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Mechanical Behavior of Additively-Manufactured Gyroid Lattice Structure under Different Heat Treatments

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Abstract

Gyroid lattice structures, known for high stiffness and specific strength, are gaining attention for their energy absorption ability. However, energy absorption and strength of the gyroids are two desired properties, which vary contradictory. This study investigates manipulating properties on lattices using post-processing operation instead of modifying dimensions with consequent changes in weight and production cost. The challenge is that a particular post-processing heat treatment may improve one property, while it may be detrimental to other ones. The compressive properties of 17-4 PH stainless steel gyroid lattice structures fabricated using laser beam powder bed fusion (LB-PBF) method is investigated. Compressive properties such as load bearing capacity, crashing strength, and energy absorption are determined and the trends in their variation are discussed. Based on the experimental results, heat treating lattices with CA H900 procedure improves energy absorption and strength considerably, while increases crashing force, as well.

Introduction

Additive manufacturing (AM), a layer wise fabrication technique has enabled designers to develop parts with complex geometries such as lattice structures, which may not be possible to fabricate using traditional subtractive manufacturing processes. One of such example of lattice structures are gyroids, which is a surface based lattice and exhibits both high stiffness and strength, making it suitable for fabricating lightweight structural components that can be used in aerospace and automotive industries [1]. Shrestha et al.[2] studied the tensile behavior and failure of gyroid lattices at various volume fractions. The properties of lattice in compression and tension maybe different due to nature of their structure. However, before these structural components can be used in load bearing applications, their mechanical properties under compression is important to study. Maskery et al. [3] emphasized the importance of this feature in the design of packaging materials and personal protective equipment such as armor. Ullah et al. [4] developed the design concept to improve energy absorption of typical aerospace sandwich components (similar to gyroid lattices), and in a practical application, Ferro et al. [5] successfully implemented lattice structure as impact absorber for external impact (bird strike) and embedded anti-icing/de-icing system for wing leading edges of a high-performance executive aircraft. Abueidda et al. [6] investigated mechanism of compression and failure of gyroid structures and defined their mechanical properties experimentally and computationally at different relative densities. In another study, Zhang et al. [7] classified gyroids failure mechanisms. This study is important, since failure mechanism has determinantal effect of strength. Bonatti and Mohr [8] demonstrated that all shell-lattices provide substantially higher stiffness and strength than optimal truss-lattices of equal mass. They discussed failure mechanisms of these new structures in another paper [9]. In order to improve the energy absorption of lattice structure, Yang et al. [10] designed and manufactured graded gyroid cellular structures with varying gradient directions as well as uniform structure. They investigated surface morphology and mechanical response of these structures under compressive loads.

Several above-mentioned methods are examined in the literature to modify lattice behavior which mainly lead to new design for gyroids. However, the authors of this paper tried to improve lattice properties without altering geometry. Considering determinantal effects of heat treatments on mechanical properties of bulk metals, the effect of different heat treatment procedures on the mechanical properties of gyroid lattice structure under compressive loading are studied in this paper. 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, significance of the improvements is discussed.

Material and Experimental Procedures

The compression coupons were fabricated using 17-4 PH stainless steel (SS), which is used in various load bearing applications in aerospace, marine, and nuclear industries due to its high yield and ultimate strength along with high corrosion resistance [2]. 17-4 PH SS powder with size distribution ranging from 15-45 µm was utilized to fabricate the specimens in Renishaw AM 250, a LB-PBF machine under argon environment. The Renishaw suggested process parameters presented in Table 1 were used for the fabrication process. In the second column, the nominal scanning speed was calculated.

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

Laser power (W)	Scanning speed (mm/s)	Hatching distance (mm)	Layer thickness (µm)
115	777.8	0.11	30

Computer aided design (CAD) file was generated in SolidWorks for Gyroid lattice compression samples. The overall length was 15 mm consisting of 6 gyroid unit cells each with the length of 2.5 mm and 0.4 mm thickness. Manufacturability and observation of deformation in cells were the concerns for selection of dimension and number of cells. QuantAM build preparation software was used to generate computer aided manufacturing (CAM) file readable by Renishaw AM 250. Figure 1 indicates fabricated samples on the baseplate.

