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Comparison of mechanical and geometrical properties of octet lattice structures using the electron beam melting

Elektron ışın eritme yöntemi kullanılarak sekizli kafes örgü yapıların mekanik ve geometrik özelliklerinin karşılaştırılması

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Abstract

Additive manufacturing methods allow to produce complex geometries such as lattice structures. Aim of this study is to identify octet truss lattice structure's mechanical capabilities. Firstly, octet truss structure designed and used to fill specimens. Specimens 1, 2 and 4 with wall and lattice structure, specimen 3 only with lattice structure and also a filled specimen are modelled. Modelled tensile specimens are additively manufactured from Ti-6Al-4V with Electron Beam Melting method. A comparison between specimens having same structural design (1, 2 and 4) has been made to gain insight about consistency of EBM method. Tensile experiments have been made with all of the specimens and tensile strength difference that can be considered significant determined among specimen 1, 2&4. Specimen 3 resulted not to be a practical approach as it showed poor tensile strength values. Lastly, tensile stress results of filled specimen are shared and compared with the other types of specimens. These results are providing a good sight for assessment of both octet truss structure and EBM manufacturing technology.

Keywords: Lattice structures, Octet truss, Ti-6Al-4V, Additive manufacturing

Özet

Katmanlı üretim yöntemleri, kafes yapıları gibi karmaşık geometrilerin üretimine izin veren yeni bir teknolojidir. Bu çalışmanın amacı sekizli kafes yapısının mekanik özelliklerini belirlemektir. İlk olarak, kafes yapısı oluşturulmamış ve tamamen dolu bir numune kullanılmıştır. 1,2 ve 4 numaralı numuneler duvar kalınlıkla kafes yapıdan modellenmiş, yalnızca 3 numaralı numune duvar kalınlıklı sekizli kafes yapısından oluşturulmuştur. Modellenen çekme numuneleri, Elektron Işını Eritme yöntemi ile Ti-6Al-4V'den malzeme kullanılarak üretilmiştir. EBM yönteminin tutarlılığı hakkında fikir edinmek için aynı yapısal tasarıma (1, 2 ve 4) sahip numuneler arasında bir karşılaştırma yapılmıştır. 1, 2 ve 4 numaralı numuneler arasında önemli sayılabilecek gerilme mukavemeti farkı belirlenmiştir. Numune 3, zayıf gerilme mukavemeti değerleri göstermiştir. Son olarak, doldurulmuş bir numunenin çekme gerilmesi sonuçları paylaşılmış ve diğer numunelerin sonuçlarıyla karşılaştırılmıştır. Bu sonuçlar hem sekizli kafes yapısı hem de EBM üretim teknolojisinin değerlendirilmesi açısından önemlidir.

Anahtar kelimeler: Kafes yapıları, Sekizli örgü kafes yapılar, Ti-6Al-4V, Eklemeli imalat

1 Introduction

3D printing of metals, additive manufacturing (AM), is a process that produces 3-dimensional geometries layer-by-layer until the whole shape is acquired. This technology gives the opportunity to manufacture complex geometries. With this opportunity, much more optimized part designs can be achieved especially in terms of weight reduction. Different requirements of different designs resulted appearing of various types of AM methods. One of these AM methods is powder bed fusion (PBF). It offers great dimensional accuracy in producing complex-shaped parts as can be seen in Figure 1.

Electron Beam Melting is a type of PBF manufacturing. It differs from the other PBF systems with its energy source. Most of the other systems are using laser as an energy source while EBM uses electron beam. An advantage of EBM process over the other PBF processes is lower residual stress effect on the parts [2, 3]. Considering residual stresses mostly effects the fatigue life of the parts, this advantage of EBM makes it more attractive than the other PBF methods.

