

Mechanical Behavior of Additively Manufactured 17-4 PH Stainless Steel Schoen Gyroid Lattice Structure

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Abstract

In this study, the mechanical properties of additively manufactured 17-4 PH stainless steel Schoen Gyroid lattice structures were investigated under monotonic tensile loading. Based on the results obtained from the monotonic tensile test, relationship between tensile properties and relative density of Schoen Gyroid was also established based on the Gibson-Ashby equations. Four different types of gyroid structures with varying volume fractions were designed by altering thickness and length of the unit cell and then fabricated in horizontal direction using a laser powder bed fusion (L-PBF) process. Monotonic tensile tests were conducted under displacement control mode with the speed of cross head movement set to be equivalent to the strain rate of 0.001 s^{-1} . Monotonic tensile results showed a decrease in stiffness and a slight increase in elongation to failure with the decreasing volume fraction among different lattice structures. A good correlation between the material properties (maximum force and stiffness) and volume fraction was also obtained using Gibson-Ashby type relationship. Furthermore, maximum force normalized by the volume per unit length was calculated to determine the effect of cell thickness and length on the resulting mechanical properties. Normalized force versus displacement plot illustrated an increase in stiffness with the increase in unit cell thickness. Whereas, lattice structures with similar cell length and cell thickness exhibited similar normalized maximum force as well as stiffness values.

Keywords: Monotonic tensile test; Lattice; Schoen Gyroid structure; Additive manufacturing; 17-4 PH SS

Introduction

Additive manufacturing (AM) techniques of fabricating parts by adding layer by layer has enable designers to develop parts with complex geometries, which may not be possible to manufacture using traditional subtractive manufacturing techniques. Additionally, increase in demand for higher fuel efficiency and reduction in green house emission in aerospace and automobile industries has steered developers to investigate lightweight materials for fabricating structural components. As a result, fabrication of complicated lattice structures using AM processes are gaining attention as an alternative method to increase the strength to weight ratio by

removing materials from non-critical areas within a structural component [1]. Similarly, lattice structures or solid foams are also a topic of interest in bio medical industries as a method to reduce stiffness of the implant material similar to that of human bones to prevent stress shielding [2-4]. However, before these structural components with various lattice structures can be used in load bearing applications, their mechanical properties based on relative density is important to study.

Zhang et al. [3] conducted a thorough review on the current status and challenges associated with different types of Ti-6Al-4V lattice structures fabricated via selective electron beam melting (SEBM) method primarily used in orthopedic implant applications. This study established a comparison between the mechanical properties under compressive loading obtained for different lattice structures and human bone. Mechanical properties such as ultimate compressive stress, compressive yield stress and modulus value of SEBM lattice structures decreased with the a decrease in density of lattice. Furthermore, ultimate compressive stress for SEBM Ti-6Al-4V lattices were reported to be comparable and in some cases higher than the human cancellous bone. In addition, modulus of SEBM Ti-6Al-4V were comparable to the human cancellous bone, but it was significantly lower compared to human cortical bones. A good correlation between the mechanical properties with density of the lattice structure using Gibson-Ashby model was also presented in the study. Khaderi et al. [5] studied the mechanical properties of unit cell of gyroid lattice using finite element analysis and attempted to relate them to the relative density. It was found that for the gyroid lattice, the relationship between modulus of elasticity and shear modulus with the relative density was a quadratic function.

In this study, mechanical properties of Schoen Gyroid lattice structure with different volume fractions are studied under monotonic tensile loading. The tensile coupons were fabricated using 17-4 PH SS, which is used in various load bearing applications in aerospace, marine, and nuclear industries due to its high yield and ultimate tensile strength along with high corrosion resistance. In this manuscript, the material and experimental procedure used to fabricate the specimens and to run the tests are presented followed by important results obtained from the experiments. Finally, valuable conclusions drawn from this study are presented.

Material and Experimental Procedures

17-4 PH SS powder with size distribution ranging from 15-45 μm was utilized to fabricate the specimens in Renishaw AM 250, a laser powder bed fusion (L-PBF) machine under argon environment. The process parameters presented in Table 1 were used for the fabrication process.

