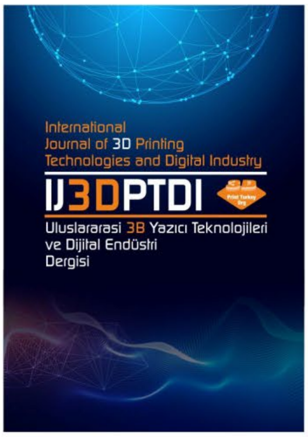

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TENSILE BEHAVIOUR OF TI6AL4V LATTICE STRUCTURES PRODUCED BY LASER POWDER BED FUSION AND DESIGN CRITERIA

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ABSTRACT

Although additive manufacturing (AM) technology has many advantages in manufacturing complex geometries, it is not always possible to have desired results and performance due to its inherent limitations. This situation becomes crucial in manufacturing of lattice structures that are commonly used in aerospace, biomedical, etc. areas. The lattice structure design is easier with AM technologies, therefore process and lattice parameters must be carefully reviewed especially on biomedical properties. Titanium alloys are widely used for additive manufacturing of those implants with laser powder bed fusion (LPBF) technology. By doing so, we are able to achieve porous, lightweight and durable bone implants that aim to reflect bone properties. Due to these benefits of lattice structures and their ease of design, many studies focus on lattice structures, but their design, manufacturing and implementation features have not been completely deduced. As such, lattice topology and design may affect mechanical properties of the parts and manufacturing quality. In this aspect, three different strut-based lattice topologies (octahedron, dodecahedron and star), as potential bone implant structures were selected and tensile test specimens accommodating these topologies were manufactured with Ti6Al4V powder using laser powder bed fusion (LPBF). All the manufactured specimens were subjected to tensile tests and the results were reported.

Keywords: Additive Manufacturing, Lattice Structures, Laser Powder Bed Fusion, Ti6Al4V, Tensile Test, Orthopedic Bone Implants.

1. INTRODUCTION

Additive manufacturing (AM) is one of the continuously developing, popular and widespread production methods. Traditional manufacturing methods may be unsuitable for the production of complex lattice structures. However, AM technologies ensure to achieve this goal [1]. Laser powder bed fusion (LPBF) is one of the most commonly used AM technologies that use thermal laser energy to melt and deposit alloy powders layer by layer [2]. 3D complex geometries are freely produced as near net shape components by the CAD data of the part [3].

Lattice structures are a form of periodic porous structures which are unique three-dimensional cell structures formed by continual unit cells and can be easily manufactured with LPBF [4]. Unit cells are specified by the geometrical dimensions and bonding of their elements which are linked at specific interchange sections. These sections are related to their topological features [5]. Lattice structures can be classified as many aspects and the most common types are strut-based and triply periodic minimal surfaces (TPMS) [6]. In this study, it was focused on the strut-based lattice structures.

Strut-based lattices can be easily optimized and their features altered due to the desired specifications with unit cell and process parameters [7]. Mechanical, acoustic, thermal, dielectric, damping, biocompatibility and many other properties are obtained in this way [8]. Especially biomedical studies can be beneficial with lattice structures and their features. Metallic orthopedic implants are desired to be close in mechanical and biocompatible properties of human bone. Reducing the stiffness through lower values and less elasticity modulus are the utmost objectives during manufacturing implants because of alloy characteristics [9]. Titanium and its alloys are widely used because of their biomedical adaptation and Ti6Al4V is one of the common alloys [10]. However, titanium has a high elasticity modulus (~90-110 GPa) and it must be reduced for biomedical applications due to the stress shielding phenomenon. Stress shielding causes an elastic modulus miss-match effect between the Ti implant and the bone tissue and bone tissue is damaged over time which causes unable to sustain its function [11-12]. The porous and lattice structures of titanium parts can reduce mechanical properties to appropriate levels and prevent stress shielding. However, since it is not clear to what extent unit lattice designs and porosity ratios will decrease the mechanical properties, the reduced properties of newly developed lattice designs should be investigated with standard mechanical tests such as tensile and compression tests [13-14].