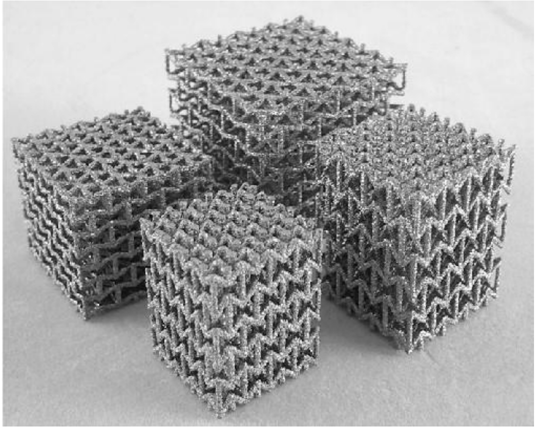

Figure 1. EBM produced lattice structures [1]

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Octet truss structures have not been thoroughly explored in the past, and, hence, we chose to conduct this study [4-12]. The octet truss lattice structure is illustrated in Figure 2. Fuller (1961) researched this structure and prepared the most detailed report of its properties [13]. The octet truss was offered as a method of 3D field filling with an efficient truss structure in a variable cell size. The nodes form a specially defined face-centred cubic structure, as shown in Figure 2(b).

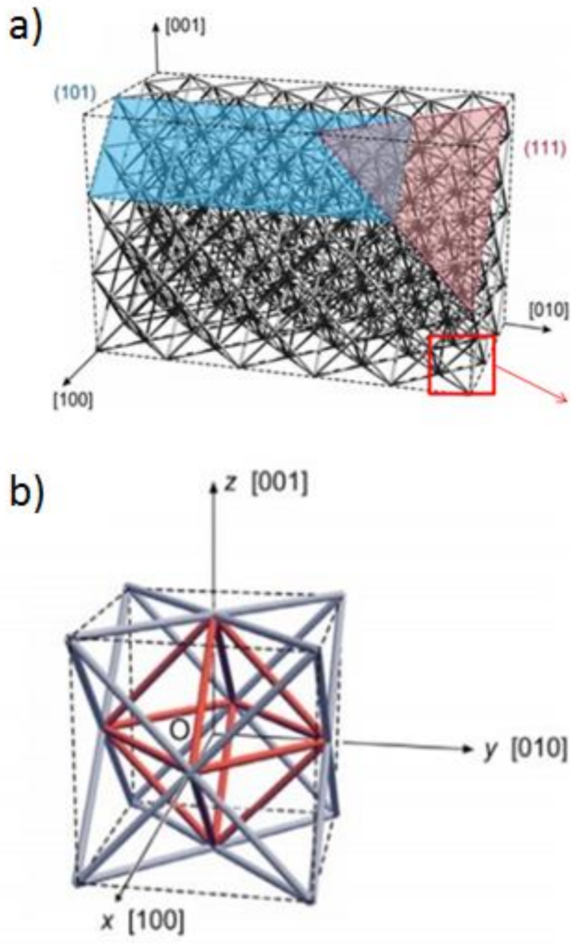

Figure 2. (a) 3D packaging of unit cells constructing an octet truss. (b) A centric octahedral cell composed of 12 struts that have 8 tetrahedrons at their boundaries. This composes a unit cell of the face-centred cubic crystal-symmetry in the octet truss lattice. The intersection of 12 struts is a node of the octet truss [8].

Dong et al. (2015) used snap-fit and vacuum brazing method in order to produce 2% to %16 relative density octet-truss lattice structures from Ti-6Al-4V sheets. The study proved that octet-truss structures performs better than mechanical properties over other cellular materials [8]. Deshpande et al. (2001) [9] made a research on aluminium alloy casted octet-truss structures and the results showed that these structures can be alternative against metallic foams with the aim of obtaining lightweight structures [9]. It is extremely efficient to use lattice structures comprising octet trusses for the production of high-density materials, as they provide high performance [14]. Li et al. (2008) [15] studied lattice block which is investment casted with aerospace quality. Experiments under compression, bending and impact points that high strength and ductility can be reached [15]. Figure 3 illustrates the raw material Ti-6Al-4V, Al-7Si-0.3Mg [9], and Ti-6Al-2Sn-4Zr2Mo alloys [15, 16], for the space modelling lattice structures under the density-dependent modulus of compression load and foams with low density (metal, polymer, and alumina).

