HIGH DENSITY SELECTIVE LASER MELTING OF WASPALOY®

K.A. Mumtaz*, N. Hopkinson*, P. Erasenthiran*
*Rapid Manufacturing Research Group, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK.
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Abstract

In this work, high density Waspaloy® specimens were produced using specially assembled laboratory equipment by Selective Laser Melting (SLM). SLM of Waspaloy® powder was performed using a high power pulsed Nd:YAG laser. The laser parameters pulse energy (J), pulse width (ms), repetition rate (Hz) and scan speed (mm/min) were varied. Process parameter optimization was achieved using factorial analysis to investigate the relationship between specific processing parameters and the formation of Waspaloy® specimens. The optimized processing parameters produced Waspaloy® specimens that were 99.3 % dense. The resultant laser melted specimen's height, width and contact angles were measured. Specimens were also observed for the occurrence of porosity.

1.1. Solid Freeform Fabrication

SFF is a family of material additive manufacturing processes that enable quick manufacture of physical models from CAD data [1]. The principal advantage of SFF processes is the ability to quickly manufacture parts of virtually any complexity or geometry entirely without the need for tooling. SFF technologies seek to improve upon conventional processing technologies through a reduction in processing steps, reduction in use of materials and reduction in fabrication time and cost.

There exists a need to rapidly fabricate functional fully-dense metal parts without the requirement of hard tooling [2]. Several SFF methods have been developed to produce fully functional end use metal parts, these include Electron Beam Melting (EBM), Ultrasonic Consolidation (UC), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS) Selective Laser Melting (SLM) and Laser Engineered Net Shaping (LENS™) [3].

Research efforts have demonstrated the great potential available within laser processing to manufacture metal components with microstructures and mechanical properties equivalent to or superior to conventionally processed materials [4]. The greatest potential for laser based SFF processes may lie within its capability to directly manufacture fully dense metallic components from powder in a single step [5] as well as the manufacturing of specialized functional applications [6]. Schwendner et al. [7] believes laser based SFF is a viable technology for the direct fabrication of metallic components. This is due to the versatility, accuracy and ease at which high temperatures can be generated by lasers to melt powdered metal [8]. SLM has the potential to fabricate high density fully functionally end use parts in a single step without the requirement of extensive post processing. This is because the process uses a high power laser to completely melt powered metal from a powder bed, enabling high density processing with the requirement of minor surface finishing such as machining and polishing.

1.2. Selective Laser Melting

SLM is a tool-less manufacturing technique that is driven by the need to process near full density metal components with mechanical properties comparable to those of bulk materials [9]. This additive manufacturing technology fabricates parts by selectively melting layers of pre-deposited metal powder using a focused laser beam. The process begins with the deposition of a thin layer of powder. A laser beam with a defined intensity is then scanned across the surface at points that correspond to the cross section of the component. The heat generated by the laser produced a melt pool that causes localized bonding between powder particles [10].

As the laser beam moves away from the melt pool, the molten material is solidified forming a fully dense structure. Each layer is melted deeply enough to fuse it to the underlying layer. Another layer of powder material is then spread onto the previously melted layer and the process is repeated. Material particles that are not melted or not fused remain loose and may be removed once the component is completed. In addition this loose powder acts as a supporting agent for the structure. Figure 1 shows a schematic of this process.

