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Research paper

Material Characterization on SS316L Manufactured by Additive Manufacturing: a Comparative Study to Rolling Process

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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; Rolling Process; 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 study, 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]. SLM do not have the design limitations that traditional manufacturing systems have, enabling them to assemble complex geometries without huge increment 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 numerous points of interest contrasted with conventional machining, low surface quality is one of the significant downsides in the process. At the same time, porosity can be presented in the produced part if no re-melting process is done [4].

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] [5]. It has been reported and highlighted that even minor changes in any preparing parameters can give huge effect on the final material properties, both physical and microstructure [6].Although SLM has been impressively enhanced from the previous couple of 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 isn't beyond a reasonable answer, although a few investigations have concentrated on the "bailing" effect, the penetration of the laser into the powder bed, the coupling instrument between the laser and the material and the solidification of the powder on the substrate plate [8].

In this study, SS 316L powder was chosen as a feedstock powder because of its excellent fluidity [4] [7]. Furthermore, another benefits founded in this material which prior to low-cost and easy to find, making it a reasonable in the medical industry as a biocompatible metal bone implant. According to [9], the great mechanical properties got from SS 316L open the utilization of the innovation if the corrosion properties are kept to those inherent to wrought products (by a solution heat treatment–hyper quench). Together with AM, it is appropriate for these applications as inserts or prostheses can be individualized with low customization costs [10].

2. Experimental procedure

The SS 316L specimens were fabricated by using SLM process. The processing parameters used in this study shown in Table 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 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. The specimens were built in two orientations: vertically built and horizontally built.

Table 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-diretional
6	Oxygen content	< 0.1%

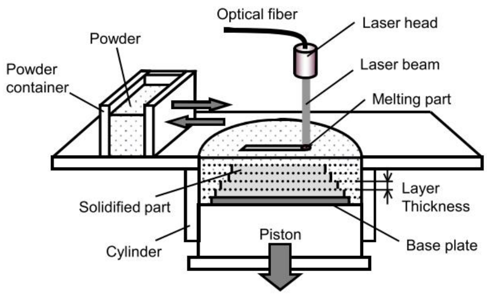


Fig. 1: Experimental equipment for selective laser melting process.

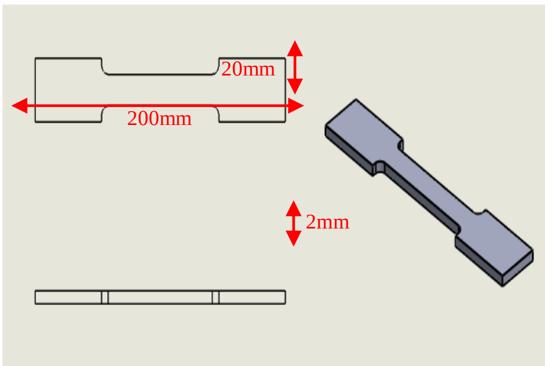


Fig. 2: Dog bone sample.

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 be 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 3.

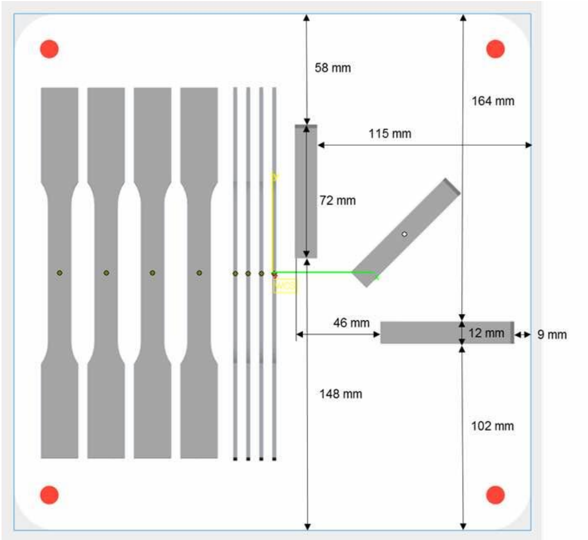


Fig 3: Dimension of the substrate plate.

3. Result and discussion

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 Tensile behaviour

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), (P5: parallel direction) and (S9: perpendicular direction). Figure 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.