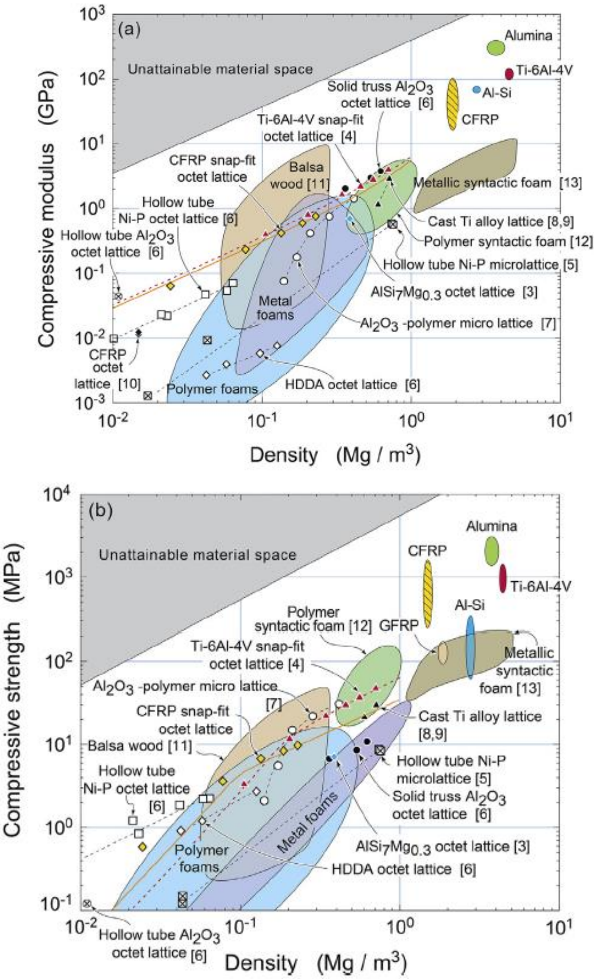

Figure 3. Comparison charts of material (a) stiffness and (b) strength under compression against density (Mg/m^3). Zones that cannot be achieved under ambient conditions are indicated by the grey shaded areas [7].

Similar structures produced by electrodeposition of Ni–7P [17, 18], were manufactured from carbon-fibre laminate composites [19] produced by investment casting methods. The modules and strengths of the foams and lattices were scaled by the raw materials [20]; however; foams are essentially more malleable and weaker than their topological counterparts (made from the same material and density). Metal alloys with low density at milimeter intervals are useful structures for strut-diameter lattice structures in stress-assisted aerospace industries [9] and 3D additive production methods [21, 22]. However, the strength to weight ratio of aerospace materials must be extremely high; therefore, these operations remain difficult. Aluminium and magnesium alloys are widely used in this industry. As the strength-weight ratio of titanium alloys is twice or more times better than aluminium alloys, there is a special interest in these alloys in order to produce octet truss structures. In addition, numerous titanium alloys can easily exceed the limits of aluminium or magnesium-based light metal alloys at continuous service temperatures [23]. Another advantage of titanium alloys is their high corrosion strength, and they are widely used in chemical processing equipment for this reason [24]. Ti-6Al-4V is the most comprehensively used titanium alloy and makes up half of the total titanium use [24]. Its main use in aircraft structural components and turbine engines is in fasteners [25, 26]. Titanium alloy lattice structures are manufactured by using investment casting methods to provide aerospace-quality standards [27,16].

The price and confusion of the titanium investment manufacturing process is excessive, and hence, there is insufficient data on the mechanical properties of titanium-based lattice structures as functions of relative density [27,28].

