Compressive Properties of Bio-Inspired Reticulated Shell Structures Processed by Selective Laser Melting

Haoran Wang, Dongdong Gu,* Kaijie Lin, Lixia Xi, and Luhao Yuan

Owing to reasonable stress, large rigidity and large span, the reticulated shell structure is widely used in the field of aerospace industry. However, its hard-to-process nature hinders, the progress of design optimization, and experimental investigation. In this paper, a series of reticulated shell structure, inspired from the diving bell of the water spiders, is designed and fabricated by selective laser melting (SLM) additive manufacturing technology from AlSi10Mg powder. The effects of strut diameter on dimensional accuracy, densification behavior, and mechanical properties of SLM-processed reticulated shell structures are investigated. The results show that all the SLM-processed reticulated shell structures exhibit high relative density (>99%), which decrease with the increase of strut diameter. The load–displacement curves of all reticulated shell structures exhibit a similar trend including three distinct stages. The structure with strut diameter of 1.25 mm (D1.25) has relatively high specific energy absorption, and energy absorption capability. The fracture mechanism of SLM-processed reticulated shell structures with different strut diameters is analyzed through a combination of finite element simulations and experimental observations. With an increasing strut diameter, the dominant mechanism changes from stress-controlled to porosity-controlled fracture.

1. Introduction

The reticulated shell structure, as a popular grid structure for aerospace applications, has the combined characteristics of the truss structure and the shell structure, and possesses the advantages of high safety, good economic performance, and strong applicability.[1] At present, most researches on reticulated shell structures focuses on stability analysis, buckling and path tracking, and elasto-plastic simulations with large deformation.[2–6] Only a few researchers have carried out structural optimization of reticulated shell structures, aiming to reduce structural weight.[7,8] On the other hand, reticulated shell structures are hard-to-process by traditional manufacturing methods, resulting in high manufacturing cost and long production cycles. Therefore, experimental investigation of reticulated shell structures remains challenging, leading to a wide concentration on theoretical analysis and finite element simulation instead of manufacturing.

In the past decades, we have witnessed significantly scientific and industrial improvements of additive manufacturing (AM) technology.[9–11] From 2010 to 2015, the compound annual growth rate of the AM industry was about 30%, reaching about 5.1 billion US dollars in 2015.[12] Selective laser melting (SLM) is one of the most promising AM technologies, of which the layer-wise feature enables direct fabrication of near net-shape parts from powder based on three-dimensional CAD models. By optimization of process parameters, near-full dense components with relative density of ≈99.5% can be fabricated by SLM.[13–19] Lightweight components with complex structures and excellent mechanical properties have been successfully built by SLM technology,[20,21] and increasing amount of studies have been recently devoted to investigate the mechanical properties of SLM-processed lightweight structures.[22–29] Zhang et al.[22] fabricated three types of porous structures including cubic, topology optimization and rhombic dodecahedron, and investigated the energy absorption mechanism and stress distribution of porous structures at the initial stage of deformation through experiments and finite element simulations. Qiu et al.[23] studied the effects of laser power and scanning speed on the surface morphology, internal pore, and mechanical property of SLM-processed cellular lattice structures. Sun et al.[24] also investigated the mechanical property of functionally graded lattice structures fabricated by SLM, demonstrating that samples with graded density had a higher plateau stress and specific energy absorption than those of samples with uniform density.

With the development of SLM technology, a number of natural structures have been exploited to achieve superior mechanical properties. Among them, the most representative example is the honeycomb structure. Chantarapanich et al.[30] investigated the feasibility of design and production of a three-dimensional honeycomb via SLM for aeronautical applications. The SLM-processed honeycomb structure exhibited desired mechanical properties applied as aircraft interior compartment components.

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Liu et al.\cite{31} studied the quasi-static and dynamic compressive responses of additively manufactured AlSi10Mg parts with three kinds of honeycomb structures, namely, single-scale honeycomb, hierarchical honeycomb with two and three levels of hierarchy. The results showed that the hierarchical honeycombs offered higher energy absorption capacity than that of single-scale honeycomb.

