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ORIGINAL PAPER

Manufacture by Selective Laser Melting & Physical Behaviour of Commercial 316L Stainless Steel

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ABSTRACT

Selective Laser Melting is one of the technologies used to fabricate 3D sample directly through high energy focused laser. This method has a high potential in fabricating biocompatible material 316L stainless steel for biomedical implant devices. The final properties of the product fabricated by SLM is controlled by initial processing parameters. This paper aims to study the effect of building orientation during the fabrication process of SLM on the dimensional accuracy of the fabricated 316L stainless steel. The dimensional accuracy was measured and analysed for three different as-built sample conditions fabricated through SLM process at three different build orientation which are at 0°, 45° and 90° building orientations. It is found that 0° building orientation exhibits the lowest dimensional accuracy compare to others which are contributed by the deformation that occurs during sample fabrication.

INTRODUCTION

316L stainless steel is widely used for biomedical applications. This is due to the contribution of good combination of high to strength-to-weight ratio, good biocompatibility, good mechanical properties as well as good corrosion resistance. 316L stainless steel has a low carbon with high nickel and chromium content. A low carbon content helps to prevent corrosion (Kurgan *et al.*, 2012). 316L stainless steel is commonly used for application in the implant (Parsapour *et al.*, 2012).

Enhancement of mechanical properties such as hardness and strength have been notified as crucial requirements of biomaterials (Antunes *et al.*, 2010; Bordjih *et al.*, 1996), as these may improve the bearing capability and wear resistance of implants (Calin *et al.*, 2013). It is a vital issue in medical devices industry to understand the relationship between the implant production process and the final implant properties.The conventional processing technology adopted by the medical devices industry including casting, machining, powder metallurgy are high in time, material and energy consumption in their processing steps. In present years, automation and digitizing have earned an attention in fabricating medical products. Direct laser manufacturing methods allow fabrication of an efficient and tailored production of complex 3D biomedical devices without the need of pre- or post processing (Attar *et al.*, 2014; Yan *et al.*, 2014).

Selective Laser Melting (SLM) is one of the additive manufacturing (AM) methods that demonstrate its value as part of the 21st century's manufacturing infrastructure. In SLM, complex three-dimensional metal parts can be made directly according to a CAD data (Yan *et al.*, 2014). It involves a process in which metal components are built up, layer-by-layer, from bottom up, using a powdered raw material that is melted by a high energy focused laser which promotes its consolidation. The process continues until a full part is completed (Gu *et al.*, 2012; Zhang *et al.*, 2013). SLM has a wider range of advantages when compared to the conventional manufacturing methods. In medical area, the given geometric freedom can be utilized to manufacture implants with new functionalities such as hollow structures, graded porosity (Sallica-Leva *et al.*, 2013), adapted rigidity or surface structure. Apart from that advantage, SLM is more precise, uses less material, reduce the weight of the final product, which leads to positive impact on the environment, and cut out expensive steps in traditional engineering processes (Zhang *et al.*, 2013), reduces the number of businesses involved in the supply chain, cut down on waste and transportation costs. Nevertheless, SLM true strength is the ability to allow manufacturing of bespoke part with complex geometries matching the mechanical properties of parts conventionally manufactured in series for example, cast and cut (Attar *et al.*, 2014). In addition, this method is compatible with 316L stainless steel composition and the macrostructure can be graded in controlled ways.Therefore, this technology is suited to be adopted in the biomedical field.

SLM study of 316L stainless steel has recently received great deal of attention and is still developing (AlMangour *et al.*, 2017; Attar *et al.*, 2014; Ma *et al.*, 2017; Montero Sistiaga *et al.*, 2016; Riemer *et al.*, 2014; Shifeng *et al.*, 2014; Wang *et al.*, 2016). The properties of SLM parts do not rely only on microstructure but also on typically porous defects and their morphology, just like conventionally fabricated parts, which are controlled by initial processing parameters (Hanzl *et al.*, 2015). For this reason, most of the recent-day studies have shown interest to understand how processing parameters affect microstructural evolution in SLM.

