Anisotropy Assessment of 3D Printed 316L Alloy Produced by Selective Laser Melting

Abstract:

Additive Manufacturing (AM) technology has recently attracted a great amount of attention due to its potential to produce complex parts with precise geometries. Selective Laser Melting (SLM) is a promising AM method that offers incredible benefits to the medical industry and is widely used for the fabrication of metallic implants with a vast variety of materials selection. One of these materials is 316L stainless steel, which because of its unique properties including particular corrosion resistance, biocompatibility, and affordable price, is highly used in the biomedical industry. Considering the critical role of implants, it is necessary to understand their mechanical behavior in each direction of the 3D printing process. Therefore, investigating the relationship between mechanical and microstructural characteristics of 3D printed biomedical alloys in all directions is of great importance. In this study, we fabricated a 316L sample using SLM and compared its anisotropic behavior with a conventionally produced one. The comparison has been done by the means of evaluating mechanical behavior and microstructural analysis in three dimensions. For this purpose, compression and microhardness tests along with X-ray diffraction analysis (XRD), Optical Microscopy (OM), and Scanning Electron Microscopy (SEM) were carried out. The results reveal the undeniable role of type, size, and distribution of imperfections created during the 3D printing process on the anisotropic performance of fabricated parts.

Keywords: Additive Manufacturing, Selective Laser Melting, 3D Printing, Anisotropy, 316L Alloy

1) Introduction

It is anticipated that additive manufacturing processes will act as the founders of the fourth industrial revolution due to their phenomenal features. Additive manufacturing includes a broad set of processes that share one characteristic; in all these processes the digital information of the three-dimensional design of the desired part is given to the relevant device and the part is made layer by layer to the top. Selective Laser Melting (SLM) is one of the most efficient methods in manufacturing complex parts and various alloys and has been able to attract a lot of attention in recent years. During the SLM process, a product is formed by selectively melting successive layers of powder through the interaction of a laser beam. Rapid solidification of weld pools in this process causes complex heat transfer patterns and temperature gradients, leading to preferential grain growth. Using SLM we can produce parts with more geometry complexities and higher production efficiency in comparison with conventional manufacturing methods. Moreover, we can produce parts with desired mechanical properties and delicate dimensional accuracy. Hence, a very broad perspective can be imagined for this method. As an example; compared to the conventional methods 316L biomedical equipment fabricated by SLM represent outstanding mechanical properties owing to their unique microstructure. However, it should be mentioned that this excellent performance can only be obtained by the optimum process parameters and the least defects. The scanning strategy and the complex heat pattern during the process result in the production of some defects which adversely affect the mechanical properties and thus cause anisotropy. Jeon et al. investigated the effect of imperfections on the anisotropy of tensile behavior and reported that the main reason for anisotropy is the shape of the holes. In an interesting work conducted by Casati et al. it was observed that the defects existing in the layer boundary are the main reason. As reported by Qin and co-workers; adjustment of SLM scanning parameters can result in lower porosities and crack density but given the nature of the SLM procedure, the anisotropy cannot be completely eliminated. Therefore, by considering the anisotropy factor in the fabrication of a particular item we can enhance its performance and this shows the importance of researching anisotropy assessment.

In a work conducted by Mertens et al., different 316L tensile samples with different main orientations were produced with the help of SLM. They observed a strong anisotropy of mechanical properties regarding the microstructures and the processing parameters. Hitzler and co-workers studied the in-plane anisotropy of SLMed 316L samples and they found out that this anisotropy is adjustable and with two parameters of rotation angle and limitation window can be modified. In another work, Yang et al. studied the effect of the anisotropic microstructures on the wear performance of 316L samples. They analyzed the microstructure of the top, side, and front surfaces and reported that the wear behavior is isotropic under high load while under low load wear anisotropy becomes more noticeable, especially on the side surface that has the highest and the lowest wear owing to columnar structure's different slipping resistance along the different sliding directions.

Based on the author's knowledge, most of the articles that have investigated the anisotropy in parts made with SLM have been such that they made samples in different building directions and then reported which sample had better properties. But in these circumstances, using the word anisotropy may not seem very appropriate, because this is more of an investigation to building direction on the properties, and also, in reality, it is not very practical for items that one of their dimensions is much longer than the two other ones. A hip orthopedic implant can be a good example (Fig. 1); if this implant is to be made by SLM, it should be placed horizontally inside the platform for various reasons, including the use of less energy and time and the need for much fewer supports. Therefore, in this situation, it is better to examine the properties of a sample made horizontally in different directions, which is the definition of anisotropy examination. This examination is very efficient in mechanical analysis. For instance, if we need 100 MPa of force tolerance in a specific direction for a specific jaw and face implant, this anisotropy calculation can help us to consider this coefficient in the designing procedure of the implant. Or even if we give this coefficient to mechanical simulation calculations, it will give us much more accurate results.

Figure1- Schematic of a hip orthopedic implant.

The following article is the outcome of the results obtained and the analyzes carried out from the initial part of the project, the main goal of which is to make orthopedic implants using the SLM method. Considering the very high and vital role of the yield strength and hardness of the alloys that implants are made from in determining their biomechanical behavior, and also from the fact that complete and accurate information about the hardness and yield strength of the 316L alloy made by the method SLM is not available in different directions, we decided to specifically investigate the anisotropy pattern in the mechanical properties of 316L alloy made by SLM method and compare the results obtained with a similar sample made by the rolling method. Therefore, in this research, the compressive strength and hardness of alloys produced by both SLM and rolling methods have been evaluated and their relationship with microstructural characteristics has been investigated.