AlSi10Mg has many excellent properties, such as good strength-to-weight ratio, good fatigue strength, and excellent corrosion resistance, and has been widely applied in the field of aerospace.\cite{32} In this paper, a reticulated shell structure inspired from the diving bell of the water spider, was designed.\cite{33} A series of reticulated shell structures with different strut diameters were fabricated by SLM technology of AlSi10Mg powder. The effects of strut diameter on dimensional error, densification level, pore distribution, mechanical properties, and energy absorption capacity of SLM-processed reticulated shell structures were studied. Combining the microstructure observation and finite element simulations, the fracture mechanism of SLM-processed reticulated shell structures was elucidated.

2. Experimental Section

Water spider (Argyroneta aquatic) is the only spider which lives and hunts under water.\cite{34} Its diving bell, where the water spider stays underwater, can endure impact of water current and last for a prolonged period of time, because of the unique cross-linking structure of diving bell. Figure 1a shows the diving bell structure, where the cross-linking of spider silk can be clearly seen. A CAD model of the reticulated shell structure inspired from the diving bell was built accordingly (Figure 1b). In the reticulated shell structure, the angle between intersecting rods was set as 60 degrees and the height-to-span ratio of the reticulated shell structure was 1/5, based on the previous literature.\cite{35} The strut diameters ($\phi$) applied in this work were 0.75, 1.00, 1.25, and 1.50 mm, and structures with these strut diameters were coded as $D_{0.75}, D_{1.00}, D_{1.25},$ and $D_{1.50}$, respectively. Four categories of nodes can be obtained from the reticulated shell structure: N1 is the top node of the structure; N2 represents the middle node of the structure; N3 and N4 are representative of the intersections of two rods and three rods at the bottom ring, respectively.

Reticulated shell components with different strut diameters were manufactured using a SLM machine (SLM-plus) developed by Nanjing University of Aeronautics and Astronautics (NUAA) and the principle of SLM processing is shown in Figure 2a. The SLM system consists of a YLR-500-WC ytterbium fiber laser (IPG Laser GmbH, Burbach, Germany) with a maximum power of $\approx$500 W and a spot size of 70 $\mu$m, an automatic powder spreading device with a flexible blade, an inert argon gas protection system and a computer system for process control. The raw material AlSi10Mg with a mean particle size of $\approx$20.5 $\mu$m was used in this study. The morphology of powder and its particle size distribution are presented in Figure 2b. The parameters of SLM process applied in this study are listed as follows: the laser power $= 400$ W, scanning speed $= 2200$ mm\ s$^{-1}$ and layer thickness $= 30$ $\mu$m.

The as-processed reticulated shell components were removed from the substrate by electrical discharge machining (EDM) after SLM. The relative density of reticulated shell components was calculated according to the Archimedes principle. The components were ground and polished following the standard metallographic procedures. The pore distribution of cross-sectioned components was observed by OLYMPUS PMG3 optical microscope (OM). Prior to compression tests, components were

![Figure 1. a) A diving bell of water spider and the cross-linking structure of spider silk,\cite{34} b) CAD model of the reticulated shell structure and the position of different nodes.](image-url)
cleaned with detergent, followed by 5 min ultrasonic bath in alcohol and finally dried in hot flowing air. Compression tests were conducted at room temperature on a CMT5205 testing machine (MTS Industrial Systems, China) with a displacement rate of 1 mm min⁻¹. After compression tests, the fractured surfaces were characterized using a field emission SEM (Hitachi S-4800, Japan).

Energy absorption (EA) has been widely employed to determine the energy absorption capacity of structures, which can be expressed as follows:

$$EA = \int_0^d F(x)dx$$  \hspace{1cm} (1)

where $F(x)$ is the instantaneous crushing force during the compression process, $d$ is the effective deformation of structures. It is supposed that $EA$ is the area beneath the force–displacement curve.

Specific energy absorption (SEA) is a key crashworthiness indicator to evaluate the energy absorption capacity of structures when taking the structural mass into consideration. The expression can be mathematically given as follows:

$$SEA = \frac{EA(d)}{m}$$  \hspace{1cm} (2)

where $EA(d)$ is the total absorbed energy described in Equation (2), $m$ is the structural mass.