Several different design approaches were examined in the literature to conclude tensile testing of lattice structures because the repeatability of manufacturing is challenging for AM lattice structures [15-16]. Some issues may occur such as recoater blade damages during manufacturing when the design of lattice structures is not suitable and the uniformity of parts is affected this way [17]. This situation also affects the tensile test properties due to the incompatibility of manufacturing. Researchers studied different methods to overcome these problems. Dingye et al. [18] reported that manufacturing lattice tensile test structures as different cross sections and build directions. They showed these design parameters affect tensile properties. Also, some successful designs were manufactured without defects and introduced for tensile test implementation. Ananda et al. [19] designed lattice structures with several lattice topologies. Their design was provided with a 6 mm hole on the grip section to prevent any torsional stress on the lattice structure. Yang et al. [20] used heat treatment on their lattice structure design. However, the authors did not report the effect of these procedures and compare them with not implemented specimens.

It can be seen that the repeatability of the manufacturing of tensile test specimens and their test fulfillment were inadequate and needed further research due to design aspects. Manufacturing of lattice tensile test specimens are challenging process despite of many studies in this area. Strut-based topologies may be more challenging when they are produced as thin strut diameters. In this aspect, two different groups of tensile test specimens with different support designs were introduced in this study. Dodecahedron, star and octahedron lattice structures manufactured as tensile test specimens and their design effects were discussed both on manufacturability and mechanical test feasibility.

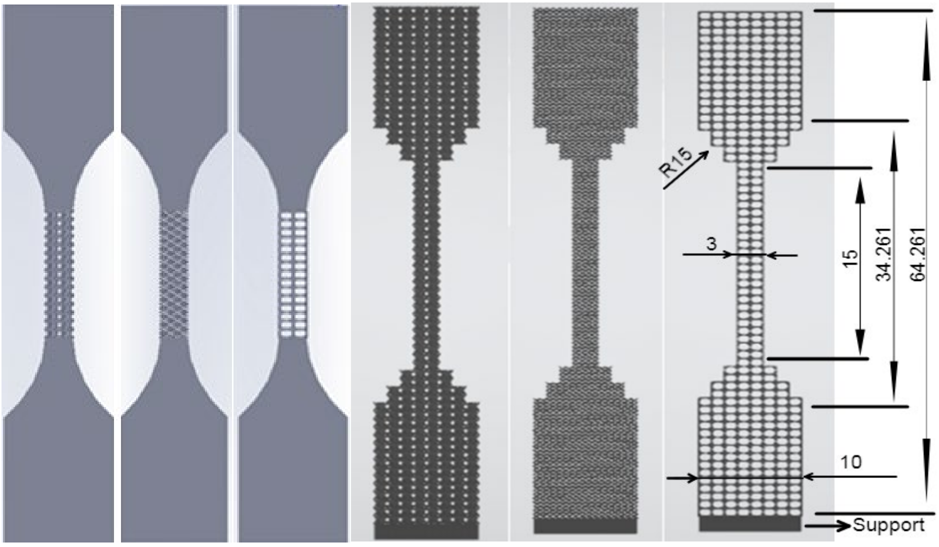
2. MATERIAL AND METHOD

The tensile test specimens accommodating three different lattice structures were manufactured by laser powder bed fusion (EOSINT M280-200W) using Ti6Al4V powder as octahedron, star and dodecahedron topology. The chemical composition of Ti6Al4V (EOS Ti64) powder supplied by the same company is given in Table 1. Process parameters were selected from default parameter sets (i.e., skin exposure type) included in EOS PSW software. Specifically, 170 W laser power, 1250 mm/s scan speed, 30 µm layer thickness and 100 µm hatch distance were used during the manufacturing of the test specimens. Manufacturing was carried out Z-axis for all parts and designs.

Table 1. The chemical composition of Ti6Al4V powder (%) [22]

Ti	Al	V	Fe	O	N	C	H	Y
88	6.7	4.5	0.2	0.1	0.1	0.1	0.1	0.2

Tensile test specimen designs were completed in accordance with ASTM-E8/E8M-16a standard [23-25], as shown in Fig. 1. The thickness of the specimen was 2.5 mm. Three different lattice structures were chosen as dodecahedron, octahedron and star. Siemens NX version 12.0 (Siemens AG, Germany) was used for the design of strut base structures. In this study, two different design strategies were followed, as shown in Fig. 1. In the first design strategy (i.e., Fig. 1(a), (b) and (c)), tensile test specimens have lattice structures at gauge section while in strategy two (i.e., Fig. 1(d), (e) and (f)), the entire body of specimens have been covered with lattice structures. Here note that 2 mm volume support structures were included in these designs.