Table 1: Process parameter used to fabricate the L-PBF 17-4 PH SS specimens

Laser power (W)	Scanning speed (mm/s)	Hatching distance (mm)	Layer thickness (μm)
115	777.8	5	30

Four different types of specimens with different volume fractions with Schoen Gyroid lattice structure unit cell were manufactured in the horizontal direction as shown in Fig 1. Table 2

shows different volume fraction and cell dimensions utilized for each type of specimen. Since the volume fraction of the parts depends on the unit cell thickness and length, three specimens were designed with constant cell thickness, while changing the cell length. Two of the specimens had same cell length with different cell thickness. One set of fully dense specimen designed according to ASTM E8 [6] with dimensions shown in Fig. 2 was also fabricated in horizontal direction to determine the benchmark mechanical properties. The specimens were cut from the base plate and were subjected to CA H1025 heat treatment procedure, which was observed to exhibit both high strength and ductility based on the study currently under preparation on the effects of heat treatment on the mechanical properties of L-PBF 17-4 PH SS. The specimens were first solution treated at 1922 °F for half an hour then air cooled to room temperature. The solution heat treated specimens were further subjected to an ageing process at 1025 °F for four hours and again air cooled to room temperature. Finally, the monotonic tensile tests were conducted following ASTM E8 [6] at the displacement rate equivalent to the strain rate of 0.001 s^{-1} using a MTS servo hydraulic load frame with 100 kN capacity.

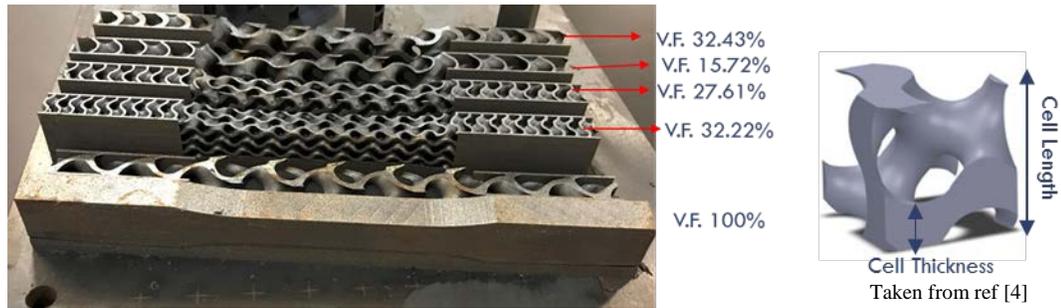


Figure 1: L-PBF PH 17-4 SS Schoen Gyroid lattice structures with different volume fractions built in horizontal direction along with a schematic of unit cell showing cell length and cell thickness.

Table 2: Different cell length and thickness used to introduce variation in volume fraction during the design of Schoen Gyroid lattice structures.

Volume fraction	32.2%	27.6%	15.7%	32.4%
Cell Length (mm)	1.8	2.2	3.9	3.9
Cell Thickness (mm)	1	1	1	2.5

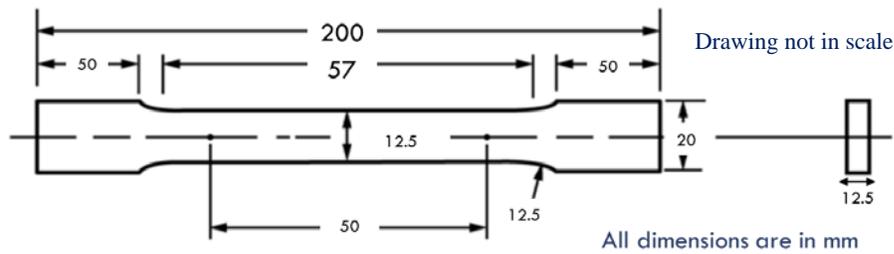


Figure 2: Specimen geometry for monotonic fabricated based on ASTM E8 standard [6].