In this study, the effect of building orientation during SLM fabrication process on the dimensional accuracy of the fabricated 316L stainless steel samples was investigated as the main aims of this work. This paper reported that SLM was able to produce a high dimensional accuracy of SLM samples.

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MATERIALS AND METHOD

Powder Materials and SLM Process

316L stainless steel powder supplied by SLM Solution GmbH, Germany, in this work was nitrogen gas atomized. The powder had spherical shape and its mean powder particle size is 30 µm. Several dog-bone samples with three different building orientations namely 0°, 45° , and 90° building orientations were manufactured using an SLM®125HL machine under a high-purity Ar atmosphere containing no more than 100 ppm oxygen. The samples were fabricated on the SLM platform or substrate as shown in Fig. 1. The machine equipped with a 400 W Yb:YAG fiber laser. The processing parameters are listed in Table 1.

Table 1 Process parameters utilised for 316L SS SLM samples fabrication.

Processing Parameters	Nominal Values (mm)
Laser Power	275 W
Scanning speed	760 mm/min
Layer thickness	50 µm
Platform temperature	180°C
Argon gas consumption in operation	1.2 mL/min

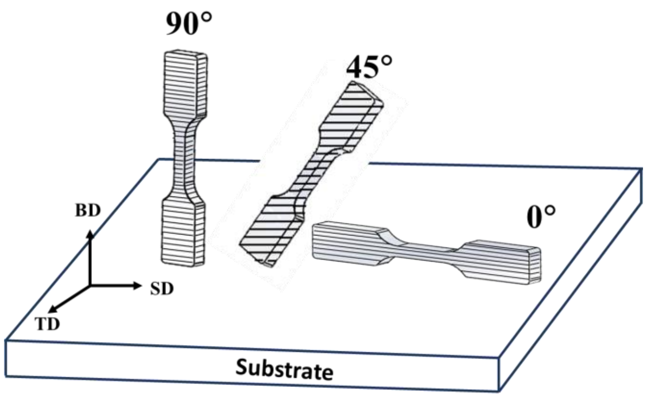

Fig. 1 Schematics drawing exhibits built samples for 0°, 45°, and 90° building orientations during SLM.

Dimensional Accuracy

The accuracy relates how closely a manufacturing machine's output complies with a tolerance within a specified dimensional range. Dimensional accuracy is measured to assess how accurate the geometrical features of as-built SLM fabricated samples are with the CAD data. The calculation was based on Eq. (1).

$$\%\ accuracy = (| N_o + N_a | / N_o) \times 100 \qquad (1)$$

Where N_o is nominal value and N_a is actual value. The nominal values of the CAD samples are as shown in Table 2. Four main points of samples were measured which are the thickness of the sample (thickness), the largest width of the sample (width 1), width at the gauge (width 2), and length of the sample (length). Fig. 1 shows the digital vernier caliper with ± 0.01 sensitivity employed.

Table 2 Nominal values from the tensile 3D CAD data.

Dimension	Nominal Values (mm)
thickness	4.0
width 1	9.5
width 2	3.0
length	63.0

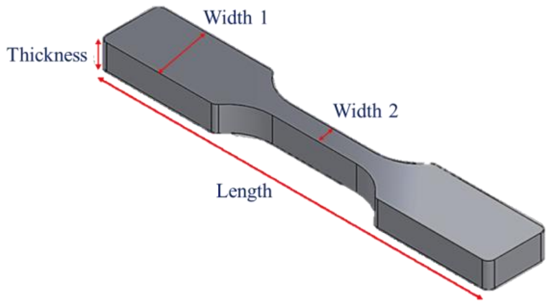

Fig. 2 Schematics drawing showing nominal values of a dog-bone sample.

