Selective Laser Melting of thin wall parts using pulse shaping

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Abstract

Pulse shaping is a technique used to temporally distribute energy within a single laser pulse. This provides the user an added degree of control over the heat delivered to the laser material interaction zone. Pulses that induce a gradual heating or a prolonged cooling effect can be generated with peak power/pulse energy combinations specifically tailored to control melt pool properties and eventual part formation. This investigation used a pulsed 550 W Nd:YAG laser to produce thin wall Inconel 625® parts using pulse shapes that delivered a variety of different energy distributions. Parts built with and without pulse shape control were measured for width, top and side surface roughness. The efficacy of pulse shaping control is discussed including potential benefits for use within the Selective Laser Melting process. Pulse shaping was shown to reduce spatter ejection during processing, improve the top surface roughness of parts and minimise melt pool width.

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1. Introduction

Industry is becoming increasingly interested in Solid Freeform Fabrication (SFF) technologies to produce fully functional metal parts. This family of processes involves a layer-wise shaping and consolidation of material (e.g., powder and wire) allowing parts to be produced with a high geometric freedom directly from a CAD model. The use of SFF has also the potential to drastically reduce the time period between the initial conceptual design of a part and its actual fabrication. A group of SFF technologies known as Direct Metal Laser Fabrication (DMLF) utilize lasers to consolidate material. One such DMLF process known as Selective Laser Melting (SLM) builds metal parts by melting powder from a powder bed using a laser.

1.1. Selective Laser Melting

SLM is a powder bed process that begins with the deposition of a thin layer of powder onto a substrate. A high power laser raster scans the surface of the powder, the heat generated causes powder particles to melt and form a melt pool which solidifies as a consolidated layer of material (Santos et al., 2004). Once the layer has been scanned another layer of powder is deposited and is again melted by the laser and solidifies to form the next layer of the part. Fig. 1 shows a schematic of this process. Powder particles that are not melted remain loose and are removed once the component is complete. Supports are required to anchor down certain unsupported features due to shrinkage and curling of solidifying material. This restricts the process geometric freedom and incurs further post-processing operations to remove supports.

The main advantage of SFF processes such as SLM is the capability to build complex geometries that would otherwise be difficult or impossible to produce using conventional manufacturing processes. This is due to the versatility, accuracy and small spot size of a laser beam. The possibility to build thin wall parts to a high resolution complements the technology’s main advantage and extends its manufacturing capabilities. However the production of metal parts via SLM has many difficulties. Many processing issues arise due to the use of a high power laser to fully liquefy material from a powder bed. High heat input often causes an increase in material vapourisation and spatter generation during processing. Surface roughness is another SLM issue that is influenced by particle melting, melt pool stability and re-solidifying mechanisms.

1.2. Surface roughness and part resolution

The surface roughness of a part is critical in many applications with some applications requiring a surface roughness of 0.8 µm or better to avoid premature failure from surface initiated cracking (Dalgarno, 2007). Commercial powder bed machines such as MTT’s Realizer and EOS M270 often require post-processing operations such as surface machining, polishing and shot peening to attain final part surface finish.

The top surface roughness of a solidified melt pool can be affected by a rippling effect that occurs due to surface tension forces exerting a shear force on the liquid surface. This is primarily due to a surface temperature difference between the laser beam and the solidifying zone caused by the motion of the laser beam. As
the thermal gradients reduce, gravity and surface curvature counteract the external shear force and eventually restores the surface height of the melt pool to the free level (Ramos et al., 2003). However, viscous forces delay this relaxation process and quick melt pool solidification time often ensures that complete relaxation is not fully achieved.

The roughness of a part can also be affected by a phenomenon known as balling. Balling is the breakup of the melt pool into small spheres. It occurs when molten material does not wet well to the underlying substrate due to high surface tension differences generated as a result of variations in thermal properties across the melt pool (Fuh et al., 1995; Kruth et al., 2003; Morgan et al., 2004). Thermal gradients cause a thermocapillary flow of a fluid within the melt pool from regions with low surface tension to regions with high surface tension, known as Marangoni convection (Rombouts et al., 2006). The breaking up of the melt pool into smaller entities reduces the variation in melt pool surface tension. Balling can increase with the generation of excessive molten material or if viscosity within a melt pool is too low (Agarwala et al., 1995). Kruth et al. (2004) stated that when the total surface of a molten pool becomes larger than that of a sphere with the same volume, the balling effect takes place. Balling is a severe impediment on interlayer connection, it decreases part density and increases top/side surface roughness. The side roughness of a part can also increase due to partially melted, entrained powder particles that stick and agglomerate to the outer edge of the solidified melt pool known as “satellite formation” or “hillocks” (Tolochko et al., 2004; Elsen, 2007). Satellite formation mainly occurs when powder particles are not given enough time or heat to penetrate the melt pool before melt pool solidification.

