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SLM OF Ti-6Al-4V SINGLE MELT-TRACKS UNDER DIFFERENT LAYER THICKNESS AND SURFACE ROUGHNESS

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ABSTRACT: The smallest feature that can be built using the selective laser melting (SLM) process is limited by the width of a single melt-track which can be minimized by lowering the laser energy input. However, melt-tracks could become unstable under low energy input due to insufficient melt pool penetration into the underlying layer. In this study, Ti-6Al-4V single melt-tracks are deposited using 3 different laser energy inputs (343, 240, 133J/m) on selected build layers starting from the sandblasted substrate on layer 1, to layer 45. The layer thickness and surface roughness ($P_q$) of the underlying layer progressively increase from 12±10μm to 46±24μm and 4.3±0.1μm to 25±6μm respectively across the initial build layers. The width and continuity of the melt-tracks are measured across those layers and it is found that the track width increases with laser energy input but is not sensitive to layer thickness and the surface roughness of the underlying layer. The single melt-tracks processed with a 343J/m energy input remains continuous throughout all 45 build layers due to sufficient melt pool penetration into the underlying layer. The single melt-tracks processed under the 240J/m energy input is continuous from layers 1-7 but breaks up into discontinuous tracks from layer 9 onward when the layer thickness and surface roughness ($P_q$) exceeds 42±17μm and 17±2μm respectively. The single melt-tracks processed under 133J/m energy input is continuous on layer 1, discontinuous from layers 3-5, and undergoes complete “balling” from layer 7 onward where the layer thickness and surface roughness ($P_q$) exceeds 36±17μm and 18±2μm respectively. It is shown that the smallest printable feature, which corresponds to the width of a single melt-track, is mainly affected by the laser energy input while the continuity of such melt-tracks is maintained by limiting the layer thickness and surface roughness to sufficiently small values.

KEYWORDS: SLM, Ti-6Al-4V, melt-tracks, layer thickness, track width, additive manufacturing

INTRODUCTION
The major advantage of SLM as a manufacturing process lies in its ability to produce geometrically complicated parts that are either impossible or too costly for conventional subtractive manufacturing techniques to produce (Sing et al. 2017). Some of these parts may include intricate features such as pin fins in a heat exchanger (Kirsch et al. 2017, Wang et al. 2018, Wong et al. 2009) or the thin struts in lattice structures (Leary et al. 2016, Sing et al. 2018, Yan et al. 2014). The smallest feature that can be built using the SLM process corresponds to the width of the narrowest melt-track and can be minimized by limiting the laser energy input. However, the stability of the melt-tracks is partly dependent on having sufficient melt pool penetration depth into the underlying layer (Yadroitsev et al. 2010). Hence, there is naturally a minimum energy input which must be maintained for each layer thickness to ensure sufficient melt-pool penetration and stability. The minimum feature size is thus equivalent to the narrowest
width of a stable single melt-track produced under a specific layer thickness. While several researchers have investigated single-track formation under different laser parameters (Aboulkhair et al. 2016, Wei et al. 2017, Yadroitsev, 2010), these studies have often been conducted on a relatively smooth substrate under a fixed powder thickness. In a realistic SLM process, roughness on the part surface is often much greater than that of the initial substrate (Calignano 2018) and it is also not necessary to maintain a constant layer thickness throughout the entire build process. For instance, a small layer thickness could be used during the melting of intricate structures while a large layer thickness can be used for the processing of coarser geometries within the same part to increase production speed. In this research, single melt-tracks of Ti-6Al-4V are deposited across 45 build layers to better understand the changes in melt-track continuity and track width under different combinations of layer thickness, surface roughness, and laser energy input. In addition, the minimum feature size and its corresponding processing parameters will be identified.

