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Additive Manufacturing of 316L Stainless Steel

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Abstract*: Additive manufacturing (AM) is a process of making parts by adding ultrathin layers of materials such as liquid, powder or sheet material layer by layer using 3D printing machine with the aid of a computer-aided design (CAD) software from 3D model data. Intricate, complex parts with graded material can be fabricated with ease. However, additively manufactured parts can vary in physical and mechanical properties with conventionally manufactured parts. In this final year project, AM was done using metal powder of 316L stainless steel alloy owing to good corrosion resistance, ductility and strength. The main objectives for this project are to fabricate 316L stainless steel using AM and to study the physical and mechanical properties of the addictively manufactured specimens compared with electrical discharge machining (EDM) wire cut specimens. A standard specimen bone shaped were manufactured in accordance with ASTM E8 and followed by physical and mechanical testing. From the testing and analysis, 316L stainless steel samples manufactured via AM route have the ultimate tensile strength ranged from 514 to 520 MPa while EDM specimens ranged from 574 to 576 MPa, the yield strength of AM specimens ranged from 385 to 390 MPa while EDM specimens ranged from 350 to 355 MPa, and the average elongation at failure of AM specimens are 45% while EDM specimens are 66%. From this project, it shows that AM specimens have comparable physical and mechanical properties with EDM specimens.

***Keywords* : Additive manufacturing (AM), 316L stainless steel, electrical discharge machining (EDM), mechanical properties.**

I. INTRODUCTION

Additive Manufacturing (AM) is a new manufacturing approach to produced parts and products via 3D printing machine. Powder metals are melted layer by layer successively with the same layer thickness which is set by engineer in the 3D printing machine. Layer thickness for metal ranging from 30 to 50 µm depending on material used. For example, SS316L recommended layer thickness is 50 µm while for Aluminum is 30 µm. The parts will be printed with support structures to keep the parts fixed on a position on the build plate which will be removed after the printing process is done. These parts can be printed in one piece thus saving a lot of time compared to the conventional machining that would take more parts to be assembled together to get the same parts.

Back in 1960s, the first attempt to create solid objects from photopolymers using a laser took place at Battelle Memorial Institute which conducted by intersecting two laser beams of differing wave length in the middle of a vat of resin to solidify the material at the point of intersection [1]. The first commercially available additive manufacturing (AM) system in the world with stereolithography is SLA-1 by 3D Systems in 1987 which uses laser to solidify ultraviolet (UV) light-sensitive liquid polymer. Metal powder additive manufacturing started to commercialize by various manufacturers in 1990s such as EOSINT M250 by EOS in 1994, Laser-Engineered Net Shaping (LENS) metal powder system by Optomec in 1998, Controlled Metal Buildup (CMB) machine by Röders and also ProMetal Rapid Tooling System RTS-300 by ExtrudeHone in 1999 [1]. However, one of the issues in using AM is the differences in properties and microstructures of manufactured parts. The part will be produced with different build orientation, laser scanning speed or degree of build, which technically will affect the properties and microstructures.

Stainless Steel 316L (SS316L) is one of the most popular materials besides Aluminum Alloys, Cobalt Based Alloys and Titanium Alloys that are currently used as raw materials for additive manufacturing. SS316L are mainly used for parts in medical devices, automotive parts, marine heavy industries and also aerospace industries due to its high strength, good ductility, good weldability and high corrosion resistance [2].

Additive manufacturing (AM) or also known as 3D printing is a technology that is used to manufacture parts by adding ultrathin layers of materials such as powder or wire material layer by layer. Besides 3D Printing, additive manufacturing is used to be called as rapid prototyping [3]. Laser is used to melt the upper layer so that each layer bonds to the preceding layer of melted material. AM uses data from computer-aided-design (CAD) software to direct the printer to deposit material such as metal powder, layer by layer, in precise geometric shapes after laser selectively melts the metal powder on each layer. CAD software also helps in translating drawn design into ultrathin slice of layers to be printed. Over the past decade, AM has garnered much attention because of its advantages such as shorter lead times and better design freedom than subtractive manufacturing [4]. Rapid prototyping of porous structures and prototypes were done using AM methods for more than 20 years already [5].

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Nowadays, using certain AM processes with materials such as steel, aluminum or titanium, dense parts can be manufactured reliably [6]. AM industry is expanding extensively, where billions in expansions was recorded for 2014 alone [7].