The minimum achievable feature size (resolution) has great influence on part accuracy. Dimensional tolerances and repeatability are key factors with any DMLF technology. Minimum resolution is of high importance in the design of functional parts, e.g., for thin walls or open cell structures in medical applications. Thin walls are an example for so-called positive minimum feature size (smallest solid part possible) while open cells are an example for negative minimum feature size (smallest gap size possible) (Rehme and Emmelmann, 2005).

Surface roughness and part resolution are all heavily dependent on laser processing parameters and melt pool control. A technique known as pulse shaping has been shown to extend the degree of control over a laser’s energy distribution and therefore has the potential to improve the control over melt pool formation, stability and eventual part properties (Fig. 2).

1.3. Pulse shaping

A pulsed laser emits bursts of energy that consist of a fixed amount of energy for a specified duration. Pulse shaping is a technique used to temporally distribute energy within a single laser pulse. It can also be defined as a variation in power supplied to a laser to change the shape of the output pulse and subsequently the heat distribution within the pulse (Kanzler, 2006). Changing the energy distribution within a pulse can completely change the melting behaviour of a material. Pulse shaping can be accomplished by dividing the pulse’s current used to excite a laser flash lamp into as many as 20 individual sectors and specifying the duration and peak power of each sector. The current supplied causes the flashlamps to emit light that is absorbed and amplified by the Nd:YAG crystal (only for Nd:YAG laser). This amplified light is emitted in
short bursts/pulses through various focusing lenses and eventually onto a work piece as shown in Fig. 3. The electric current supplied is therefore one of the main factors that dictate the characteristics of the laser pulse. This allows the user to specifically tailor the energy distribution to the nearest 0.5 ms within a single laser pulse. The electric current supply is set using a Hgt control ranging from 0% to 100%, 0% indicates no current and 100% indicates maximum current. Fig. 3(a) shows an example of a standard pulse's demand profile. This is known as a Rectangular pulse shape or "top hat" pulse shape with power densities remaining nominally constant throughout the pulse. Rectangular pulse shapes are the simplest and most extensively used laser pulse shape within academia and industry containing only one energy sector. This pulse shape is fed to the flashlamps but due to the filter effect a more realistic output profile of the laser is represented in Fig. 3(b). With most solid state lasers such as the Nd:YAG, the use of a Rectangular pulse shapes can be extended allowing a further improved control over laser processing.

Pulse shaping research has mainly focused on the use of two certain pulse shapes and the amount of spatter generated during processing. The degree of plasma plume generated during processing was also measured during processing. A plasma plume is ionised metal vapour that can exert a recoil pressure on the melt pool. Increases in plasma plume intensity are directly related to increases in spatter ejection (Park and Rhee, 1999) leading to powder bed contamination and obstruction of powder depositor/leveller. Plasma plume height was measured using a fixed digital video camera and computer software ImageTool to identify a link between the use of certain pulse shapes and the amount of spatter generated during processing.

2. Experimental methodology and testing

A variety of Ramp Up and Ramp Down pulses were generated when producing thin wall parts measuring 25 mm in length from four 100 μm powder layers. Parts were built on a 10 mm thick steel substrate. The pulse shapes employed were progressively increased in duration and overall energy. The effects of pulse shaping on part top/side arithmetic average surface roughness ($R_a$) and width were tested. Sample surface $R_a$ was measured three times for each sample using a TalySurf CL 2000. The TalySurf evaluated 12.5 mm of the samples surface with a cut-off length of 2.5 mm. Fig. 5 illustrates the surfaces of the thin wall part that were measured for roughness. Sample width was measured using digital callipers along three segments of the sample's length.

The most effective pulse shapes were identified and used to produce larger thin wall test parts 25 mm in length built from 80 μm to 100 μm powder layers. These were tested for $R_a$ in multiple directions (including vertical side $R_a$). Laser repetition rate and scan speeds remained fixed at 40 Hz and 400 mm/min, respectively throughout all experimentation. These were based upon parameters developed by Mumtaz and Hopkinson (2008) when optimising laser process parameters in producing thin wall Inconel 625® with low top/side $R_a$ using non-pulse shaping techniques.

