Influence of laser parameters and complex structural features on the bio-inspired complex thin-wall structures fabricated by selective laser melting

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\begin{abstract}
The lobster-eye structure exhibits unique optical performance and finds its application in aerospace. However, the lobster-eye structure is highly complex and hard to process using traditional subtractive manufacturing methods. In this work, complex thin-wall structures, inspired by the lobster eye, were fabricated by selective laser melting (SLM) with AlSi10Mg powder. The influence of key laser parameter, namely laser power, on the densification behavior, dimensional accuracy, surface roughness and forming defect of SLM-processed lobster-eye parts was systematically investigated. Particular emphasis was placed on the impact of laser power and structural features on the inner surface roughness. Results revealed that the relative density of SLM-processed lobster-eye parts exhibited a similar trend with bulk parts against the laser power. The small dimension feature of thin-wall structures contributed to the higher relative density of lobster-eye parts comparing with that of bulk parts. The roughness of inner surfaces and outside surfaces showed completely different responds to the laser power, and the inner surface morphology behaved differently among positions. All these special surface phenomena were contributed to the combined impact of the laser parameter and the particular geometry of the lobster-eye structure. Finally, considering the optical function and post-processing, an optimal laser power was determined for the SLM-processing of lobster-eye components.
\end{abstract}

\section{1. Introduction}

During the millions of years of evolution, the nature life has developed the optimized natural structures to survive in the cruel natural competition. According to specific living environment, natural structures exhibit unique functions. Qin et al. (2015) claim that the topological design of spider-web provides the properties of light-weight, high strength and elasticity. Habibi et al. (2015) find that the functionally-graded hollow structure of bamboo delivers excellent flexibility and fracture toughness. Finnemore et al. (2012) find that the ordered multilayer structure of nacre performs remarkably high toughness and resilience. Chen et al. (2016) believe that the continuous directional water transport on the peristome surface of nepenthes alata is contributed to the unique nano/micro-structure on the surface.

In the field of optical application, natural structures also show outstanding performance. One of the most representative instances is the lobster eye (Fig. 1a). The eye of lobster is composed of numerous small square channels arranging over a spherical surface. Each channel is long and narrow, with its central axis goes toward to the center of the spherical surface. Angel (1979) finds that, light entering the channel array from different angles is focused through grazing-incident reflection and form a single image on the curved retina of lobster (Fig. 1b), thanks to the unique structure. The lobster-eye structure optics possess the advantages of light-weight, small size and wide field of view, which is perfected for the application of aerospace. Currently, the fabrication methods applied to process lobster-eye structures are basically subtractive manufacturing. For instance, Peele et al. (2007) apply LIGA method to produce lobster-eye optics with a graphite substrate. However, due to limitation of subtractive methods, the high aspect ratio channel is hard to fabricate.

The channel-array structures of lobster eye can also be treated as complex thin-wall structures consisting of two groups of thin walls perpendicular to each other. For the fabrication of these complex thin-wall structures, additive manufacturing (AM) technology has significant advantages over traditional subtractive (such as milling and machining) or formative manufacturing (such as casting and plastic

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Received 25 June 2018; Received in revised form 2 November 2018; Accepted 1 December 2018
Available online 03 December 2018
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forming) technologies. Due to the layer-wise nature, AM technology is more competitive than traditional manufacturing to fabricate parts with a high level of complexity. Many efforts have been devoted into the research of additive manufacturing of thin-wall structures. Till now, various AM technologies have been applied to fabricate thin-wall structures. Bontha et al. (2006) use laser melting deposition (LMD) to fabricate thin-wall Ti6Al4V parts and predict solidification microstructure using thermal process maps. Denlinger et al. (2015) apply electron beam melting (EBM) to build Ti6Al4V thin-walls and investigate the evolution of residual stress. Boegelein et al. (2016) employ selective laser melting to fabricate complex thin-wall structures. Due to the high energy density and coarse size of feeding raw material, the surface quality and dimensional accuracy of products, fabricated by the deposition-based technologies and EBM, are worse than that of parts fabricated by SLM. Therefore, SLM technology has been widely used to fabricate thin-wall parts with fine feature and complex structures.