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

Figure 1. Schematic representation of the revised dimensions of the tensile specimens in accordance with the ASTM-E8/E8M-16a standard. All dimensions were the same for both design groups (a-star center latticed, b-dodecahedron center latticed, c- octahedron center latticed, d-star full lattice, e-dodecahedron full lattice, f-octahedron full lattice. The thickness of the specimen was 2.5 mm.

However, the samples were broken due to the recoater blade crash during manufacturing process of specimens (a), (b) and (c), thereby new support structures were designed and included in those specimens using Magics software. The details for these supports are given in the next section.

All the lattice structures were produced as thin strut build which has not been mostly studied in the literature. The strut diameter was chosen as 0.25 mm and the unit cell dimensions were chosen as 1.25 mm x 1.25 mm x 1 mm (*x*, *y* and *z*, respectively). In this way, the topological pore size has been increased.

On the other hand, the following corrections were made after the raw design for full lattice structures (i.e., Fig. 1(d), (e) and (f)).

Some of the open-ended profiles on the tensile specimens are secured to avoid the need for support structures [26]. It has been seen that the design of the descending form of stair steps is important both for production and performing a suitable tensile test (Figure 2).

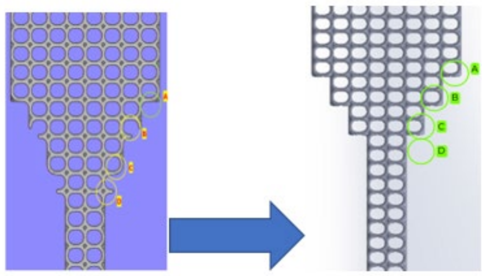


Figure 2. Constructing the openings (B, C, D) in the picture to the structure indicated by A is shown on the right (octahedron).

Likewise, there were some outward struts in star lattice specimens. Thus, a similar modification procedure was also applied to this specimen, as shown in Figure 3.

Such disturbances occur during the lattice construction of the raw design due to the topological effects of lattice structures [7].

Therefore, these types of defects did not occur in dodecahedron lattice topology (Figure 4). In order to preserve the common design method, changes were made as same as other lattice topologies.

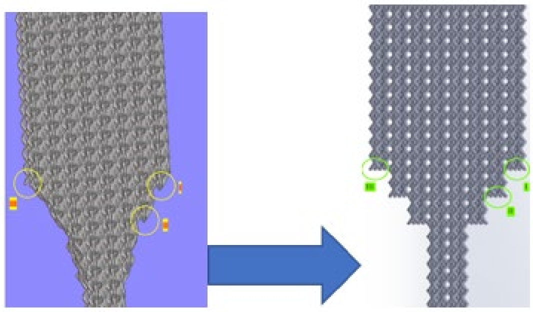


Figure 3. In star lattice structure, the parts that do not closed-contact the parts from the bottom or sides (I and II) and the parts that do not close contact from the bottom point (III).

Tensile tests were performed using a calibrated universal mechanical tester (Instron 8872, Instron, USA). All the tests were performed at a constant strain rate of 0.1 mm/min and specimens were placed centrally.

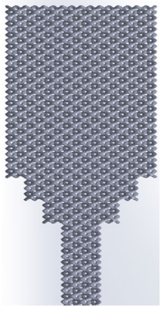


Figure 4. The final version of the dodecahedron lattice structure with stair steps.

The elastic modulus was calculated using slope of the linear elastic section in the stress-strain curve. Non-linear sections were not taken for calculation. Here note that Excel program was used for all the calculations.

On the other hand, scanning electron microscopy (SEM) investigations on the manufactured specimens were completed via Zeiss EVO LS 10 (Zeiss, UK) with a secondary electron detector.

3. EXPERIMENTAL FINDINGS

3.1. Contact Support Structure Design of Center Latticed Structure

During the manufacturing process, multiple recoater blade crashes occurred due to thin sections of the lattice structures. Consequently, due to the low stiffness of the samples, all the samples were broken and the manufacturing process was interrupted. These failed manufacturing results are given in Figure 5.