Fig. 5. Top/side $R_a$ measurement of thin wall part.

2.1. System setup

The SLM system used within this investigation included a GSI Lumonics JK701H Nd:YAG laser. The laser has a TEM$_{00}$ Gaussian
profile, a spot size of 0.8 mm and a maximum power output of 550 W. The pulses of laser energy generated by the flash lamps are fed through a 01 mm silica optical fibre delivery cable to the laser head and are deflected through 90° by a reflecting optic. The light is focused and passes through the laser nozzle onto the powder bed. Powder is deposited onto a steel substrate that is itself placed on a processing table that is driven by a 2-axis CNC controlled machine. The laser head remains static during processing but can move along the z-axis prior to processing. Argon gas was fed through the laser nozzle onto the processing area at a rate of 10 ml/s to protect the parts from the effects of oxidisation. Pulse shape monitoring was undertaken using an externally fitted digital storage PC oscilloscope (PicoScope 3205) to measure and analyse voltage waveforms.

2.2. Material characterisation

Inconel 625® powder (Sandvik Osprey, UK) was supplied sized to 53 ± 25 μm. The exact particle size distribution was measured to be a $D(v, 0.1)$ of 22.51 μm (10% of the volume distribution is below this value), $D(v, 0.5)$ of 45.48 μm (volume median diameter, 50% of the distribution is above and 50% is below this value) and $D(v, 0.9)$ of 58.59 μm (90% of the volume distribution is below this value).

3. Experimentation

Ramp Up and Ramp Down pulse shapes were used to produce thin wall parts. A total of 56 parts were produced, tested and compared to the properties of parts produced using a standard Rectangular pulse shape (non-shaped) developed in other work (Mumtaz and Hopkinson, 2009). It was envisioned that the use of pulse shaping would offer a more precise and tailored control over the heat input and would allow a refining and improvement over the use of standard Rectangular pulses.

3.1. Standard Rectangular pulse (non-pulse shaped)

Fig. 6 shows the standard Rectangular pulse shape used in producing a thin wall part (0.49 mm in width) with low top ($9 \mu m$) and side $R_s$ ($10 \mu m$) developed in other work (Mumtaz and Hopkinson, 2008). This pulse was produced without the use of pulse shaping and was used for comparison with parts produced using pulse shaping techniques. An image of the central portion of the top surface of the thin wall part is also displayed within the figure. The average peak power of this pulse was 1.4 kW, however the maximum peak power as a result of overshoot was 1.8 kW. It was observed that overshoot not only occurred with the pulse's power but also with the pulse's duration. Instead of being set at a minimum 0.5 ms in duration the pulse extends to 0.7 ms, this extension increases the heating time and potentially the volume of liquid produced and width of the part. During processing a plasma plume of approximately 5 mm in height was produced from the processing area.

3.2. Ramp Up and Ramp Down pulse shapes results

A variety of Ramp Up and Ramp Down pulse shapes were generated and used to process four layers of Inconel 625®, each with a layer thickness of 100 μm. The Ramp Up pulses varied from 1.7 ms to 10 ms and contained pulse energies and peak powers ranging from 0.6 J to 2.2 J and 0.7 kW to 1 kW, respectively. Note, it was not possible to produce Ramp Up pulses shorter than 1.7 ms in duration due to the nature of pulsed laser generation creating an initial spike at the beginning of the pulse. This needed to be eliminated in order to allow gradual Ramp Up power delivery. This was only achieved with extension of the pulse duration above 1.7 ms. Ramp Down pulses were easier to generate and varied between 1 ms and 10 ms and contained pulse energies and peak powers ranging from 0.5 J to 2.5 J and 1.3 kW to 2 kW, respectively. The ranges of Ramp Up and Ramp Down parameters are shown in Table 1.