Production of metal parts transitions from prototyping is the major factor of future growth for AM industry [7]. 3D printing is forecasted by Siemens to be 500% cheaper and more than 400% faster in the next few years with it global market anticipated as high as 7.7 billion by year 2023 [8].

II. METHODOLOGY

A. Fabrication of Specimen

In this study, the materials used were 316L stainless steel powder with nearly spherical shaped particles having an average diameter of 40 µm from SEM observation at magnification of 300X (Fig. 1). The powder was coated with Platinum before SEM process using sputter coating technique by Polaron SC7620 Sputter Coater.

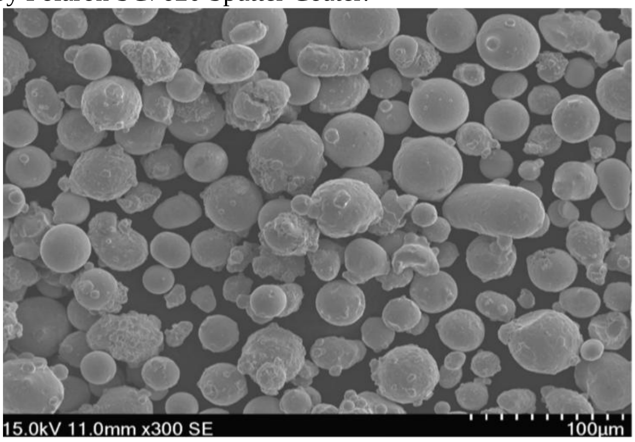

Fig. 1. Microstructure of SS316L powder under SEM.

B. Drawing of Specimen in CAD Software.

The specimen was drawn in CAD software which is Catia V5R20 (Fig. 2) according to ASTM E8M dimensions of rectangular tension test subsize specimen (Table-I and Fig. 2) and saved in .stl file format.

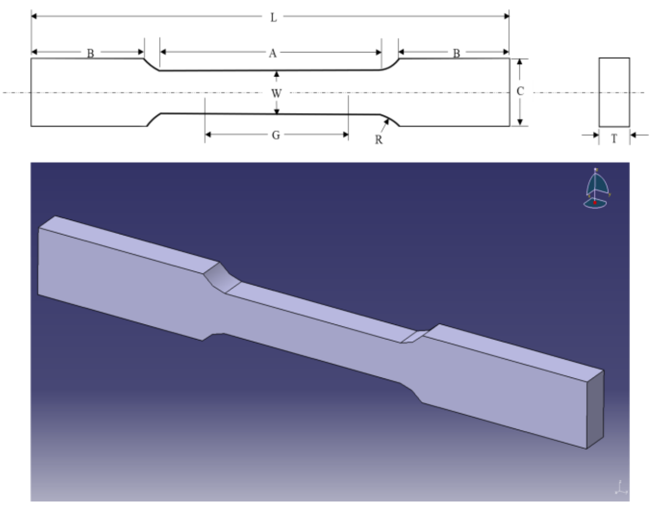

Fig. 2. ASTM E8M tension test subsize specimen drawn in CAD software and according to standard used in [9].

Table-I: Dimension of subsize rectangular tension test specimen based on ASTM E8M.

Location	Dimension, mm
G - Gage Length	25.0 ± 0.1
W - Width	6.0 ± 0.1
T - Thickness	6
R - Radius of Fillet	6
L - Overall Length, min	100
A - Length of reduced section, min	32
B – Length of grip section, min	30
C – Width of grip section, approximate	10

C. Printing of Specimen

The fabrication of the specimen was done using a SLM 280 HL system from SLM Solutions (Lübeck, Germany). The SLM process makes use of a 400W IPG fiber laser. The thickness of the layer is defined by 50 µm and the total layers are 1998 layers including 200 layers of support structures. The specimens were printed 30° slanted to avoid from warping that might occurred if printed horizontal. The printing is done in vacuum chamber with inert Argon gases environment and Oxygen level is maintained below 0.1% to avoid defects such as oxidation that might occurred. Fig. 3 shows the samples after the 3D printing was finished.

After printing process, hand grinding followed by shot peening processes were done on the specimen. Hand grinding process was done to separate the specimens from the build plate and supports structures while shot peening process to increase strength and relieve stress in specimens.

Fig. 3. Samples after 3D printing was done.

D. Hardness Measurement

Hardness measurements of specimens were done using Instron Series 600 Wilson Rockwell utilizing Rockwell A scale which used load of 60 kgf with 120° diamond cone indenter. The depth of penetration recorded by the machine digital reading for all specimens with unit of HRA were tabulated.