Experimental Results and Discussions

Load versus displacement curves obtained for various lattice structures with different volume fraction for horizontally built specimens are shown in Fig. 3. The material properties including maximum force required to break the specimen, stiffness, and elongation to failure obtained for different lattice structures as well as for fully dense specimens are reported in Table. 3. As seen from the results, with increasing volume fraction, the force required to break the specimen also increased, as highest force (191 kN) was required to break the fully dense specimen, while lowest amount of force (6.4 kN) was needed to break the lattice specimen with 15.7% volume fraction. On the other hand, among the specimens with different lattice structures, elongation to failure was observed to increase with decreasing volume fraction. The lattice specimen with volume fraction of 32.4% exhibited lowest elongation to failure (1.8%) whereas; highest elongation to failure (13%) was seen for the specimens with volume fraction of 15.7%. Furthermore, the stiffness calculated as the slope of the elastic portion of load versus displacement plot was seen to decrease with decreasing volume fraction. Such a result can be beneficial in applications such as bio-medical implants as reduction in stiffness in implant materials is preferred to match the stiffness of human cortical bone and prevent stress-shielding. From the load versus displacement plot, an interesting phenomenon of load fluctuation was also observed in the lattice specimens. Drop in load resulted from the failure of a portion of the lattice structure due to localized stress concentration, while the remaining portion of the lattice structure still has load bearing capability and consequently, the value of load increases again. These drop and rise in the value of load causes the load fluctuation. This behavior can also be an important aspect of lattice structures to be used in structural components in fail-safe designs to detect problems in the system before a catastrophic failure.

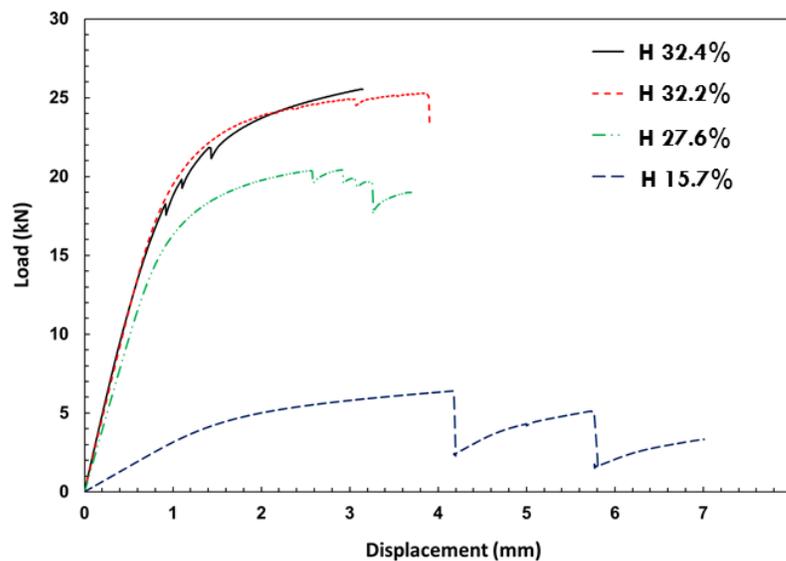


Figure 3: Engineering load-displacement responses for L-PBF PH 17-4 SS specimens.

Table 3: Tensile properties of L-PBF PH 17-4 SS Schoen Gyroid lattice structures with different volume fraction along with fully dense specimen.

Volume Fraction	Max. Load (kN)	Stiffness (kN/mm)	% Elongation
100%	191	113	6.6
32.4%	25	26	1.8
32.2%	24	22	5
27.6%	18	17	6
15.7%	6.4	3.5	13

Due to the possibility of large number of combination of lattice structures with different volume fractions, it is not always feasible or practical to characterize the mechanical properties of each combination of lattice structures. Therefore, a mathematical model that can relate the mechanical properties with the volume fraction can be a helpful tool during the design process of lattice structures based on the desirable mechanical properties. In this study, the Gibson-Ashby type relationship is widely used for establishing the relationship between mechanical properties and volume fraction of unit lattice cell structure was employed and given as [7, 8]:

$$\frac{\sigma}{\sigma_0} = C \left(\frac{\rho}{\rho_0} \right)^{1.5} \quad (1)$$