**EXPERIMENTAL METHODS**

Single melt-tracks of Ti-6Al-4V were deposited on layer 1, 3, 5, 7, 9, 11, 15, 25 and 45 (Figure 1) using the SLM250HL machine which is equipped with a 400W laser that has a spot diameter of \(~81\mu m\). The single melt-tracks were deposited using 3 different laser parameters as shown in Table 1 along with a bi-directional scanning strategy that rotates through 90° between build layers (Figure 1c). To create an increasing layer thickness and surface roughness across build layers, an initial \(~25\mu m\) thick powder layer is spread over the sandblasted Ti-6Al-4V substrate on layer 1 and the build platform is set to lower by 50\(\mu m\) after every layer. As will be shown in the measurement results, this creates an increasing layer thickness and surface roughness (\(P_s\)) for the initial \(~7-9\) build layers before leveling off to relatively steady values thereafter. The spherical metal powder used has a diameter of 20-63\(\mu m\) and an untapped density of 50.5\(\pm\)0.5%. The layer thickness and surface roughness measurements for each build layer were measured over an area of 5.26mm\(^2\) and 4.20mm\(^2\) respectively using the VK-X200 3D laser scanning confocal microscope by Keyence. It should be noted that the layer thickness values reported does not refer to the thickness of unconsolidated powder but rather the average height difference between the solidified layer and the underlying layer (Figure 1b). Track widths were measured using an optical microscope. Width measurements are taken for continuous and discontinuous tracks but not for melt-tracks that undergo sever “balling”. For the discontinuous tracks, width measurements are taken along its continuous segments.

![Figure 1](image_url)

Figure 1. a) Single melt-tracks and raster-tracks deposited on selected build layers b) height profile data used to compute layer thickness and surface roughness c) scanning strategy used
Table 1: Laser parameters

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<th>High energy (HE)</th>
<th>Moderate energy (ME)</th>
<th>Low energy (LE)</th>
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<tr>
<td>Laser Power, P (W)</td>
<td>120</td>
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<tr>
<td>Scanning Speed, V (m/s)</td>
<td>0.35</td>
<td>0.5</td>
<td>0.9</td>
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<tr>
<td>Hatch Spacing, h (μm)</td>
<td>80</td>
<td>80</td>
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<tr>
<td>Energy Density, E=P/V (J/m)</td>
<td>343</td>
<td>240</td>
<td>133</td>
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MORPHOLOGY OF MELT TRACKS
The morphology of the melt tracks is shown in Figure 2. Under the high energy (HE) input, all melt-tracks remain continuous across the 45 build layers (Figure 2a,d,g,j). Under the moderate energy (ME) input the melt-tracks start to break up into shorter segments from layer 9 onwards and remain discontinuous until layer 45 (Figure 2h&k). The melt-tracks processed under the low energy (LE) input appear continuous on layer 1 but immediately becomes discontinuous on layer 3 and 5 (Figure 2c&f). Beyond layer 5 severe “balling” is observed for all LE processed melt-tracks (Figure 2i&l). The reason for the different appearance of melt-tracks on layer 45 is due to the different melt pool penetration depth of the HE, ME and LE laser parameters. As shown in Figure 3a, the HE processed melt-track is well embedded within the underlying layer hence it remains stable and continuous. In comparison, the ME processed melt-track has significantly less penetration into the underlying layer (Figure 3b). Thus it is only marginally stable and is susceptible to breaking up into discontinuous segments when subjected to perturbations from a rough surface. Under the LE input, the melt-track barely penetrates beyond the powder layer and the severe lack of contact between the LE processed melt-track and the underlying layer results in the “balling” of the melt-tracks (Figure 3c).

Figure 2. Morphology of melt-tracks processed using high energy (a, d, g, j), moderate energy (b, c, h, k), and low energy (c, f, i, l) laser input at selected build layers. Orange arrows indicate a discontinuity in melt-tracks.
Figure 3. Cross-sectional views of melt-tracks processed using high energy (a), moderate energy (b), and low energy (c) laser input on layer 45.