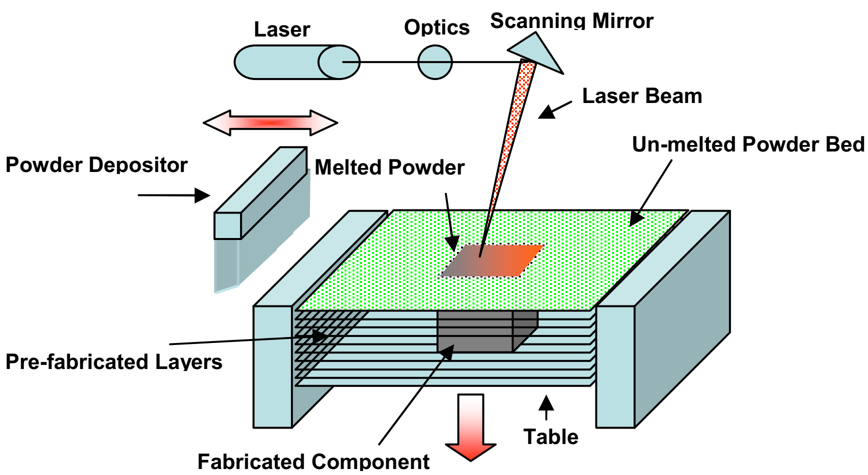


Figure 1 Selective laser melting process

SLM requires no binder or major post processing operation order to achieve final part properties. Single step processing by SLM can produce cost savings realized by the elimination of conventional multi-step thermo-mechanical processing. Design features such as internal cavities or over-hanging features can be made without joined assemblies. Hard to process materials such as intermetallics, refractory metals, and high temperature alloys can be processed [8].

The potential for using SLM to fabricate full density functional metal components can cut processing time, reduce cost and improve the performance of a component compared to those produced via conventional processing. Due to the SLM continuously improving process parameters (smaller layer thickness, smaller spot size, etc.), Kruth et al. [11] states that the resulting fabricated parts have mechanical properties better than those produced by indirect SLS as well as bulk metal properties. However producing these end use parts in a single step is not an easy process. There are many processing issues and problems that can arise.

1.3. High density processing using SLM

The majority of functional parts or tools require a high density, as this improves part strength and avoids defects such as crack formation and eventual part failure. A high density part is formed when there is a reduction in porosity/voids within a structure. Porosity usually develops in laser melting processes when trapped gas is not allowed to escape or when powder particles have not fully melted [12]. It has been demonstrated that low porosity can be achieved with higher laser powers, implying that the pore/void level can be reduced with extra heat input [5]. The power level can be increased or energy density can be adjusted by reducing laser feedrate speed or increase repetition rate [13]. Work conducted by Niu et al. [14] shows that decreasing scan feedrate improved part density for laser processed powdered steel.

Another important factor that must be considered within SLM to ensure the successful production of multiple layered parts is the wettability of a melt. Wettability affects how successfully fusion between material particles will occur and consequently the level of porosity. Contact angle is the angle made between an individual melted beads of material and the surface to which it has melted (shown in Figure 2). A higher contact angle usually denotes improved wettablility and reduces defects such as porosity and delamination [9]. Another disadvantageous phenomenon arising from a reduced wettability is balling. It occurs when the molten material does not wet the underlying substrate due to surface tension and can affect surface flow causing fully molten metal to re-solidify as a series of balls [8]. This results in a rough and bead-shaped surface, obstructing a smooth layer deposition and decreasing the density of the produced part.

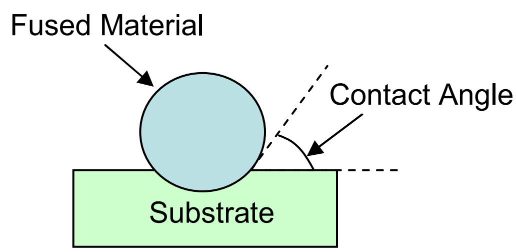


Figure 2 Cross-section of a fused bead and the contact angle it makes with substrate

The success of SLM as a rapid prototyping and rapid manufacturing technology will result mainly from its capability to process a variety of materials to a high density without the need of post processing. However parts fabricated directly from a high power laser beam create a variety of problems when processing metal powder due to the high heat input generated by the laser. These problems include material vaporization, lack of fusion, part porosity, part shrinkage etc. High residual stresses and material shrinkages are created as parts cool [15], shrinkage also makes it difficult to achieve a high geometric accuracy. Material can warp, leading to cracking and delamination. Eliminating residual pores while maintaining surface quality is an obstacle that further complicates matters with the use of high powered lasers. It is due to these factors that the range of commercially used powdered metals for processing via SLM is still limited today [13]. It is still the subject of major research studies [14] and development in order to gain widespread acceptance within industry [16].

Due to the large amount of problems associated with full density processing, it is critical to have knowledge about laser material processing so as to avoid processing difficulties and setbacks. Correct understanding will allow an operator using a SLM system to vary and control the large variety of processing parameters. Achieving a fine balance between the laser processing parameters is something that is fundamental to the production of high density fully functional metallic parts. The operator will then be able to quickly identify any problems within part fabrication and make proactive decisions to improve the process. This will allow for successful, reliable and repeatable metal fabrication [17].