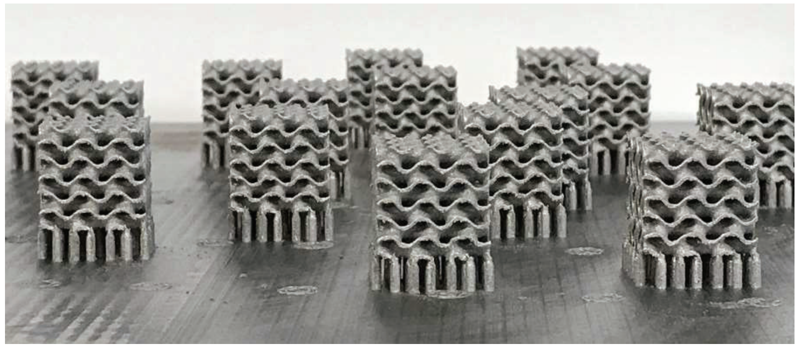


Figure 1: LB-PBF PH 17-4 SS Gyroid lattice compression samples

Beside As-Built samples, three widely-used heat treatments were used to examine wide range of post-processing operations. These include CA H900, CA H1025, and CA H1150 described in Table 2 (referring to Refs. [11-12] for more information).

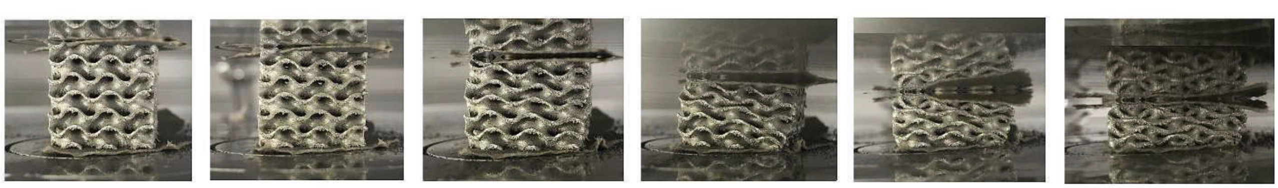
Table 2. Heat treatment procedures [11-12]

Procedure	Temperature (°C)	Duration (hour)	Quenching environment
CA H900	1050	0.5	Air cooled
	482	1	Air cooled
CA H1025	1050	0.5	Air cooled
	552	4	Air cooled
CA H1150	1050	0.5	Air cooled
	621	4	Air cooled

Finally, the compression tests were conducted following ASTM E9 [13] using a MTS servo hydraulic load frame with 100 kN capacity. Each experiment was repeated to ensure the repeatability of the tests and reliability of the obtained data.

Experimental Results and Discussions

Gyroids deform almost uniformly up to complete densification (collapse of the structure). This behavior helps them act as spring-damper system and absorb significant amount of energy before complete collapse. Figure 2 shows how the gyroid structure deforms to a complete densification.



(a) (b) (c) (d) (e) (f)

Figure 2: Stages of the deformation of As-Built gyroid structure up to densification at (a) 1 mm, (b) 2 mm, (c) 4 mm, (d) 6 mm, (e) 8 mm, (f) 10 mm deformation.

Figure 3 indicates the recorded compression force (shown positive here) versus the deformation imposed to the sample. General trend of variation is similar, but in case of CA H900 samples (defined as the samples heat treated by CA H900 procedure) there is a sudden drop in force in the middle of collapse. Noting that CA H900 samples are brittle [11-12], they are prone to brittle fracture and sudden rupture, while other samples deform more uniformly. As-built samples behave like those with CA H1150 heat treatment. In fact, the long process of cutting samples from base-plate after printing plays as heat treatment procedure with very gradual cooling.

