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Investigation of Compressive Stresses of Stainless Steel 316L Diamond Lattice Structures Under the Effect of Spherical Connections Produced by SLM Additive Manufacturing

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Abstract: In this study, the compressive stresses of dodecahedron diamond lattice structures have been investigated. The finite element method has been used for Stress analysis. After the simulation, it was found that more stresses are applied at the junction of the struts of this structure due to the application of compressive force. For this purpose, the connection point of the structure's struts was strengthened by spherical connections, and a new type of dodecahedron structure was created. The validation and effect of spherical connections in compressive stresses have been evaluated experimentally. Two types of diamond lattice structures are made of stainless steel 316L by the SLM method. The results show that in the same condition, the use of spherical connections with twice the diameter of the structure's struts helps to strengthen the structure and increase its compressive strength by 18% compared to the simple structure.

Keywords: Additive Manufacturing, Compressive Stresses, Lattice structures, Spherical Connections, Stainless steel 316L

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Research paper

1 INTRODUCTION AND LITERATURE REVIEW

Additive manufacturing technologies are known for their ability to fabricate parts with complex geometries. Lattice structures use this ability to create parts with a high strength-to-weight ratio and other desirable structural qualities [1-2]. These structures have the potential to reduce the weight of components in the aerospace and biomedical industries with a new approach to incremental fabrication [3]. Using these structures more effectively reduces the time and cost required to make additive metals.

Numerical and experimental studies have been carried out in this field. In previous research, the properties of foam and lattice structures have been investigated, and by analyzing the mechanical properties of cellular solids, a wide range of properties for alternative structures have been presented [4]. This research has been used to investigate Maxwell's stability criterion and the bending behavior of the structure in the current research. A comprehensive summary of experimental data on mechanical response is presented by examining the design, construction, and performance of SLM lattice structures, a source of experimental and design data for AM tools has been provided to designers [1]. In addition, research with the design of 9 lattice structures with relative density, the geometric quality of stainless steel 316L construction, and the manufacturing capability of the SLM technique have been examined, and reasons for the deviation of the dimensions of the lattice struts with the designed struts have been determined [5]. The use of a series of experimental tests on the mechanical properties of random metal foams and regular lattices with titanium grade 5 number 3 has been evaluated by the EBM technique according to the unit cells of the lattices to ensure that the mechanical properties under what type of conditions have measured independently of the size [6]. In the current study, to obtain the desired mechanical properties from the experience of the aforementioned research, select the appropriate number of unit cells in the structure used. In a doctoral thesis, a wide range of mechanical properties of titanium grade 5 diamond structure made by the EBM technique has been analyzed, and its working method is a suitable reference for the current study [7]. An early study reported an article that was presented at the 13^{th} International Conference, which investigated the lattice structures made of nickel-based superalloy by SLM, and various mechanical tests were performed on them, and their anisotropy was also investigated [8]. Since stainless steel 316L has been used in the current study using the SLM method, the compression test results presented in the mentioned research have been reviewed and taken into consideration in the current study. In previous research, the effect of construction direction and strut length on 4 compressive mechanical characteristics of BCC structure under quasi-static axial compressive loading was investigated using finite element analysis, and two types of lattices were created and analyzed [9]. The effect of strut length mentioned in the previous research was used and the compatibility of the length of the strut with its diameter was considered. The application of the lattice structure, according to the selected material, will have the ability to be used in an environment with high temperatures. It should also be noted that due to the presence of chromium, this alloy has acceptable corrosion resistance [10-11].

In the previous studies and works of researchers, structures have been studied from the point of view of product stylization. In this research, in addition to maintaining the above advantage, the effect of compressive stresses on this structure was investigated and the critical places where the stress is high were identified, with the results obtained in the places where the struts of the structure are connected, spherical connections were added to the structure to strengthen and optimize, this operation created a new dodecahedron structure that is stronger than the previous structure. Therefore, a piece made with a structure is expected, it is suggested that it can be used in places where the applied stress level is equal to the experimentally measured resistance of this structure. Apart from industrial use, this structure may also have the possibility of being used in medical applications due to its good corrosion resistance. The analyses performed and the computational approach of this study can be used for materials that have better medical applications. For example, making the same structure and using it for medical implants made with titanium will be practical [3].