RESULTS AND DISCUSSION

Dimensional Accuracy

From Fig. 3, it was found that 90° building orientation samples have higher dimensional accuracy compare to 0° and 45° building orientations with 5.75% and 1.70% differences, respectively. Meanwhile, 0° building orientation shows the lowest value of dimensional accuracy with 93.27%. On the other hand, the percentage of dimensional accuracy exhibits by 45° building orientation is slightly lower than the 90° building orientation, which is 97.32%.. It can be deduced from the results that the manufacturing process of SLM at different building directions do give effects on the dimensional accuracy. In spite of this, all sample conditions can be said are above 90% of dimensional accuracy.

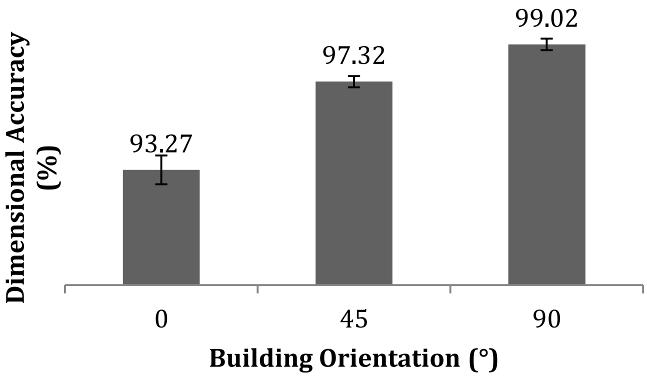

Fig. 3 Dimensional accuracy (%) for different condition of samples.

Deformation

Three different as-built sample conditions were fabricated through SLM process. From Fig. 3, it is known that 0° exhibits the lowest dimensional accuracy compare to others. From the observation, it can be seen that the sample fabricated by using 0° building orientation exhibits a deformation. Fig. 4 shows the as-built samples for 0° building orientation exhibit distortion or buckling deformation with 7.5 mean degrees of deformation. It happened at the bottom part of the sample that faced the surface of the SLM substrate. However, the same pattern cannot be seen for the 45° and 90° building orientations. The deformation occurred during the fabrication processes in the SLM chamber. Fig. 5 illustrates that a sample together with its support attached were both experienced deformation.

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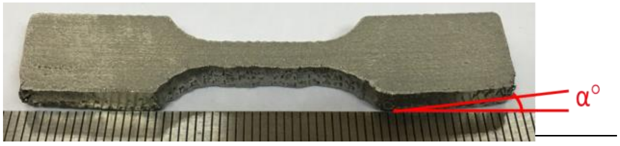

Fig. 4 As-built samples of 0° building orientation shows deformations with angle α° occurred at the bottom surface of the sample..

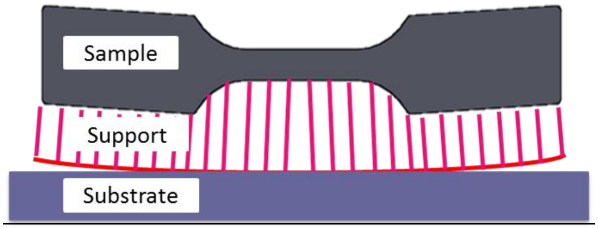

Fig. 5 Dimensional accuracy (%) for different condition of samples.

(Shiomi *et al.*, 2004) reported that the part distortion is caused by tensile residual stresses that occurred due to high temperature gradients developed by rapid heating and cooling during part formation. This rapid heating and cooling rate is common for direct laser process including SLM. On the top surface and at the boundary between the consolidated structure and substrate, the stresses were found to be extremely high (Furumoto *et al.*, 2010). A numerical model proposed or genesis of residual stresses in SLM part were done by (Van Belle *et al.*, 2012). They calculation of residual stresses shown that the residual stresses were also huge at the top as well as at the interface area of the substrate and sample. The 0° building orientation sample shows a bigger area of contact with the substrate as compared to the substrate.

CONCLUSION

SLM samples have been successfully fabricated at different building orientation namely 0°, 45°, and 90° building orientations. It is found that 0° building orientation exhibits the lowest dimensional accuracy compare to others. This is contributed by the deformation that occurs during sample fabrication. It is believed that the deformation that occurred is due to the residual stresses that exit due to the rapid heating-cooling of sample fabrication.

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