

Metallurgical and structural investigation on SS316L specimens manufactured by additive manufacturing using SLM

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Abstract

As one of additive manufacturing (AM) technologies, selective laser melting (SLM) which uses higher energy input enabling fully molten powder bed materials is nowadays increasingly applied to build full dense components without post processing. In the present work, specimens made of stainless steel powder SS 316L were to be processed using SLM 280 HL, characterized and compared to commercial rolled sheet product with similar material and shape. The powders have been melted to form dog-bone specimen with two build up orientation using fixed major process parameters such as laser power, hatching distance and layer thickness as well as scan speed. The characterization starts with the mechanical properties and followed by microstructural analysis. While tensile strength and elongation were the main concern on mechanical properties to be discussed based on rolling and layer direction, the macro and micro analysis will focus on grain structure and fracture surface as well as the process quality. The material characterization was conducted using tensile test, optical microscopy and scanning electron microscopy. It is found out that the built-up direction, inclination angle and process quality play a big role on ductility and distortion using SLM. Although the rolled specimen showed significant difference of material strength compared to AM, the rolling direction however does not give conclusive results which can be referred to. It is expected that this basic characterization study will provide basic information and estimation towards the strength of material and final quality product prior to commencement of real product manufacturing.

Keywords: Additive Manufacturing, Tensile Strength, SLM, SEM, SS 316L

1. Introduction

Additive manufacturing (AM), is a group of processes that join materials to make objective from three-dimensional (3D) model data, usually layer-by-layer, and as opposed to subtractive manufacturing methodologies [1]. There are in fact a number of different subtypes of additive manufacturing including 3D printing, Wire Arc Additive Manufacturing (WAAM) and Selective Laser Melting (SLM).

In this studies, the microstructure and the tensile strength of the produced part from the SLM has been investigated. SLM are classified as powder bed fusion technologies where thermal energy selectively fuse regions of a powder bed [2]. According to [3], molten pools with similar top surface temperatures can have significantly different subsurface shapes, resulting in different cooling rates at different locations across the melt pool which potentially leading to different microstructures. The residual stresses created during the SLM process are the sum of the effects of hardening derived from the rapid changes of temperature gradient during solidification. According to [4], when the heat source is removed, the material cools down and contracts more than the material that is present in the surrounding zone and residual stresses are thus created. On the other hand, SLM do not have the design constraints that conventional manufacturing techniques have, allowing them to build complex geometries without significant increase in building time. In addition, they require no tooling or molds and enable the fabrications of several patients' implants in the same batch, they are able to provide greater freedom

of design to product developers and significantly lower the customization cost [3]. Although the SLM process provides many advantages compared to conventional machining, low surface quality is one of the major draw-backs encountered in the process. At the same time, porosity can be presented in the produced part if no re-melting process is done [5].

By varying processing parameters, point distance and exposure time, few studies have been conducted to identified the effect of a modulated laser system on Stainless Steel 316L (SS 316L) based on the tensile strength of the produced parts, its surface finish, the microstructure, hardness and the porosity [1]. It has been reported and highlighted that even minor changes in any processing parameters can have large effects on the final material properties, both physical and microstructure [6].

Although SLM has been considerably improved during the past few years, structural deformation, balling, and crack, cannot be easily avoided, including laser power, laser beam scanning speed, hatch distance, layer thickness and material-based input parameters [7]. Unfortunately, the interaction between these parameters is not clearly understood, although several studies have focused on the "bailing" effect, the penetration of the laser radiation into the powder bed, the coupling mechanism between the laser beam and the material and the solidification of the powder on the substrate [8].

In this study, SS 316L powder was chosen as a feedstock powder because of its excellent fluidity [5] [7]. Furthermore, another benefits founded in this material which prior to low-cost and easily available, making it a suitable in the medical industry as a biocompatible metal bone implant. According to [9], the good

mechanical properties obtained from SS 316L open the use of the technology if the corrosion properties are kept to those inherent to wrought products (by a solution heat treatment–hyper quench). Together with AM, it is well suited for these applications as implants or prostheses can be individualized with very low customization costs [10].

