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Reviewed Paper

MECHANICAL PROPERTIES OF BIOCOMPATIBLE 316L STEEL RHOMBIC DODECAHEDRON LATTICE STRUCTURES

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Abstract

Additive manufactured lattice structures have the potential of enhancing many of today's engineered products manufactured by traditionally methods. The former provides the capability of altering the mechanical, thermal and acoustic properties of structures through the use of lattices. However, more investigation is needed to better understand the manufacturability and the mechanical behavior of sandwich structures. This paper investigates the influence of strut size on the global stiffness and the compressive strength using compression testing of sandwich structures. Digital Image Correlation (DIC) analysis is applied to determine the local strain distribution during the compression test. It is found that the compressive strength increases linearly with increased lattice strut diameter. Moreover, based on DIC the maximum strains are observed in the strut connection regions.

Introduction

During the first decade of the 21st century, the rapid development of Additive Manufacturing (AM) methods has led to a variety of processes and materials that could produce geometrically complex parts. This is especially important for complex internal geometries, like conformal cooling channels or internal pneumatics. The most common process for fine metal geometries is laser powder bed fusion. This process can produce parts with material properties close to that what is observed in forged parts [**1**]. Despite the progress and new possibilities, however, still the majority of the manufacturing industry does not regard AM as a serious manufacturing process alternative. There are many reasons for this: Firstly, the most profound one is that there is no tradition for designing parts intended for production by AM. Secondly, building parts by AM is not cheap or "rapid" compared to conventional machining—and the cost increases with building time and the amount of material added to the part. On the other hand, while the cost of conventional machining increases with the amount of material removed, it is considerably faster than AM for shaping massive objects. Furthermore, machining has a much wider array of alternative materials, and it is a well-known process capable of producing parts with a precision and surface finish that is very different from what can be produced by AM. Hence, employing lattice structures is a way to make AM more competitive in industry, since this strategy may simultaneously decrease product weight and increase value. Production cost decreases due to less material consumption, which may imply less building time. In addition to this, lattice structures offer the capacity to customize the mechanical properties as for the case of implants [2], [3]. Some of the structures could, for example, enhance car safety and reduce the weight while improving energy absorption capabilities of systems [4].

There are many different geometry configurations that can be assembled into truss constructions. As proposed by Ashby(2006), the most important concept in analyzing mechanical behavior is the distinction between a stretch and a bending-dominated structure [5]. The stretch dominated structure is exceptionally stiff and strong relative to its weight. The Eiffel tower in Paris or a truss bridge are good examples of such stretch dominated structures. Such structures are often filled with triangles, as triangles are structurally stable without any bending forces. Therefore, the higher forces are seen in the axial direction of the truss beams. On the other hand, a bending-dominated structure is not as stiff and strong, but may absorb significant energy under external compression. These structures are typically constructed from polygons of more than three angles. This reduces the stiffness of the structure as large bending moments occur at the connecting edges of the polygons, bending the individual members of the truss. The result is a more flexible structure [6].

Published studies on mechanical properties of structures are carried out by changing the thickness or the size of the structure [7], [8]. Another alternative is to change the angles in the unit cells, creating different geometric configurations and internal constraints between individual members. The common state of all the studies is that none of them has constrained external edges. This is an issue regarding how the lattice structures are used and hence how they interact with the surroundings and loading conditions. Often the structures are built on the inside of a surface or as a sandwich structure, which make the ends constrained to different degrees. The boundary condition at the top and bottom layer influences the force path and the deformation and may create local stress concentrations. It is therefore important to understand the behavior of the geometrically-complex, constrained lattice structures. This is especially important for bending-dominated structures, as they have a tendency to be more flexible.