This study is focusing on tensile properties of octet-truss lattice structures which built with EBM. Experiments made on five specimens that fabricated at the same time in the machine. Three specimens (1,2,4) containing wall along with the lattice structure and specimen 3 do not have any addition, only lattice structure. Also a filled specimen without any pores. Purpose of producing specimens 1,2 and 4 from same CAD model is measuring consistency of EBM machine and process parameters. With the aim of determining effect of wall addition to the specimens, a comparison made between specimen 1 and specimen 3. After that, both types of specimens compared with filled specimen. Numbers of specimens are meaningless as they were given to the specimens with the order of taking out from machine plate The article should include main titles such as Abstract, Introduction, Material and methods, Results and discussion, Conclusions and References.

2 Material and methods

2.1 *Electron beam melting process*

All the specimens in this research were produced with ARCAM Q20. It is an EBM machine with production volume of Ø350×380 mm and is suitable for the production of critical parts, such as turbine blades for airplanes. The electron beam melting is fully capable of producing dense metal parts. A strong electron beam (7 kW) is used to form a layer by melting the metal powders in accordance with the geometry obtained from the 3D CAD model. The 3D CAD model of the piece is divided into 2D slices, usually 0.1–0.07 mm thick, with special software. The arithmetic mean surface roughness Ra is approximately 25–35 mm [28,29]. The electron beam melting process works according to the kinetic energy principle of electrons. The electrons emitted from the filament accelerate towards a very high-speed building platform by forming an electron beam. When these electrons collide with the metal powder, the speed of the electrons decreases and the kinetic energy is transformed into thermal energy to generate heat, which melts the dust particles. The electron beam is formed in an electron beam gun comprising an anode, a cathode, and electromagnetic focus and deflection units. This gun heats up and emits electrons when the electric current passes through the tungsten filament (cathode). In the meantime, 60,000 V is applied to the anode at the bottom of the filament and the extremely high potential voltage difference helps accelerate the electrons from the filament in the desired direction [30]. The resulting beam is then focused on the electromagnetic coil with the help of the focus. Then, the beam is deflected by the deflection coil to special areas on the building platform at scan speeds as high as 8,000 m/s. In a previous study, the scan rate was reported as 1,000 m/s [31]. An astigmatism coil helps to keep the beam in focus, regardless of its position on the build platform. Without the coil, the beam tends to extend from the building region to the edge, thus extending to a wider area. The whole process is conducted under vacuum. This vacuum environment overlaps the ions with those that may act as obstacles and cause the electron beam to dissipate [32, 33]. Figure 4 illustrates the components of the EBM process [34,36].

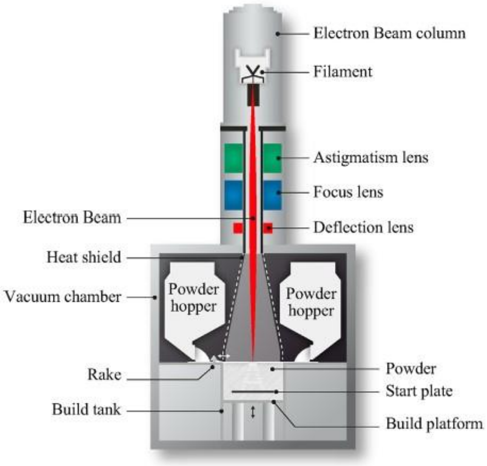

Figure 4. Main components of EBM process [30-38].

2.2 *Material properties*

Titanium alloys are commonly used in additive manufacturing technologies. In addition, titanium alloys are the most widely used materials in aerospace industries. These alloys are light-weight, and exhibit good corrosion resistance along with high strength properties. Hence, we chose to use Ti-6Al-4V in our study. According to the manufacturers, the delivered materials should have the mechanical properties listed in Table 1.