2 MATERALS AND METHODS

2.1. Material Properties

In this study, non-standard tensile tests were used to evaluate the material properties. This not only saves material and time of tests considerably but also helps to consider the effects of position and build rate in the case of the metal additive manufacturing process. Miniature test specimens similar to the standard ASTM E8 were designed and used for testing. The test was mainly conducted on the baseline material stainless steel 316L, while designing the miniature specimen, the standard architecture of the specimen was retained [12].

ASTM E8 provides test methods for tension testing of metallic materials [12]. Considering these guidelines and the previous work in the field, a sheet-type specimen with a square cross-section was designed for a miniature tensile test. These specimens could either have wedgeshaped shoulder ends for gripping. The design miniature specimen had a gage length of 5.7 mm and a width of 1.2 mm. The overall length of the specimen was 17 mm with a thickness of 0.5 mm. The gage area was nominally 1.2 mm by 1 mm. The test set-up was designed for 2000 KN ratings and grips were designed for this rating [12]. The miniature specimen follows the same architecture as the ASTM E8 standard, square cross-section test specimen. The dimensions of the miniature specimen are shown in “Fig 1”.

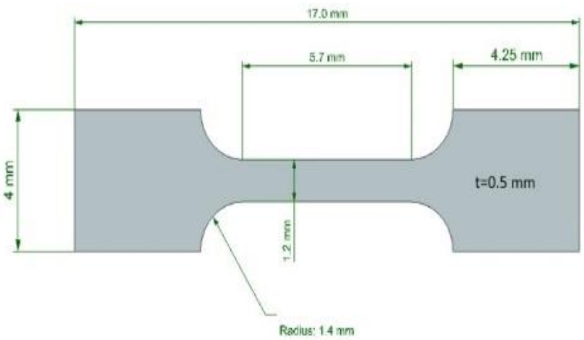

Fig. 1 ASTM E8 – Sheet type tensile test specimen [12-13].

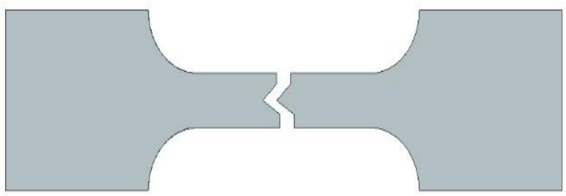

Fig. 2 Expected post failure conduction of designed miniature tensile specimen showing the failure in the gage section.

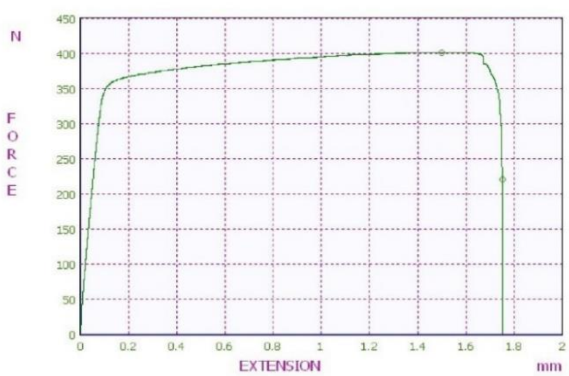

Fig. 3 Force-displacement diagram of stainless steel 316L material.

To validate the test, tensile failure should be in the design gage section. Figure 2 shows the expected post-failure condition of the tensile test specimen that would confirm the validity of the test. Tests were conducted on the ASTM E8 standard. The tensile tests were conducted with a constant speed of 0.15 mm/s on 3 Specimens. Force-displacement data was acquired from the test frame according to the diagram as shown in “Fig. 3”. According to this figure, the properties obtained for the Stainless steel 316L material are listed in “Table 1”.

Table 1 Stainless steel 316L material properties

Yield Strength, MPa	595±9
Ultimate tensile strength, MPa	671
Elongation [%]	23.8±0.5
Density, g/cm^3	7.99
Composition	10.34Ni-16.1Cr-2.62Mo-0.8Mn-0.25Si-0.06C

2.2. Hypotheses and Experimental Work

The studied structure is a simple dodecahedron diamond lattice structure shown in “Fig. 4”. Each node was connected to four struts with an angle of 109.5 degrees to each other. The struts were designed with a circular cross-section with a fixed diameter of 0.3 mm in single cells with dimensions of 3x3x3 mm and the overall dimensions of the structure are 12x12x12 mm. The periodic structure consisting of a dodecahedron structure creates a single diamond cell. The number of unit cells in each direction is 4 and a total of 64 unit cells in the structure have been used.