In an attempt to produce high density specimens with the avoidance of processing issues such as part porosity, material vaporization etc., a processing window for each new material needs to be determined experimentally. This investigation used an Nd:YAG pulsed laser to SLM Waspaloy® from a powder bed. Varying process parameters were used to produce single scanned and layered specimens. A factorial analysis methodology was initially used to identify a suitable laser processing region. Part characteristics such as height, width, contact angle and porosity were examined with the aim of developing optimized process parameters for the production of high density Waspaloy® specimens.

2. Experimental Methodology and Testing

Research performed using SLM and other laser based SFF technologies showed that important part features such as build height and width, porosity and microstructure are strongly dependent on the system's processing parameters including laser power, laser scanning speed, repetition rate etc. [15]. A quantitative understanding of the relationship between independent process parameters and the formation of single beads and layers of Waspaloy® was undertaken. Part density will depend upon the uniformity and repeatability of solidified melt, whether producing single scans, multiple layers or complex parts. Process parameters can be monitored and optimized continuously to obtain the desired part properties.

2.1. Material Properties

Waspaloy® is a nickel-based, age-hardenable superalloy with excellent high-temperature strength and good resistance to corrosion, notably to oxidation. It is used for aerospace and gas turbine engine components. Current applications include compressors, rotor discs, shafts, spacers, seals, rings and casings, fasteners and other miscellaneous engine hardware, airframe assemblies and missile systems. The Waspaloy® powder used within this investigation had a mean particle size of 63 μm, its chemical composition is shown in Table 1.

Table 1 Waspaloy® Nominal Weight Composition (%) [22]

Ni	Co	Cr	Mo	Fe	Si	Mn	Al	Ti	Cu
54.0	13.5	19.5	4.2	2.0	0.7	1.0	1.4	3.0	0.5

2.2. System Setup

A high power 550W Nd:YAG pulsed laser (GSI Lumonics JK701H) operating at a wavelength of 1.06 μm was used. The laser beam had a spot diameter of 0.8mm. The beam was carried through a fibre optics delivery system and was installed on a 4-axis CNC controlled machine. Powder layers were deposited in one direction by means of a hopper that traversed across the powder bed. Argon gas was used as a shield gas to prevent parts from oxidization. Parts were built on 43mmx30mmx4mm steel substrates.

2.2.1. Single Bead Testing

Processing parameters pulse width (ms), pulse energy (J), repetition rate (Hz) and scan speed (mm/min) all hold an impact upon the formation of SLM parts. Initially single beads of Waspaloy® were processed from a powder bed thickness of 0.9mm to gain an understanding about the laser material interactions and how the powdered Waspaloy® was subsequently formed using varied processing parameters. The single scans were 25mm in length and processed within the range of processing parameters shown in Table 2. These laser processing ranges were based upon work conducted by Su et al. [18] when using SLM to process H13 tool steel to a high density.

Table 2 Single Scan Processing Parameters

Pulse Width (ms)	Pulse Energy (J)	Repetition Rate (Hz)	Scan Speed (mm/min)
2 - 8	5 - 15	5 - 15	150 - 250

The peak power, specific energy density and spot percentage overlap values generated within this investigation are defined by equations 1-3.

Peak Power (W) = $$\frac{PulseEnergy(J)}{PulseWidth(ms)} \quad (1)$$

Specific Energy Density = $$\frac{AveragePower(W)}{Feedrate(mm/s) \times Spotsize(mm)} \quad (2)$$

Percentage Overlap = $$\left(\frac{feedrate(mm/s)}{spotsize(mm) \times repetitionrate(Hz)} - 1 \right) \times 100 \quad (3)$$

The processing region in which the material would fully fuse, not bond and vaporize at varying specific densities was initially investigated. The influence these processing parameters had on the response variables bead width, height and contact angle was measured (see Figure 3) using image tool analysis software. The percentage beam spot overlap shown in Figure 3 was varied between 60-85%. Its impact upon the response variables and wettability were also examined.