Due to the energy distribution within a Ramped Up pulse shape, melt pool generation is more likely to occur at the end of the pulse when peak power is at its highest. Leading up to the main peak power the gradual increase in laser energy heats up the material and reduces its reflectivity, allowing energy to be more easily absorbed. As a result of this energy distribution the peak power required to melt Inconel 625® was on average 0.8 kW less than that used within the Ramped Down pulse shapes. This ramping up of energy can therefore be viewed as a preheating of material, reduc-

**Table 1**

<table>
<thead>
<tr>
<th>Pulse shape</th>
<th>Pulse width (ms)</th>
<th>Pulse energy (J)</th>
<th>Repetition rate (Hz)</th>
<th>Power (W)</th>
<th>Scan speed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp Up</td>
<td>1.7–10</td>
<td>0.6–2.2</td>
<td>40</td>
<td>24–88</td>
<td>400</td>
</tr>
<tr>
<td>Ramp Down</td>
<td>1–10</td>
<td>0.5–2.5</td>
<td>40</td>
<td>20–100</td>
<td>400</td>
</tr>
</tbody>
</table>
ing the thermal energy required to achieve full melting and also the amount of plasma plume/spatter generated during processing due to a less aggressive heating regime.

Fig. 7 displays top/side $R_a$, width and plasma plume height of thin walled parts created using the variety of Ramp Up and Ramp Down pulses. Trends reveal that top $R_a$ does not vary considerably (9–15 $\mu$m) with the use of Ramp Up pulse shapes ranging from 1.7 ms to 10 ms in duration. Within laser processing of metal powders a lot of energy is required to initiate a melt pool due to high reflectivity. Once the melt pool has been initiated the latent heat of fusion has been overcome, the material’s reflectivity drops and subsequently requires less energy to remain molten. The late melt pool formation followed by rapid solidification does not allow surface profile variations to reduce through relaxation mechanisms (movement of fluid due to gravity). This in combination with the use of low peak powers (less recoil pressure) results in top $R_a$ values that do not considerably vary. Ramp Up part side $R_a$ (14–42 $\mu$m) varied more than top $R_a$ and degraded as pulse duration increased. This may be attributed to more liquid being produced with the use of longer pulse durations causing the melt pool width to expand and cause larger thermal variations across the melt pool, possibly promoting balling perpendicular to the melt pool.

However this increase in side $R_a$ is more likely to be a result of partially melted powder particles outside the melt pool agglomerating and balling up into small spherical entities, attaching to the edges of the main melt pool, otherwise known as satellite formation. A larger melt pool will have a greater thermal mass to transfer into surrounding powder particles resulting in an increase in partially melted powder particles (satellites) that attach to the edge of the melt pool. Due to the use of generally low peak powers with Ramp Up pulses, lower recoil pressures are exerted on the melt pool, possibly allowing this satellite formation to settle and attach to the edge of the melt pool. Larger recoil pressures generated as a result of higher peak powers could have improved the melt pool wetting behaviour to the substrate and potentially reduced side $R_a$ as satellites may have been forcefully detached from the extremities of the melt pool onto the powder bed. The lowest combined top/side $R_a$ ($10\mu$m and $23\mu$m, respectively) was achieved with a 1.7 ms Ramp Up pulse shape using a pulse energy of 0.7 J and a peak power of 0.8 kW (marked with “RU1” in Fig. 7 with actual pulse shape and sample produced shown in Fig. 8(b)). Due to the low peak power with the Ramp Up energy distribution a minimum level of plasma plume/spatter was generated during processing (1 mm in height). As a result of low plasma plume height the negative effects associated with spatter generation during SLM processing would be reduced. This Ramp Up pulse shape is examined further in Section 3.3.

The use of Ramp Down pulse shapes appears to have a positive effect on top/side $R_a$ with the use of shorter pulse durations (1–2 ms). Fig. 7 shows that lowest top $R_a$ of 6 $\mu$m was achieved with a 1.5 ms Ramp Down pulse with 1.1 J of pulse energy (marked with “RD1” in Fig. 7 with the actual pulse shape and sample produced shown in Fig. 8(c)). This pulse is further examined in Section 3.3. Ramp Down energy distributions promote an early melt pool formation due to the use of high peak power early within the pulse. This causes the melt pool to be more prone to expansion as further energy is used to increase the volume of liquid within the melt pool. This promotes further satellite formation as heat is given more time to dissipate from the solidifying melt pool into the powder bed forming partially melted powder particles, causing side $R_a$ to increase. This is reflected in Fig. 7 with Ramp Down side $R_a$ being generally higher than that of Ramp Up pulses at similar pulse durations. As with Ramp Up pulses, increases in Ramp Down pulse duration increases side $R_a$.