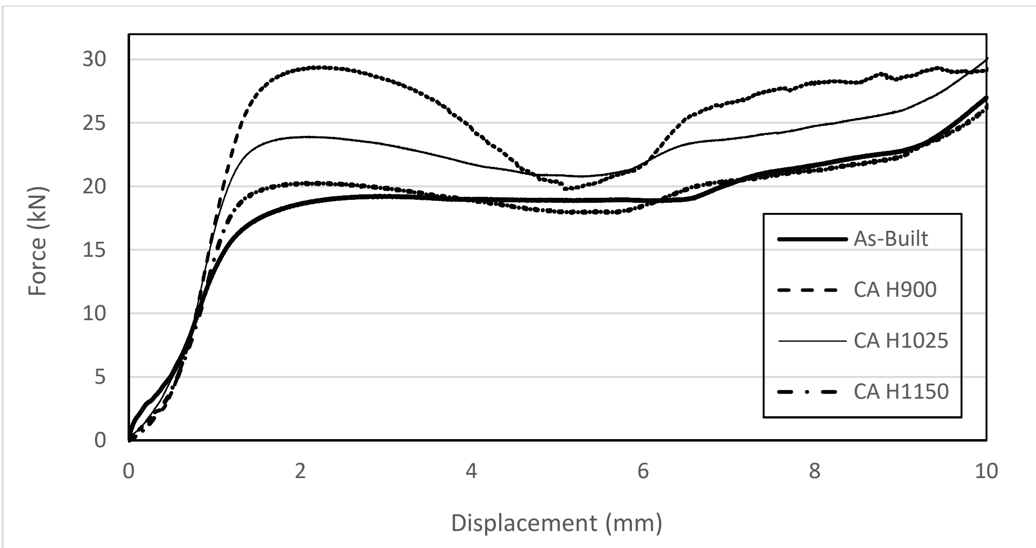


Figure 3: Force-displacement graph recorded by experiment

Identical behavior for the initial linear part of all curves in Figure 3 demonstrates that elastic behavior of lattice does not change due to heat treatment and stiffness does not change. In the other word, the elastic modulus, which is corelated to the slope of the curve in linear region remains constant. This is similar to what we observe for 17-4 PH SS standard tensile sample as well [11]. However, crashing deformation, defined in this study as maximum deformation before the appearance of permanent plastic deformation in samples, was seen to be affected by the employed heat treatment procedures. This varies the extent of elastic region and samples with CA H900 tolerate larger reversible deformation (0.55 mm larger elastic deformation in Figure 3 if compared with As-Built one)

Load bearing capacity is defined as the peak load after initial sharp increase. This is the maximum load that structure can tolerate prior to the permanent deformation. This value is important, since after this stage (yielding), lattice undergoes plastic deformation in plateau stage as load remains the same, while the deformation increases. The final stage of deformation is the densification stage in which, the load increase is not accompanied by the increase in deformation.

As it is indicated in Figure 4, the CA H900 samples are with larger load bearing capacity. This may be associated with larger yield strength for CA H900 heat-treated 17-4 PH SS. For more information regarding micro-structural change of 17-4 PH SS due to heat treatment please see Refs. [11-12].