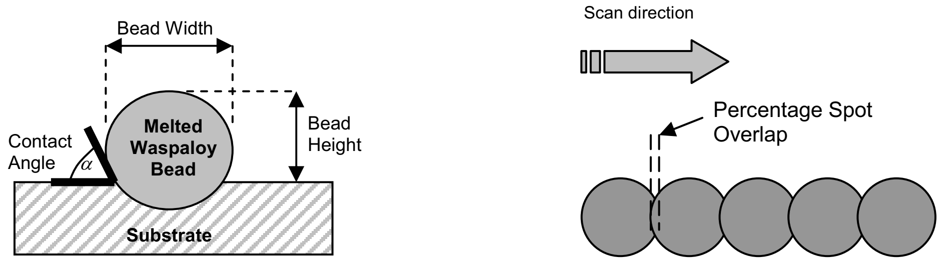


Figure 3 Cross-sectioned bead measurements and percentage spot overlap

Factorial analysis was employed using the software Statgraphics™ for the experimental design and initial analysis of results. Statgraphics™ produced a vast array of information analyzed from experimental results and suggested which processing parameters held the greatest influence upon the formation of single beads of Waspaloy®. This allowed for an accurate interpretation of results and optimization of pulse width, repetition rate and scan speed values.

2.2.2. Layers fabrication testing

Using optimised pulse width, repetition rate and scan speed parameters, layers of Waspaloy® were then fabricated at varying pulse energies of 6-9J with the aim of reducing porosity within the specimen. The layered specimens were 25mm in length, 5mm in width and consisted of three 0.4mm layers. A scanning strategy that had been successfully developed to produce high density steel parts using SLM was used for processing the layered specimen [18]. An example of the scanning and refill strategy used is shown in Figure 4. The strategy helped prevent unnecessary distortion, allowing the part to maintain a level of geometric accuracy and reduced part porosity. Scans 1,2,3 and 4 were initially performed with a 0.5mm spacing followed by a layer refill strategy and laser scans 5,6 and 7 to complete the layer. The effects pulse energies had on the occurrence of porosity and cracks within the specimen were observed using optical scanning electron microscopy (SEM) analysis.

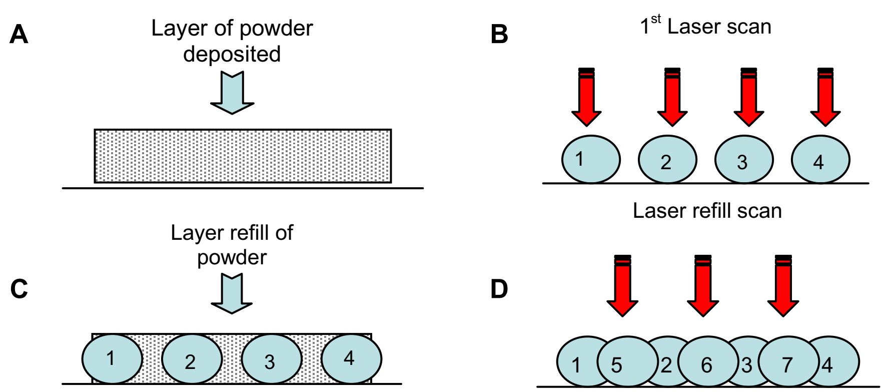


Figure 4 Cross-sectional view of fusion of layers and refill strategies

3. Results and Discussion

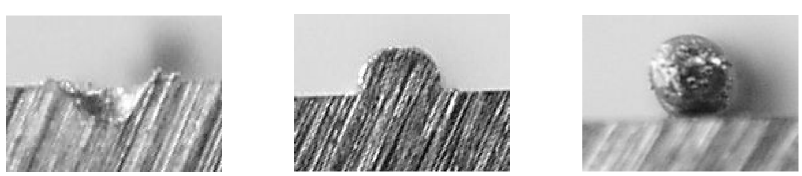
3.1. Single Scan Results

3.1.1. Bonding Region

Laser processing parameters were varied in an attempt to identify bonding regions in which Waspaloy® would fully bond to the substrate. Single beads that were 25mm in length were processed from a 0.9mm powder bed. Varying processing parameters caused the powder to fully fuse to the steel substrate, completely vaporize due to a high specific energy or would not fully fuse due to an insufficient specific energy input. Examples of cross sectioned beads that have undergone the affects vaporization, full and partial bonding are shown in Figure 5. During full laser melting the temperature of the exposed powder should exceed its melting temperature. A further increase in temperature would cause the material to vaporize. When this phase transformation occurs, the rapidly moving evaporated powder particles expand and generate a recoil pressure on the molten pool [7]. The recoil pressure associated with plasma formation was observed to move some of the powder away from the interaction zone, causing the laser to penetrate the steel substrate causing little or no bead formation. Figure 6 shows the bonding region for the material at different pulse width and specific energies, the material is more susceptible to vaporization at shorter pulse widths compared to longer pulse widths. This is a result of the greater heat intensities that can be generated at lower pulse widths. Therefore lower pulse energies should be used when using very short pulse widths in order to avoid the affects of vaporization.