$$\frac{E}{E_0} = C \left(\frac{\rho}{\rho_0} \right)^2 \quad (2)$$

where, σ is the ultimate tensile stress, E is the modulus of elasticity of lattice structure, σ_0 is the ultimate tensile stress, E_0 is the modulus of elasticity of fully dense material, C is unit cell dependent constant, and $\frac{\rho}{\rho_0}$ is the volume fraction of the lattice structures. It also has to be noted that the relationship in Eqns. (1) and (2) are based on stresses. However, due to complex geometry of the lattice structures, calculating stresses was not easy and straight forward for Schoen Gyroid lattice structures. Therefore, in this study, Gibson-Ashby type relationship was used to relate the maximum load in place of ultimate tensile stress and stiffness instead of modulus of elasticity with the volume fraction as shown in Fig. 4(a) and 4(b) respectively. A good correlation between both maximum force versus volume fraction and stiffness versus volume fraction was seen in Fig 5 as indicated by the R^2 value of 0.99 and 0.98, respectively. Furthermore, comparing equations shown in Fig 4 and Eqns. (1) and (2), a slightly different value of exponent was also obtained when replacing ultimate tensile stress with maximum load and modulus of elasticity with stiffness. This may also indicate that with a proper stress analysis, Gibson-Ashby relationship might be applicable to accurately establish the relationship between mechanical properties and volume fraction of L-PBF 17- PH SS Schoen Gyroid lattice structures.

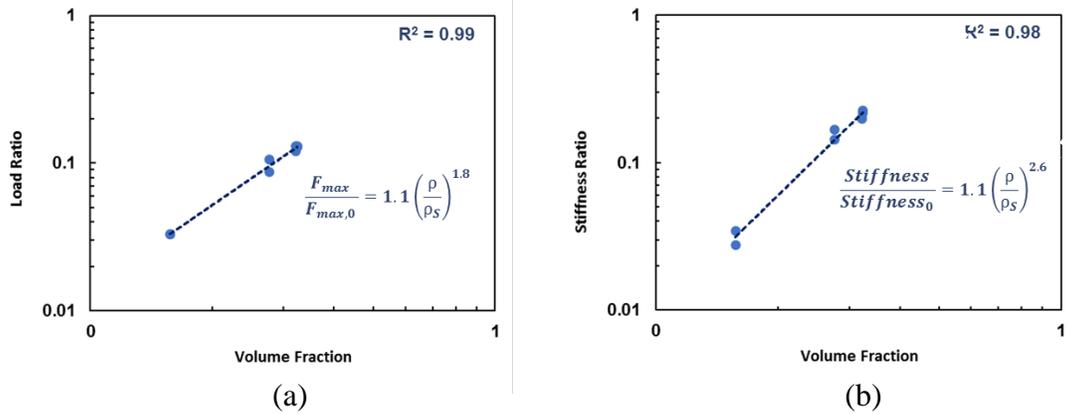


Figure 4: Relationship between (a) maximum load ratio with volume fraction and (b) Stiffness ratio with volume fraction based on Gibson-Ashby relationship for 17-4 PH SS Schoen Gyroid lattice structures.

As mentioned earlier, with the increase in volume fraction, the load required to fail the specimen also increased. As a result, a substantially large force was required to break the fully dense specimen and could not be incorporated in the maximum load versus displacement curve in Fig. 3. Moreover, as the mechanical properties of the lattice structures are mostly governed by the deformation and failure mechanism of unit cell, a method to normalize the maximum force with volume per unit length was conducted to better understand the effects of cell thickness and cell length on the tensile properties of L-PBF 17-4 PH SS Schoen Gyroid lattice structures. Normalized maximum force was calculated for each lattice structure and fully dense specimen by dividing maximum force with the volume of 25 mm of material cut from the gage section of the specimen. The volume of the cut section was calculated based on measured mass and density, taken as 7.75 gm/cm^3 from literature [9]. Finally, normalized maximum force was plotted against displacement and shown in Fig. 5. Material properties including normalized maximum force and stiffness obtained from the normalized max force versus displacement of different Schoen Gyroid lattice structure are shown in Table 4. Interestingly, normalizing maximum force collapsed all the curves for different lattice structures as well as fully dense material within a smaller range compared to the curve obtained from maximum load versus displacement plot in Fig. 3. Furthermore, Table 4 also showed some effects of unit cell thickness and cell length, as normalized maximum force calculated for specimen with volume fraction of 32.4% was similar to the one obtained for the specimen with volume fraction of 15.7%. However, the stiffness taken as the slope of the elastic part of normalized maximum force versus displacement curve was much higher for specimen with 32.4% volume fraction and 2.5 mm cell thickness (16 kN/mm^4) compared to the specimen with 15.7% volume fraction and 1 mm cell thickness (9 kN/mm^4) and identical cell length of 3.9 mm. However, comparing the mechanical properties between specimens with similar cell length and cell thickness (specimens with 32.2% and 27.6% volume fraction), both normalized maximum force and stiffness were observed to be similar. Therefore, these results may suggest that there is a need to determine an accurate method to calculate the stress distribution in the unit cells of Schoen Gyroid lattice structure to determine its mechanical properties and to establish a relationship between the material properties and volume fractions of different lattice structures.

