Acoustic Properties of 316L Stainless Steel Lattice Structures Fabricated via Selective Laser Melting

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Abstract: A bulk specimen and two different lattice sandwich structures composed of 316L stainless steel were fabricated via selective laser melting. This study analysed the acoustic properties, including sound insulation and sound absorption, of the three kinds of structures, which were produced via selective laser melting under the same process parameters. The results showed that the difference in the unit structures, rather than microstructural difference, was the main reason for the difference in acoustic properties between the samples. Under the same process parameters, the microstructure of the different structures had the same cell structure. However, the sound absorption properties of the lattice sandwich structures were better than those of the bulk sample in the measured frequency range of 1–6.3 kHz. The lattice sandwich structure with $2.5 \times 2.5 \times 2.5 \text{ mm}^3$ unit structures exhibited excellent sound insulation properties in the frequency range of 1–5 kHz.

Keywords: selective laser melting; 316L stainless steel; lattice structure; sound insulation properties; sound absorption properties

1. Introduction

Metal lattice structures are periodic material structures composed of nodes and rods [1,2]. Lattice structures have light weight and high specific strength and exhibit various thermodynamic characteristics. A lattice structure is suitable for use as a heat dissipating medium [3–5]. Moreover, a lattice structure can be used in impact and explosion systems [6], acoustic vibration dampers, microwave absorption structures and drive systems [7]. Lattice structures have good acoustic properties, which is extremely important for research in aerospace and marine fields. Traditional fabrication methods for metal lattice structures include the punched hole/mesh drawing method [8], perforation/stretching method, metal wire weaving method [9–11], and the investment casting method [12–15]. However, these traditional processes have some shortcomings, such as substantial waste of raw materials, the need to make special dies in advance and the inaccuracy of the produced metal lattice structures; these shortcomings make it difficult to form small and complex metal lattice structures.

Selective laser melting (SLM) is an additive manufacturing technology that can be applied to rapidly produce complex three-dimensional structures without fixtures or moulds [16]. The metal powder located on the metal substrate is melted with a high-energy density laser beam and deposited layer by layer [17]. Moreover, in SLM processing, the production cycle is short, and the material utilization rate is high [18]. The characteristics of SLM enable this approach to be used to fabricate metal lattice structures. Note that 316L stainless steel, a common metal material, is often used as a raw material to fabricate lattice structures because of its good corrosion resistance, heat resistance, low price, good welding properties and biocompatibility [19–21]. Allen [22–26] established a theoretical model for the vibration and sound insulation of lattice sandwich structures with four simply supported

edges and an acoustic-vibration coupling control equation for lattice sandwich structures under plane harmonic excitation according to Reissner's sandwich plate theory of shear deformation. Alijani and Amabili et al. [27–29] simulated the sound transmission loss (STL) of lattice sandwich structures at low frequencies to verify the rationality of the numerical theoretical model. Koehnen et al. [30] studied the mechanical properties of an SLM-produced lattice structure and analysed the influence of its microstructure on the mechanical properties. Zhang et al. [31] studied the energy absorption characteristics and analysed the stress distribution and failure mechanism of SLM-produced lattice structures under compressive loads. However, little research has been conducted on the acoustic properties of SLM-produced lattice structures.

In this work, bulk lattice structures and lattice sandwich structures of 316L stainless steel were prepared via SLM. Then, the microstructure of the SLM-produced bulk and the two different lattice structures was compared. The acoustic properties, including sound absorption and insulation, of the SLM-produced bulk and the two different lattice sandwich structures were also compared and analysed, and a structure with superior acoustic properties was obtained. Based on the transmission loss mechanism of sound energy in the three different structures, the sound insulation properties and sound absorption properties of each structure were discussed.

2. Materials and Methods

2.1. Materials

The metal powder materials in this experiment were 316L stainless steel spherical powders prepared via gas atomization. The diameters of the powders were in the range of 13–53 μm . The microscopic morphology of the powders is shown in Figure 1. The composition of the 316L stainless steel powders analyzed by inductively coupled plasma (ICP) emission spectrometry is shown in Table 1. The substrate material was 304 stainless steel.