As the pulse width increased the specific energy required for complete bonding of Waspaloy® increased. A lack of bonding occurred at specific energies below 5 (J/mm^2) regardless of the pulse width due to an insufficient heat input.

It has been shown that heat generated by the laser and its intensity over a defined area had a considerable effect upon the fusion of the Waspaloy® powder.



(a) **(b)** **(c)**

Figure 5 Cross-sectioned beads, **(a)** effect of vaporization, **(b)** full melting and **(c)** lack of fusion

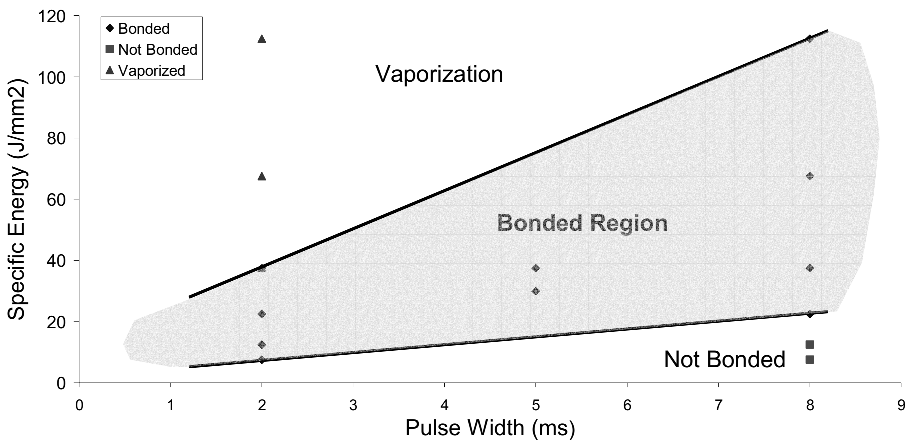


Figure 6 Specific Energy (J/mm^2) against Pulse Width(ms)

3.1.2. Bead Width and Height

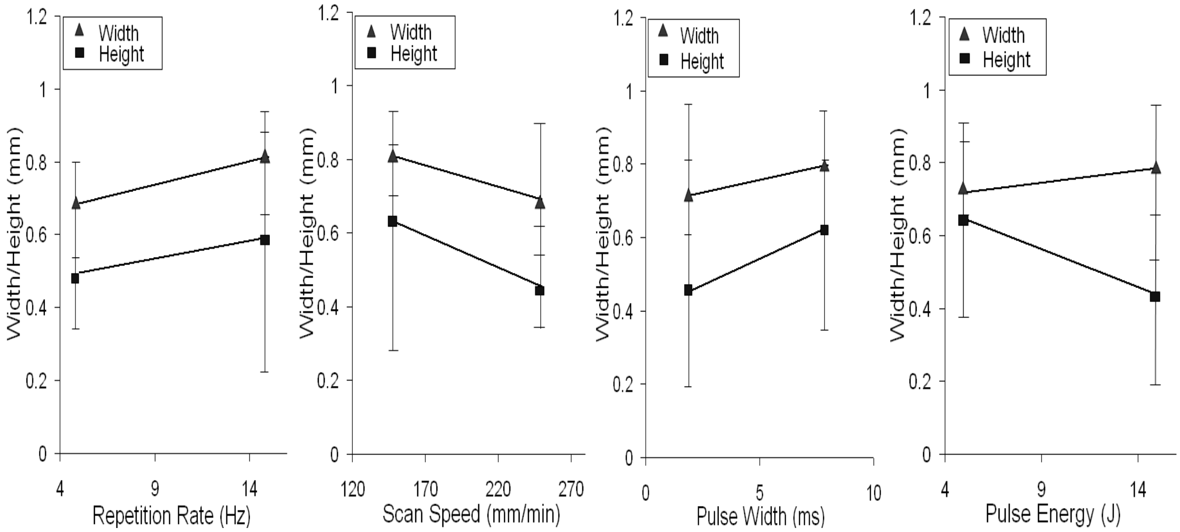
Figure 7 shows the effects that repetition rate, scan speed, pulse width and pulse energy had on the formation of bead width and heights of fully bonded specimens.

