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**The Influence of Build Parameters on the Compressive Properties of Selective Laser
Melted 304L Stainless Steel**

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Abstract

Process parameters used during Selective Laser Melting (SLM) process have significant effects on the mechanical properties of the manufactured parts. In this study, the influence of two build parameters (build orientation and hatch angle) on the compressive properties of 304L stainless steel was evaluated. SLM 304L samples were manufactured using three hatch angles, 0°, 67°, 105° and two orientations, z-direction and x-direction, and tested using a compression frame according to ASTM E9-09. Bulk density was measured according to ASTM C373-17 before compression. Properties evaluated were the bulk density, yield strength, strength at 15% plastic-strain and strength at 30% plastic-strain. Results showed that bulk density varied minutely with respect to variation in hatch angle and build orientation, but compressive yield strength and plastic flow stress were strongly influenced by these two process parameters. Highest compressive yield strength was measured when samples were built in the x-direction using hatch angle 67°.

Keywords: Additive manufacturing; SLM; stainless steel; hatch angle; build orientation

Introduction

Selective Laser Melting (SLM) is a type of additive manufacturing method that has gained greater interests over the last years due to its cost, flexibility and build capacity (i.e. ability to manufacture parts with extremely complex geometries). However, across board implementation of this manufacturing technique is lacking due to the inability to accurately predict the mechanical properties of the produced part. Process parameters such as; material parameters, build parameters etc., are known to greatly influence the mechanical properties of SLM parts. Understanding the interactions between these parameters as well as their effects on microstructure and mechanical properties is very important to researchers. Several investigations have been carried out with the aim of understanding the influence of some of these parameters on mechanical response[1]–[3].

Guan *et al* [1] studied the effects of the build parameters, hatch angle, build direction, slice thickness and overlap rate, on the tensile properties of SLM stainless steel. They observed that

tensile properties of SLM parts are dependent on the interval number ‘N’ and the build orientation, and samples built vertically with a higher number of deposited layers exhibited the best tensile properties. Popovich *et al* [2] investigated the causes of anisotropy in the SLM process. It was concluded that process parameters played an important role in anisotropy because they controlled arrangement of planes of pores, residual stresses and grain growth (elongation and direction) in parts produced. Tolosa *et al* [3] investigated the effects of build orientation on the tensile properties of SLM 316L stainless steel. It was concluded that regardless of the build orientation the tensile properties of the SLM stainless steel was always exceeded that of 316L stainless steel.

304L stainless steel is a type of austenitic stainless steels which exhibits good corrosion resistance as well as excellent mechanical properties. Mechanical properties of 304L stainless steel are dependent on the processing conditions as well as the loading type [5]. SLM a layer-by-layer selective melting process has a series of process parameters which may affect the final 304L stainless steel mechanical properties. A lot of work has been published with major focus on understanding the effects of these process parameters on tensile properties of 304L stainless steel [5]–[7] but little work has been done with respect to compressive properties hence the purpose of this study. In this study 304L stainless steel was quasi-statically compressed to study the effects of hatch angle, 0°, 67° and 105°, and build orientation, horizontal and vertical, on the compressive response.

Material and Experimental Procedure

Material and manufacturing process

Selective laser melted 304L stainless steel was analyzed quasi-statically in compression. Renishaw AM 250 machine at Missouri S&T was used to fabricate octagonal parts using 304L stainless steel powder. The steel powder particles used ranged from 15µm - 63 µm in size and the chemical composition is shown in Table 1. The processes for fabrication using this AM machine include: (1) deposition of thin layer of powder by the recoater; (2) melting and bonding of powder layer by laser beam; (3) lowering of build platform, deposition of another layer of powder and re-introduction of laser beam. Octagons were produced by the repetition of the above-mentioned process in an Argon filled environment.