Figure 1. Microscopic morphology of the 316L stainless steel powders.

Table 1. Composition of the 316L stainless steel powder (wt.%).

Fe	Cr	Ni	Mo	Mn
64.32	17.95	12.04	2.44	1.83

2.2. Experimental Procedure

Bulk and lattice structure specimens were produced with SLM equipment for microstructural analysis and acoustic property testing. The unit cell of the lattice structure was Dode-medium. The Dode-medium structure is an Auxetic structure [32], which is composed of regular tetrahedron structure with good stability. It is a structure with negative Poisson's ratio and Poisson effect. Compared with ordinary porous structure, Auxetic structure has higher compressive strength and better functional body stability [33]. Computer-aided drafting (AutoCAD 2018, Autodesk Inc., San Rafael, CA, USA) illustrations of different unit cells and acoustic test specimens consisting of a periodic arrangement of

unit cells are shown in Figure 2. The laser beam was set to contour mode in the layers, and the laser beam was rotated 67° clockwise between layers using Materialise Magics 21.0 software (Materialise Inc., Leuven, Belgium). The process parameters were in the range of the forming process parameters of 316L stainless steel mentioned in reference [17]. The dimensions of the lattice structure unit cell in the Type I lattice sandwich structure were $5.0 \times 5.0 \times 5.0 \text{ mm}^3$, whereas the dimensions of the lattice structure unit cell in the Type II lattice sandwich structure were $2.5 \times 2.5 \times 2.5 \text{ mm}^3$. By optimizing the laser power, scanning speed, layer thickness, hatch spacing and hatch offset, the optimum process parameters for fabricating lattice structures and dense bulk samples were determined ($\rho > 99.0\% \rho_{th}$, wherein ρ_{th} is the theoretical density of bulk materials without any defects [30]). Specimens were fabricated by AFS-M260 SLM equipment (Longyuan AFS Co., Ltd., Beijing, China). The oxygen content in the producing environment was 300–1000 ppm. The SLM process parameters are shown in Table 2.

Figure 2. CAD (computer-aided drafting) illustrations of the SLM (selective laser melting) specimens: (a) unit cell of Type I lattice sandwich structure ($5 \times 5 \times 5 \text{ mm}^3$), (b) unit cell of Type II lattice sandwich structure ($2.5 \times 2.5 \times 2.5 \text{ mm}^3$), (c) bulk cube for comparison, (d) Type I lattice sandwich structure for acoustic property testing, (e) Type II lattice sandwich structure for acoustic property testing, and (f) bulk cylinder for acoustic property testing.

Table 2. Process parameters for the production of 316L stainless steel bulk and lattice structure specimens via SLM (Selective laser melting).

Laser Power (W)	Beam Diameter (μm)	Scanning Speed (mm/s)	Layer Thickness (μm)	Hatch Spacing (mm)	Hatch Offset (mm)
200	75	500	30	0.05	0.06

The microstructure at the strut node of the SLM-produced lattice structure unit cells and the cross section of the bulk specimen were observed with an MR5000 optical microscope (Nanjing Jiangnan Novel Optics Co., Ltd., Nanjing, China) and a JSM-6480A scanning electron microscope (JEOL Ltd., Tokyo, Japan). The surface of the specimen receiving the incident sound wave was polished. The sound insulation properties and sound absorption properties of the three different SLM-produced acoustic specimens were measured by the impedance tube method using a VA-Lab acoustic test system (BSWA Technology Co., Ltd., Beijing, China). The acoustic property test system, which is shown in Figure 3, consists of a power amplifier, an impedance tube kit, acoustic material test equipment and a personal

computer (PC). The measured frequency ranged from 1 kHz to 6.3 kHz. The specimens used in the acoustic test were SLM-produced cylindrical bulk and lattice sandwich structures with diameters of 30.0 mm and heights of 11.5 mm. The measurements were conducted in accordance with ISO 10534-2:1998. The atmospheric temperature during testing was 25.9 °C, the relative humidity was 29.2%, the atmospheric pressure was 101,325.0 Pa, the atmospheric density was 1.2 kg/m³, the sound velocity was 346.674 m/s, and the characteristic impedance of air was 408.478 Pa·s/m. The results of the sound insulation property and sound absorption property tests, which were measured by the acoustic test system, were octave spectrum data. Three sound insulation property tests and three sound absorption property tests were conducted for each specimen, and the test results were output as the data of three groups of test results and the data of their average values. These data are described in curves.