In order to analyze the stress distribution and fracture mechanism of reticulated shell structures under compression, finite element analysis (FEA) was conducted using the ANSYS software. The tetrahedral unit were employed as mesh for the reticulated shell structure, in which each node possessed six degrees of freedom. Convergence analysis of mesh size was conducted to optimize mesh size. After the meshing process, 250 000 elements and 90 000 nodes were generated. Material properties of AlSi10Mg for the FEA are listed in Table 1. The reticulated shell structures were sandwiched between two rigid flat plates, which simulated the compression conditions. The top plate was freely moved in Z direction at a constant velocity, but fixed in other directions. The bottom plate was fully fixed in all directions. The automatic node-to-surface contact was employed to describe the contact interface between the reticulated shell structure and the rigid plates, and the frictional coefficient between them was set as 0.1.

3. Results

The geometries of all reticulated shell structures were identical except that the strut diameter varied. After SLM processing, the

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**Table 1. Properties of AlSi10Mg.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g cm⁻³]</td>
<td>2.65</td>
</tr>
<tr>
<td>Young's modulus [GPa]</td>
<td>71.6</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
<td>300</td>
</tr>
<tr>
<td>Tangent modulus [GPa]</td>
<td>2.7</td>
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strut diameter was measured by Vernier caliper to evaluate the forming accuracy of SLM process. At least ten measurements from different positions of the structure were conducted to obtain an average value. The strut diameters measured from SLM-processed reticulated shell structures are presented in Figure 3. The results showed that for each structure the measured strut diameter was larger than that of the design value by 4.9–6.9%, which is similar to the reported results. [23,24] These increments of strut diameter was mainly caused by the attached un-melted powder or stair-stepped effect. [25] It is noted that the error bar increased with the increase of diameter from 41.4 μm (D0.75) to 65.7 μm (D1.50).

Under the same laser processing parameters, reticulated shell components with different strut diameters exhibited slight variation in relative densities. As shown in Figure 4, a maximum relative density (≈99.5%) was obtained for D0.75. With the increase of strut diameter, the relative density showed a continuous decrease to a value of 99.1% for D1.50. The corresponding OM images obtained from the same position of four reticulated shell components were presented in Figure 4 as insets. Near-full dense structures can be observed from those OM images. However, with the increase of strut diameter, some pores were formed near the surface of structures, which was also reported by Zhang et al. [36]

In order to further reveal the densification behavior of reticulated shell components, the microstructure on different positions was characterized. The D1.00 component was selected as a representative and the corresponding OM images taken from different positions are shown in Figure 5. The top node (N1), the rod structure, and the middle node (N2) all exhibited high densification and only few pores were distributed on the edge of the structure. No obvious difference in terms of densification can be found for these three positions. The surface of struts appeared rough, which is due to the large amount of overhanging surfaces during the SLM processing of reticulated shell components. These surfaces resulted in the step effect and adhered powders on the surfaces. [37]

Figure 6 depicts load–displacement curves of all components and three distinct stages can be found from all curves. At the first stage, the applied load value increased with the displacement, but the increased rate of load significantly changed when the displacement exceeded a certain value. This changes can be explained as follows: at the very beginning, the portion of component directly contacted with the loading plate was the top node (N1) and the solid-to-space ratio barely changed; as the displacement further increased, the solid-to-space ratio of the contact area with the loading plate reduced due to the radial nature of the reticulated shell structure, and led to a reduction of the load value increased rate. At the second stage, a sudden reduction of load was observed with further increasing displacement. The explanation for this load reduction will be discussed later. At the last stage, the load exhibited an increasing trend and reached a maximum value until failure. At this stage, the change of increasing rate of load value was also observed, and the explanation was similar to that of the first stage. It is worth noting that the D1.50 component exhibited the highest load value in the overall compression process, followed by D1.25, D1.00, and D0.75 components. Similar observations have been also reported by Tancogne-Dejean and Mohr. [38] The SLM-processed components with a smaller rod diameter showed higher maximum displacement. It may be related to the greater strain at the outer strut for a larger rod in bending. [23] At the same time, this might be related to the relative density of SLM-processed components (Figure 4). Because large amounts of pores made negative contributions to the ductility of components, thus lowering the maximum displacement. [39]