An increase in repetition rate caused the respective bead widths and heights to increase. This is because the total amount of energy delivered to the interaction site is increased, this directly effects the melt pool as the surface tension draws local material into the melt.

An increased scan speed reduces the energy input per unit length imparted to the material. This drop in energy causes less powder melting to occur due to a decrease in laser material interaction time and subsequently reduces the bead width. Parts produced at quicker scan speeds will encounter a reduction in incident energy that could lead to higher porosity within a part. However scan speeds that are too slow may lead to vaporization of the material as a longer laser material interaction time occurs.

At higher pulse widths the duration the material is exposed to the laser is increased. The longer the melt pool is maintained at an elevated temperature the more powder that will be consolidated into the melt pool, producing larger bead widths and heights. This increase in pulse width does not automatically imply a reduction in part porosity or a successfull bonding to an underlying layer due to a decrease in peak power and material penetration depth.

Increasing pulse energies between 5-15J produced larger bead widths and smaller bead heights due to an increase in heat intensity, aiding the full melting of powder. The overall volume of the powder available does not change considerably, which allows the bead width to spread out with a reduction in height.



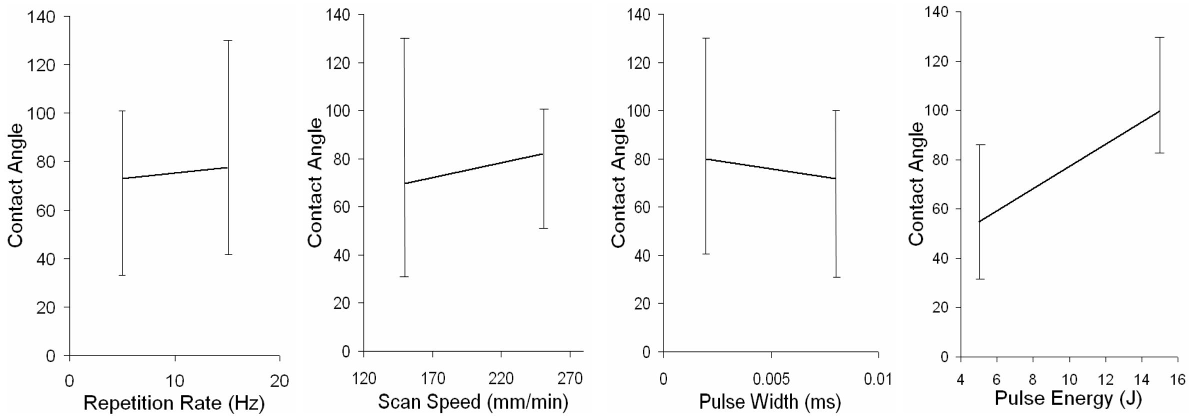
(a) **(b)** **(c)** **(d)**

Figure 7 Single bead, processing parameter against bead width/height

3.1.3. Bead Contact angle

Figure 8 shows the effects that varying processing parameters have on the formation of bead contact angles. An adjustment in repetition rate did not cause the contact angle made between melt and substrate to vary a significant amount. An increase in scan speed produces smaller, flatter beads due to the surface tension, which increases the contact angle. An increase in pulse width produces a longer laser material interaction time, this increases the amount of material drawn into the melt pool. However the heat intensity would subsequently reduce causing the contact angle to also reduce. This is because there is not enough heat input to fully melt the material and so the molten component does not have enough energy for the capillary forces to spread the material out. An increase in pulse energy allowed for an increase in contact angle. The higher heat input caused the material to undergo phase changes and spread out producing flatter beads with higher contact angles.

An increase in repetition rate, scan speed and pulse energy increased contact angle. Pulse energy held the greatest effect upon contact angle increase and therefore held the greatest influence on the wettability of the melt.