Materials and Experiment

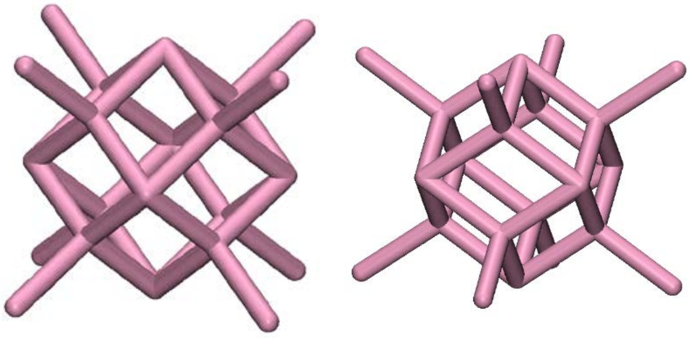

Figure 1 - Rhombic Dodecahedron unit cell from two view angles.

There are many ways to design bending-based unit cell configurations. The criterion in this study was to have a small unit cell with a high degree of anisotropy and produceability. These criterions where met by employing the so-called Rombic Dodecahedron structure seen in **Figure 1**. This structure consists of twelve rhombuses with 70° and 110° angles, making up a small pointy ball. Placing four unit cells together forms a fifth cell, with equal geometry as the cells around it. The structures were created using 3-matic™ form Materialise™.

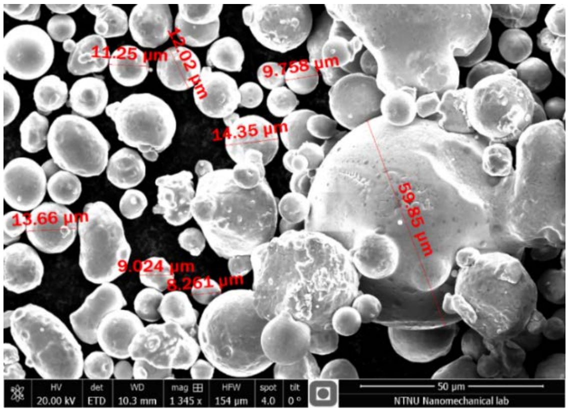

Figure 2 - Recycled powder used to manufacture the lattice structures

The machine used in making the test samples was a Concept Laser M2 with a 200W Nd:YAG laser. This is a laser powder bed fusion machine that handles many different metals, including reactive materials. The parts were manufactured without build strategy for minimizing stresses, as the structures are separated. The parts were produced with a laser effect of 200 W and laser speed along the layer at 800 mm/s, with a layer thickness of 30 µm. The focus diameter of the laser has a Gaussian distribution with 3σ within a diameter of 150 µm, and the distance between the laser line movements is therefore set to be 105 µm, which is standard for this type of machine.