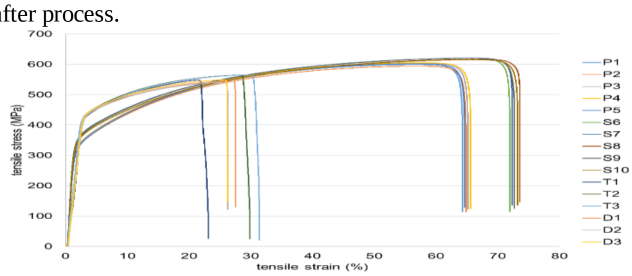


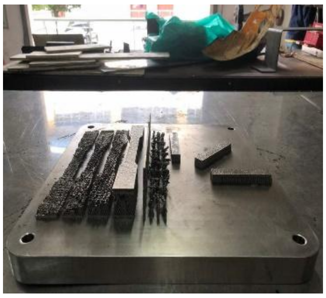
Fig. 4: Tensile test for each specimens from SLM and rolling process

Table 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.

Table 2: Summarized table for the

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
3	P5	15058.64	602.3455	57.72229
4	S9	15499.27	619.9709	63.95554

Meanwhile, for the rolling process specimen S9 shows highest value of UTS than any other specimen which resulted 620MPA while specimen P5 has second highest value of UTS equal to 602.3MPA.


(a)


(b)


(c)

Fig. 5: Printed specimens from SLM process: (a) front view, (b) top view, and (c) isometric view

Figure 5 shows the type of layer boundaries direction of each SLM process. There are three type of layer boundaries direction commonly use in SLM process. In this paper, the layer boundaries directions that to be considered are: vertical, horizontal and horizontal with inclination. Figure 6 shows the schematic diagram of three different layer boundaries direction.

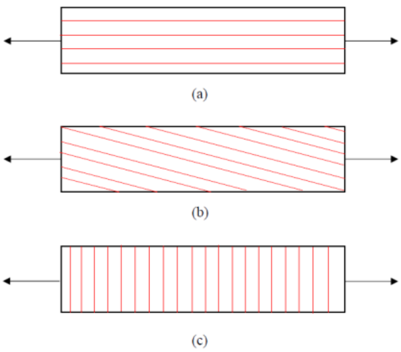
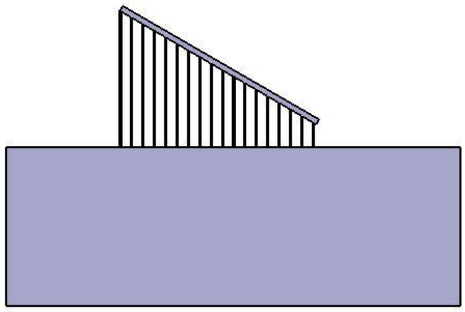


Fig. 6: Layer boundaries for SLM specimen according to build-up direction: (a) vertical, (b) horizontal with inclination angle and (c) horizontal without inclination angle.

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 [12]. The tensile properties of SS 316L stainless steel SLM parts, built with different orientations as shown in Figure 6. It shown a multi-layer melt pool overlapping during the process respectively. (a) Represent horizontal layer boundaries process, (b) Represent vertical layer boundaries process, (c) Represent horizontal orientation without inclination. Different build orientation and inclination angle of the produced sample resulting layer boundaries direction. Figure 7 shown two different building orientation. It was observed, from the result of tensile test, that samples built with horizontal layer boundaries process SLM has greater UTS compare to sample with vertical layer boundaries process SLM has lower UTS values and higher ductility than those built horizontal.


(a)

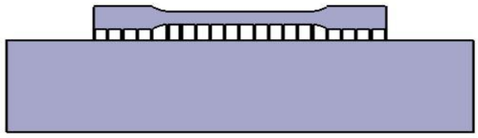
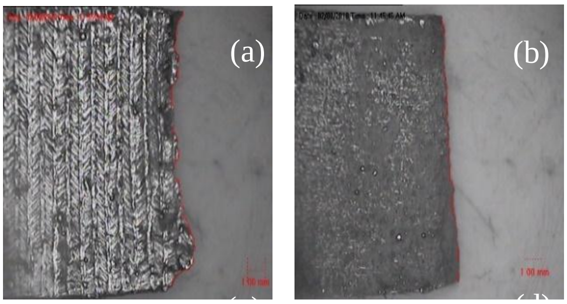

(b)

Fig. 7: (a) Sample D3; horizontal build direction, (b) Sample T3; vertical build direction.