2. Experimental Process Chain of Forming and Welding

The SS 316L specimens were fabricated by using SLM process. The processing parameters used in this study shown in Table 2.1. The scan speed used was 700mm/s. A commercial SS 316L powder was used. The fabrication takes place inside a closed build chamber with Argon atmosphere in order to maintain an oxygen content of less than 0.1%. The average particle size of SS 316L powder was about 10-45µm and the SLM machine used was SLM 280 HL, which incorporated a 280 x 280 x 350 mm³ chamber and a 400 W maximum laser power. Figure 2.1 shows a schematic diagram for SLM process [11]. The specimen geometry was a dog bone shape with the dimension of 200 x 20 x 2 mm as shown in Figure 2.2. The

specimens were built in two orientations: vertically built and horizontally built.

Table 2.1: SLM process parameters.

No.	Description	Parameter
1	Laser power	245W
2	Hatch spacing	0.12mm
3	Layer thickness	50µm
4	Scan speed	700mm/s
5	Scan strategy	Bi-directional
6	Oxygen content	< 0.1%

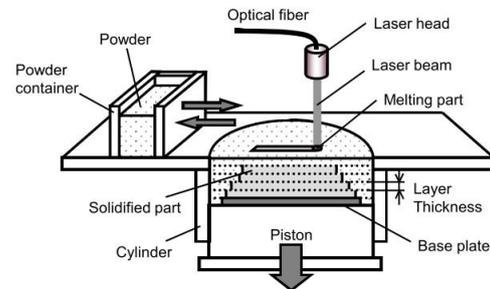


Figure 2.1: Experimental equipment for selective laser melting process.

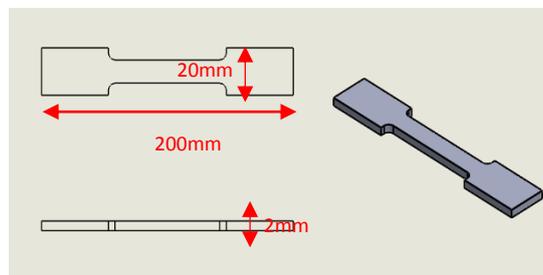


Figure 2.2 : Dog bone sample.

The microstructure of the sample were examined by using scanning electron microscopy (SEM) in order to investigate the cross section in both longitudinal and transverse view. The light microscopy was used in order to investigate the breaking point of the produced sample after tensile test.

The sample with dog bone shape have been tested by using Instron 3380 in order to investigate the mechanical properties which prior to the tensile strength for each samples.

Moreover, in SLM process, the quantity of printed sample can vary according to the dimension of substrate plate. By utilizing the area of the substrate plate, time and money constraints can be reduced. In this study, 11 samples were printed on the substrate plate. The dimension of the substrate plate shown in Figure 2.3.

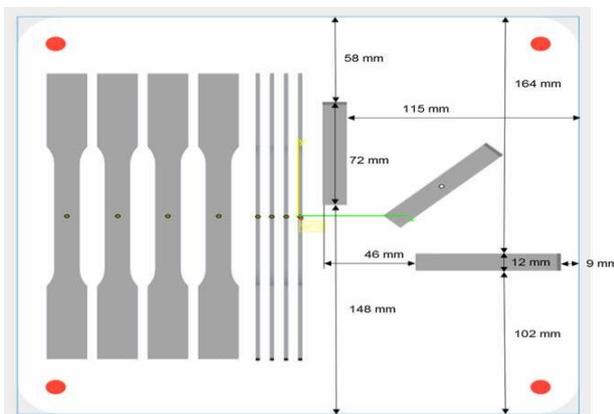


Figure 2.3: Dimension of the substrate plate

3. Investigation Result on Metallurgical and Structural Analysis

Results for the mechanical property and microstructural analysis for the produced specimen from different process and built-up direction have been investigated. New finding on the effect of layer boundaries direction towards tensile loading become more interesting due to the capability on increasing the mechanical properties of specimens.