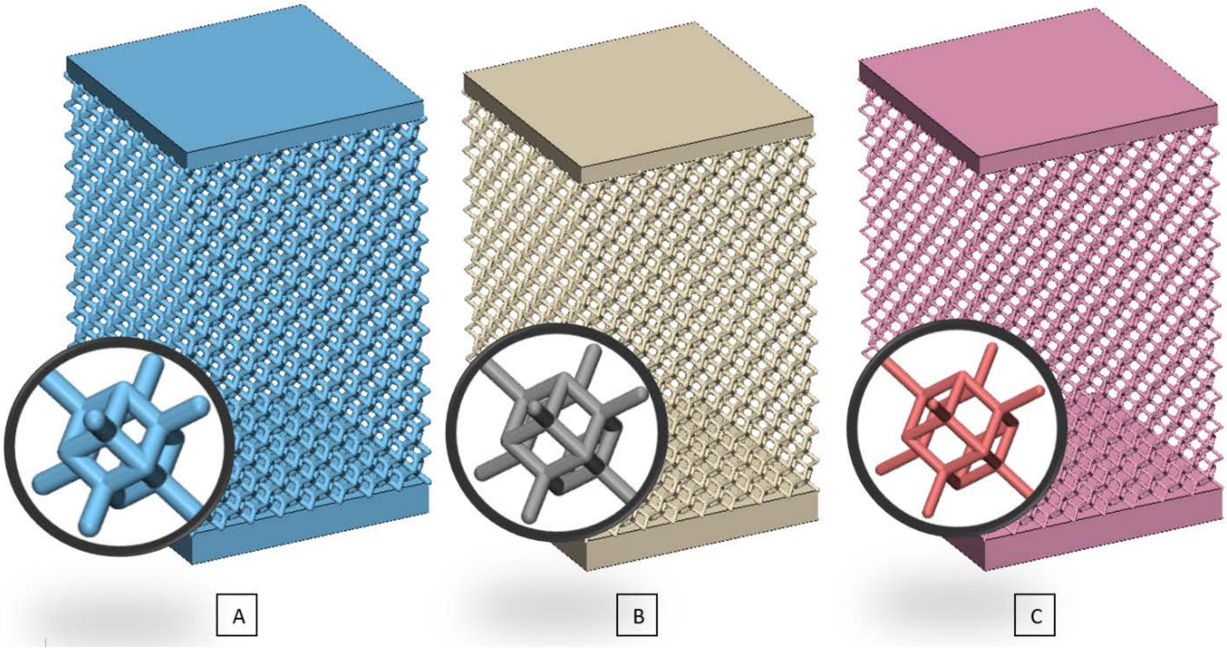

Figure 3 – The three test samples with unit cell size of 5 mm x 5 mm x 5 mm. The size of the lattice structures are 40 mm x 40 mm with a height of 60 mm. A) Truss diameter 1 mm B) Truss diameter 0.7 mm C) Truss diameter 0.5 mm

The samples were built in the stainless steel biocompatible material 316L. This is a powder that has been recycled multiple times. Hence, the samples are a worst-case scenario when it comes to powder homogeneity and roundness. **Figure 2** shows an SEM image of the powder. The tested hardness of the manufactured parts is ~20.7 HRC. According to the data sheet, the yield stress of the material is 470 N/mm^2 and the hardness is 20 HRC, with a tensile strength of 570 N/mm^2. The quasi-static compression testing is performed at room temperature, using an Instron 1342 universal testing machining with 100kN load cell. The Rhombic dodecahedron lattice structure was compressed with a speed of 5mm/min, allowing quasi-static conditions. The local deformations are determined using high-speed camera. Digital correlation image analysis is applied using an Allied Vision Stingray F504B to quantify the strain distribution during the compression test.

Using the Rhombic Dodecahedron unit cells from **Figure 1**, an experiment was set up with a unit cell size of 5 mm x 5 mm x 5 mm and changing strut diameters. The struts were produced in diameters of 1 mm (A), 0.7 mm (B) and 0.5 mm (C) as displayed in **Figure 3**. The figure illustrates the 40 mm x 40 mm structures with a height of 60mm. Hence, the structures can fit eight unit cells in both directions along the massive section, and twelve unit cells in the between the massive sections. Each structure contains 768 unit cells in total.

Results and Discussion

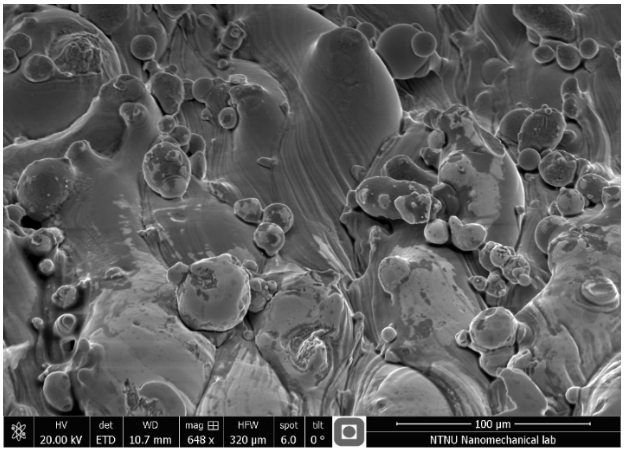

Figure 4 - SEM image of partially melted particle on the surface of the truss of the lattice structure

Figure 4 displays an SEM-image of the lattice beam. The additive manufactured truss present similar geometry as in the initial design model defined in the CAD file. A detailed inspection reveals bounded particles on the truss surface. Santorinaios et al. [9] reported similar observation in previous studies. The partial re-melting of the powder is considered being an important factor for this observation; although the geometry of these imperfections are different from the “balling”. Furthermore, the size of the element on the truss surface has the same average size as the raw material, which supports the hypothesis of partial melting of steel powder.