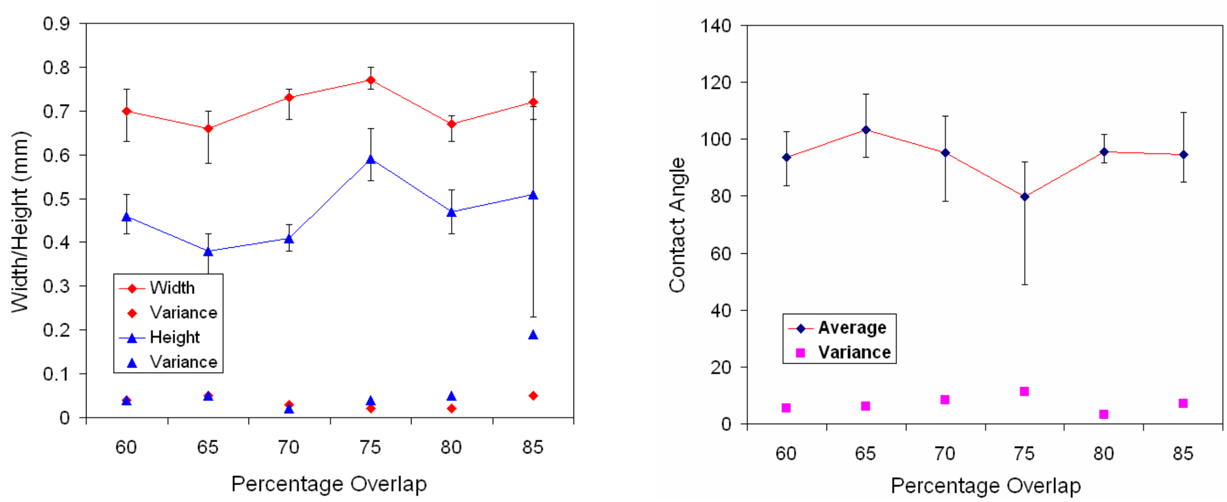


(a) **(b)** **(c)** **(d)**

Figure 8 Single bead processing, processing parameter against contact angle

3.1.4. Spot overlaps

The relationships between bead width, height and contact angle with varying spot overlap are shown in Figure 9(a) shows that the bead width and height varied as the spot overlap was increased. The bead width did not vary a considerable amount between 60-85% overlap. At 70-80% overlap, a trend in increasing and decreasing bead height was observed. Bead height is at it's lowest at 65% overlap and it's highest at 75%. There is a similar trend between the increase and decrease in bead width and height at specific overlaps. Figure 9(b) shows that the contact angle steadily drops and then rises between 70-80%. The trend shown in this graph is a reflected image of the trends displayed for both bead width and height values in Figure 9(a). As bead width and height increase, the contact angle reduces. As the bead width and height decrease the contact angle increases. The bead contact angle is highest (103°) at an overlap of 65%, achieved at a scan speed of 168mm/min and repetition rate of 10Hz.



(a) **(b)**

Figure 9 Single bead, percentage overlap against **(a)** width/height and **(b)** contact angle

The single bead investigation allowed for certain process parameters to be optimised. Pulse width 5ms, repetition rate 10Hz and scan speed 168mm/min were found to be the best suited parameters for the production of consistent well formed beads with a high contact angle. The effects of varied pulse energies were further investigated and optimised with the production of multiple layers of Waspaloy®.

3.2. Layers of Waspaloy®

Layered specimens that were 25mm in length, 5mm in width and consisted of 3 layers (0.4mm layer thickness), this specimen is shown in Figure 10.