3.1. Metallurgical Analysis

Based on Figure 3.1, it shows the macrograph images of the specimen from two different build orientation which is horizontal and vertical build. The specimen from SLM process have brittle characteristic due to the presence of porosity inside the specimen. According to previous research, during SLM process, several defect exists in SLM parts such as balling effect which may result to poor surface finish. Thus, residual gas content, unmelted powder and oxidized particles may lead to porosity of the component [12].

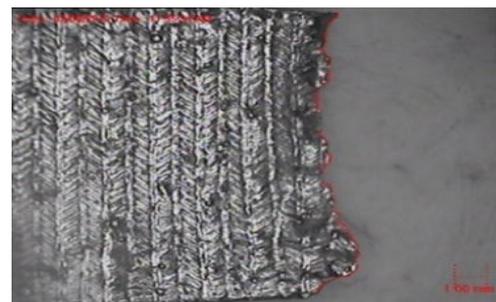
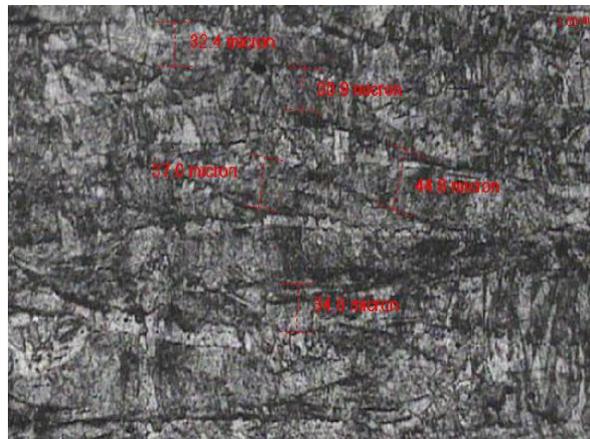
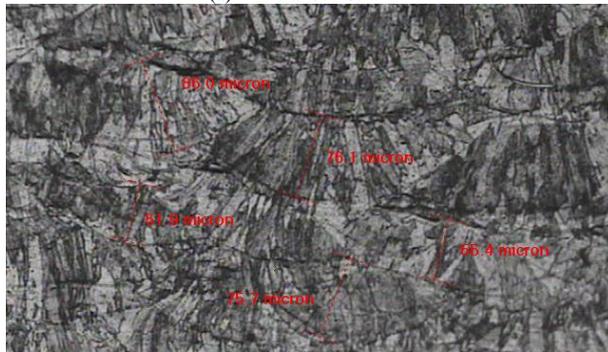


Figure 3.1: Macrograph image of the breaking point on sample SLM process with horizontal build-orientation (top) and vertical build-orientation (below)

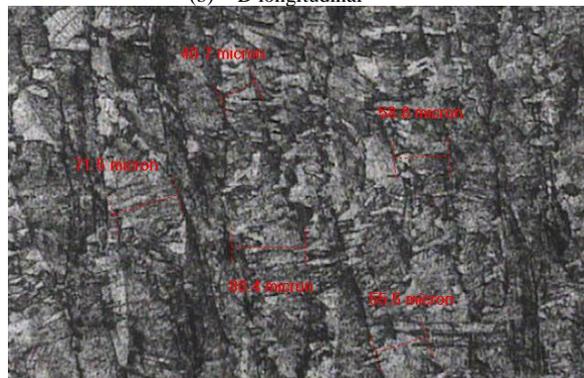
Figure 3.2 shows the micro-structure analysis for the SLM sample with different build-orientation by using macroscopic analysis. In this paper, only at the breaking point is to be considered. Based on Figure 3.2 (a), it clearly shown that the dimension of the melt pool of sample D and T have slightly increased. This is due to the tensional force during tensile test which affect the elongation of the microstructure of the SLM part.