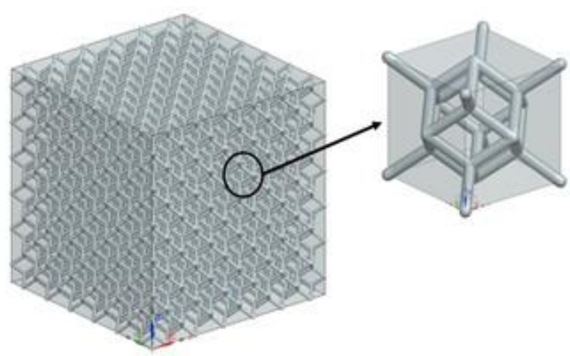

Fig. 4 Simple diamond lattice structure.

For preliminary investigation, a unit cell of the structure with the boundary conditions shown in “Fig. 5” was subjected to a compressive test simulation in the software. In the numerical solution to apply the boundary conditions and accurate loading, the constraint boundary conditions were used in which the grid is placed between two plates so that the upper and lower levels are tied to completely rigid plates while all the other four sides of the grid are unrestricted [14]. These plates are considered representative of the jaws of the compression testing machine.

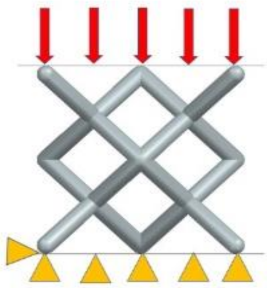

Fig. 5 Constraint boundary conditions.

The vertical behavior of contact between the lattice structure and the indicated plates is rigid (Hard) and the tangential behavior is also defined without friction. The isotropic material is considered and the effects of strain rate are ignored. For the numerical solution, the relationship between the deformation and stress of the material is considered in the form of the entire plastic range. The relevant diagram and data points defined in the software are given in “Fig. 3”.

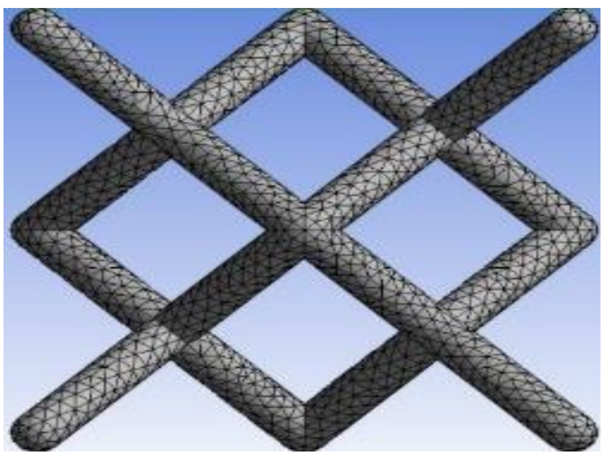

Fig. 6 4 Nodes rigid 3D shell mesh.

A meshing is shown in “Fig. 6”, the used element type is a 4-node rigid 3D shell element. This type of element provides high performance in terms of computing time and accuracy of results which fulfils the purpose of this study, which is to investigate axial compressive stresses. As shown in “Fig. 7” in the numerical solution of the simulation of the unit cell compressive test, it was found that more stresses are applied to the structure at the connections of the struts.

So, knowing this, the connection between the struts was strengthened by spherical balls and a new structure was created which is shown in “Fig. 8”. In the structure with spherical connections, the radius of the spheres was considered 0.6 mm.

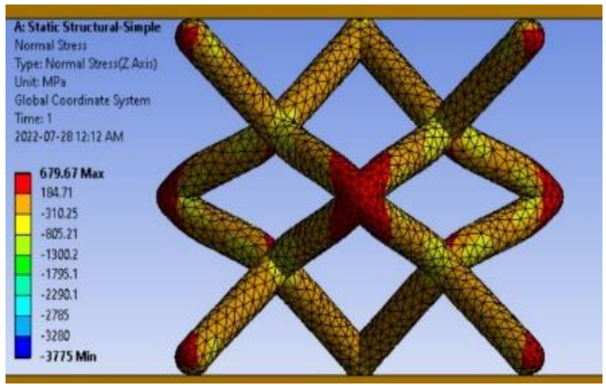

Fig. 7 Normal Stress in the simple diamond lattice structure.

