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<th><strong>Title</strong></th>
<th>Process parameter optimization for additively manufactured stainless steel 316L parts by selective electron beam melting</th>
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ABSTRACT: An experimental study of process parameter optimization for stainless steel 316L
(SS316L) parts additively manufactured by selective electron beam melting (SEBM) was carried
out. The process parameters for different stages, particularly in the in-fill hatch melting stage, were
optimized in this study. Near-fully dense (>99%) SS316L parts have been successfully fabricated
with well-melted surfaces. Microstructural characterization was performed on the as-SEBM-built
SS316L parts with the optimal process parameters. It revealed that near-equiaxed grains were
formed, which is distinctive from the counterparts additively manufactured by other SEBM
processes. The mechanism for the formation of near-equiaxed grains was discussed in detail. This
paper provides an insight into fabricating SS316L parts with high density and desirable
microstructure via SEBM process.

KEYWORDS: additive manufacturing; selective electron beam melting; stainless steel 316L;
process parameter optimization; near-equiaxed grain structure

INTRODUCTION

Selective electron beam melting (SEBM) is a promising powder-bed fusion metal additive
manufacturing (AM) technology for near-net-shape complex parts fabrication (Tan et al., 2015). It
uses a high-energy electron beam emitted from tungsten filament at 60KV to selectively melt the
metallic powder bed in a layer by layer manner directed by computer aided design (CAD) model
(Wang et al., 2016). SEBM processing takes place at a high temperature and in a vacuum
environment, resulting in no residual stress, no contamination and excellent mechanical properties
of built materials (Cheng et al., 2014). These benefits make SEBM favorable for aerospace and
biomedical applications (Kok et al.; Tan et al., 2016).

Stainless steel 316L (SS316L) is a grade of austenitic stainless steel with outstanding corrosion
resistance, good weldability, high strength and ductility, and relatively low cost. It is therefore
widely used in in marine and offshore, automobile, petrochemical plants and nuclear reactors (Zhong
et al., 2017). A lot of studies have been carried out on AM-processed SS316L alloy. Kurzynowski
et al. varied laser power and scanning strategy to evaluate their impact on microstructure and
mechanical properties of Selective Laser Melting (SLM) processed SS316 parts (Kurzynowski et
al., 2018). Sun et al. studied how to significantly improve the build rate while maintaining a high
relative density for SLM-built SS316L parts (Sun et al., 2016). Wang et al. used SLM to fabricate
SS316L parts with an exceptional combination of strength and ductility that surpass their
conventional counterparts (Wang et al., 2018). However, very few studies were conducted on
fabricating SS316L alloy using SEBM. Although Zhong et al. performed mechanical tests and
microstructural characterization on SEBMed SS316L parts at both room and elevated temperatures,
its process parameters were not optimized, as lots of lack-of fusion defects occurred when large layer thickness was used (Zhong et al., 2017).

In this work, SEBM process parameter optimization for a SS316L coarse powder was carried out. Then a microstructural characterization was performed. Finally, the mechanism for the formation of such grain structure was discussed. This work provides an insight into fabrication of full-density SS316L alloy using SEBM.

MATERIALS AND METHODS

Selective electron beam melting process
An EBM A2XX system (Arcam EBM, Sweden) was used to fabricate the SS316L samples. The layer thickness was set at 50 μm to ensure good interlayer fusion of powder bed. The EBM build chamber was vacuumed to a pressure below 10⁻⁴ bar. Then the electron beam heated a stainless steel start plate with a dimension of 150 × 150 × 10 mm³ until it reached a temperature of 850 ºC. During this stage, the powder bed was sintered to lock the start plate. Then the layer wise fusion process started, which comprised of raking, preheating, contouring and melting. The rake blade uniformly distributed the powder on the start plate. Then preheating started, where a highly defocused electron beam rapidly scanned over the entire area of start plate to sinter the powder. The purpose was to increase the thermal and electrically conductivity of powder bed so that the negatively charged powder bed would not explode. In the contouring step, a highly focused electron beam traced the border of the sample, followed by melting. This was an in-fill hatching step which selectively melted the metallic powder bed in an interlay cross snake-shaped scanning pattern with a 90° rotation at alternative layers. This step directly determined the mechanical property of SEBM as-built samples. Afterwards, the build table was lowered by 50 μm, then the abovementioned process was repeated until the entire part was completed, followed by a slow cooling in vacuum environment. The samples for process parameter study were 30 × 15 × 10 mm³ cuboids.

Powder material
A gas-atomized spherical SS316L precursor powder was used in this work, with a size range of 45-105 μm (TLS Technik GmBH, Germany). The chemical composition of the powder is listed in Table 1. Morphology of the powder was examined using a field emission scanning electron microscope (SEM; JEOL JSM-7600F, Japan), as shown in Figure 1. The powder is spherical in shape overall, with small satellites attached to some larger particles, which were formed during the gas atomization process where the small liquid droplets were attached to larger ones.