The EA and SEA of different components, calculated according to Equation (1) and (2), are charted in Figure 6b. The EA value increased with the increase of strut diameter and the D1.50 component exhibited the highest EA value of 4.9 J. Unlike the changes of EA with strut diameter, the SEA showed different trend, which continuously increased from 1.05 J g−1 for the D0.75 component to a value of 1.72 J g−1 for that of D1.25 component, and then showed a slight decrease to 1.62 J g−1 for that of D1.50 component. It can also be clearly seen from the graph that the SEA values for D1.25 and D1.50 was much higher than those for D0.75 and D1.00. This observation is in good agreement with the results reported by Tancogne-Dejean. [40]
They found that lattice structure with a larger strut diameter possessed higher specific energy absorption capability and proposed that the meso-structural response of metallic lattice materials under compression changed from an unstable twist mode to a stable buckling free mode with the increase of strut diameter.

As the reticulated shell components with different diameters exhibited similar load–displacement curves, the $D_{1.50}$ component was selected as an example to reveal the deformation process during compression test. Four key points taken from the inflection point between two adjacent stages and failure of load–displacement curve corresponded to Point I, II, III, and IV, and were shown in Figure 6a. The deformation process of structures was directly recorded by video camera, and the photographs captured at the four points were showed in Figure 7a. When the displacement exceeded Point I, the top node (N1) suddenly subsided and lost contact with the loading plate, resulting in the sudden decline of load as discussed above. As the displacement reached Point II, the loading plate contacted with the N2 nodes, leading to an ascent of load value. When the displacement increased from Point III to Point IV, the increased ratio significantly changed from 0.19 to 0.51 (Figure 6a). This was because the subsided top node had contact with the bottom plate, contributing to a higher increase ratio of load value. Finally, fracture was initiated and occurred at the node of N3 (marked by red dot circle in Figure 7a) when the displacement reached Point IV.

Although fracture occurred at the bottom nodes for all reticulated shell components, the broke nodes varied by strut diameter. Specifically, for structures with a relatively small strut diameter ($D_{0.75}$ and $D_{1.00}$), fracture occurred at N3 node (intersections of two rods), while fracture occurred at N4 node (intersection of three rods) for $D_{1.25}$ and $D_{1.50}$ components. The fracture surfaces of the reticulated shell components after compression tests were examined by SEM. As seen from low
magnification SEM images, the fracture surface of the $D_{1.00}$ component was coarse without smooth area, while the fracture surface of the $D_{1.50}$ component consisted of coarse and smooth area. A close examination of SEM images revealed that a large amount of ductile dimples existed in the coarse area instead of on the smooth fracture surface. In addition, some opened-up pores with various diameters were observed from both fracture surfaces, and the amount of opened-up pores on the fracture surface of $D_{1.50}$ component was larger than that of the $D_{1.00}$ component. Similar fracture surfaces of SLM-processed AlSi10Mg structures are also reported in literatures,[20,23,24] where the opened-up pores were suspected to be the initiation of fracture.

4. Discussion

In order to reveal the fracture mechanism of reticulated shell components with different strut diameters, FEA simulation was conducted to investigate the stress distribution of the structure.
during compression process. To ensure the accuracy of the FEA model, the simulation results of load displacement curves were compared with the experimental results conducted under the same compression conditions (Figure 8). It can be seen from Figure 8 that the load–displacement curves obtained by the FEA simulation exhibited a similar trend to that of the compression experiments. The simulation curves are somewhat higher than those of experiments even though both curves in the whole compression process are of the same order of magnitude. This difference is because the simulation was carried out under the ideal conditions. Instead, the defects formed in the structure unavoidably affected its performance during the compression process, leading to a relatively low load under the same displacement. Another remarkable difference is that no distinct change in load at Point I can be found when compared the results of FEA and experiments. As the sudden reduction of load at the Point II was attributed to the subsiding of the top node, the top node was taken flattened without subsidence during the whole process of compression by FEA simulation. Overall, the load–displacement curves evaluated by the FEA simulation were in good agreement with those obtained from compression experiments. Therefore, the proposed FEA model could provide reference values for analyzing the stress distribution of reticulated shell structures during deformation process.