Table 1:-304L Stainless steel powder chemical composition

| Element | Cr | Ni | Mn | Si | Cu | N | O | C | P | S | Fe |
|---------|------|-----|-----|------|-----|------|------|-------|-------|-------|---------|
| Wt% | 18.5 | 9.9 | 1.4 | 0.63 | 0.1 | 0.09 | 0.02 | 0.015 | 0.012 | 0.004 | Balance |

Three hatch angles 0°, 67° and 105° (labeled as A, B, and C respectively) and two build orientations (x-orientation and z-orientation) were studied. Figure 1 shows the two orientations of specimens that were manufactured. The effects of these variations were evaluated based on changes in bulk density, yield strength, strength at 15% strain and strength at 30% strain.

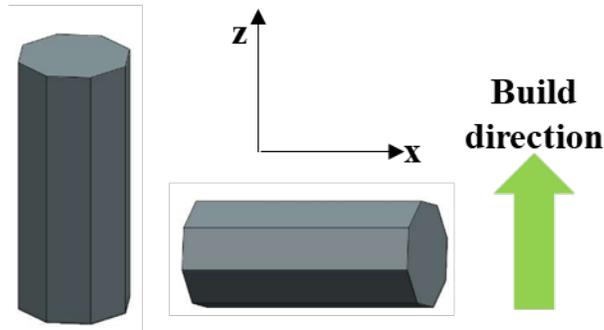


Figure 1:- Build directions used to manufacture coupons

Bulk density

Mechanical properties of materials are negatively influenced by the presence of pores. In the SLM process presence of unmelted powder, lack of fusion as well as gas entrapments are some of the major causes of porosity [8]. Density was determined using Archimedes' Method. The compactness (density) percentage increases as the percentage of pores reduce. The bulk density can be calculated using equation 1.

$$\rho^* = \frac{D}{D - S} \quad (1)$$

where ρ^* is the measured bulk density, D is the dry weight of the specimen, S is the saturated weight

Quasi-Static Compression Test

Test coupons with aspect ratio 3:1 (elastic region) and 1:1 (plastic region) were later machined from the manufactured octagons using a CNC lathe.

Cylindrical coupons were prepared for compression testing using CNC lathe according to the ASTM E9-09 standard. Coupon dimensions used during this study had an average length of 26.29mm and a diameter of 8.47mm (aspect ratio of length to diameter ~ 3:1) for the large samples, while the smaller samples averaged a length of 8.79mm and diameter of 8.44mm (aspect ratio ~ 1:1). Compression tests were performed in a 370 MTS frame according to the ASTM E9-09 standard. Crosshead speed of the frame was fixed to obtain an initial strain rate of $5 \times 10^{-4} s^{-1}$ in the sample. Force and displacement were tracked during tests and used to calculate and plot the stress-strain curve. The yield strength, strength at 15% plastic-strain and strength at 30% plastic-strain were extrapolated from the resulting stress-strain curves.

Results and Discussion

Bulk density

The bulk densities of the investigated build variations are presented in table 2; where A1 and A2 are specimens built with hatch angle 0° in the z-direction and x-direction respectively, B1 and B2

are specimens built with hatch angle 67° in the z-direction and x-direction respectively and C1 and C2 are specimens built with hatch angle 105° in the z-direction and x-direction respectively. It can be seen that percentage porosity is maximum when the specimen is built in the z-direction and hatch angle 0°. However, it is important to note irrespective of the selected hatch angle and build orientation, the manufactured specimens were always between 98.62% and 98.81% dense which is typical for SLM parts. There were no outliers in the data indicating that altering hatch angle and build orientation caused no major increase in the porosity of the samples.

