Mechanical properties and deformation behavior under compressive loading of selective laser melting processed bio-inspired sandwich structures

Kaiming Hu\textsuperscript{a,b}, Kaijie Lin\textsuperscript{a,b}, Dongdong Gu\textsuperscript{a,b,*}, Jiankai Yang\textsuperscript{a,b}, Haoran Wang\textsuperscript{a,b}, Luhao Yuan\textsuperscript{a,b}

\textsuperscript{a} College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, 210016, Jiangsu Province, PR China
\textsuperscript{b} Jiangsu Provincial Engineering Laboratory for Laser Additive Manufacturing of High-Performance Metallic Components, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, 210016, Jiangsu Province, PR China

\textbf{Abstract}

Sandwich structures are widely used in aviation and aerospace applications because of their outstanding characteristics of light-weight, excellent energy absorption and continuous compression behaviors. Nature has provided us with extraordinary resources to meet the demanding for modern industry. In this study, inspired by the microstructures of the Norway spruce stem, four light-weight sandwich structures were designed and manufactured by selective laser melting (SLM). The structures had good formability using an optimized laser processing parameter setting. The uniaxial compression tests of SLM-processed bio-inspired sandwich structures were conducted to evaluate their specific compressive strength and energy absorption performance. Finite element analysis was employed to study stress distributions in structures during compression tests and analyze fracture mode combining with the observation of fracture surface morphology. The experimental and numerical results indicated that the gradient structure, with tube size gradually decreasing from top and bottom plate towards the center, exhibited the highest specific absorption energy, ultimate strength and specific strength, which was 5.73 J/g, 214.8 MPa and 98.99 MPa/(g/cm\textsuperscript{3}), respectively. The FEA results revealed that the arrangement of tubes significantly affected the stress distribution and fracture locations of structures. The gradient structure, with the highest specific absorption energy and ultimate strength, had the most uniform stress distributions, contributing to its excellent compressive performance.

1. Introduction

The sandwich structures have high bending and buckling resistance [1,2], excellent energy absorption capability [3,4], and thermal insulation property [5–7] and are widely used in aviation and aerospace fields. For sandwich structures, many factors [8] can affect their mechanical properties and the design of core structures is one of the key factors. During the past few decades, many literature focus on the influence of core design on the mechanical properties of sandwich structures and demonstrate that the parameters of core structures, such as arrangement and size of cells [9], relative density of cores [10] and wall thickness of cells [11], greatly influence the compressive behavior of sandwich structures. With the maturation of manufacturing technologies, increasing amount of sandwich structures with complex core structures are designed, including corrugated cores [12–16], honeycomb cores [17–19], lattice/truss cores [20–22] and metal foam cores [23–25].

After billions of years of evolution, the structures of living organisms have developed outstanding properties and provided inexhaustible prototypes for technical improvements and innovations [26,27]. In order to meet the demand for light-weight sandwich structures in the aerospace field, many bio-inspired complex structures with superior performance have been designed and evaluated in recent years [28–30]. However, due to the complexity of bio-inspired structures, numerical simulation is commonly applied to study the mechanical performance of structures [31–36]. Peng et al. [37] designed bio-inspired honeycomb column thin-walled structures and investigated the crushing behavior and energy absorption characteristics using numerical simulation. Liu et al. [35] analyzed the crash responses of bio-inspired aluminum honeycomb sandwich structures and found that the specific energy absorption increased obviously under high impact velocity and the crashworthiness characteristics were more sensitive to core length compared with the core height.

The emerging of the high-performance bio-inspired structures drives...
the development of manufacturing technologies. Additive manufacturing (AM) [39,40], a novel manufacturing technology, has created new opportunities for the design and fabrication of structures with multi-scale [41,42], multi-material [43–45] and multi-function [46]. AM technology has many advantages, such as less waste, freedom of design and high automation, which has been widely applied in diverse industries, including aeronautical, automobile and bio-implantation fields [47–49]. In recent years, selective laser melting technology, one key technology of AM, also finds its application in the fabrication of complex bio-inspired structures. Wang et al. [50] fabricated a lightweight structure inspired by the elytra of beetle using SLM and analyzed its energy absorption and bearing capacity using compression test and finite element simulation. Yang et al. [51] designed a bi-directionally corrugated-core sandwich panel, inspired by the mantis shrimp. Bio-inspired components with high forming precision and quality were successfully fabricated by SLM and the energy absorption behavior was investigated through the combination of experimental tests and numerical simulation.