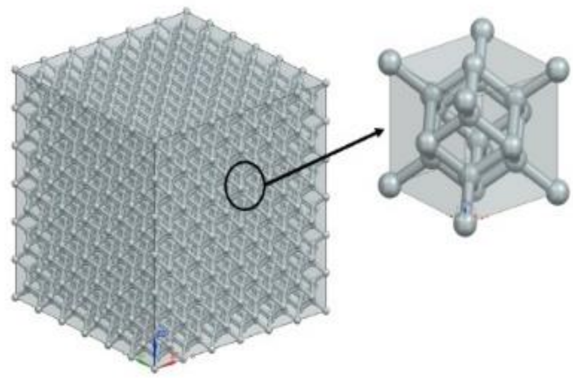

Fig. 8 Reinforced dodecahedron lattice structure.

The meshes and boundary conditions in the reinforced structure unit cell were considered exactly like the simple structure unit cell. As shown in “Fig. 9”, in the numerical simulation, a unit cell of the new reinforced structure was investigated and it was found that by performing this operation, the stresses at the connections of the struts are reduced.

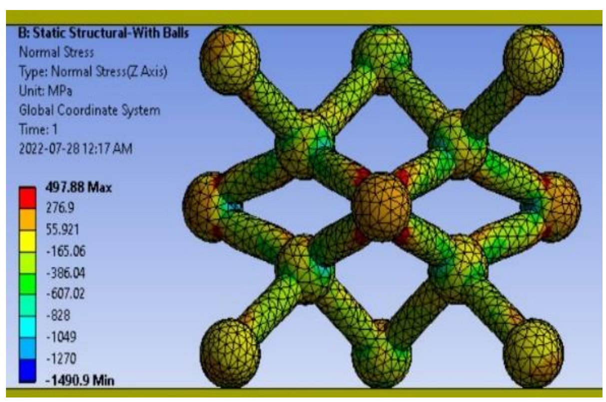

Fig. 9 Normal Stress in reinforced lattice structure.

As shown in "Figs. 10 and 11" two samples of each structure have been fabricated using SLM additive manufacturing technology. Selective Laser Melting (SLM) is an additive manufacturing method that is used to fabricate different types of complex components using a layer-by-layer approach. The parts are produced directly from three-dimensional computer-aided design data by melting the powdered material layer-by-layer with the aid of laser power. The characteristics and performance of the process are given in ISO/ASTM 52904 standard.

Compressive mechanical testing of both the simple structure and the structure with spherical connections was done experimentally. All lattice models were selected based on a preliminary investigation of the effect of spherical connections between struts.

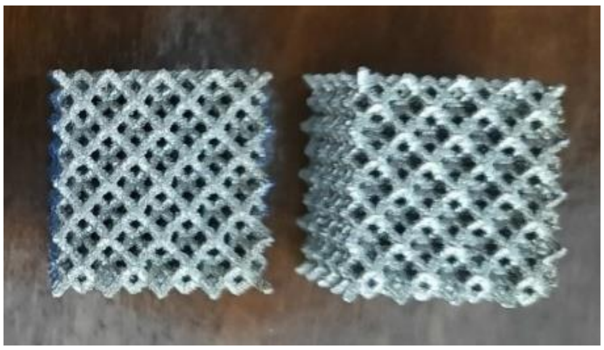

Fig. 10 Simple diamond lattice structure.

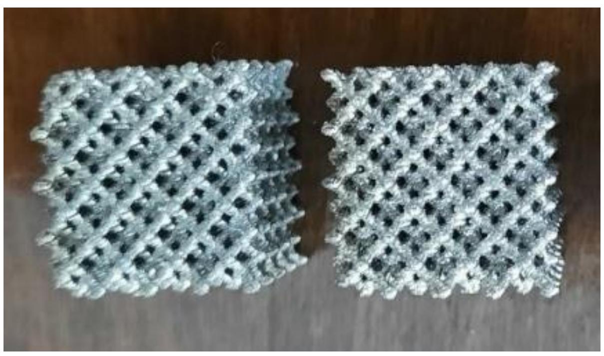

Fig. 11 Lattice structure with spherical connections.