Figure 3. Acoustic property test system.

3. Results and Discussion

3.1. Microstructure of the SLM-Produced 316L Stainless Steel Bulk and Lattice Structure

The SLM-produced acoustic specimens of the Type I lattice sandwich structure, Type II lattice sandwich structure, and bulk are shown in Figure 4. The microstructure of the SLM-produced bulk is shown in Figure 5. Figure 5a shows that the average width of each elongated columnar structure is approximately 75 µm, which is consistent with the diameter of the laser beam. Therefore, the long columnar structure is determined to be the molten pool. The distinct long columnar pool boundary can also be observed in the reference [30]. The sizes of the molten pools are not equal, and the directions of the melting channels of the cladding layers are inconsistent. The angles of the melting channels of different cladding layers are measured to be 67°. Because the observation plane of the microstructure was obtained by artificial treatment of the metallographic specimen, the observation plane was not absolutely horizontal, and the morphology of the upper cladding layer can be observed. In addition, because the laser scanning mode adopted 67° rotations between each layer, the angle between the directions of the cladding channels of different cladding layers can be clearly observed to be 67°.

Figure 4. SLM-produced 316L stainless steel samples of the Type I lattice sandwich structure, Type II lattice sandwich structure and bulk for acoustic testing.

Figure 5. (a) Optical micrograph and (b) SEM (scanning electron microscope) micrograph of the 316L stainless steel bulk fabricated via SLM revealing the morphology of molten pool. (c,d) SEM micrographs showing the observed cell structure can be formed at the boundary of the molten pool and other areas. Two kinds of substructures consist of cell structures: strip-like substructures and spherical substructures.

The microstructure of the SLM-produced bulk was observed under scanning electron microscopy. Figure 5c,d shows that there was an obvious cell structure. The observed cell structure can be formed at the boundary of the molten pool and other areas; the size of the cell structure is relatively uniform. Two kinds of substructures consist of cell structures: strip-like substructures and spherical substructures. A similar molten pool, substructure and cell structure can also be observed in both the Type I lattice structure strut (Figure 6) and the Type II lattice structure strut (Figure 7).

Figure 6. (a) Optical micrograph and (b) SEM micrograph of the 316L stainless steel Type I lattice structure fabricated via SLM revealing the morphology of molten pool. (c,d) SEM micrographs showing the observed cell structure can be formed at the boundary of the molten pool and other areas. Two kinds of substructures consist of cell structures: Strip-like substructures and spherical substructures.

Figure 7. (a) Optical micrograph and (b) SEM micrograph of the 316L stainless steel Type II lattice structure fabricated via SLM revealing the morphology of molten pool. (c,d) SEM micrographs showing the observed cell structure can be formed at the boundary of the molten pool and other areas. Two kinds of substructures consist of cell structures: strip-like substructures and spherical substructures.

The above analyses show that there are many cell structures in the microstructure of the SLM-produced 316L stainless steel bulk, Type I lattice structure strut and Type II lattice structure strut. The size of the cell structure is approximately the same in these three structures. Therefore, there is no significant difference in the microstructure of the three different structures produced by the same SLM process parameters.

3.2. Acoustic Properties of 316L Stainless Steel Lattice Structures

3.2.1. Sound Insulation Property Analyses

Sound insulation properties are usually measured by the sound transmission loss (STL). The sound insulation property test results for the SLM-produced bulk specimen, Type I lattice sandwich structure specimen (the size of unit cell in the interlayer is $5 \times 5 \times 5 \text{ mm}^3$), and Type II lattice sandwich structure specimen (the size of unit cell in the interlayer is $2.5 \times 2.5 \times 2.5 \text{ mm}^3$) are shown in Figure 8.