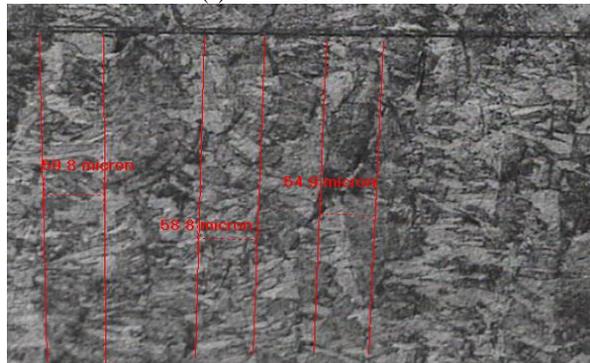
(a) D transverse



(b) D longitudinal



(c) T transverse



(d) T longitudinal

Figure 3.2 Microstructure analysis for the SLM sample with different build-orientation by using macroscopic analysis.

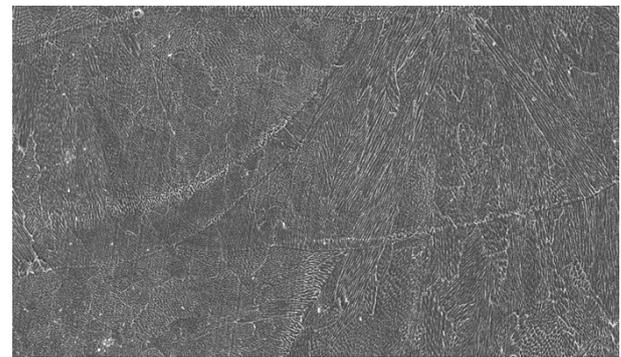
3.2. SEM Analysis

All The microstructure analysis on the SLM part have been investigated by using SEM analysis. A Scanning Electron Microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. By doing SEM, the image of the microstructure from the longitudinal view for each samples can be produced. In this study, 2 samples have been investigated by considering the breaking point of each samples as shown in Table 3.1.

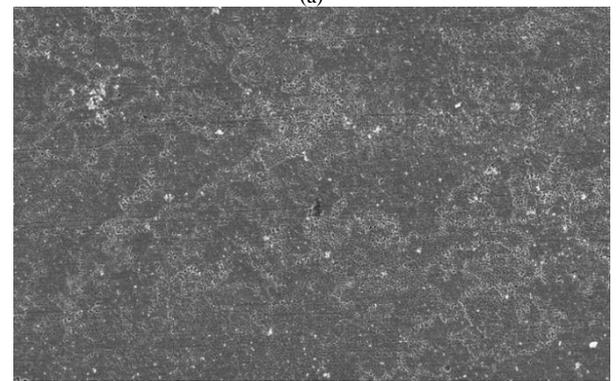
Table 3.1: Tested SLM samples in SEM analysis

Sample	Section
T	Breaking point
D	Breaking point

By using SEM, magnificent of x700 have been used in order to get the image of grain structure for each samples. Microstructure is an important characteristic which can influenced the mechanical properties of the product. Based on the result of SEM images from sample T and D. Clearly, it shown that the microstructure of sample from T and D have a developed dendritic and cellular morphology. According to [13], the mechanical properties cannot be improved significantly compared with their conventionally built counterparts. This microstructure is formed as a result of rapid solidification due to very high cooling rates encountered in SLM.



(a)



(b)

Figure 3.3: SEM images from longitudinal view at the breaking point: (a) Sample D longitudinal from SLM process, (b) Sample T longitudinal from SLM process.

3.3. Structural Analysis

Based on the result obtained. It was clearly shown that rolling process have higher mechanical properties than SLM process. In this paper, only the highest value of ultimate tensile strength (UTS) from different process and different build-up orientation have been considered: T3 (SLM: vertical orientation), (D3: horizontal orientation). Figure 3.4 shows the result from tensile test for each specimen which produced from SLM and rolling process. Each specimen has different tensile result base on their layer boundaries direction after process.