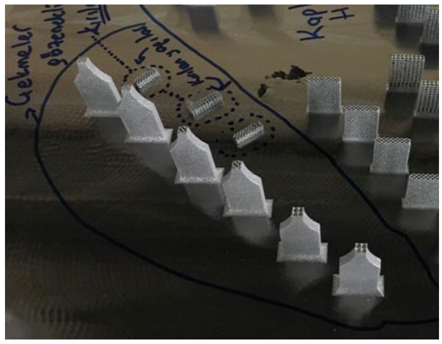


Figure 5. Failed manufacturing of tensile test specimens

To prevent this situation, first the shell support structure was designed. This support structure did not contact the tensile specimen and there is an approximately 0.15 mm gap between the support structure and the test specimen. Based on the manufacturing experience, it was thought that this support structure might not provide enough strength to the test specimen to withstand the forces coming from the recoater. To guarantee the success of the second manufacturing, two contact support structures were created in the second support design, as seen in Figure 6. These supports were placed in the direction which is perpendicular to the recoating direction, and they have contacts in the radiused portions of the specimen whereas there is no contact between the support structure and test specimens in the gauge portion. Note that approximately 0.15 mm clearance was provided in this section. As such, the manufacturing of all the specimens was completed successfully, as shown in Figure 7.

Figure 6. Contact support structures (a) and their relationships with lattice topology (b).

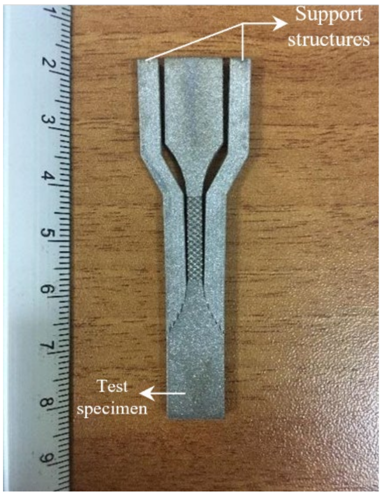


Figure 7. Manufactured tensile test specimens with contact support structure design.

Detailed inspection of the support structure-tensile test specimen interface was performed by the SEM. As can be seen from Figure 8, clearance between the support structures and test specimen gradually increases from the direction of the building platform to the top of the specimens due to residual stress in the support structures. This phenomenon allows us to easily remove the support structures from the specimen.

3.2. Tensile Tests

Three test specimens for each design were manufactured and tested. Stress-strain curves of tensile test specimens of center latticed structure design can be seen in Figure 9. The fractured test samples were given in Figure 10.

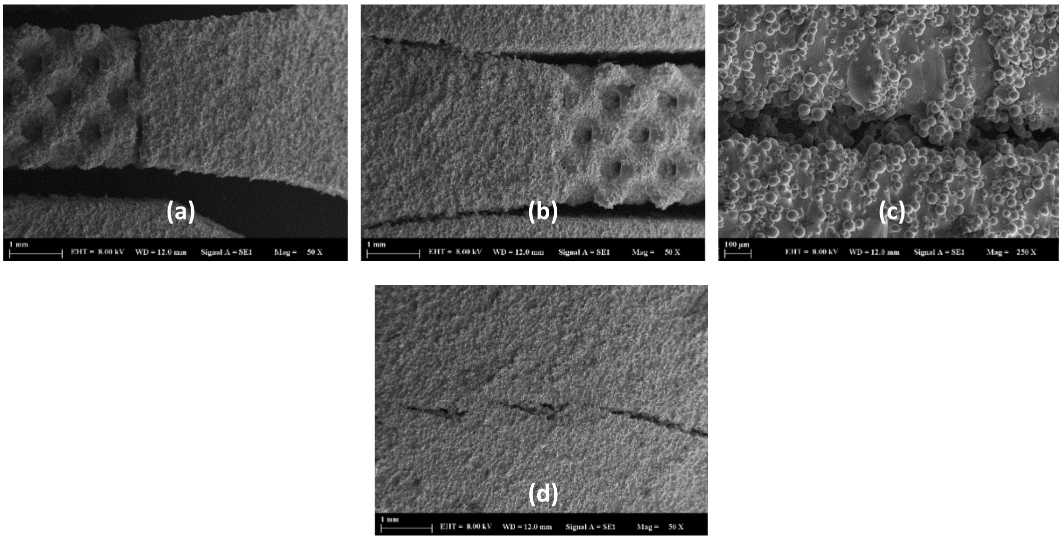


Figure 8. The support structure of center latticed sample design (Lattice-bulk structure transition (a), support structure-specimen transition (b), wide support structure separation lines (c) and tight support structure separation lines (d)).