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E. Tensile Test

One of the objectives for this project is to determine the properties of SS316L mechanical properties such as 0.2% yield stress and ultimate tensile stress. Tensile test was performed to determine these properties by pulling on specimen until it breaks. How the specimen reacted to the forces applied will be plotted in the stress-strain curve. An uniaxial tensile test was performed using Instron 3382 based on ASTM E8 (Fig. 4). The crosshead speed was set to 10 mm/min per ASTM E8 standard.

F. Microstructure Analysis by Scanning Electron Microscope (SEM) on the Fracture Surface

In order to observe microstructures of the fracture surface for both AM and EDM specimen, SEM was used.

III. RESULTS AND DISCUSSION

A. Hardness Test

Based on the results of Rockwell hardness test using A scale, EDM specimens were recorded to have the highest reading with 65.6 HRA on specimen 2 while the highest reading for AM specimens only 61.1 HRA. The lowest reading recorded is 47.7 HRA for AM specimens while 48.7 HRA for EDM specimens. Total average hardness calculated for both AM and EDM specimens were nearly similar as seen in Table-II and III.

Table-II: Rockwell Hardness result of AM specimens.

Specimen	Rockwell Hardness A Scale Reading (HRA)		
	Minimum	Maximum	Average
1	48.7	55.1	52.33
2	52.9	61.1	56.05
3	47.7	54.6	51.45
4	52.0	55.6	53.55
Total Average			53.34

Table-III: Rockwell Hardness result of EDM specimens.

Specimen	Rockwell Hardness A Scale Reading (HRA)		
	Minimum	Maximum	Average
1	49.5	53.6	52.17
2	50.3	65.6	56.00
3	48.7	54.5	51.93
4	51.6	54.5	53.28
Total Average			53.33

B. Tensile Test

Tensile test was done for both AM and EDM sample by using 4 specimens for each batch respectively. From the data obtained, yield strength (MPa) and ultimate tensile strength (MPa) are obtained. The data from the machine were recorded on intervals of time, so the calculated values were also based on intervals of time. The data were used to plot stress-strain curves which are used to analyze mechanical properties of the tested specimens (Fig. 4 and 5). Stress-strain curves display the amount of stress (σ) exerted to the specimens during testing which is in the y-axis and strain (ε) is the x-axis. The stress-strain curves for AM specimens can be seen in Fig. 4 while Fig. 5 for EDM specimens.

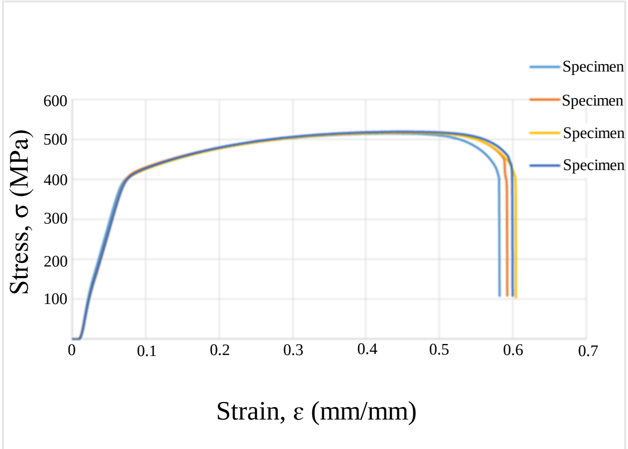

Fig. 4. Stress-strain curves obtained from the uniaxial tensile test for AM specimens.

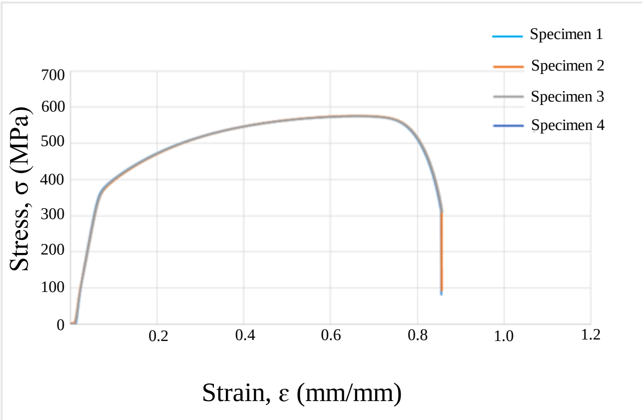

Fig. 5. Stress-strain curves obtained from the uniaxial tensile test for EDM specimens.