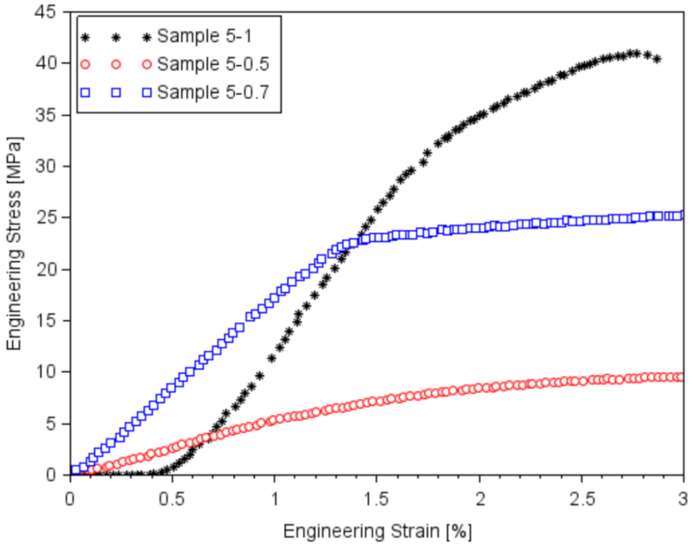

Figure 5 – Stress-strain curve for the sandwich structure under a strain rate of $\dot{\varepsilon} = 0.09s^{-1}, T = 26$℃

Figure 5 shows the obtained engineering stress (force-to-area ratio) in MPa and normalized deformation ('engineering strain') in % during a compression test with a constant displacement of 5 mm/min applied at the top surface of the lattice structure. The same conditions were applied to all the samples. For each single sample, the test was repeated three times. A summary of the obtained results in terms of average compressive 'yield strength' for different strut geometry is listed in Table.1.

Table 1 – Average compressive yield strength

Strut diameter	Average Compressive yield strength
0.5 mm	5.5 MPa ±0.5
0.7 mm	21.5 MPa ±2.3
1.0 mm	42 MPa ±3.5

The evaluation of the relative stiffness based on the 316L Young's modulus and the relative density of the structure shows a linear behavior. The strut thickness increases linearly with the relative stiffness. This observation is in accordance with the results obtained for other structures by Ashby [5]. **Table 1** shows the influence of increasing the strut dimeter from 0.5 mm, 0.7 mm and 1 mm on average yield stress. As shown in **Figure 6**, the increase of the density by 40 % and 100% increases the stiffness by a value of 3 and 5 respectively. It is suggested that further investigation of the connection points is needed in order to relate the size of the connection and its geometry to the stiffness of the structure.

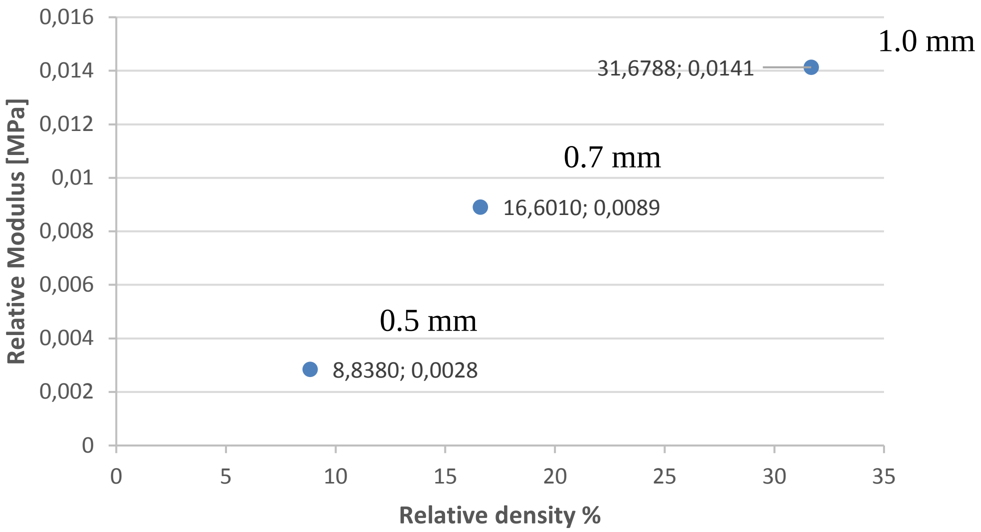

Figure 6 - Influence of the density through control of strut thickness on relative stiffness