Figure 8. Sound insulation property curves of the three different structural acoustic specimens. (The thin line curves and dotted line curves in this figure are the octave spectrums of each group of sound insulation property test. The three heavy line curves in this figure are the average value curves of the octave spectrums of the three structures).

According to the sound insulation curves, as shown in Figure 8, when the test frequency is between 1 kHz and 6 kHz, the sound insulation properties of the SLM-produced bulk acoustic specimen are stable and good, and the STL is always approximately 30 dB. When the frequency reaches 6 kHz, the STL significantly reduces, and the sound insulation properties decrease. By observing the sound insulation curves of the two lattice sandwich structures, it is found that the STL of the Type I lattice sandwich structure specimen is equal to that of the bulk specimen at 5.4 kHz, and the sound insulation properties of the Type I lattice sandwich structure are lower than those of the bulk from 1 kHz to 5.4 kHz. However, when the frequency is higher than 5.4 kHz, the sound insulation properties of the Type I lattice sandwich structure are better than those of the bulk. The STL of the Type I lattice sandwich structure shows a minimum value at a frequency of 2.37 kHz; thus, 2.37 kHz is the resonant frequency of the structure [34]. When the frequency is less than the resonant frequency, the STL decreases as the frequency increases. When the frequency is larger than the resonant frequency, the STL increases as the frequency increases. The sound insulation properties of the Type II lattice sandwich structure are higher than those of the bulk when the frequency is between 1.6 kHz and 6 kHz, and the sound insulation properties are only slightly lower than those of the bulk when the frequency is between 1 kHz and 1.6 kHz.

In order to verify the reliability of the experimental results, the formula for the average sound insulation in actual engineering is expressed as follows [26]:

$$M = m/S \quad (1)$$

$$\bar{R} = 13.5 \lg M + 14 \quad M \leq 200 \text{ kg/m}^2 \quad (2)$$

where m is the mass, S is the media layer area, $\bar{R}$ is the average STL, and M is the density of the media layer.

When the thickness of the media layer is only 10 mm, the thickness is negligible. According to formulas (2.1) and (2.2), three different cube specimens with dimensions of $10 \times 10 \times 10 \text{ mm}^3$ were arranged periodically using the three different unit cells shown in Figure 2a–c. The average STL values of these specimens are shown in Table 3.

Table 3. Average STL (sound transmission loss) values of the three different structural cube specimens.

Properties	SLM-Produced Cube Bulk Specimen	Type I Lattice Structure Cube Specimen	Type II Lattice Structure Cube Specimen
Mass (g)	7.053	1.483	2.190
Density of Interlayer (kg/m^2)	0.705	0.148	0.219
Average STL (dB)	11.950	2.799	5.096

When the frequency is between 3.6 kHz and 6 kHz (i.e., away from the resonant frequency), the STL of the Type II lattice sandwich structure is approximately 1.8 times that of the Type I lattice sandwich structure at the same frequency, as shown in Figure 8. According to the comparison of the average STL values of the three different structural cube specimens in Table 3, the average STL of the Type II lattice structure cube specimen is 1.8 times that of the Type I lattice structure cube specimen, which coincides with the actual sound insulation property test results, as shown in Figure 8. Because there is no lattice structure in the SLM-produced bulk, the interlayer is smaller than that of Type I and Type II lattice sandwich specimens. The reflected acoustic energy of the acoustic wave can be improved by the larger interlayer and the reflection of the acoustic wave on the lattice structure strut [34]. This discrepancy makes the sound insulation properties of the two special “bulk/lattice structure/bulk” lattice sandwich structures better than those of the bulk specimen when the frequency is higher than 5.4 kHz.