The mechanical properties of AM and EDM specimens are determined from the curves are yield strength (MPa), ultimate tensile strength (MPa) and elongation %. The yield strength obtained for AM specimens ranging from 385 to 390 MPa are higher compared to EDM specimens that have yield strength ranging from 350 to 355MPa. Yield strength of AM specimens recorded are lower compared to documented values in the literature [10] and [11] while [12] recorded lower yield strength than AM specimens. Ultimate tensile strength for AM specimens recorded are ranging from 514 to 520 MPa while for EDM specimens the ultimate tensile strength ranging from 574 to 576 MPa. Ultimate tensile strength that are documented in literature [10] – [12] are relatively higher than AM specimens. For the ductility of specimens, it is determined by the percentage of elongation recorded during testing. AM specimens recorded an average elongation of 45% while EDM specimens recorded an average elongation of 66%. When compared to documented values in literature [10] – [12], AM specimens have higher ductility. Differences in recorded data on AM specimens with literature may be due to alteration of laser scanning speed, build orientation and the machine used.

Besides that, different crosshead speed would lead to different reading of elongation %. Our crosshead speed was set to 10 mm/min which same as [13] while other researchers such as [14] which set the crosshead speed to 5mm/min and [12] at the speed of 3 mm/min. Average yield strength, average ultimate tensile strength and average elongation of both specimens are compared with literature in Table-IV below.

Table-IV: Comparison of Mechanical Properties of AM and EDM specimens with literature.

	Average Yield Strength, MPa	Average ultimate Tensile Strength, MPa	Average Elongation at Failure, %
AM	388	517	45
EDM	353	575	66
Rawn [10]	527	629	-
Montero [11]	500	630	-
Marbury [12]	376	637	26
Lackey [13]	472	576	-
Hitzler [14]	590	699	33

From the analysis of fracture surface by SEM, EDM specimens show the presence of cellular dendritic substructure while AM specimen has a quasi-cleavage plane. Cellular dendritic substructure could contribute to the high strength obtained in tensile test for EDM specimens [11]. The lower strength and higher ductility of AM specimens contradicted with results reported in literature [10], [11]. AM specimens have higher yield strength, but lower ultimate tensile strength may due to finer microstructures. Small grains and fine microstructures have grain boundaries that act as barrier to dislocation of motion thus increase the strength of AM specimens [10]. On usual occasions, yield strength and ultimate tensile strength of AM specimens should be high but due to the microstructures of AM specimens are too fine, they may limit the strain hardening process [10]. Dislocations move through the crystal lattice as the metal plastically deforms during strain hardening process while dislocation motion generates new dislocations continuously. The present of grain boundaries are higher in fine grain microstructures compared to coarse microstructures. Grain boundaries increase yield strength by delaying dislocation motion. Dislocation of motion may be hindered by too fine of microstructures to a point that too low new dislocations form before cuts off motion of grain boundary that significantly impaired the strain hardening process [10].

C. Microstructure of Fracture Specimen

Based on the image obtained SEM analysis on the fracture surface, the ductile fracture mode is determined by existence of parabolic dimple-like structures. The density and depth of the dimples are different for AM and EDM specimens from careful inspections on the fracture structures. By comparison of both AM and EDM specimen, EDM specimens have higher density and depth in comparison to AM specimens. This shows that EDM is more ductile, than AM, which explains the longer elongation observed in EDM from the tensile test.
Fig. 6 (a) shows the image fracture surface of the AM specimens under SEM at 100X magnification while Fig. 6 (b) shows the EDM specimen under the same magnification. It can be observed that both specimens display the presence of pores on the fracture surface.

(a)

(b)