In this work, a series of novel light-weight sandwich structures inspired by the microstructure of the Norway spruce stem was designed and fabricated by SLM. Uniaxial compression tests were applied to evaluate the mechanical properties of the bio-inspired structures. Subsequently, the finite element analysis (FEA) was conducted to analyze the stress distributions of different structures under uniaxial compression loading. Through the combination of finite element analysis and experimental observation, the deformation behavior and the fracture mechanism of the bio-inspired sandwich structures were revealed.

2. Materials and methods

2.1. Structure design and SLM processing

The sandwich gradient structures, proposed in this paper, were inspired by the Norway spruce stem (shown in Fig. 1). From the cross-sectional SEM images of the Norway spruce stem, it is clear to find that the cell size gradually changes toward the center. More specifically, from the edge of the stem to the center, the cell size decreases first and then increases. In order to investigate the influence of gradient configuration on the compression performance, four sandwich structures with a different arrangement of hollow tubes were designed and presented in Fig. 1 b - e. No gradient structure (NG) with identical tube size (wall thickness 0.7 mm and external diameter 4 mm) was designed as a control group and its solid volume was equal to gradient structures (Fig. 1b). All of the three gradient structures were composed of two layers of big tubes and four layers of small tubes. For the gradient structure A (GA), two layers of big tubes were arranged in the center and two layers of small tubes were placed next to the top and bottom plate, respectively (Fig. 1c). In the gradient structure B (GB), the arrangement of big tubes and small tubes was opposite to the GA structure, a layer of big tubes was adjacent to the top and bottom plate, respectively, and four layers of small tubes were arranged in the center (Fig. 1d). For the gradient structure C (GC), a layer of small tubes was adjacent to the top and bottom plate, respectively, and the other two layers of small tubes were located in the center of the structure, sandwiched by big tube layers (Fig. 1e). The wall thickness of big tubes and small tubes was both 0.5 mm. The external diameter of big tubes and small tubes was 4 mm and 2 mm, respectively. In addition, the overall dimensions of four structures were 20 mm × 20 mm × 17.2 mm and the thickness of the top and bottom plate for all structures was 1 mm. In order to ensure the sound connection between tubes, an overlapping displacement between tubes was set as 0.3 mm.

The SLM equipment used in this work was self-developed by Nanjing University of Aeronautics and Astronautics (Fig. 2a). The SLM equipment consisted of YLR-500-SM ytterbium fiber laser with the highest power 500 W and spot size 70 μm. Based on previous research, an optimized parameter setting was used in this work, which was laser power 250 W, hatch spacing 80 μm, scanning speed 800 mm/s and layer thickness 50 μm. Ti6Al4V powder with a spherical morphology was used in this work (Fig. 2b). In order to improve the quality of SLM-processed components, the building direction was consistent with the axial direction of the tubes, and the as-fabricated Ti6Al4V bio-inspired sandwich structures were shown in Fig. 2c. Samples for tensile tests were fabricated along with the bio-inspired sandwich structures using the identical parameters. A representative stress-strain curve of the SLM-processed Ti6Al4V was presented in Fig. 1d, and the mechanical properties was presented in Table 1.

2.2. Microstructural and mechanical property characterization

The SLM-processed samples for metallurgical examinations were cut, grounded and polished according to standard procedures. The cross-sectional pore distribution of components was observed by an optical microscope (OM, OLYMPUS PMG3). The etchant (distilled

![Fig. 1](image-url). The design of bio-inspired sandwich structures: a, The cross-sectional microstructure of the Norway spruce stem [52]; bio-inspired sandwich gradient structures: b, no gradient structure (NG); c, gradient structure A (GA); d, gradient structure B (GB); e, gradient structure C (GC).
water: HNO₃: HF = 50: 3: 5) was prepared, and the OM was used to observe the microstructure after etching. Uniaxial compression tests of the SLM-processed bio-inspired sandwich structures were conducted at room temperature using a universal testing machine (CMT5205) and the displacement rate was set as 1 mm/min. The fracture surface morphologies of SLM-processed bio-inspired sandwich structures after the compression tests were observed by a scanning electron microscope (SEM, JSM-6360LV).

2.3. Crashworthiness indicators

From the load-displacement curves of compression tests, two important indexes, namely energy absorption (EA) and specific energy absorption (SEA) [53–55], can be obtained to evaluate the bearing and energy absorption capacity of bio-inspired sandwich structures. The energy absorption (EA) indicates the capacity of absorbing energy during compression, which is determined by the integral area of the load-displacement curve. The equation of energy absorption can be expressed as follows:

\[ EA(d) = \int_0^d F(x)dx \]  

where \( F(x) \) is the instantaneous compression force and \( d \) is the total compression displacement.