Table 1. Chemical composition ranges for SS316L

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>≤0.03</td>
<td>≤2.00</td>
<td>≤1.00</td>
<td>≤0.04</td>
<td>≤0.03</td>
<td>16.00</td>
<td>2.00</td>
<td>10.00</td>
<td>≤0.10</td>
<td>Balance</td>
</tr>
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</table>
Density measurement
The density of the samples was measured by densitometer (Mettler Toledo; XS204) using Archimedes Method. Five repetitive measurements were taken for each sample. In practice, this method usually gives a lower density value. Therefore, image analysis was also used as a complimentary method. The samples were hot-mounted in epoxy resin and mechanically polished. Afterwards, the images of the mirror surface were taken under optical microscope (OM; ZEISS Axioskop 2 MAT). Density was obtained by using imaging software to calculate the percentage of porous areas of the images. Ten images were captured for each sample.

Microstructural characterization
The as-polished solid samples were etched by immersion of 20 minutes using Kroll’s reagent (2 ml HF, 6 ml HNO3, 92 ml distilled water). The morphology of precursor powder granules and the microstructure of etched solid samples were then observed under SEM.

RESULTS AND DISCUSSION

Process parameter study
In SEBM melting step, numerous geometry-dependent process parameters are involved. However, in preliminary process parameter optimization, only the key parameters, namely Focus Offset (FO) and Speed Function (SF), are considered. Table 2 lists a matrix of FO from 5 to 10 mA and SF from 70 to 170. FO is an additional current running through the respective coil to alter the focal plane from its zero position (Schwerdtfeger et al., 2012). SF is an index that determines the relationship between transverse beam speed and beam speed (Price et al., 2014). In general, a high SF or a high FO produces low energy density, resulting in a porous surface due to insufficient fusion of powder granules. On the contrary, a low SF or a low FO produces high energy density, which over-melts the sample and induces an uneven surface. Ideally, a well-melted surface should be flat and dense. Therefore, by observing the top surface condition of solid samples, the process window can be narrowed down to a range indicated by S1 to S9.

The relative density from S1 to S9 is illustrated in Figure 2. All the samples can reach a high relative density of >99.3%. The shape of the two curves are consistent with each other. It should be noted that the true density lies between the two curves. Overall, an increasing SF results in lower porosity, whereas FO has negligible effect on density. Although S4, S5, S7 and S8 have a higher relative density, their top surfaces are uneven due to minor over-melting. Therefore, the process parameters of both S6 and S9 are selected as optimized parameters for SEBM-built SS316L alloy.
Table 2. DoE table of process parameter optimization for EBM fabrication of coarse powder SS316L samples; the corresponding results showing over-melted, well-melted and porous top surfaces.

<table>
<thead>
<tr>
<th>SF</th>
<th>70</th>
<th>90</th>
<th>110</th>
<th>130</th>
<th>150</th>
<th>170</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 mA</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>8 mA</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 mA</td>
<td>S4</td>
<td>S5</td>
<td>S6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 mA</td>
<td>S7</td>
<td>S8</td>
<td>S9</td>
<td></td>
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Figure 2. Density graphs acquired from Archimedes method and image analysis method for parts fabricated using SS316L powder

**Microstructure**

Figure 3 reveals the microstructure of SEBM-as-built SS316L sample. No melt pool boundaries are visible, as opposed to their SEBM-ed counterparts. It was because the elevated build temperature in SEBM process dissolved the boundaries. Similar phenomenon was also observed in previous studies, where the laser-based AM processed SS316L samples were post heat-treated (Sistiaga et al., 2016; Yadollahi et al., 2015).

It is also found that the grains are near-equiaxed grains, with a grain size of 25 to 50 μm. This microstructure is distinctive from most metal AM processed SS316L alloy, which typically exhibits columnar grain structure (Zhong et al., 2017). The formation of columnar grains is induced by directional solidification, where the grains grow along the highest thermal gradient which is also the build direction. Nevertheless, near-equiaxed grain structure is rarely seen in SEBM-ed samples. Körner et al. tried to reduce line offset and increase beam speed in order to obtain equiaxed grain structure for Inconel 718 samples using SEBM (Körner et al., 2014). Using the same material, Raplee et al. adopted point melt strategy to promote formation of equiaxed grains, as opposed to the standard continuous line melt strategy in SEBM (Raplee et al., 2017). The underlying mechanism that determines the grain structure is depicted in Figure 4, which is controlled by thermal gradient and liquid-solid interface velocity. Therefore, it is hypothesized that the SEBM process window for SS316L lies within the equiaxed growth zone. However, this hypothesis needs to be further verified by simulation.
Figure 3. Microstructure of SEBM as-built SS316L sample under Backscattered Electrons (BSE) mode

Figure 4. Solidification map for Inconel 718 depicting columnar to equiaxed transition (Dehoff et al., 2015)

CONCLUSIONS

Near-fully dense SS316L samples were successfully built by SEBM under two sets of optimized process parameters. High FO coupled with high SF produced porous parts, whereas high FO coupled with high SF produced over-melted parts. The samples exhibit near-equiaxed grain structure. It is hypothesized that Arcam processing window lies within equiaxed growth region.

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REFERENCES