As can be seen from the graphs, the high resonance problem experienced during the tensile tests and the resulting faulty graph curves occurred during this test phase. With all these evaluations, it was decided to not interpret the tensile test results. As can be seen in the figure below, the samples fractured at the lattice transition zone except octahedron-2 specimen. The thin strut diameter and design aspect prevented obtaining the desired results from tensile tests.

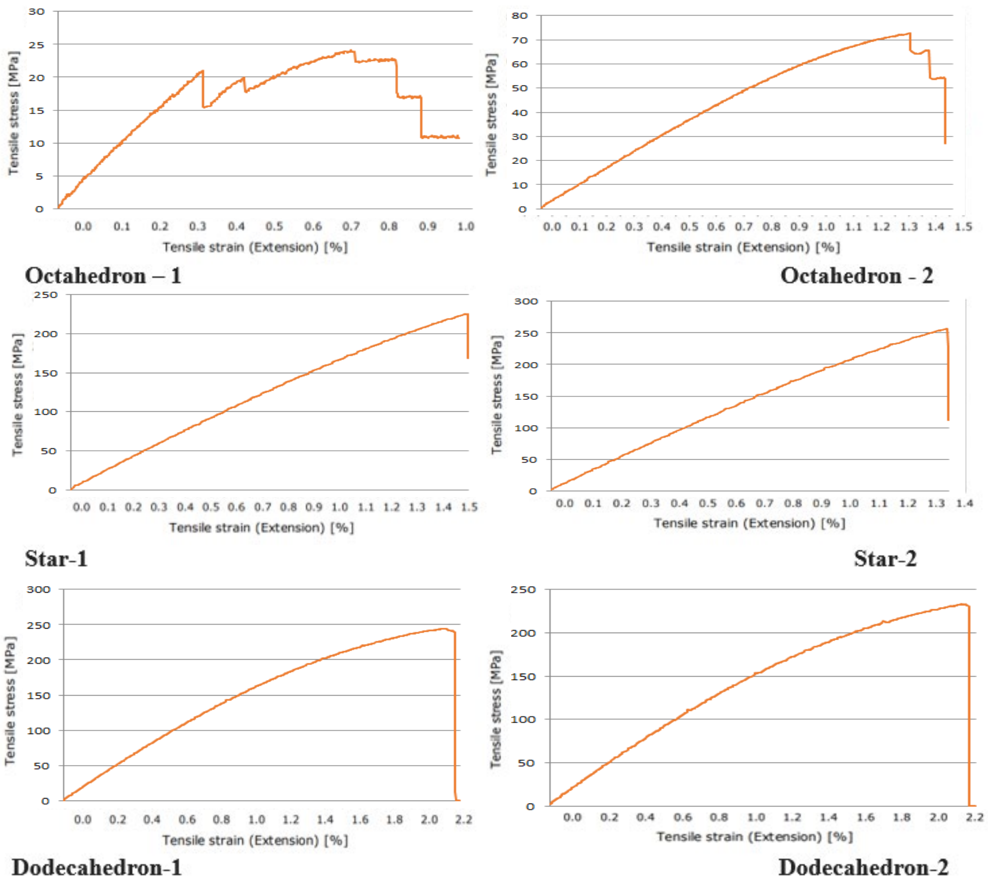


Figure 9. Stress-strain curves of tensile test specimens with center latticed structure design.

Stress-strain curves of full lattice structure designs were given in Figure 11. The fractured test samples were given in Figure 12.

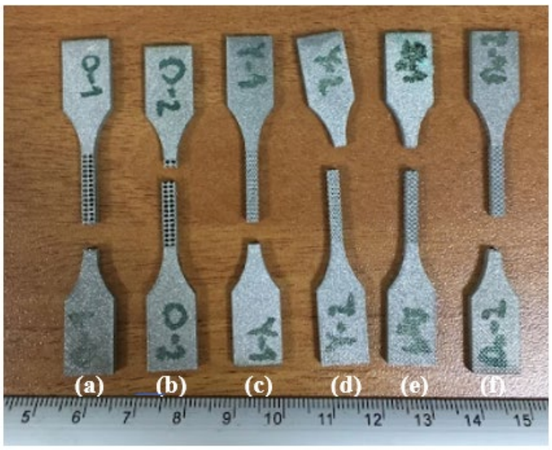


Figure 10. Fracture points of parts at the end of the tensile tests. Octahedron (a and b), star (c and d) and dodecahedron (e and f).

