPW laser processing. Nevertheless, there are several parameters to take into consideration to achieve a certain weld profile. Now that the FLMIP have been established in MPPW seam welding, they could also be explored in wobbling. Comparing seam and wobble welding for similar applied energy per unit length would be ideal for understanding which technique gives better weld shape control, quality, productivity and efficiency.

11.3.5 Dissimilar metal joining

Further investigation is required in section 9. Larger beam diameters and different weld patterns are recommended to increase the bonding area and consequently, the weld strength. An MPPW laser with higher average power should be used to improve the weld shape flexibility.

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