After the experimental test and analysis, the final bearing force of the part is considered with two criteria: The end limit of linear deformation and the ultimate limit of tolerable force can be derived by dividing the force number by the equivalent area of the structure, the tolerable nominal stress in this structure.

To validate the simulation, the experimental validation of the simple structure and reinforced structures with SLM additive manufacturing technology was made with the Noura-M100P machine in MAPNA Turbine Engineering and Manufacturing Company (TUGA). Optimized manufacturing process parameters are used to obtain the desired structure of stainless steel 316L with the highest quality [15]. The experimental results of the compressive test of the simple structure were compared with the experimental results of the reinforced structure with spherical connections. It should be noted that the compressive test of the manufactured samples is by ISO/IEC17025 standard.

3 RESULTS AND DISCUSSION

The experimental test piece has experienced failure in many places. For better clarification, the crushed parts after the experimental tests are shown in "Figs. 12 and 13".

Fig. 12 Simple lattice structure after compressive test.

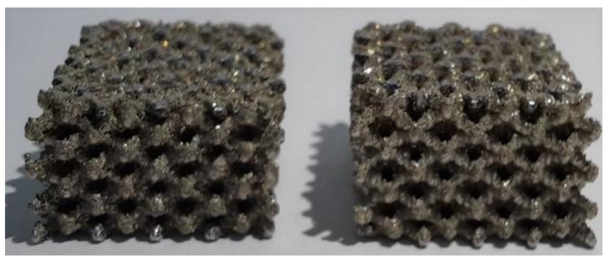

Fig. 13 Reinforced lattice structure after compressive test.

The graph obtained is the experimental comparison of the compressive test of the simple lattice structure and the reinforced lattice structure with spherical connections, which is shown in "Fig. 14".

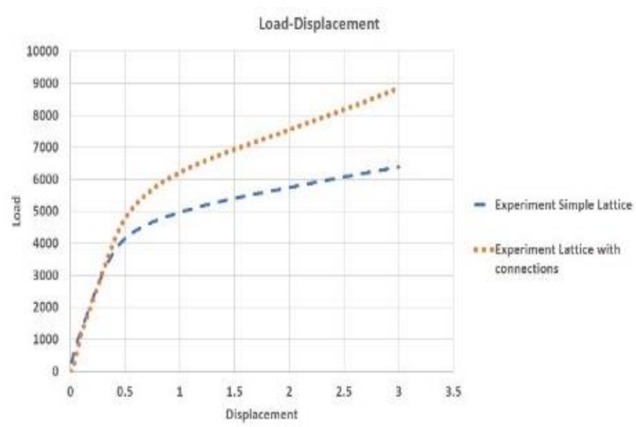

Fig. 14 Load-displacement comparison diagram of simple structure and reinforced structure with spherical connections.

The remarkable note about this figure is the improvement of the maximum force that the structure can tolerate using reinforced connections. This study shows the improvement of mechanical resistance by adding reinforcement (balls) at the junction between the struts.

In line with the application of this structure, the nominal tolerable stress obtained from the experimental test for the ultimate force-bearing limit of the simple structure is equal to 42 MPa and for the linear end limit is 27 MPa. In this situation, the proposed structure can be used for applications that have temperature tolerance, corrosion, and stress levels equivalent to the above values. In addition, due to the very high porosity, high solid-to-fluid heat transfer capability is expected for this structure. Therefore, in cases where it is necessary to cool a hard surface resistant to corrosion, this structure can be used.

4 CONCLUSIONS

The purpose of this study is to investigate the compressive stresses of the diamond lattice structure under the effect of spherical connections. Increasing the compressive strength of the structure can be an effective step in making it more practical. The results of the simple lattice structure showed that the most compressive stress occurs at the connection point of the struts, therefore, spherical connections have been used to strengthen the strut. Under the same conditions, the use of spherical connections with a diameter of 0.6 mm in the structure increases the compressive strength compared to a simple diamond structure by about 18%.

According to the experimental results and obtaining the maximum nominal stress of 42 MPa, the use of this structure is applicable for parts whose stress is equivalent to this value. It is important to note that the weight of this type of lattice structure has decreased by about 10 times compared to the weight of a solid structure with the same dimensions.

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