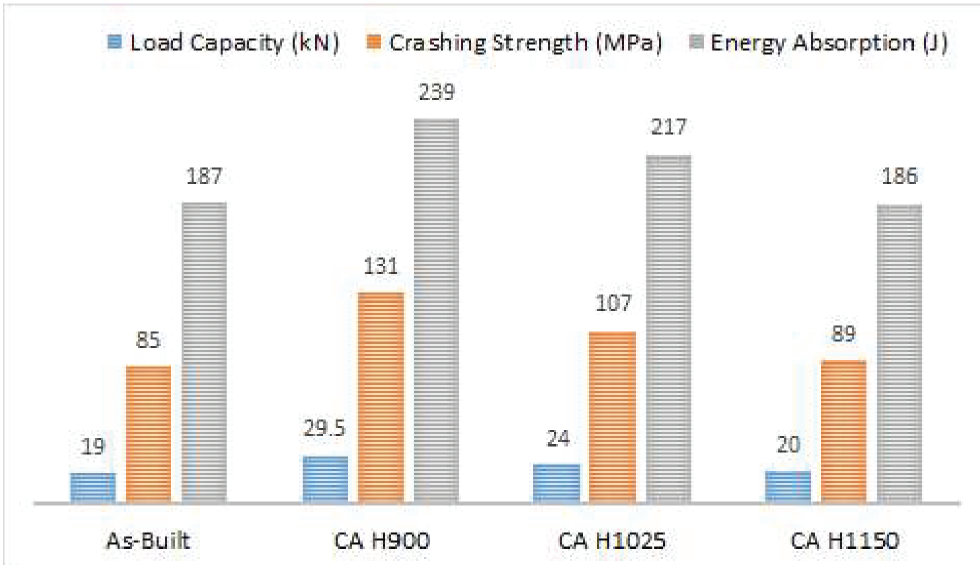


Figure 4: Load bearing capacity, crashing strength, and energy absorption for different lattices

Crashing strength of lattices were calculated as the ratio of maximum load (load capacity) to apparent area (nominal contact area). This is a little higher than plateau force, which characterizes lattice strength after post-yield softening. Smooth and clear plateau region can be observed in more ductile cases including As-Built and CA H1150 specimens. In addition, it can be seen in Figure 4 that CA H900 sample has the highest strength, while As-Built and CA H1150 are with at least 30% less crashing strength. Again, this behavior correlates well with the trend of variation of the yield strength of 17-4 PH SS with heat treatment reported in Refs [11].

The area under the load-displacement curve (up to 10 mm deformation) is considered as energy absorbed due to collapse of the structure. The result of calculation based on trapezoid numerical method is indicated in Figure 4, which demonstrates that the gyroid lattice subjected to CA H900 heat treatment procedure exhibited 30% higher energy absorption capability when compared to the As-Built specimens. It has to be noted that the elastic part of absorbed energy which will be released after unloading is not excluded from the calculated total absorbed energy in the current study.

In general, heat treatment can be considered as proper post-fabrication operation to manipulate mechanical properties of lattices. In contrast with the observation for brittle CA H900 heat-treated standard tensile samples, the energy absorbed up to rupture (here is full densification) increased compare to other more ductile lattices.

Conclusion

Unit cells can be classified as advanced engineering blocks of material, which may provide wired properties for lattices, unreachable by traditional structural materials. Heat treatment is examined in this study as the post-fabrication operation to modify the compression behavior of gyroid lattices. A brief summary of achievements for this study includes;

1- The post-fabrication heat treatment procedure was seen to have a minimal effect on the stiffness of the gyroid lattice structure.
2- Lattice with CA H900 heat treatment tolerates larger reversible deformation.
3- Clear and smooth plateau region was seen for more ductile lattices, while deformation for more brittle ones was associated with sudden collapse of structure in some regions.
4- Considerable improvement in crashing strength, load bearing capacity, and energy absorption of lattices were seen by implementation of heat treatment (as high as 30%).
5- If full densification is considered as the failure of lattice and consequently the energy absorbed as the toughness of lattice, using heat treatments like CA H900, which is known as the procedure to make metals more brittle, increases toughness and energy absorption of lattices. This behavior is strange if comparing with the change in wrought 17-4 PH SS properties under the same heat treatment.

If we consider apparent strength and energy absorption as representatives of strength and toughness, the result obtained in this study demonstrates that we can improve both of these properties by heat treating the lattices under CA H900 procedure. However, depending on the application, heat treatment procedure should be designed carefully. For example, in case of application in protective devices or packaging materials, increasing energy absorption by using CA H900 heat treatment may lead to increase in crash/impact load above the permissible limit. Therefore, the designers should decide for proper tradeoff among desired characteristics of structure.

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