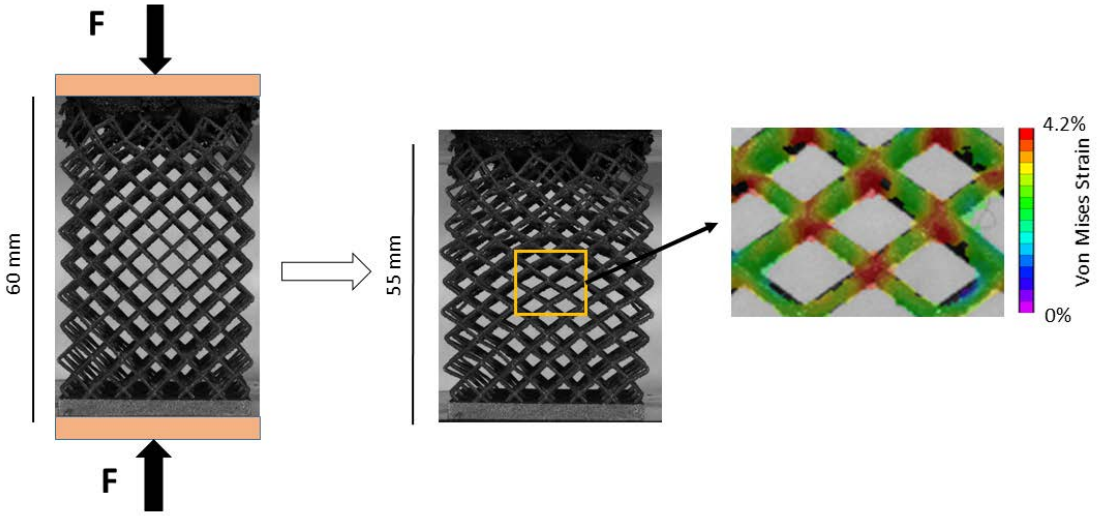

Figure 7 - Compression of the Rhombic lattice structure and the measured Von Mises strain after a reduction of initial length by 5 mm.

The DIC results suggest that the strut connections are experiencing the higher deformations. The intensity micro-strain experienced by the struts is depending on their diameter and also the unit cell size. **Figure 8** displays the DIC results for the compression testing of a rhombic dodecahedron with a lattice unit cell of 10 mm and strut diameter of 0.5 mm. The local value of von Mises strain is measured at a global deformation of the structure of 8.33%. This maximum local strain (4.0 %) is located at the strut connection points as displayed at the right-hand side of **Figure 7**. It is therefore important to understand how the manufacturing process influences the microstructure, and hence the product properties specifically at these locations. For example, the fatigue behavior of this lattice structure will depend on the microstructure defects imposed by the additive manufacturing process at these locations. This can be achieved through an optimization of the building strategy and the process parameters.

Conclusion

In this work, the influence of strut diameter on mechanical behavior in terms of nominal compressive strength and stiffness of a rhombic dodecahedron lattice-based structure is investigated. The structures are built using selective laser melting of biocompatible 316L stainless steel. The increase of the strut diameter caused a substantial increase of the mechanical properties, stiffness and weight. The DIC results showed that the thickness did not influence much the measured local strain of the strut, indicating strains mainly governed by deformation kinematics. For the configurations tested, the most strained point was observed at the connection points of the lattice structure. Future studies on micro-strain characterizations, as well as the influence of the lattice unit cell size combined and the strut diameter on deformations of individual members, are in progress and will be reported elsewhere.

Acknowledge

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