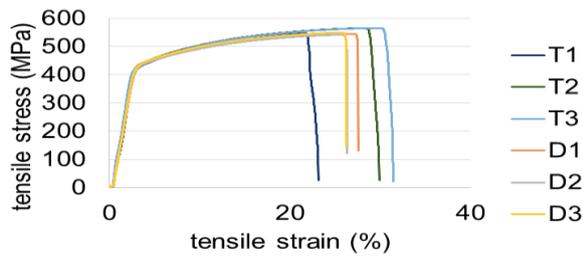


Figure 3.4: Tensile test for each specimens from SLM and rolling process.

Table 3.2 shows the summarized of each specimen stated before which prior to the load, UTS, and tensile strain. Specimen T3 have higher UTS value compared to specimen D3 which resulted 563.93MPa and 549.45MPa respectively. Even though both specimens produced by the same process, different layer boundaries direction affected the mechanical property which resulted different value of UTS. Figure 3.5 shows the printed specimens from SLM process after the specimens have been removed from the substrate plate.

Table 3.2: Summarized table for the SLM samples

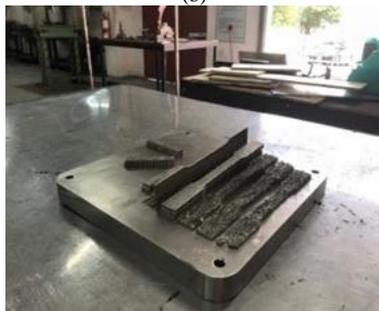
No	Specimen	Load (N)	Ultimate tensile stress (MPa)	Tensile Strain (%)
1	T3	14803.22	563.9321	30.24439
2	D3	14423.09	549.4509	25.71116



(a)



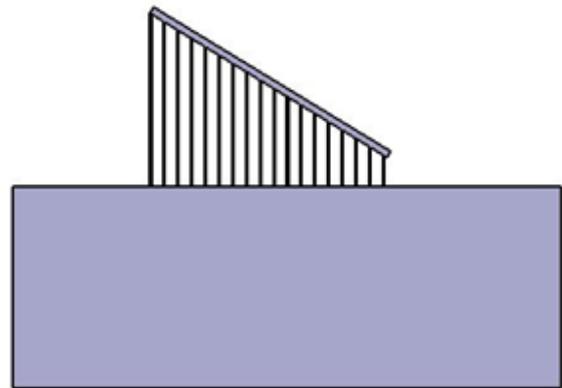
(b)



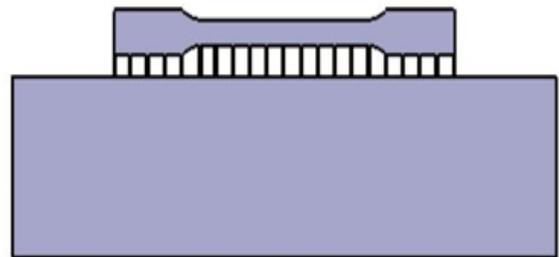
(c)

Figure 3.5: Printed specimens from SLM process: (a) front view, (b) top view, and (c) isometric view

In this paper, the layer boundaries directions that to be considered are: parallel or perpendicular. Figure 3.6 shows the schematic diagram of two samples with different build orientation. However, the anisotropy in tensile properties found in (the SLM parts has also been ascribed to the microstructural anisotropy cause by the local heat transfer condition. Which can be determined by means of the scanning strategy [14]. Different build orientation and inclination angle of the produced sample resulting layer boundaries direction. It was observed, from the result of tensile test, that samples built with horizontal build orientation has greater UTS compare to sample with vertical build orientation which has lower UTS values and higher ductility than those built horizontal.



(a)



(b)

4. Conclusion

This study gives following conclusions:

- 1) A proper laser scanning pattern and post-heat treatment are essential to obtain workpieces with a dense and uniform microstructure and with excellent performance. In this study, only one scan strategy can be used (bi-directional).
- 2) The mechanical properties of the produced sample can be affected by the pattern of layer boundaries. From the result obtained, samples with perpendicular layer boundaries towards direction of the load have lower mechanical properties compared to the parallel layer boundaries.
- 3) Image from SEM analysis shows different grain structure founded based on build orientation. Thus, different grain structure gives different value of UTS.

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