There are no minimum values on the sound insulation property curve of the Type II lattice sandwich structure, which signifies that there is no resonant frequency from 1 kHz to 6.3 kHz. The STL

is above 30 dB, and the maximum STL is 58 dB when the frequency is 6.2 kHz. When the frequency is from 1 kHz to 6.3 kHz, the sound insulation properties of the Type II lattice sandwich structure are the best among the three different structures. When the frequency is higher than 6.2 kHz, the sound insulation properties of the Type I lattice sandwich structure decrease sharply. When the frequency is higher than the resonant frequency of the Type I lattice sandwich structure, the STL of the Type I lattice sandwich structure increases with increasing frequency and reaches a maximum of 45 dB when the frequency is 6.3 kHz. According to the sound insulation property curves in Figure 8, when the frequency is lower than 6.2 kHz, the Type II lattice sandwich structure has the best sound insulation properties. When the frequency is higher than 6.2 kHz, the Type I lattice sandwich structure has the best sound insulation properties. The sound insulation performance the three structural acoustic specimens are relatively stable. Only the sound insulation curves of the Type II lattice sandwich structure fluctuate greatly in the frequency range of 3.2–6.3 kHz, but the overall trend is the same. There is no dispersion in the sound insulation performance results of the three different structures respectively.

3.2.2. Sound Absorption Property Analyses

The principle of impedance tube measurements for sound absorption properties is based on the transfer function method. The specimens used for the sound absorption tests were the same as those used for the sound insulation tests. The sound absorption coefficient is the main index used to measure the sound absorption properties. The larger the sound absorption coefficient, the better the sound absorption properties of the specimen [35]. The sound absorption curves of these three different structural acoustic specimens are shown in Figure 9. There is no dispersion in the sound absorption performance results of the three different structures respectively. When the frequency is in the range from 1 kHz to 6.3 kHz, the sound absorption coefficients of the Type II lattice sandwich structure specimen and bulk specimen are all below 0.2. Thus, neither of these materials have good sound absorption properties. The sound absorption coefficient of the Type I lattice sandwich structure is greater than or equal to 0.2 at frequencies of 1 kHz to 3.6 kHz, and resonance occurs at 2.37 kHz (i.e., the resonant frequency). The sound absorption coefficient of the Type I lattice structure reaches a maximum value [35] of 0.95. Therefore, the Type I lattice sandwich structure has excellent sound absorption properties at frequencies of 1 kHz to 3.6 kHz. This structure is a resonant sound-absorbing structure. The type I lattice sandwich structure utilizes incident acoustic waves to generate resonance within the structure, thereby consuming a large amount of energy to improve the sound absorption properties. The incident interfaces of the incident sound waves of the three different specimens are the same, so the cause of the difference in sound absorption properties is the difference between the absorbed acoustic energy and the transmitted acoustic energy caused by the interlayer of the lattice sandwich structure, i.e., the difference in reflected acoustic energy.

Lattice structure is a kind of porous material. The pores of the lattice structures used in this experiment are open pores [36]. The porosity of lattice structure depends on its relative density. The relative density is the quotient value (ρ^*/ρ_s) obtained by dividing the volume density ρ^* of the lattice structure by the volume density ρ_s of the corresponding solid material. The porosity is $(1 - \rho^*/\rho_s)$. In this experiment, the relative density of Type I lattice structure unit cell ($5 \times 5 \times 5 \text{ mm}^3$) is 14.92%, and the relative density of Type II lattice structure unit cell ($2.5 \times 2.5 \times 2.5 \text{ mm}^3$) is 25.40%. The relationship between pore size, pore shape and relative density is as follows:

When the relative density is small, the length l of the edge of the pore will greatly exceed the thickness t of the pore wall, $t \ll l$. At this time, for all the porous materials [36]:

$$\rho^*/\rho_s \approx C(t/l)^2 \quad (3)$$

where C is a constant, it is close to a unit quantity.

The relative density of Type I lattice structure unit cell is smaller than that of Type II lattice structure unit cell, so the pore edge length of Type I lattice structure unit cell is larger than that of

Type II lattice structure unit cell, indicating that the pore size of Type I lattice structure unit cell is larger than that of Type II lattice structure unit cell. Comparing the two different lattice sandwich structures, the interlayer of the Type I lattice sandwich structure is a lattice structure with a lower relative density, and its overall structure has better sound absorption properties. According to the research results in [37], for a lattice sandwich structure, if the number of pores in the interlayer of the lattice structure is excessively large, the energy absorption properties will deteriorate. If the pore size is too small, the energy absorption properties will also deteriorate. The energy absorption properties have an effective relative density range. Therefore, the sound absorption properties of the Type I lattice sandwich structure are the best among the three different structural acoustic specimens.