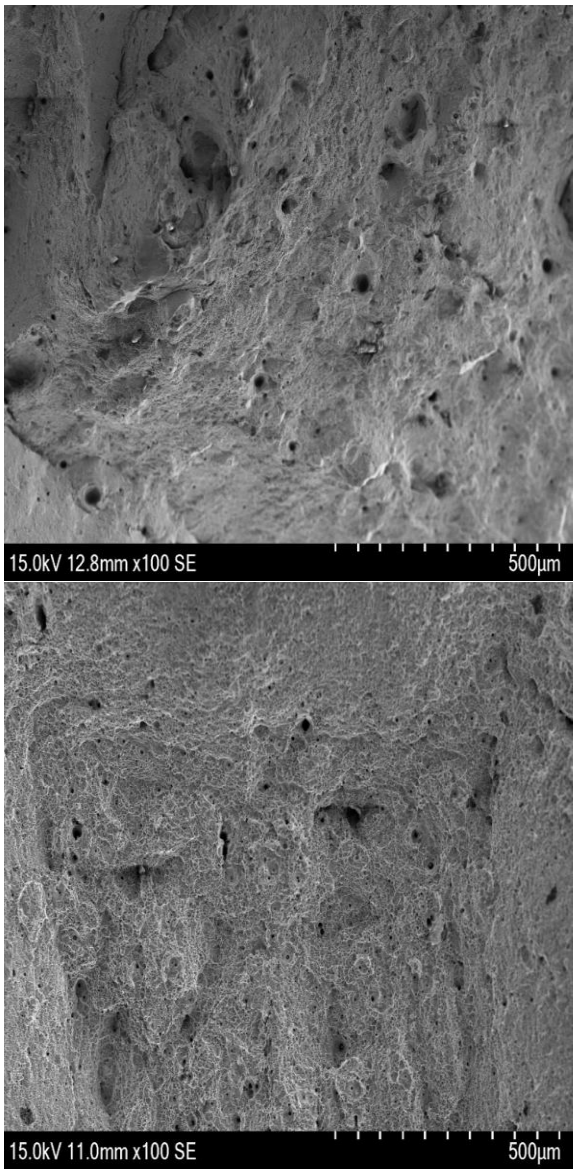

Fig. 6. (a) AM specimens and (b) EDM specimens under 100X magnification.

Fig. 7 (a) and (b) below shows the parabolic dimple-like structures on the image of fracture surface of AM and EDM specimens under SEM at 2000X magnification. Fracture surface of EDM specimen shows the presence of a cellular dendritic substructure.

(a)

(b)

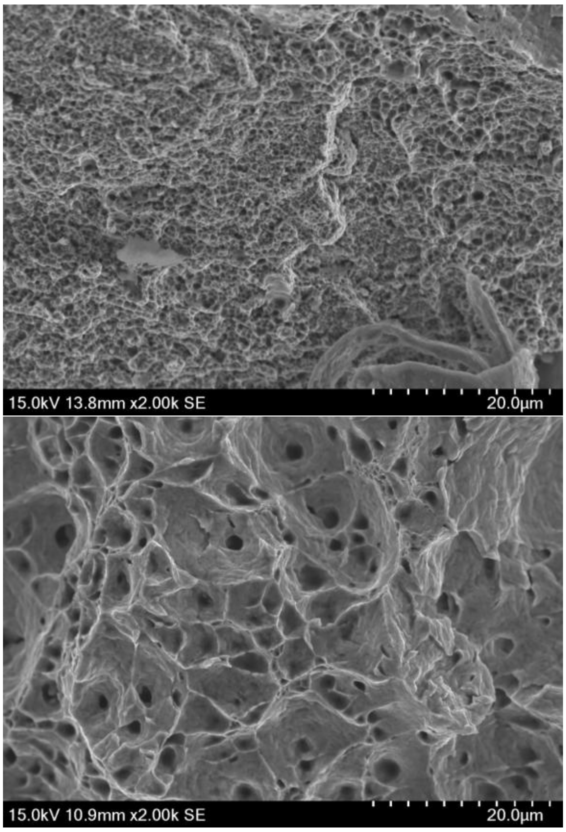

Fig. 7. (a) AM specimen and (b) EDM at 2000X magnification under SEM.

IV. CONCLUSION

SS316L AM specimens were successfully manufactured via AM. Microstructures and properties such as yield strength, ultimate tensile strength, density and hardness of SS316L manufactured via AM are determined by analysis and testing. Thus, the data are compared with SS316L manufactured via EDM.

From the comparison of SS316L AM specimen with SS316L EDM specimen, AM specimen shows comparable properties to EDM specimen. AM specimen achieved 90% ultimate tensile strength of EDM specimen, and it also have approximate 10% better yield strength than EDM specimen. The hardness of both specimens is nearly identical to each other from the results of Rockwell hardness test. AM specimen images from SEM analysis shows that it has some porosity in comparison to EDM specimen. Further microstructure analysis should be developed to study the effect of the porosity to the mechanical properties of both EDM and AM. In a conclusion, it shows that SS316L produced by AM has comparable properties to conventionally manufactured SS316L. Besides that, AM has a lot of advantages over conventional manufacturing that can be explore more in making prototypes or parts to be used in real life applications.

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