Table 2:- Variation in bulk density between different build orientations and hatch angles

| <i>Sample</i> | <i>Hatch angle</i> | <i>Build orientation</i> | <i>Density (g/cc)</i> |
|---------------|--------------------|--------------------------|-----------------------|
| A1 | 0° | z-direction | 7.890±0.003 |
| B1 | 67° | z-direction | 7.905±0.007 |
| C1 | 105° | z-direction | 7.903±0.008 |
| A2 | 0° | x-direction | 7.904±0.006 |
| B2 | 67° | x-direction | 7.891±0.006 |
| C2 | 105° | x-direction | 7.903±0.003 |

Build orientation

The build orientation selected during the manufacturing of SLM parts plays an important role in the physical and mechanical characteristics of the final product. By selecting the right orientation the required support volume, build time and cost is reduced while the part quality and mechanical properties increases. During this study, two build orientations were considered (Figure 1) for different hatch angles and their effectiveness evaluated based on the yield strength. Results show that the samples built in the x-direction (horizontally) had higher yield strengths when compared to the z-direction (vertical). We assume that the difference in compressive strengths (although little) occurs either as a result the direction of the load with respect to the columnar grains or plane of pores in the layers. However, microstructural analysis was not carried out on these samples therefore it is not certain. Figure 2a shows an example of a stress-strain curve for sample B1 which was measured using long coupons. Buckling was noticed which was the cause of the dropping stress not the ultimate stress of the material. Figure 2b shows the average yield strengths for the different build orientations and hatch angles, using the same nomenclature described for Table 2. Long coupons were used (3:1 aspect ratio) for this analysis because they defined better the elastic region of the material.

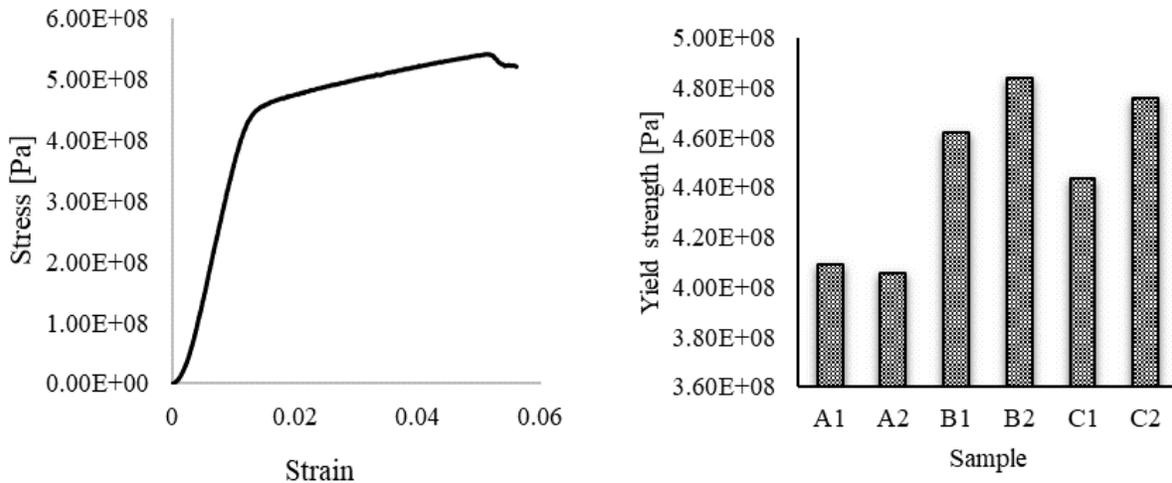


Figure 2:- Compression results from the long coupons (3:1): (a) Example of stress-strain curve for sample B1, and (b) summary of compressive yield strength of SLM 304L stainless steel

Hatch angle

Hatch angle θ° can be defined as the angle between the scanning directions of two immediate scan layers. The interval number ‘N’ is dependent on the hatch angle and can be calculated using equation 2, where HCF is the highest common factor between θ and 360 and θ is the hatch angle.

$$N = \frac{360^\circ}{\text{HCF}(\theta^\circ, 360^\circ)} \quad (2)$$

Guan *et al* [1] observed that by increasing the value of ‘N’ the tensile properties of 304 stainless steel increased. In this study samples were manufactured with hatch angles 0° , 67° and 105° thus resulting in various values of ‘N’. Table 3 shows the number of layers after which the melting line will coincide with the direction of the first layer when hatch angles 0° , 67° and 105° are selected.

