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INVESTIGATION ON THE INTEGRAL EFFECTS OF PROCESS PARAMETERS ON PROPERTIES OF SELECTIVE LASER MELTED STAINLESS STEEL PARTS

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ABSTRACT: In selective laser melting (SLM) process, several factors such as laser power, laser scanning speed and hatch spacing can affect the properties of the printed metal parts. The integral effects of all these parameters can be represented by the energy density which provides critical information to optimize the printing process. In this work, the influences of the process parameters on the density, roughness and hardness of stainless steel 316L parts printed using SLM 500HL were studied. The optimized printing parameters achieved high density, low porosity parts with improved mechanical properties. The use of the high-powered 700W laser from SLM 500HL also revealed an effective reduction in printing time without compensation in its mechanical properties.

KEYWORDS: Selective laser melting; Additive manufacturing; 3D printing; Stainless steel

INTRODUCTION
Additive manufacturing (AM), more popularly known as three-dimensional (3D) printing, has garnered much interest in recent years due to the substantial increase in demand for high performance materials with added functionalities and increased complexities in geometrical designs (Choong, Maleksaeedi, Eng, Wei, & Su, 2017; Gan & Wong, 2017). It is defined as a process of adding materials layer upon layer to build a 3D part from a computer-aided design (CAD) file (Chua, Wong, & Yeong, 2017). A wide range of materials such as metals, polymers and ceramics could be manufactured using various AM technologies. Among the AM processes, fabrication of metals has found numerous applications in many fields ranging from aerospace, automotive, medical, marine and electronics industries (DD Gu, Meiners, Wissenbach, & Poprawe, 2012; Lu & Wong, 2018). The types of AM processes for fabricating metallic parts include powder bed fusion process, metal extrusion, sheet lamination and direct energy deposition (Gokuldoss, Kolla, & Eckert, 2017).

Selective laser melting (SLM) is one of the powder bed fusion processes, which is most widely used in the AM industry. SLM uses a laser beam that melts and fuses the metal powders together. The parts fabricated by SLM tend to show improved mechanical, tribological, and corrosion properties compared to their counterparts (Prashanth et al., 2014). However, several process parameters have to be tuned carefully in order to fabricate high density parts that will lead to...
achieving desirable mechanical properties (Schwab, Prashanth, Löber, Kühn, & Eckert, 2015). Some of the critical process parameters are laser power, laser scanning speed, hatch spacing and hatch pattern, etc., which imparted significant variations on the properties of the printed parts (Suryawanshi et al., 2016).

The integral effect of all these parameters can be represented by the energy density, which provides critical information to optimize the printing process. Cherry et al. reported the occurrence of balling effects of partially melted powder when low energy density is used, leading to high porosity. High density stainless steel SS316L parts with 0.38% porosity using energy density of 104.52J/mm³ were achieved but with a low laser power of less than 200W (Cherry et al., 2015). Similarly, most of the reported SLM processes employed low laser power (Yasa & Kruth, 2011), which induce lower productivity due to slow build rate as compared to processes such as electron beam melting (EBM). High laser power was mainly used for aluminium or copper with high thermal conductivities to build high density parts (Buchbinder, Schleifenbaum, Heidrich, Meiners, & Bültmann, 2011). In this study, SS316L parts were printed via SLM using high power laser of 400W and 700W while optimizing the process parameters by varying laser scanning speed and hatch spacings. This work aims to achieve higher build rate for fabricating SS316L materials with higher power input without compromising the mechanical performance of the printed parts.

EXPERIMENTAL METHODS

The fabrication process is carried out using SLM 500 HL (SLM Solutions, Germany) that allows usage of laser power up to 700W with a laser spot size of 80μm. During the process, a recoater deposits SS316L powder material across the build platform and a laser beam scans in a bidirectional scanning strategy and melts the powder according to the slice cross-section of the 3D CAD file. The build platform is then lowered with a layer thickness of 50μm and a new layer of powder is deposited by the recoater. The process repeats itself until the entire 3D object is fabricated. Cubes of dimensions $10 \times 10 \times 10$ mm³ were printed with varying process parameters. A systematic methodology is presented in Figure 1 to investigate the influences of each varying parameters on the properties of the printed parts and to ultimately achieve the optimized parameters to print high density parts.