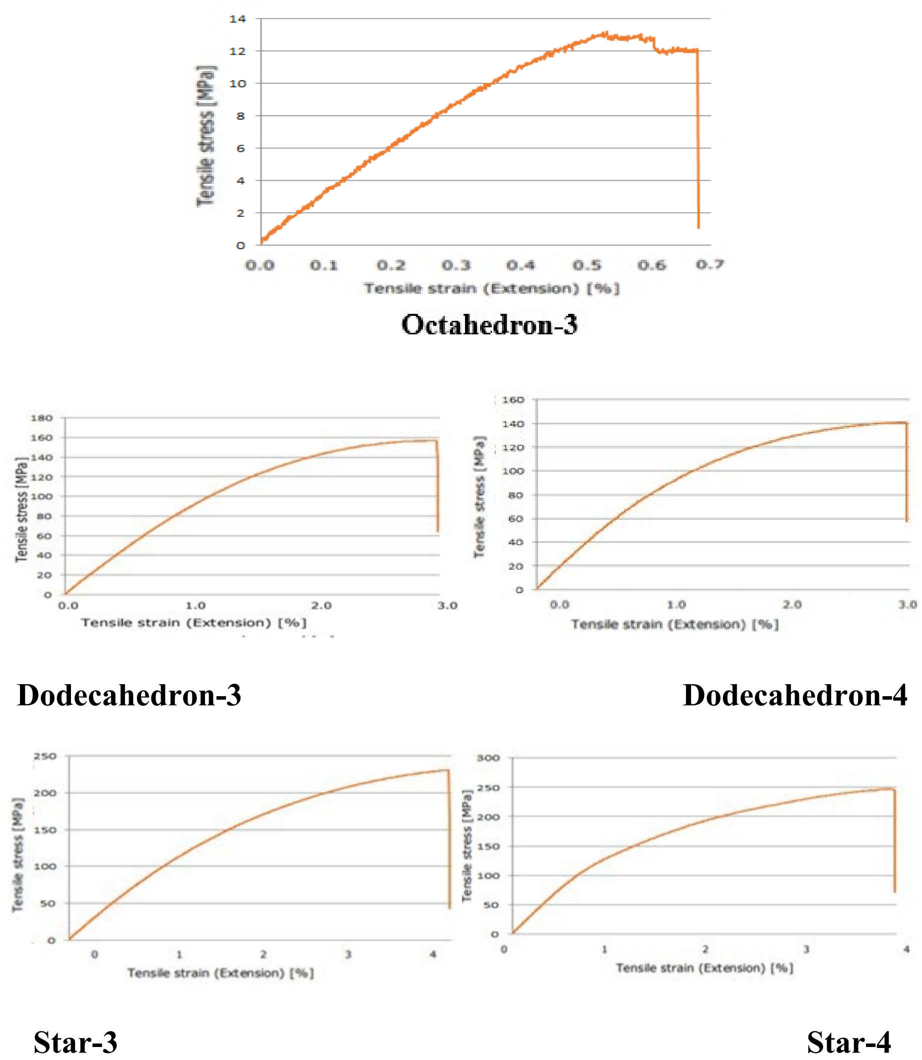


Figure 11. Tensile test results of full lattice structure design

Octahedron-3 specimen also showed a high resonance problem and it can be seen in center latticed design structures. These types of problems might be related to thin strut diameter and topological characteristics. The higher porosity of the lattice structure may have caused much more resonance problems for octahedron topology. Fracture of the star-4 specimen occurred near the center which means that this design eliminated the stress concentration problem [27]. This was a difficult problem to solve for thin strut diameter design specimens, but it has been successful as can be seen in this example. Test results were shared in Table 2. Fractures of other parts did not occur near the center as same as star-4 specimen, therefore similar example was found in the literature and the test results can be evaluated [20].

It was seen that similar results were obtained in the literature studies when the results were evaluated and that the appropriate elastic modulus was provided for bone implant applications [20, 28-30]. Star, dodecahedron and octahedron lattice structures showed the best results respectively when the elastic modulus was evaluated. Star lattices showed elastic modulus values between 10.8-14.8 GPa.. These results make them a good cortical bone implant material candidate. [31]. Dodecahedron lattices was between 7.7-7.8 GPa, while octahedron lattice was between 2.5 GPa. These lattices are more likely suitable for cancellous bone applications.