2) Materials and method:

2-1) Materials and manufacturing method

A cylindrical model with diameter and length of 12 mm and 60 mm, respectively, was designed in SOLIDWORKS software; the model then was printed using Noura M100 P SLM machine with a maximum power of 300 W. Spherical 316L powder with a diameter less than 65 µm was used in this process. Table 1 shows the chemical composition of the utilized powder. The printing process was accomplished within 90 minutes using optimized parameters, resulting in a part composed of 501 layers with a thickness of 30 µm. Fig. 2 schematically shows the sample's building direction and scanning pattern during printing. As it is clear, the sample is located in the XY plane and the Z axis shows the building direction. In order to reduce the number of porosities in the printing procedure, the scanning angle was 67 degrees as shown in Fig. 2. Moreover Argon was used as a shielding gas to prevent the sample from oxidizing. After the process, the samples were separated from the supports and the platform using a wire cut and then the unmelted powders attached to their surface were removed using sandblasting. For comparison with the printed sample, the rolled rod of the same alloy with the same dimensions was prepared according to ASTM A276.

Table 1. Chemical composition of primary powder of 316L alloy used in the SLM process

Element	C	Mn	Si	P	S	Cr	Ni	Mo	Fe
Min, wt.%	-	-	-	-	-				Bal.
Max, wt.%	٠,٠٣	٢	١,٠٠	٠,٠٤٥	٠,٠٣٠	١٨	١٤	٣,٠٠	

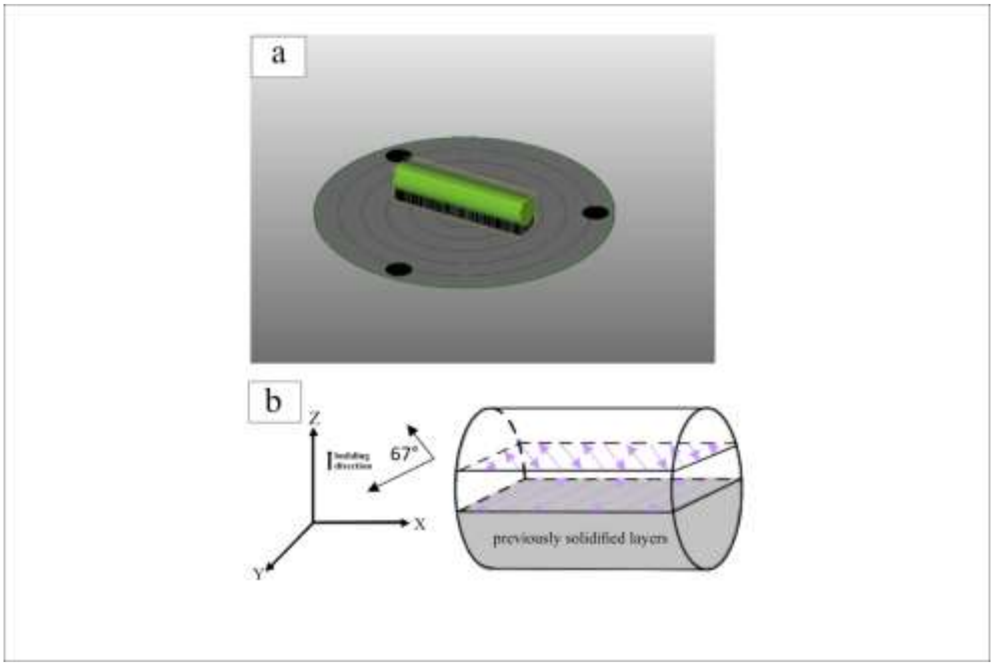

Figure 2- a. sample and struts and b. Schematic showing the building direction and scanning angle in SLM method

2-2) Microstructural characterizations

The density of both printed and rolled specimens at room temperature was determined by the Archimedes method and then the porosity percentage of each sample was calculated using the following equation.

$$V\% = \left(1 - \frac{\rho_A}{\rho_B}\right) * 100$$

Where ρ_A is the calculated density using Archimedes method and ρ_B is the theoretical density of 316L alloy (7.99 g/cm^3).

To investigate the microstructure, the cross-section of the samples was cut in three different coordinate directions using a wire cut. The specimens were grounded using SiC papers (up to #3000) and then polished using a diamond paste. The electro etching was done on rolled samples using 60 % nitric acid solution using 1 v for 60 s. On the other hand, SLMed samples were electrolytically etched with 10 % oxalic acid using 20 v for 8 s. Optical Microscopes and a Scanning Electron Microscope of S360 Cambridge were used to take microscopic images. To study the existing phases, the X-Ray Diffraction test was conducted using Bruker model D8 Advance with a Voltage of 40 Kv and current density of 40 mA.

2-3) Mechanical examinations

Cylindrical pressure test' samples with a length of 4.5 mm and a diameter of 3 mm were prepared by wire cut from both rolled and printed samples in three different directions. The test was conducted at room temperature using a 25-ton Instron machine with a strain rate of 10^{-3} s^{-1} and continued up to 50 % strain. The force-displacement curves for each sample were recorded during the test, and then engineering stress-strain diagrams were drawn. Using the 0.2 % offset method the amount of yield stress has been achieved; moreover, the stiffness and Young's modulus were calculated for every three directions. The hardness of the samples was measured in all three directions through the Vickers microhardness method at room temperature. The test was done using an indenter with a diameter of 1 mm, a dwell time of 15 s, and an applied force of 100 g.

3) Results and Discussions

Unfinished!