![Figure 1. Systematic methodology to achieve optimized process parameters for SS316L.](image)

A preliminary study (Phase I) was performed to investigate the process parameter window that enabled the fabrication of SS316L parts using high power input of 700W. The energy density can be derived from the equation: $Q = P / (v \times h \times t)$, where $Q$ is the energy density, $P$ is the power input, $v$ is the scanning speed, $h$ is the hatch spacing and $t$ is the layer thickness. The energy density was set between 50 and 200 J/mm², while layer thickness and hatch spacing were fixed at 50μm and 100μm respectively. 5 samples were printed for each parameter set and the parameters were given in Table 1.
Table 1. Process parameters for Phase 1 fabrication of SS316L samples.

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<tr>
<th>Laser power $P$: 700W;</th>
<th>Layer thickness $t$: 50μm;</th>
<th>Hatch spacing $h$: 100μm</th>
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<tr>
<td>Energy density $Q$ (J/mm$^3$)</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Scanning speed $v$ (mm/s)</td>
<td>2800</td>
<td>2000</td>
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The printed samples were then tested to determine their density based on the Archimedes method using Archimedes Principle. Each sample’s weight was measured in both air and ethanol. Given the ethanol’s density, the density of the sample can be obtained. The top surface roughness of the samples was measured using a confocal microscope (VK-X160K Keyence 3D Laser Scanning Confocal Microscope, USA) and hardness of each sample was determined using Rockwell B hardness test (Matsuzawa Rockwell Hardness Tester, Japan). Upon obtaining the sample with the highest density, the laser power (Phase 2: $200 \leq P \leq 700$W) and hatch spacing (Phase 3: $40 \leq h \leq 140$μm) were subsequently optimized while repeating the characterization process in Figure 1.

RESULTS AND DISCUSSION

Optimization of energy density for high-powered laser fabrication

SS316L cubes were successfully printed with energy density ranging from 70 to 190J/mm$^3$ using high laser power of 700W. However, samples printed using too low energy density (50J/mm$^3$) or too high energy density (200J/mm$^3$) experienced delamination from the build platform as depicted in Figure 2.

Figure 2. (a) Successful print of SS316L for $70 \leq Q \leq 190$ J/mm$^3$. (b) Delamination of parts printed using low energy density of 50 J/mm$^3$.

Despite using high laser power input, partial melting of powder is still evident due to low energy density. This causes unfavorable wetting characteristics that prevent the printed cubes to attach to the platform and this phenomenon is in congruent to the findings from Cherry et al. On the other hand, delamination also occurred under high energy density with high power input. The localized high energy input induces fast solidification that leads to large thermal gradients in the printed parts. The differences in thermal shrinkage causes a large buildup of thermal stresses which results in premature failure by cracks or delamination (Vrancken, Wauthlé, Kruth, & Van Humbeeck, 2013). Hence, too low or too high energy density should be avoided to achieve successful printing.
Based on the successfully printed samples’ density measurements (Figure 3a), printing SS316L cubes using an energy density of 100 to 110J/mm$^3$ gave the highest density of 7.92g/cm$^3$. In correspondence to the typical density of an annealed SS316L bar of 8g/cm$^3$, the cubes obtained high density of >99%. Similarly, the parts printed with 110J/mm$^3$ energy density also gave the lowest average surface roughness of 16.9μm (Figure 3b). As the energy density input increases, the powder are more evenly melted which reduces the occurrence of holes or balling effect (Dongdong Gu & Shen, 2009). This explains the samples being denser as energy density increases, while the surface of the printed parts become smoother. However, surface roughness increases when energy density is above 110J/mm$^3$ as the high energy input causes vaporization of low temperature melting elements that leads to accumulation of pores which also reduces density. In addition, the result from Rockwell hardness test attained the highest hardness of HRB 90.25 for an energy density input of 110J/mm$^3$. Therefore, this preliminary study has proven the successful fabrication of SS316L parts with high-powered laser given that energy density is optimized at 110J/mm$^3$.