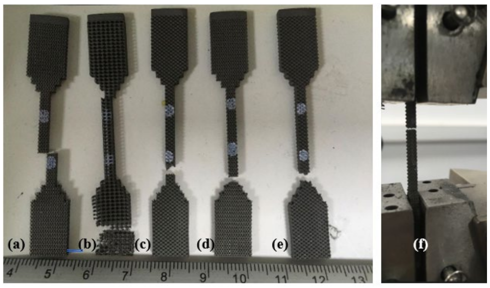


Figure 12. Star-4 (a), octahedron-3 (b), dodecahedron-4 (c), star-3 (d), dodecahedron-3 (e) and fracture example (f)

Table 2. Tensile test results of full lattice structure design

Specimen	Maximum Tensile Stress (MPa)	Maximum Tensile Strain (mm/mm)	Maximum Load (kN)	Elastic modulus (MPa)	Fracture Elongation (%)
Octahedron-3	13.25	0.04	0.86	2460.8	0.6
Star-3	231	0.03	1.44	14823.47	3.1
Star-4	247.24	0.03	1.54	10824.84	3.3
Dodecahedron-3	157.1	0.25	0.98	7843.24	2.8
Dodecahedron-4	141.35	0.25	0.88	7789.96	2.6

Fracture surface images were obtained by SEM investigations (Figure 13). The presence of shallow dimples and the formation of flat planes (smooth) indicate brittle fracture for octahedron lattice and the overall fracture morphology caused this appearance [32]. Numerous dimples and high tear ridges show higher ductility for star and dodecahedron and also show high toughness [33]. There are also cleavages in these lattice structures which provide quasi-cleavage tensile failure mechanism [34]. Star lattice has higher quasi-cleavage behavior than dodecahedron lattice.

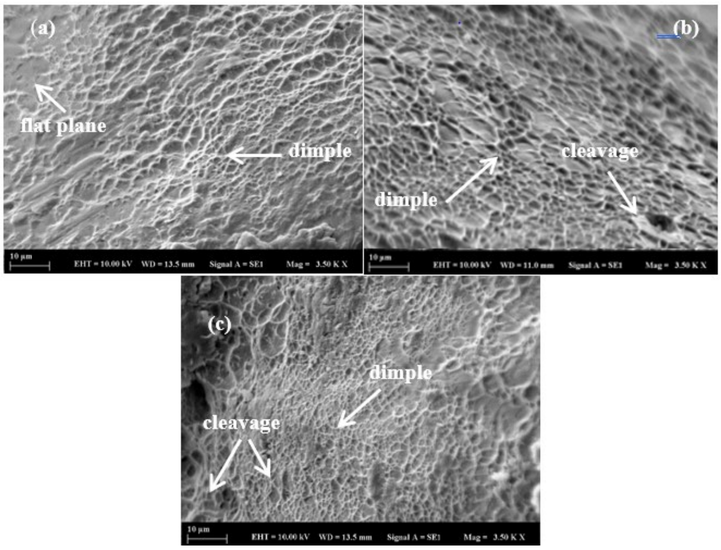


Figure 13. Fracture morphology SEM images of octahedron (a), dodecahedron (b) and star (c).

4. RESULTS

The tensile test is less preferable than the compression test because of the necessity of proper design for thin strut lattice structures. Successful manufacturing is related to proper design optimizations and secondary modifications such as post-process treatments. In this study, Ti6Al4V strut-based lattice structure designs and tensile test properties were examined for biomedical applications. Design optimization effects were shown. Dodecahedron, star and octahedron lattice topologies were used and manufactured by LPBF. The following observations were made after the study.

The proposed designs were successfully completed and their manufacturing was performed with two different support structures . Both designs were compared and their advantages and disadvantages were discussed. It was seen that full lattice structure designs were more suitable for tensile tests. Undesirable situations occurred on center latticed structure design during tensile tests and test results could not be obtained. It was seen that the star lattice topology had better mechanical performance than the other two lattice topologies after examining results from the full lattice structure design. Dodecahedron and octahedron lattice topologies followed star lattice topology respectively. It was seen that all three lattice topologies were suitable for biomedical implant applications due to their mechanical properties.

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