LAYER THICKNESS, ROUGHNESS & TRACK WIDTH ACROSS BUILD LAYERS
The reason for the initiation of melt-track discontinuity in the ME and LE processed tracks on layer 9 and 3 respectively is due to the change in layer thickness across the build layers (Figure 4). When the layer thickness exceeds the melt-pool penetration depth of a specific energy input, instabilities such as discontinuity and “balling” begin to set in. The ME and LE processed tracks becomes discontinuous when the layer thickness reaches 42±17µm on layer 9 and 20±12µm on layer 3 respectively. The LE processed tracks turn discontinuous at lower layer thickness due to its shallower penetration depth and consequently earlier loss of contact between the melt pool and the underlying layer. The large deviations reflected in the layer thickness error bars are due to the surface roughness of the solidified layer. The observation of an increasing layer thickness from layer 1 to layer 9 is due to a corresponding increase in powder thickness. Since the untapped powder is ~50% solid, a 100µm thick layer of loose powder would ideally consolidate into a 50µm dense layer upon melting. The initial powder thickness of ~25µm deposited on layer 1 is below this steady state value of ~100µm. As a result, the powder and layer thickness progressively increases from layer 1 to 9 until a steady state value is reached. The surface roughness (Pt) is also observed to follow a similar trend where it increases from the layer 1 to layer 9 before leveling off horizontally thereafter. This suggests that surface roughness scales proportionally with layer thickness and that roughness can be tailored using appropriate layer thickness selection.

Even though layer thickness and surface roughness changed from 12±10µm to 46±24µm and 4.3±0.1µm to 25±6µm respectively across 45 build layers, the width of the HE, ME and LE processed tracks has remained consistent. Width measurements beyond layer 5 for the LE processed tracks are not taken due to severe “baling”. The average width across all build layers for the HE, ME and LE processed tracks are 166±6µm, 141±8µm and 109±10µm respectively. Since the track width is only affected by the laser parameter, while the stability/continuity of the melt-track is controlled by the layer thickness, one simply has to choose the appropriate laser parameter from Figure 4 to match the minimum feature size and use the maximum layer thickness within the region where the melt-tracks remain continuous. For instance, if a wall thickness of ~145µm is desired, a good experimenting parameter is to use ME input along with a layer thickness of 40µm. The narrowest melt-track reported in this study is 99±8µm wide and is obtained using the LE input at a layer thickness of 12±10µm. While it is possible to further decrease the laser energy input to produce narrower melt-tracks, the layer thickness of 12±10µm (powder thickness of ~25µm) cannot be decreased further due to the use of a spherical powder with 20-63µm diameter. Hence, the melt track processed at even lower energy inputs may not have sufficient penetration depth to melt through the ~25µm powder thickness and establish an intimate contact with the underlying layer to create a stable melt-track. As such, the 99±8µm wide melt-track is regarded as the smallest feature that can be deposited in this study with the use of 20-63µm powder size. While the layer
thickness and laser settings reported here may be used for the printing of thin wall and struts, the track width is likely an underestimate of the actual wall thickness. This is because the conduction heat loss in a thin feature is lower than that of the large solid base used in this experimental setup. Hence, more energy will be retained in the melt-pool deposited over a thin feature, leading to larger melt-tracks. Nevertheless, the data presented functions as a starting point for the processing of thin features and the track widths reported reveals the lower limit in feature size for the combination of laser spot diameter and powder size used in this study.

Figure 4. The plot of layer thickness, surface roughness & track width against layer count for high energy processed tracks (a), moderate energy processed tracks (b), and low energy processed tracks (c).
CONCLUSION
Ti-6Al-4V single melt-tracks have been deposited across 45 build layers where layer thickness and surface roughness ($P_q$) increased from $12\pm10\mu m$ to $46\pm24\mu m$ and $4.3\pm0.1\mu m$ to $25\pm6\mu m$ respectively. The findings are as follows:

- Track width decreases with the lowering of laser energy input but is not significantly affected by the range of layer thickness and surface roughness investigated.
- The stability and continuity of melt-tracks are strongly dependent on the layer thickness and surface roughness.
- The selection of powder size and layer thickness becomes critical when the feature size decreases to the width of a single melt-track of ~100$\mu m$ or less.

ACKNOWLEDGMENTS
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