During Ramp Down pulse shape generation an unexpected pulse shape was generated. A 1 ms pulse was split into two sectors, the first sector was set to 39 Hgt and the second sector to 0 Hgt. It was expected that the pulse would follow the same energy distribution as that of the optimised 0.5 ms Rectangular pulse (reaching 0.7 ms in duration) as the power would essentially only be present within the first 0.5 ms sector. However the result was unexpected with the pulse’s total duration being Suppressed down to 0.5 ms (marked with “S1” in Fig. 7 with actual pulse shape and sample produced shown in Fig. 8(d)). By inserting a second sector with a demand of 0 Hgt the pulse duration is effectively reduced in order to achieve zero power between 0.5 ms and 1 ms (second sector). The Suppressed pulse shown in Fig. 8(d) had the same peak power as the standard optimised Rectangular pulse (1.8 kW) but with 0.3 J less energy and shorter duration (0.2 ms shorter). This resulted in a sample measuring 0.42 mm in width (Suppressed pulse and sample are shown in Fig. 8(d)). The width of the sample was reduced compared to the Rectangular pulsed sample due to reduced pulse duration and pulse energy as in Fig. 8(a). A shorter laser on-time restricted the melt pool width as heat had less time to conduct radially from the centre of the melt pool inhibited satellite formation at the edges of the melt pool. Lower pulse energy reduces the volume of liquid produced within the melt pool. The high peak power at the beginning of the pulse is sufficient to generate a melt pool that very rapidly solidified. The low pulse energy caused plasma plume to be restricted to 3 mm. The combination of low melt pool width...
and sufficiently high peak power allowed the sample to possess a low top/side $R_a$ of 10 $\mu$m.

3.3. Test part validation

Initial pulse shape experimentation in Section 3.2 had identified three pulse shapes that potentially held advantages over the use of the standard non-shaped Rectangular pulse. These advantages include improvements to part properties such as surface roughness, part width and reduction in plasma plume/spatter generation during processing. In order to validate and test the effectiveness of these pulse shapes, taller thin wall parts were built. These thin wall parts were 25 mm in length and consisted of 80 $\mu$m and 100 $\mu$m powder layers. Three test parts were built for each of the four different pulse shapes. The test parts were measured for top $R_a$ and side $R_a$ in horizontal and vertical directions. The results for the test parts produced using a standard Rectangular pulse and the three effective pulse shapes are shown in Fig. 9.

3.3.1. Results and discussion

Fig. 9 shows the results of surface $R_a$ and width of the thin wall structures made using the different pulse shapes. Fig. 10 shows the side view of some of the thin wall parts produced.

3.3.1.1. Rectangular pulse. The Rectangular pulse as expected produced thin walls ($0.62 \pm 0.04$ mm in width) with a top $R_a$ values ($9 \pm 2$ $\mu$m) lower than that of side $R_a$ ($13 \pm 4$ $\mu$m horizontal and $15 \pm 5$ $\mu$m vertical). It was discovered that the side $R_a$ in the vertical direction was higher than that of the side $R_a$ in the horizontal direction. This could be a result of interlayer connections between melted layers of powder increasing $R_a$ in this direction. Measuring side $R_a$ along the horizontal axis will only take into consideration one layer. Measuring in the vertical axis measures across multiple layers, a melted interlayer connection has the potential to increase side $R_a$. The thickness of the thin walled structure measured $0.62 \pm 0.04$ mm with a standard deviation of 0.03. Using the same laser parameters a thin walled part produced from four layers measured lower at 0.49 mm (Section 3.2). This variation in measured wall thickness could be related to the multiple reheating cycles and heat build-up when producing tall parts. Four 0.1 mm layer will produce a thin wall not more than 0.4 mm in height, there would not be a larger degree of heat buildup as the substrate would very quickly conduct heat away from the thin wall structure (Morgan et al., 2001). The processing of further layers (80 layers in this case) will cause the average width of the wall to increase due to multiple reheating cycles and build up of heat within the bulk of the processed Inconel structure. More heat buildup will cause the melt pool to expand as more heat is available for powder particles to melt. This expansion of the melt pool with taller specimens may also be a reason why the side $R_a$ in the horizontal direction for the test parts are higher than those produced from four 0.1 mm layers. Fig. 10 shows the side view of the thin wall structure produced using a Rectangular pulse. The top and edge profile for the structure is flat and consistent. This indicates that the heat input delivered to the material was sufficient in creating flat consistent melt pool
that did not suffer from part distortion as a result of excessive heat input. The height of plasma plume generated during processing using the Rectangular pulse was approximately 5 mm, the same result measured in early experiments employing the same pulse shape.