Table 1. Key mechanical properties for EBM-produced components [37]

	EBM as-built
Yield Strength (MPa)	950
Ultimate Tensile Strength (MPa)	1020
Elongation to Fracture (%)	14
Hardness (HV)	327
Elastic Modulus (GPa)	120

3 Experimental setup

3.1 *Modelling the specimen*

In this study, the specimen was modelled with SpaceClaim [39]. First, a unit octet truss geometry was modelled, as shown in Figure 5. This unit geometry was duplicated to fill the specimen. According to the dimensions given in Table 2, the specimen modelled and shown in Figure 6.

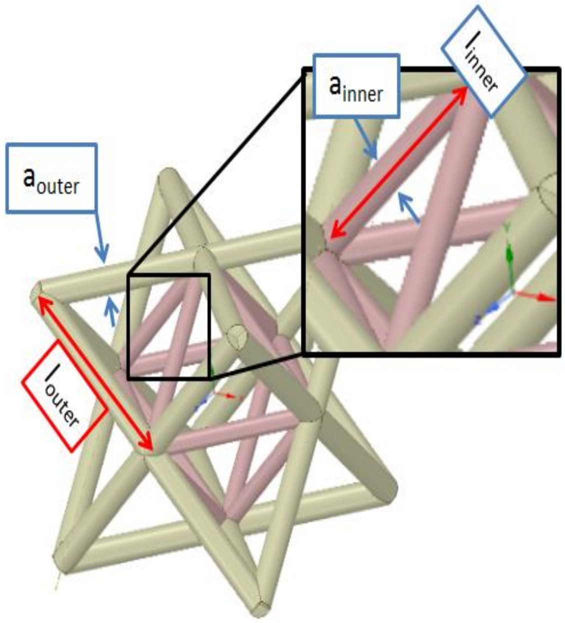

Figure 5. Unit octet truss geometry

Table 2. Details of unit octet truss geometry

	Inner Beams	Outer Beams
a = strut diameter (mm)	0.08	0.1
l = length of each strut (mm)	0.71	1.41

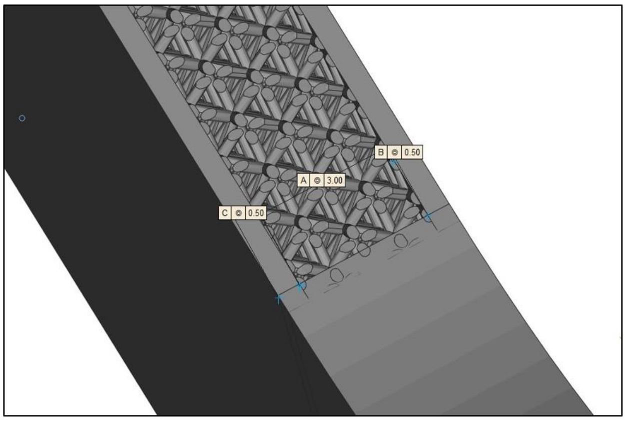

Figure 6. Isometric view of octet truss part of specimen

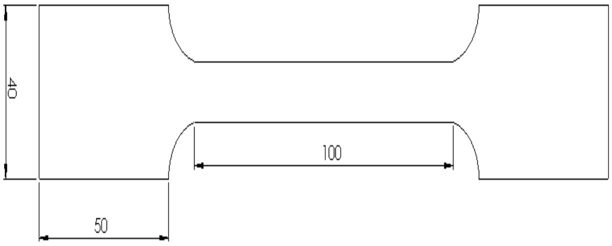

Figure 7. Specimen dimensions

Figure 7 shows the dimensions of specimens and the thickness is 4 mm. Relative density percentage at the octet-truss sections is 30% for all the specimens.

3.2 *Tensile test setup*

Tensile tests made with Instron 8802 hydraulic test machine in Figure 8 by ASTM D3039 standard [40]. Width and thickness values of specimens entered to the system with the test speed of 0.5 mm/min.