![Figure 3](image)

Figure 3. (a) Density measurements and; (b) top surface roughness of SS316L printed parts with varying energy densities from 70 to 190J/mm$^3$.

**Influences of process parameters on properties of SLM printed parts**

Given that this study focuses on printing with high power input, Phase 2 involves varying the laser power from above 200 to 700W (keeping energy density at 110J/mm$^3$) and the effects of laser power on part densities and surface roughness are reflected in Figure 4. To a low degree of error, a laser power of 300W gives the best density of 7.928g/cm$^3$, followed by 400W with a density of 7.9268 g/cm$^3$. Further increase in laser power above 400W will lead to fall in density as seen in Figure 4a due to keyholing effects (King et al., 2014). When laser power is too high, the intense heat transfer to a small volume of powder is sufficient to vaporize some powder that form a deep hole in the melt pool. Subsequent melting of powder will cover and trap the hole which causes increase in porosity. To compensate for the high-power input, the laser scanning speed has to increase to maintain energy density at 110J/mm$^3$. The heat transfer per unit time becomes too low to ensure complete melting, hence leading to coarse powder formation which gives rougher surface (Figure 4b). The previously used 700W laser power only differs slightly with 0.1% lower in density as compared to that of 300W laser, but it potentially print parts at a faster build rate. Hence, a high laser power of 400W can be considered to achieve fast printing without compensation in build properties.
Upon optimizing the laser power to be 400W, Phase 3 investigates the influences of hatch spacing on the properties of the printed parts as shown in Figure 5. From Figure 5a, it can be observed that a low hatch spacing of 40µm gives a very poor and inconsistent density, while the highest density occurred at 120µm, with a density of 7.9196 g/cm³. Due to thermal conductivity, the melt pool will be larger and deeper than the 80µm laser spot size. When the hatch spacing is set between 80 to 140µm, the melt pool is wider than or as wide as the hatch spacing, which leads to higher density. For small hatch spacing, there will be occurrence of remelting due to double scanning of melt tracks since each scan line is too close to each other. A large amount of remelting will result in forming greater melt pool which is undesirable as there will be insufficient powder for forming subsequent melt pools. As such, small hatch spacing contribute to less dense parts. Moreover, the remelting of powder results in high roughness. Hence, larger hatch spacing of 140µm attains the lowest roughness value. However, a hatch spacing of 100µm would be more favorable since a high hardness value of HRB 91.2 is achieved. The hardness value of printed parts reduces when hatch spacings are too large, powder would end up partially melted, leaving presence of voids that affect the properties of the printed parts.

Subsequently, tensile coupons based on the optimized parameters of energy density (110J/mm³), laser power (400W) and hatch spacing (100µm) were printed to test for their mechanical performance. The tensile test results revealed an ultimate tensile strength of 580MPa which is comparative to other SLM printed SS316L parts which achieved 600MPa under low laser power (Niendorf et al., 2013). On the other hand, printing with high laser power produces printed parts
with improved fracture strain of 27.02% which is 1.25times higher than the fracture strain of 12% by Delgado et al (Delgado, Ciurana, & Rodriguez, 2012).

CONCLUSION
This study investigated on the influences of the using high-powered laser to fabricate dense SS316L parts. The optimized printing parameters achieved high density, low porosity parts with improved mechanical properties. The use of the high-powered laser also revealed an effective reduction in printing time without compensation in its mechanical properties.

REFERENCES