Figure 9. Sound absorption property curves of the three different structural acoustic specimens. (The thin line curves and dotted line curves in this figure are the octave spectrums of each group of sound absorption property test. The three heavy line curves in this figure are the average value curves of the octave spectrums of the three structures).

According to the principles of sound absorption and sound insulation, the smaller the reflected sound energy is, the better the sound absorption properties. Moreover, the smaller the transmitted sound energy is, the better the sound insulation properties. Therefore, the same material or structure has difficulty balancing the optimal sound absorption properties and the optimal sound insulation properties [26]. Therefore, the sound insulation or sound absorption properties are usually considered separately. For the sound insulation properties, when the frequency is between 1 kHz and 6.2 kHz, the Type II lattice sandwich structure has the best sound insulation properties. When the frequency ranges from 6.2 kHz to 6.3 kHz, the Type I lattice sandwich structure has the best sound insulation properties. For the sound absorption properties, when the frequency is 1 kHz to 5.4 kHz, the Type I lattice sandwich structure specimen has the best sound absorption properties. When the frequency is 1 kHz to 6.3 kHz, the Type II lattice sandwich structure specimen and SLM-produced bulk specimen have poor sound absorption properties, which are essentially equivalent to a lack of sound absorption properties. Referring to Sections 3.1 and 3.2, the microstructure is not the main reason for the difference in sound absorption properties and sound insulation properties of these three different structures. The trends of the sound absorption curves of the Type I and Type II lattice sandwich structures are not the same, but the difference in the trends is related to the pore size and porosity in the interlayer of the lattice sandwich structure. The lattice structure with a larger pore size and higher porosity demonstrated better sound absorption properties in the middle and high frequency stages [38].

4. Conclusions

The 316L stainless steel bulk and lattice sandwich structures were fabricated via SLM. The microstructures of the SLM-produced bulk and lattice structure strut were analysed. The sound insulation and sound absorption properties of the SLM-produced bulk and lattice sandwich structures were compared and analysed according to the transmission loss mechanism of sound energy. The following conclusions can be drawn from this study:

(1) The microstructures of the SLM-produced bulk, Type I lattice structure strut, and Type II lattice structure strut all had the obvious morphology of the molten pool. The cell structure in the interior and boundary of the molten pool had a relatively uniform size. The microstructures of the SLM-produced bulk and lattice structure struts had little difference under the same technological parameters. Therefore, the microstructure of the structure struts was not the main factor affecting the sound absorption and insulation properties of the different structures. The differences in porosity and pore size in the cell structure were the main reasons for the difference in acoustic properties of these three different structures.

(2) When the frequency was from 1 kHz and 6.2 kHz, the Type II lattice sandwich structure had the best sound insulation properties. When the frequency was higher than 6.2 kHz, the Type I lattice sandwich structure had the best sound insulation properties, and the sound insulation properties of both of the lattice sandwich structures were better than those of the bulk. Therefore, the sound insulation properties of this special “bulk/lattice structure/bulk” lattice sandwich structure were better than those of the bulk at medium and high frequencies. The two 316L stainless steel SLM-produced lattice sandwich structures exhibited excellent sound insulation properties from 1 kHz to 5 kHz.

(3) The Type I lattice sandwich structure was a resonant sound-absorbing structure, which used the incident acoustic wave to generate resonance in the structure, thereby consuming a large amount of energy to improve the sound absorption properties. Because the size of the unit cell in the interlayer of the Type I lattice sandwich structure specimen was larger than that of the Type II structure, the lattice structure in the interlayer of the Type I lattice sandwich structure had a lower relative density. The Type I structures had better sound absorption properties than the other structures. The sound absorption properties of the “bulk/lattice structure/bulk” lattice sandwich structure were better than those of the bulk at medium and high frequencies (1–6.3 kHz).

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