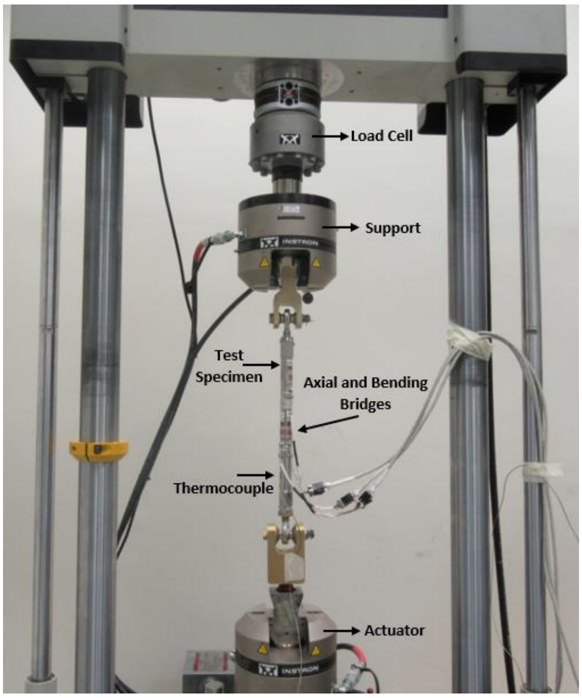

Figure 8. Tensile experiment setup

4 Results and discussions

Additive manufactured parts may not be accurate to the design. Due to high temperatures, non-uniform powder dimensions etc. the resulted parts are not identical even if they are based on the same design and manufacturing parameters. In order to research, the specimens 1, 2 & 4 (Figure 9) were built using the same solid design & process parameters and tested under the same conditions.

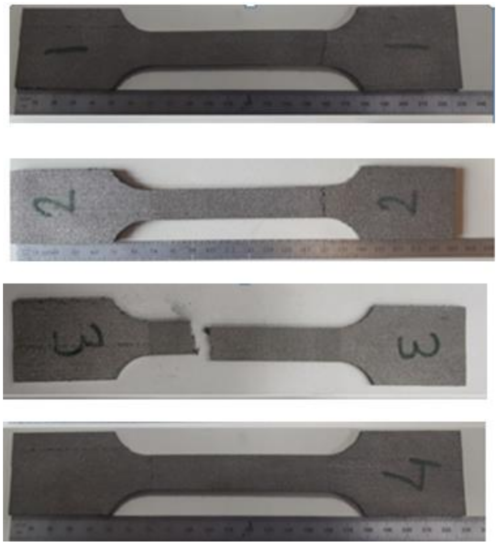

Figure 9. Octet-truss specimens

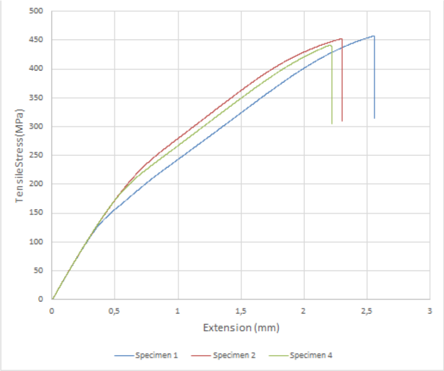

Figure 10. Tensile test data of specimens 1, 2 & 4

Table 3. Experimental ultimate tensile stress values of specimens 1, 2 & 4

Specimen Number	Ultimate Tensile Stress (MPa)
1 (wall+lattice structure)	457.0
2 (wall+lattice structure)	452.43
3 (lattice structure only)	211.2
4 (wall+lattice structure)	441.32

Figure 10 and Table 3 shows the difference occurred due to manufacturing method. Ultimate tensile stress difference between the best performed specimen 1 and worst performed specimen 4 is 15.7 MPa which is equal to 3.5%. If the analytical results taken into account which is 474.77 MPa, the gap against specimen 1 is 17.77 MPa and this gap is equal to 3.8%.