Table 3:- Relationship between hatch (θ°) angle and interval number (N)

| Hatch angle (θ°) | 0° | 67° | 105° |
|--------------------------------|-----------|------------|-------------|
| Interval number (N) | 1 | 360 | 24 |

The relationship between ‘N’ and plastic flow stress are shown in figure 3. True stress at 15% and 30% plastic strains were compared using short samples built in the z-direction. It was deduced from figure 2 that since samples built in the z-direction exhibited lower yield strengths (when compared to x-direction) they would deform more plastically before reaching the machine limit (100 kN). Therefore, samples built in the z-direction were selected for further investigation.

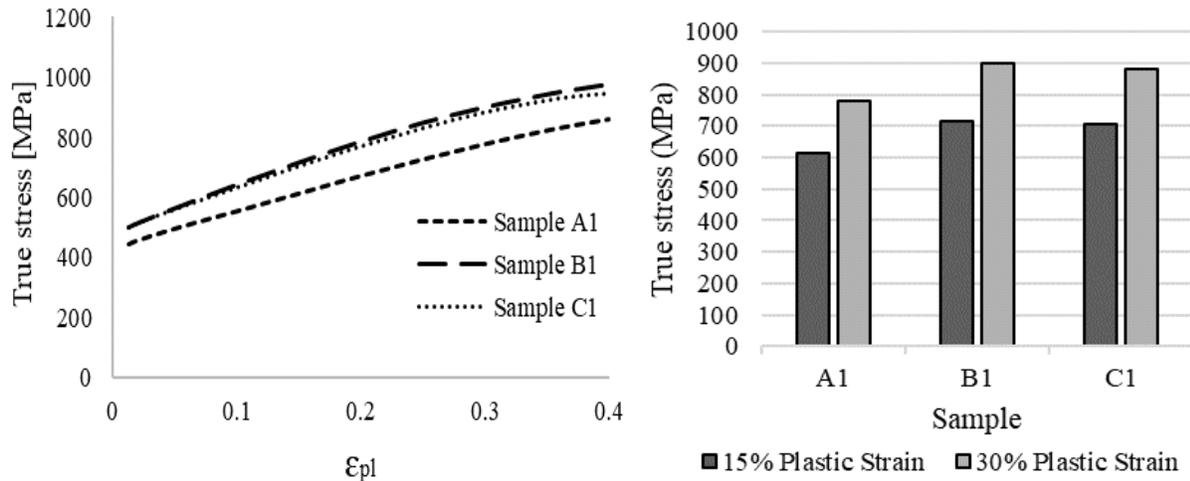


Figure 3:-Compression results from short SLM samples for different hatch angles (0° , 67° and 105°): (a) True stress-true strain curves and (b) comparison of true stress at 15% and 30% plastic strains.

From the data in Figure 3, it can be seen that Samples A showed the lowest flow stresses when compared to other configurations. Additionally, the deviation in the flow stress for A is higher when comparing the repetitions. This could show problems of the manufacturing process using this configuration. For Samples B and C, flow stresses are similar, especially at low plastic strains. In average, flow stresses are only 3% higher in B than C. However, deviations in C are higher than B, especially at higher plastic strains.

Conclusion

In order to investigate the effects of build parameters on the compressive properties of SLM 304L stainless steel, samples were manufactured with three hatch angles (0° , 67° , 105°) and two orientations (z-direction and x-direction) using the Renishaw AM 250 machine at Missouri S&T. The main summary from this study are as follows:

There exists a relationship between the bulk density and the investigated build parameters. However, due to the minute variations recorded during this study it was concluded that the hatch angle and build orientation are not major controllers of bulk density in the SLM of 304L stainless steel.

Hatch angle and build orientation strongly influences the compressive properties of SLM 304L stainless steel. During this study it was observed that the highest yield strength and flow stresses were recorded when hatch angle 67° was selected. This was attributed to the reduction in single direction grain growth and defect generation in the samples caused by the high interval number 'N'. Samples built horizontally (x- direction) also showed higher yield strengths when compared those built vertically (z-direction).

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