The specific energy absorption (SEA) assesses the absorbed energy per unit mass of a structure, which is an important factor to compare the energy absorption efficiency of different structures. The specific energy absorption is determined by the following equation:

\[ SEA(d) = \frac{EA(d)}{m} \]  

where \( m \) is the mass of a structure. \( EA \) is the energy absorption value of a structure, which is defined by Eq. (1).

2.4. FEA model and boundary conditions

To better understand the deformation behavior of the bio-inspired sandwich structures under compression loading, nonlinear explicit finite element code ANSYS LS-DYNA was conducted. The compression process was performed by a dynamic explicit procedure and a numerical finite element simulation model was shown in Fig. 3. In order to balance between simulation accuracy and computational cost, the mesh size of the rigid plate and the gradient structure was determined as 1 mm and 0.3 mm, respectively. During the simulation process, a rigid plate was placed on the top and bottom of the gradient structure, respectively. The contacts between the rigid plates and the structure were set as a surface to surface contact and the friction coefficient was set as 0.2 [56]. Besides, the displacement rate of the top rigid plate was 1 mm/min and the bottom rigid plate was fixed. The material property of the SLM-processed Ti6Al4V, showed in Table 1, was used in the FE model.

3. Results and discussion

3.1. Formability and microstructure

In order to avoid the influence of formability on mechanical properties, the optimal processing parameters were applied to manufacture the bio-inspired sandwich structures. The mass of different SLM-processed components was closed to each other (showed in Table 2).
Table 2
The mass of SLM-processed Ti6Al4V bio-inspired gradient structures.

<table>
<thead>
<tr>
<th>No gradient structure</th>
<th>Gradient structure A</th>
<th>Gradient structure B</th>
<th>Gradient structure C</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2 ± 0.023 g</td>
<td>17.6 ± 0.02 g</td>
<td>17.4 ± 0.025 g</td>
<td>17.1 ± 0.027 g</td>
</tr>
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Fig. 3. Numerical finite element simulation model: meshing and boundary conditions.

Fig. 4. The macro-photograph and the cross-sectional OM images of the SLM-processed GA structure: a, macro-photograph of the polished side face of the SLM-processed GA structure; b, OM image of the annular ring position; c, OM image of the intersection position (pores and adhered particles are marked by black arrows).
gradient structure A (GA) was selected as a representative, and the macro-photograph and the cross-sectional OM images were presented in Fig. 4. An almost fully dense structure can be clearly seen from the OM images, only a small number of pores were found (Fig. 4 b & c). During the SLM-processing, a molten pool was generated by a high-energy laser beam, the laser melted the metal powder at an extremely fast speed. During the solidification of liquid metal, gases were trapped inside the molten pool and formed bubbles [57–59]. Due to the fast cooling rate, the molten liquid cannot fill the bubbles in time and lead to the formation of pores [60–63] Besides of the pores in structures, partially melted particles adhered on the edge of the node can also be seen in Fig. 4c, which increased the surface roughness of the structures. The phenomenon of adhered particles was a common problem for selective laser melting. During the laser processing, the residual heat from
the molten pool partially melted powders near the surface of the solid part and led to the adhesion of particles [64].

Fig. 5a showed the etched cross-sectional microstructure at the annular ring and intersection positions of the GA structure. The OM micrographs demonstrated that the SLM-processed component mainly consisted of fine acicular microstructures. The XRD spectrum of the SLM-processed GA structure was presented in Fig. 5b. It can be clearly seen that only \( \alpha' \)-martensitic phase can be detected from the component, indicating that the fine acicular microstructures observed in Fig. 5a was \( \alpha' \)-martensitic phase. The SLM processing had large heat input and rapid cooling process and led to the forming of acicular \( \alpha' \)-martensite, which was a typical microstructure of SLM-processed Ti6Al4V. Similar results have been reported by some researchers [65–67]. Under the identical SLM-processing parameters, all components exhibited similar microstructures with the GA structure.

### 3.2. Mechanical properties

In order to investigate the compressive performance of the SLM-processed bio-inspired sandwich structures, uniaxial compression tests were carried out at room temperature. The load-displacement curves of different sandwich structures were presented in Fig. 6a. From the load-displacement curves, NG and GC structures directly fractured after the maximum force. However, for GA and GB structures, after the maximum force, the force abruptly decreased to a plateau before the final fracture. Fig. 6b presented the peak crush force of different sandwich structures. The GB structure exhibited the highest peak crush force of 85.9 kN, followed by the NG structure (81.3 kN), the GC structure (77.6 kN) and the GA structure (60.6 kN).