Figure 11. Specimen 1 (wall+lattice structure)

Figure 12. Specimen 3 (lattice structure only)

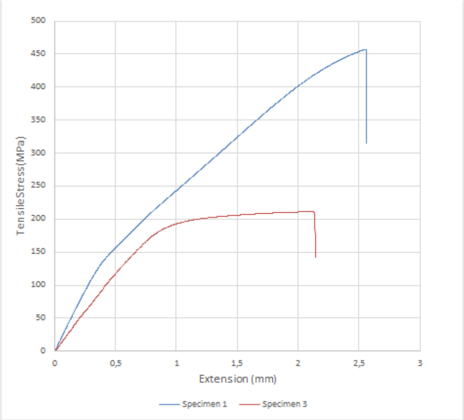

Figure 13. Tensile test data comparison of specimen 1 & 3

To investigate effects of wall addition on strength of the parts, specimen 3 manufactured without wall structure as shown in Figure 12. Comparing to the specimen 1, specimen 3 could achieve less than half tensile strength with a value of 211.2 MPa as can be seen in Figure 13. Considering cracks appears on the outer surfaces at the beginning, specimens consisting wall structure resisted much higher loads before failure, thus specimen 3 failed earlier due to this reason.

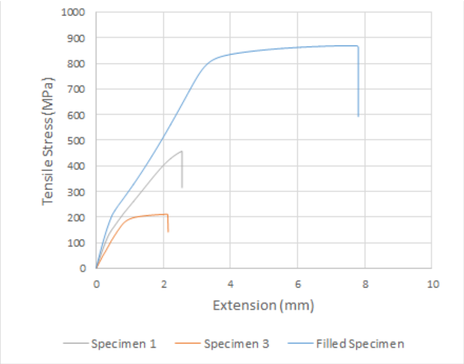

Figure 14. Tensile test data of specimen 1, 3 & filled specimen

The chart shown in Figure 14 represents the results from three different types of specimens. Specimen 1 which is made from wall and lattice structure, specimen 3 only lattice and also filled specimen without any empty spaces through the whole geometry. Filled specimen has 868.9 MPa tensile strength that means filled specimen is 190% better than specimen 1 and 412% better than specimen 3 in terms of tensile strength.

5 Conclusions

Additive manufacturing can be considered as a recent technology. Exploring this technology to understand what are the gives and takes, determine advantages and disadvantages is a crucial task. Taking into consideration EBM is a manufacturing method, exploration mostly starts with strength of the produced parts for engineering. Also one of the promises of additive manufacturing is allowing to build complex shapes. Hence, this paper focused on these subjects. Four of the tested specimens include octet-truss structures, three of them have wall and one without it. Also a filled specimen has been built. After tensile tests, wall structure addition proved to be an effective method to increase the strength more than twice times as specimens with wall achieved 457 MPa ultimate tensile strength comparing to the 211.2 MPa of specimen which doesn't have wall. It adds extra weight to the part but considering the strength increase it is likely going to be neglected. Octet-truss specimens are compared with the filled specimen to see the achievements of lattice structure with its 30% density. The result values are promising. EBM is a special type of powder bed fusion additive manufacturing since its heat source is electron beam, not laser. In this study, not only the strength of the octet-truss lattice but also the consistency of EBM method is investigated. Three specimens produced from the same solid model and with the same process parameters. Specimen 1 showed 457 MPa tensile strength while Specimen 2 showed 452.43 MPa and Specimen 4 with 441.32 MPa. If three of these specimens had the same geometry after manufacturing, then they would show almost the same ultimate tensile stress results since the tests applied on the specimens under the same conditions. Difference between the strongest and weakest specimen is 15.7 MPa which is equal to 3.5%. Depending on the designer and design, these results can be considered as significant or insignificant. Octet-truss lattice structures proved to be a worthy approach to reduce weight from the parts while still meeting the necessary strength. Additive manufacturing combined with lattice structures is an attractive combination for the studies on lightweight parts.

Acknowledgement

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Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): 5%

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