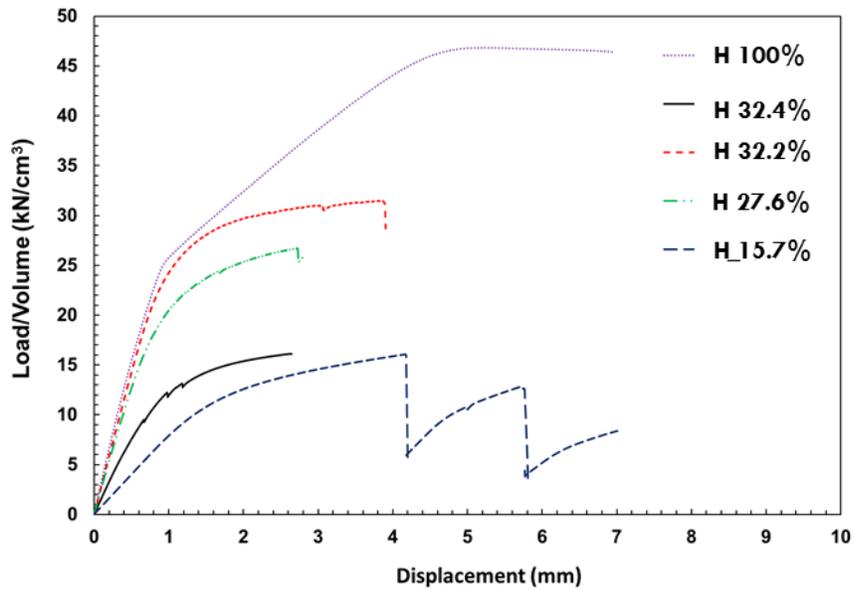


Figure 5: Normalized maximum load versus displacement plot 17-4 PH SS Schoen Gyroid lattice structures with different volume fractions along with fully dense specimen.

Table 4: Tensile properties of L-PBF PH 17-4 SS Schoen Gyroid lattice structures with different volume fractions along with fully dense specimen based on normalized maximum load.

Volume Fraction	Max. Load/Vol (kN/mm ³)	Stiffness
100%	4600	28
32.4%	1600	16
32.2%	3000	28
27.6%	2900	28
15.7%	1600	9

Conclusions

In this study, monotonic tensile properties and effects of unit cell length and thickness of 17-4 PH SS Schoen gyroid lattice structures fabricated using a laser powder fusion process were investigated. Based on the results obtained from the tensile tests, the following conclusions were drawn:

1. Maximum force required to break the specimen increased, while elongation to failure decreased with the increase in volume fraction.
2. Significant reduction in stiffness was also observed with the decrease in volume fraction, which can be a desirable property in biomedical applications to reduce the stress shielding

effect between the bone and implant, which results from the large difference between the stiffness of bone and implant material.

3. Acceptable correlation between the ratio of maximum force and ratio of stiffness with the volume fraction was established using Gibson-Ashby type relationship.
4. Maximum force was normalized by volume per unit length and plotted against the displacement revealing the influence of unit cell thickness and cell length on the stiffness of the lattice structures. For the lattice structures with similar cell length, stiffness increased with the increase in the value of cell thickness, while the normalized maximum force was similar between the two specimens.
5. For lattice structures with identical cell thickness and similar cell length, the values of stiffness was also comparable.

Results from the current study show that the material properties of lattice structures may be correlated by incorporating the effect of unit cell thickness and cell length. Therefore, stress analysis using finite element tools is required to conduct a complete study on the effect of unit cell dimensions on the overall mechanical properties, including ultimate tensile strength, modulus of elasticity, and yield strength of different lattice structures.

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