The absorption energy and the specific absorption energy of the bio-inspired sandwich structures were calculated according to Eq. (1) and Eq. (2), and the values were charted in Fig. 7a. The energy absorption of the GB structure was 99.68 J, which was the highest among all structures. And the energy absorption of NG, GA and GC was 76.18 J, 61.46 J and 54.47 J, respectively. At the structure design stage, all the four structures were designed to have the identical solid volume and overall dimensions, and the mass of SLM-processed components was closed to each other (Table 2). Therefore, the trend of specific absorption energy was similar to that of energy absorption, which was also presented in Fig. 7a. The above results indicated that the GB structure had the best energy absorption capacity.

In order to further investigate the bearing performance of the SLM-processed sandwich structures, the concept of specific strength of structures was introduced in this work [50]. The specific compressive
The strength of a structure is defined as follows:

\[ \sigma_s = \frac{\sigma_u}{\rho_s} \]  

(3)

where \( \sigma_s \) is the specific compressive strength, \( \sigma_u \) is the ultimate compressive strength and \( \rho_s \) is the density of a structure.

For cellular and lattice structures, the density can be calculated by the following equation [68]:

\[ \rho = \rho_\hat{S} \times \rho_0 \]  

(4)

where \( \rho_0 \) is the density of the material, \( \rho_\hat{S} \) is the relative density, which can be expressed as follows [69–71]:

\[ \rho_\hat{S} = \frac{V_s}{V_c} \]  

(5)

where \( V_s \) is the solid volume, \( V_c \) is the apparent volume.

According to the above equations, the ultimate compressive strength and specific strength of SLM-processed bio-inspired sandwich structures were presented in Fig. 7b. The results showed that the GB structure had the highest ultimate strength (214.8 MPa) and specific strength (98.99 MPa/(g/cm\(^3\))). Comparing the specific strength with other SLM-processed structures reported in literature, such as lightweight sandwich structures (54.39 MPa/(g/cm\(^3\))) [53] and lattice structures (20.0 MPa/(g/cm\(^3\))) [70], the structures, proposed in this work, exhibited superior compressive properties.

### 3.3. Deformation behaviors

According to the trend of force-displacement curves, four SLM-processed structures can be classified into two categories, namely direct fracture (the NG and GC structures) and non-direct fracture (the GA and GB structures). To investigate the deformation progress of structures, the frames, captured from the video of four different structures recorded during their compression tests, were presented and compared in Fig. 8. For the NG structure, obvious deformation can be observed when the displacement exceeded 1 mm (marked by yellow arrows). When further increased the displacement to 1.62 mm, the structure severely damaged and the fracture occurred along the diagonal direction, which indicated that the shear fracture was the dominant fracture mechanism for the NG structure. Because of the occurrence of shear fracture, the NG structure was completely destroyed, leading to the direct fracture (Fig. 6a). Similar shear fracture was also witnessed in the GC structure when the displacement increased to 1.26 mm. For the GB structure, when the displacement reached 1 mm, obvious deformation was observed which mainly occurred at the top layer of big tubes (marked by yellow arrows). When further increased the displacement to 1.62 mm, some big tubes in the top layer damaged resulting in the drop of force in the force-displacement curve (Fig. 6a). With the proceeding of the compression test, the un-damaged tubes in the top layer still provided bearing capacity and led to the rise of force in the force-displacement curve (Fig. 6a). When the displacement exceeded 1.85 mm (position of the second peak), the un-damaged tubes in the top layer gradually damaged until the final fracture. Similar deformation process was observed in the big-tube layers of the GA structure.

The finite element analysis (FEA) was applied to simulate the stress distributions in structures and analyze the failure mechanism of structures. First of all, in order to verify the accuracy of numerical simulation results, the simulated force-displacement curves of different structures.
were compared with the experimental curves (Fig. 9). Because the influence of processing accuracy and defects on the mechanical performance was ignored during the numerical simulation, the simulated curves were higher than the experimental curves. However, the trend of simulated force-displacement curves was similar to that of the experiment curves. In addition, for the GA and GB structures, the second peak appeared in the simulated force-displacement curves. Therefore, it can be drawn that the FEA model was reliable.