3.3.1.2. Ramp Up pulse. Section 3.2 had identified that a Ramp Up pulse had been particularly useful in minimising plasma plume/spatter generation during processing. This pulse used the same pulse energy as that of the Rectangular pulse but instead spread the energy over a period of 1.5 ms (as opposed to 0.7 ms) and operated at a lower peak power of just 0.8 kW (as shown in Fig. 8(b)). Compared to the other three pulse shapes, the Ramp Up pulse was the most successful in its reduction of spatter generation producing only 1 mm of plasma plume. This observation of lower spatter ejection during processing is consistent with other researches that have employed Ramp Up pulse shapes to laser weld metal sheets (Katayama et al., 1993; Fujinaga et al., 2000; Gower et al., 2005; Pan et al., 2005). As expected the side $R_a$ (17 ± 8 μm horizontal and 22 ± 5 μm vertical) of parts processed using this pulse degraded as a result of increasing pulse duration due to satellite formation. Late melt pool generation and rapid melt pool solidification occurred as a result of the Ramp Up energy distribution, this produced a lower volume of liquid present within the melt pool and subsequently a smaller part width (0.6 ± 0.02 mm with a standard deviation of 0.01). Fig. 10 shows the side view of the thin wall structure produced using the Ramp Up pulse. The top edge profile of the structure is not completely flat and consistent. It is possible that the use of low peak powers caused bulges on the top surface to appear. Low peak powers exert lower recoil pressures on a melt pool. The recoil pressure contributes to reshaping of the melt pool from a spherical structure to a flatter wider profile. Generally the shape of the melt pool is dominated by surface tension forces which are affected by melt pool temperature variations. If inconsistencies exist within the melt pool and powder bed, recoil pressures can then assist the melt pool in acquiring a more uniform consistent shape (due to a mechanical force compacting the surface of the melting pool). If lower recoil pressures are present then the inconsistencies that form during melt pool solidification will be more heavily influenced by thermocapillary flows and surface tension caused by thermal temperature variations. The low heat input and low HAZ produced as a result of the Ramp Up energy distribution may alleviate processing issues associated with shrinkage, residual stress build-up and cracking.

3.3.1.3. Ramp Down pulse. The Ramp Down pulse had been identified in Section 3.2 as the pulse that would produce parts with the lowest top $R_a$. This pulse had the same peak power as the Rectangular pulse but contained a higher pulse energy of 1.1 J spread over a longer duration. Fig. 9 shows the result of this pulse, the top $R_a$ and side $R_a$ (horizontal and vertical) were measured to be 8 ± 3 μm, 26 ± 5 μm and 28 ± 7 μm, respectively. The top $R_a$ of the parts was lower than any of the other parts produced with other pulse shapes. The high temperature generated using this pulse increased the melt pools viscosity, this combined with the increased melt pool solidification time assisted the movement and spreading of molten material reducing variations in overlapping melt pools. As expected the side $R_a$ values were the highest out of all the effective pulse shapes. The high temperature generated using this pulse increased the melt pools viscosity, this combined with the increased melt pool solidification time assisted the movement and spreading of molten material reducing variations in overlapping melt pools. As expected the side $R_a$ values were the highest out of all the effective pulse shapes. The high temperature generated using this pulse increased the melt pools viscosity, this combined with the increased melt pool solidification time assisted the movement and spreading of molten material reducing variations in overlapping melt pools. As expected the side $R_a$ values were the highest out of all the effective pulse shapes. The high temperature generated using this pulse increased the melt pools viscosity, this combined with the increased melt pool solidification time assisted the movement and spreading of molten material reducing variations in overlapping melt pools.
pulse energy used during processing. Fig. 10 shows the side view of the thin wall part produced using the Ramp Down pulse. The top edge profile is not flat and dips towards the centre. This is possibly a result of too large a heat input causing large amounts of powder to enter the melt pool. As more powder enters the melt pool there is less material available for the laser to process in the direction of the scan causing a reduction in melt pool widths and height. During the first series of pulses, molten pools are created, which attract powder particles lying next to it under capillary action (Song, 1997). This leaves areas deficient in powder at the position of the second set of pulses and after solidification a depression is formed there. Due to the Ramp Down pulses higher energy and stronger heating effect the plasma plume/spatter generation during processing was higher as a result of 6 mm plasma plumes. The larger spatter generation with the use of Ramp Down pulses has also been observed during the laser welding of metal sheets (Tzeng, 2000; Gower et al., 2005).