As the configuration of rods was identical for all structures, the only difference was the strut diameter. Similarly, the \( D_{1.25} \) structure was used to simulate stress distribution at a displacement of 6 mm, as shown in Figure 9a. Due to the symmetry of reticulated shell structures, the stress distribution also exhibited a symmetrical feature in the structure. It can be clearly seen that the stress at the N3 and N4 positions was relatively higher than the positions of N1 and N2, and a maximum stress of 829.5 MPa was generated at N3 position (Figure 9a). The stress values of different nodes for all structures at a displacement of 6 mm are compared in Figure 10b. For all structures, the stress at N3 was always the highest, followed by N4, N1, and N2, respectively, suggesting that fracture tended to occur at N3 node. It is interesting to find that the response of stress to strut diameter was different for different nodes. With the increase of strut diameter, the stress values of N1 and N3 increased, while the stress values of N2 and N4 decreased. In addition, the difference of stress value between N3 and N4 was significantly enlarged with the increase of strut diameter.

According to the results of compression experiments, the components with smaller strut diameters (\( D_{0.75} \) and \( D_{1.00} \)) broke at the node of N3, being in agreement with the simulation results. However, the structures with larger strut diameters (\( D_{1.25} \) and \( D_{1.50} \)) fractured at the node of N4, which seemed to conflict with the simulation results. This is probably caused by the defects generated in structures, which negatively affect the mechanical behavior and leading to different fracture locations. A further examination of the microstructure of the N3 and N4 nodes for the \( D_{1.00} \) component and \( D_{1.50} \) component in Figure 10 shows that these two nodes of the \( D_{1.00} \) component (Figure 10a, b) had relatively high density with only minor pores observed on the edge of rods. This is consistent with high relative density of 99.2%, as shown in Figure 4. In this case, the stress played a dominant role in the fracture mechanism of compression process, and the structure fractured at the N3 node with a maximum stress. Based on the OM images obtained from N3 node and N4 node of the \( D_{1.50} \) component (Figure 10c, d), it can be clearly seen that the amount of pores at N4 was obviously higher than that of N3, and pores mainly distributed on the bottom of rod. The pores observed in those OM images were mainly gas bubbles trapped in the components.[36] For the components with a larger strut diameter, more tracks were scanned for each building layer, leading to
related higher molten pool temperature.\cite{39} Higher molten pool temperature usually leads to higher gas solubility in liquid metal, and thus more pores left in components after solidification and lowering the relative density (Figure 4). Comparing the geometry of N3 and N4, thermal heat tended to accumulate at N4 rather than N3 since an additional rod was built at N4, resulting in relatively high porosity at N4 (Figure 10d). During the compression test, the pores would deteriorate the compressive performance and act as the crack initiation (Figure 8b). Therefore, pores played a dominant role in the fracture mechanism of the $D_{1.50}$ component, implying that the fracture occurred at N4 node with higher porosity.

Figure 10. Cross-sectional OM images of a) N3, b) N4 of the $D_{1.00}$ and c) N3, d) N4 of the $D_{1.50}$. 
5. Conclusions

Reticulated shell structures with different strut diameters have been designed and fabricated by SLM technology. The dimensional accuracy, densification behavior and compressive properties of the SLM-processed components were analyzed. The following conclusions can be drawn:

1) Near fully dense reticulated shell components (relative density > 99%) were successfully fabricated by SLM technology of AlSi10Mg powder. Both of dimensional accuracy of strut diameter and relative density of component decreased with the increasing strut diameter.

2) The load–displacement curves of all reticulated shell components exhibited a similar trend. The component with a strut diameter of 1.50 mm possessed a maximum load-bearing capacity, while the component with a strut diameter of 0.75 mm exhibited a maximum displacement. The structure with a 1.25 mm diameter showed the highest SEA value, thus the best energy absorption capability.

3) The fracture locations of all reticulated shell structures varied with different strut diameters, which were significantly influenced by the stress distribution and pore distribution. For components with small strut diameters of 0.75 mm and 1.00 mm, no obvious difference can be found among nodes in terms of porosity. Hence, stress distribution played a dominant role in fracture process, which occurred at the node with a high stress. While for components with a relatively large strut diameter of 1.25 mm and 1.50 mm, more pores can be found at the intersection node of three rods than that of the intersection node of two rods. In this case, pore distribution made dominant contributions to fracture, which occurred at the node with higher level of porosity.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

additive manufacturing, bio-inspired, energy absorption, finite element simulation, reticulated shell structure, selective laser melting

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