The stress distributions of different gradient structures were calculated by the FEA model and presented in the left column of Fig. 10. The middle column of Fig. 10 was the failure mode predicted by FEA model and the right column was macro-images of the SLM-processed bio-inspired sandwich structures after compression tests. The damage zone and deformed zone were marked by red (middle) and white (right) arrows, respectively. For the NG structure, the stress concentrated in the center position and diagonal area of the structure, which presented an “X” shape. The highest stress was in the center and reached 1100 MPa. The simulation results indicated that the fracture occurred along the principal and secondary diagonal of the structure. The experimental results showed that the principal diagonal position of the structure was destroyed, but the secondary diagonal position only deformed. For the GA structure, the stress distribution in the structure was non-uniform. Specifically speaking, the stress of small-sized tubes was much lower than that of large-sized tubes, resulting in the fracture occurred in two layers of large-size tubes. The deformation and fracture locations predicted by the FEA simulation was consistent with the experimental results. The stress distribution in the GB structure was relatively uniform compared with other structures. A large area of stress concentration cannot be found. From the results of FEA simulation and the compression tests, the first layers of large-size tubes were destroyed under compression and only a small amount of deformation occurred in other parts of the structure. In the case of the GC structure, the stress concentrated in the layers of big tubes and reached up to 1102 MPa. According to the fracture of the structure predicted by FEA, the layers of big tubes damaged, which was in agreement with the experimental results.

3.4. Fractography

In order to investigate the fracture mode, the SLM-processed GA
structure was selected as an illustrative example and the fracture surfaces were observed by SEM (Fig. 11). As shown in Fig. 11 a, the fracture occurred at the tube wall and the crack was parallel with the axis of the tubes and perpendicular to the direction of compression. Fig. 11 b & c showed the fracture morphology of the SLM-processed GA structure. From low magnification SEM images, the fracture surfaces mainly consisted of dimple area and cleavage facet area, and the dimple area was dominated. Under the high magnification SEM image of dimple area (Fig. 11 d), the dimple exhibited small size (3–18 μm) and shallow morphology, which indicated high tensile strength, low tensile ductility [64,72–74] and low elongation [75–78]. Some researchers believed that the reason for this phenomenon can be attributed to a large amount of supersaturated solid solution of Al in Ti matrix due to the extremely high cooling speed of SLM-processing [79]. Under the high magnification SEM image of cleavage facet area (Fig. 11 e), the shell patterns can be found, which was a typical indication of brittle rupture. Apart from the fracture morphology, the compression curves can also illustrate the fracture modes of structures. According to the loading-displacement curves of Ti6Al4V bio-inspired sandwich structures shown in Fig. 6 a, the curves displayed a suddenly dropping after reaching the peak value, which indicated the brittle fracture feature [80]. Therefore, the SLM-processed bio-inspired Ti6Al4V sandwich structure exhibited a mixed mode of ductile and brittle fracture under compression loading.

It is generally known that the microstructure of the TiAl6V4 alloy depends on the cooling rate during solidification. The extremely fast cooling rate during the SLM process results in a fine acicular martensitic phase, which is a main factor affecting the mechanical properties of the SLM-processed Ti6Al4V samples. According to the literature [81], the presence of the metastable α′ martensite contributed to the enhancement of yield strength and ultimate tensile strength, but resulted in the low ductility. The preheating of powder bed during the SLM processing can effectively reduce the cooling rate [82], adjust the microstructure [83,84] and reduce residual stress in the structure [84], which could improve the ductility of SLM-processed Ti6Al4V samples. In addition, post-treatments, such as HIP treatment, could improve ductility of samples by adjusting the microstructure [81,85–87] and eliminating metallurgical defects inside components [88–91].

4. Conclusions

In this study, SLM technology was successfully applied to fabricate gradient sandwich structures inspired by the Norway spruce stem. The mechanical properties and the energy absorption behavior of the structures were evaluated by uniaxial compression experiments. In order to investigate the fracture mechanism of the bio-inspired gradient structures, the LS-DYNA finite element analysis software was applied to analyze the stress distribution and predict fracture behavior. The following conclusions can be drawn from this study:

(1) The Ti6Al4V bio-inspired gradient structures, manufactured by the optimized SLM parameters, exhibited a high relative density and
similar microstructures among structures.

(2) The mechanical properties of gradient structures under compression loading closely related to the arrangement of large and small tubes. The gradient structure, with a layer of big tubes adjacent to the top and bottom plate and four layers of small tubes arranged in the center, possessed the highest SEA (5.733/g) and specific compressive strength (98.99 MPa/g/cm³) among all structures.

(3) The results of FEA simulation revealed that the arrangement of big and small tubes significantly affected the stress distributions in bio-inspired sandwich structures. The gradient structure, with the highest SEA and specific compressive strength, exhibited the most uniform stress distribution, contributing to its excellent compressive performance. In addition, the fracture location predicted by FEA simulation was in agreement with that of the experiment.

(4) The fracture morphologies of SLM-processed bio-inspired sandwich structures consisted of shallow dimples and cleavage facets, indicating a mixed mode of ductile and brittle fracture under compression loading.

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