3.2 Macrograph analysis

Based on Figure 8, the macrograph images of the specimen from two different process shows specimen from rolling process have higher mechanical properties than specimen from SLM process. 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 [13]. Due to the higher densification of specimens from rolling process, the crack shape of the breaking point shows that the specimen from rolling process have a good ductile characteristic which can contribute to the resistance of produced specimen from breaking under tension. Based on the result from Table 3.1, it was clearly defined that the tensile strain from rolling process have higher elongation percentage compared to SLM process.



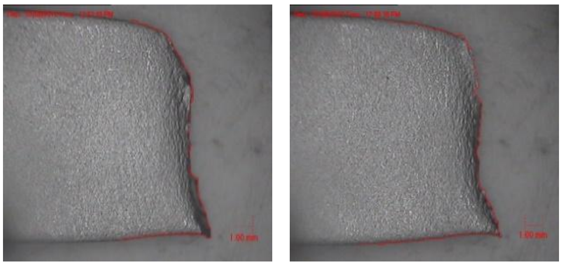


Fig. 8: Macrograph image of the breaking point on sample a) SLM process with horizontal build-orientation b) SLM process with vertical build-orientation c) Rolling process with parallel rolling direction and d) Rolling process with perpendicular rolling direction.

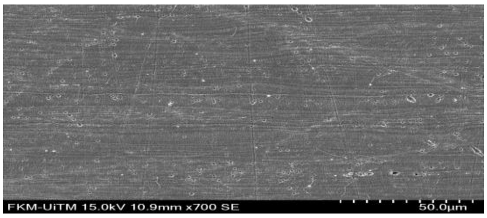
3.3 SEM Analysis

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, 4 samples have been investigated by considering the breaking point of each samples as shown in Table 3.

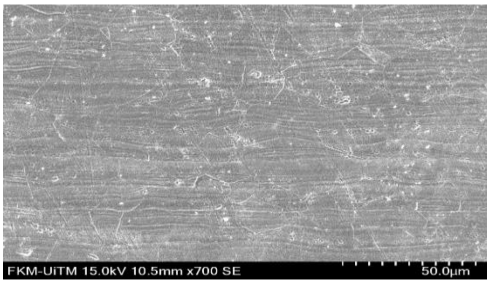
Table 3: Tested SLM samples in SEM analysis.

Sample	View	Section
T3	Longitudinal	Breaking point
D3	Longitudinal	Breaking point
P5	Longitudinal	Breaking point
S5	Longitudinal	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 [14], 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. From Figure 3.5 (a) and (b), samples from rolled process contains more porosity compared to SLM samples. This is due to the oxygen content during the process which resulted trapped air inside the sample during rolled process. Unlikely statement for Figure (c) and (d) SLM specimens, shown less porosity inside SLM samples after the process in order to control the oxygen content during SLM process.



(a)



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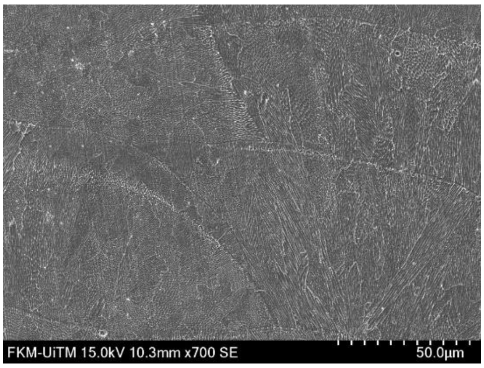

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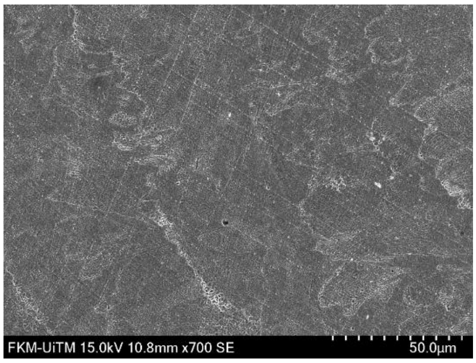

(d)

Fig. 9: SEM images from longitudinal view at the breaking point: (a) Sample P from rolled process, (b) Sample S from rolled process, (c) Sample T from SLM process and (c) Sample D from SLM process.

4. Conclusion

In this study, only one scan strategy can be used (bi-directional). A proper laser scanning pattern and post-heat treatment are essential to obtain workpieces with a dense and uniform microstructure and with excellent performance. 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. Image from SEM analysis shows different grain structure founded which prior to the process. Thus, different grain structure gives different value of UTS.

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