3.3.1.4. Suppressed pulse. The Suppressed pulse was able to minimise the laser on-time down to 0.5 ms. The pulse was also designed to contain a high peak power, low energy and short duration. Results indicate that the thin wall structure produced had a low top and side Ra (10 ± 2 µm top, 12 ± 3 µm horizontal and 15 ± 6 µm vertical) that were very similar to those produced with the Rectangular pulse. As expected the melt pool width remained low producing an average wall width of 0.56 ± 0.04 mm with a standard deviation of 0.02. This was 0.06 mm thinner than the thin wall part produced using the Rectangular pulse. In addition the part was processed using a lower pulse energy of 0.42 J, this could assist in reducing part distortion due to a lower heat build-up. Due to the melt pool width remaining relatively small, the melt pool solidified at a faster rate than that of a larger melt pool. This reduced solidification time restricts the time available for melt pool instabilities to develop and satellite formation. The low energy within the pulse reduced the plasma plume height to 3 mm such that spatter generation during processing was minimal. It should be noted that a reduction in plasma plume height may indicate a reduction in the magnitude of recoil pressure exerted on the melt pool. Fig. 10 shows the side view of the thin wall part created using the Suppressed pulse. This structure has sharp edge profiles and a level top surface, similar to that produced using the Rectangular pulse. This indicates that a correct level of material heating occurred such that Inconel successfully melted without causing too much part distortion or slumping of parts due to insufficient powder. However the bottom right corner of the thin wall part did not fully bond/attach to the steel substrate. Warping caused the Inconel 625® wall to curl away from the substrate. The low energy and short pulse duration may not have provided a sufficient enough bond between the Inconel and steel substrate. However this lack of bonding was only observed in one of three thin wall parts with the other two appearing to have fully bonded. This sharp edge profile is possibly due to the thin melt pools produced and relatively quick melting and cooling of the melt pools. Commercial systems such as MTT SLM process emit their laser output in short burst in order to minimise the HAZ and reduce part distortion. However short bursts are not able to fully simulate that of a Suppressed pulse due to the continuous wave output not generating high peak powers as those achieved with a pulsed wave laser.

4. Conclusions

Ramp Up pulse shapes generally operated at lower peak powers as compared to standard and Ramp Down pulses. This is because the energy distribution induces a gradual heating of powder particles. The materials’ reflectivity reduces as its temperature increased, this reduced the peak power required to induce full melting. The gradual heating could be viewed as preheating reducing spatter generation during processing. Ramping up was not effective in reducing top/side Ra due to late melt pool generation and use of low peak powers. However due to low heat input, Ramp Up pulses may be effective in reducing distortion due to shrinkage and thus improve the accuracy of parts and help to alleviate mechanical stresses. Ramp Down pulses shapes were able to minimise top Ra due to early melt pool generation, increased pulse duration, increased energy, reduced melt pool viscosity and more time being available for capillary and thermocapillary flows to rearrange liquid within the melt pool. The external mechanical force applied by recoil pressures was also a factor in flattening and smoothing the top surface profile of the melt. However due to the increased heating the volume of liquid present within the melt pool increased causing the melt pool to expand in width. This gave more time for heat to conduct from the melt pool into the surrounding powder, partially melt powder it and forming a small agglomerated molten spheres that attached to the edge of the melt pool, subsequently increasing side Ra.

A Suppressed pulse shape that consisted of a high peak power, low energy and short time duration proved to be the most effective pulse shape. It enabled an aggressive rapid melting and rapid cooling of material including the generation of high recoil pressures exerting an external force on the melt pool. This improved the wettability of the melt pool onto the substrate within a short space of time and flattened out the top surface profile of the melt pool. The high recoil pressure may assist in detaching any satellite formation from solidifying on the edge of the melt pool, resulting in a lower side surface roughness. As a result of the short laser on-time and low pulse energy the width of the melt pool was reduced due to less energy and less time for heat to diffuse sideways causing a narrowing of the melt region and inhibiting satellite formation. The added degree of control available through pulse shaping improved certain part properties producing superior high resolution parts with combined low top and side surface roughness.

References