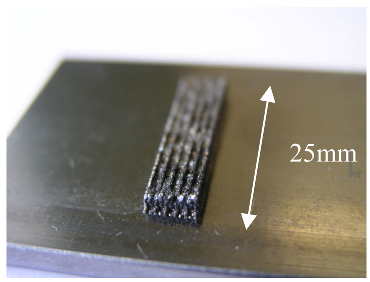
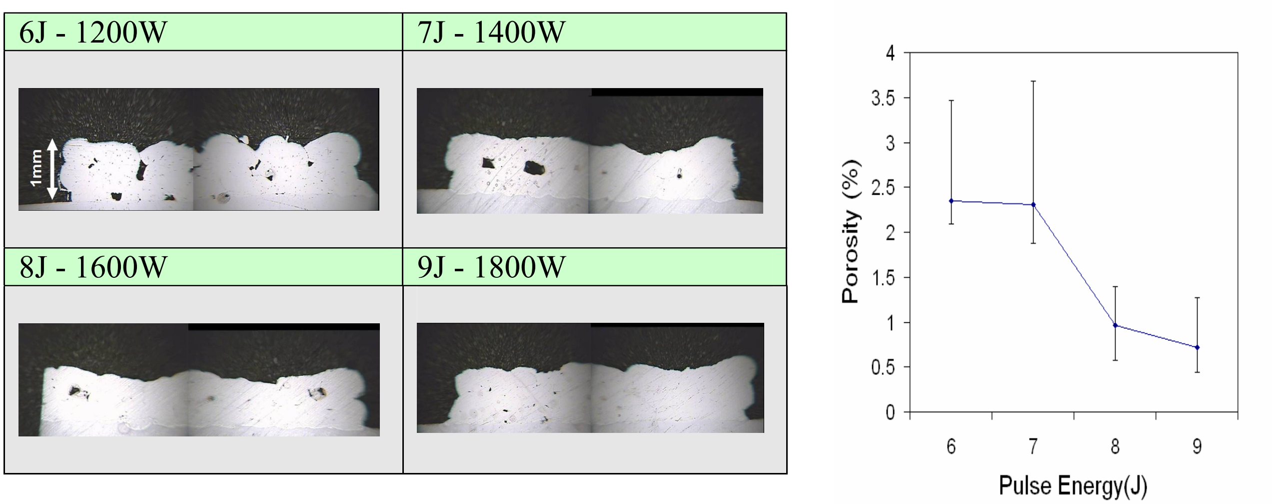


Figure 10 Layered specimen

Figure 11(a) shows the cross-sections of the fabricated specimens and the views under SEM analysis when processed with varying pulse energies. There appears to be a large amount of dimensional distortion throughout the fabricated specimens. This could be a result of the layer thickness, a high pulse width causing too much material to be drawn into melt, scan spacing, high peak power vaporizing material etc. However the geometric accuracy of the part is outside the scope of this investigation.

The darker areas or spots within specimens shown in Figure 11(a) represent the porous parts of the structure. Two types of porosity can exist within laser processed powders. A porosity due to a lack of fusion or a gas porosity that is caused due to an entrapment of gas or release of gas present within the powder particles. The Waspaloy® specimen's porosity mainly occurred along layer boundaries and the boundary between single scans within the same layer**.** Figure 11(b) shows that the specimen processed at 6J pulse energy contained an average porosity of 2.4%. The specimens porosity reduced as the pulse energy was increased. This is because the extra heat input improved the melting of the material within the melt pool and reduced part porosity. Parts were produced to an average density of 99.3% when a pulse energy of 9J was used. An increase in pulse energy results in a higher attained temperature of melt and promotes a better interlayer connection. The scanning laser beam delivered a correct amount of energy to each layer to sufficiently re-melt the previous layer without over melting the current layer. Pulse energies above 9J were tested, however the pulse energies generated high peak powers causing large amounts of material vaporization. The plasma plume generated caused the protective glass lens on the Nd:YAG laser to crack.



(a) **(b)**

Figure 11 **(a)** Layered specimen cross-sectioned under SEM analysis (X2.5) and **(b)** specimen's porosity(%) against pulse energy(J)

4. Conclusion

This paper has examined the effects of laser process parameters on the formation of Waspaloy® single bead width, height and contact angles using SLM. The results have shown interesting trends in the formation of specimens with variable pulse width, pulse energy, repetition rate and scan speed.

It was shown that higher levels of porosity were produced at lower pulse energies and the formation of these pores predominantly exists around layer boundaries. A pulse energy of 9J was sufficient to produce a part that contained an average porosity of 0.7%. The porosity conclusions may be either overestimated or underestimated since the porosity analysis was based on an area survey. However, it could provide qualitative results about the relationship between laser processing parameters and the extent of porosity within a structure.

There is still a lot of work that can be performed to develop and improve part properties. Part geometry, micro structural properties and particularly surface finish can be further investigated and optimised in an attempt to produce end use metallic parts using SLM.

5. References

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