The structure of thin-wall parts is significantly different from that of the bulk parts, leading to completely different temperature distribution and residual stress generation. The optimized SLM processing parameters for bulk parts, occurring high density and excellent mechanical
performance, might not be preferred for thin-wall parts. Therefore, most of the researches on the SLM thin-wall parts concentrate on the process parameter study. Yadroitsev et al. (2007) study the influence of scanning strategies, namely lengthwise, transversal and angular, on the formability of thin walls and find that lengthwise one is the optimal strategy for forming thin walls, which can build the thinnest wall with smallest dimensional error. Song et al. (2015) investigate the influence of laser energy and scanning speed on the thickness of SLM-processed thin walls and find that the thickness of thin walls increases with the increasing of linear laser energy density. Shishkovskii et al. (2016) investigate the relation between powder size and the key structure aspects of thin-wall parts. Results reveal that smaller powder size delivers better reproduction, thinner wall and more precise angle. Apart from the SLM process parameters, the thin-wall structure itself also affects the formability. Li et al. (2018) apply indirect coupled thermal-structural finite element model to analyze the temperature and stress distribution of thin-walls with different length during the SLM process. Results show that the different temperature history and the consequent difference of stress distribution, causing by the various thin-wall lengths, contributes to the different distortion and shrinkage behavior. Calignano et al. (2018) reveal that the constructed direction of SLM-processed walls, namely parallel and perpendicular to the recoating blade moving direction, significantly affect the formability of thin-wall structures. Calignano (2018) also find that the building angle affects the heat flow in the build component and consequently influence the surface roughness. The surface quality of thin-wall structures is a critical indicator in many applications, especially for the medical implants. Liu et al. (2018) find that, similar with the SLM-processed bulk parts, the laser processing parameters directly influence the surface roughness. Wang et al. (2016) find that for a thin-wall part, built with inclination angle to the substrate

![Fig. 3. (a) The relative density and (b) the cross-sectional OM images of SLM-processed bulk and lobster-eye parts (pores are marked by black arrows).](image)

![Fig. 4. Schematic of different thermal transfer: (a) the bulk part, (b) the thin-wall part.](image)
plane, the roughness of downward surface is always higher than that of the upward surface. Mumtaz and Hopkinson (2009) investigate the relationship between process parameters and top/side roughness of thin-wall parts. It is interesting to find that higher laser power tends to simultaneously reduce the top surface roughness and side roughness, however, lower scan speed reduces top surface roughness but increases side surface roughness.

The lobster-eye structure is widely used in optical application, the surface quality, especially the inner surface roughness, is curial for better optical performance. However, to the best of our knowledge, the relation between SLM-processing parameters and inner surface roughness of complex thin-wall structures has not been reported. In the present work, the lobster-eye parts were fabricated with the method of selective laser melting using AlSi10Mg powder. The influence of SLM process parameter and the complex structural features on the forming accuracy of the cone angle (\(\theta\)) and the thickness of thin walls (\(t\)). SLM-processed components were sliced along the height direction of the center channel. During the fabrication, cubic parts with the dimension of \(5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}\) were built alongside with each lobster-eye part, using the identical parameter setting.

2. Materials and methods

2.1. SLM processing of lobster-eye structures

2.1.1. Structure design

The thin-wall structure in this work was inspired by the lobster eye (shown in Fig. 1) and the CAD model is shown in Fig. 2(a). The designed lobster-eye structure consisted of a 9 by 9 array of channels. The opening of each channel is a square with a length of 1.5 mm, and the height and cone angle (\(a\)) of each channel is 10 mm and 2°, respectively. The thickness (\(t\)) of all the thin walls is set as 0.2 mm. The cone-angle of the whole lobster-eye structure (\(\theta\)) is 18°.

2.1.2. Powder

The powder size greatly influences the forming quality of SLM-processed components (Sutton et al., 2017). Based on our previous research, gas-atomized AlSi10Mg powder (with the mean particle size of 23 \(\mu\)m) possessed good formability and was used in this work. The SEM image of the powder and the particle size distribution are presented in Fig. 2(b).

2.1.3. SLM processing

A self-developed SLM machine (Fig. 2(c)) was applied in this work. The detail of this machine can be found elsewhere (Chen et al., 2017a). All the SLM processes were conducted under the Ar atmosphere with the oxygen content lower than 10 ppm. SLM process parameters like laser power, scanning speed and layer thickness affect the part quality (Fatemi et al., 2017). However, Sing et al. (2018) claim that the influence of laser power on the forming quality of complex components is more significant than other parameters. Therefore, the influence of laser power was investigated in this work. The laser power was varied between 325 W–425 W in 25 W increments. For all the SLM-processed lobster-eye components, the scanning speed, layer thickness and hatch spacing were constantly set as 2200 mm/s, 30 \(\mu\)m and 50 \(\mu\)m, respectively. The selection of those parameters was based on our previous research (Gu and Dai, 2016). In order to minimize the area of overhanging surface, the building direction of all components was parallel to the height direction of the center channel. During the fabrication, cubic parts with the dimension of \(5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}\) were built alongside with each lobster-eye part, using the identical parameter setting.

2.2. Characterization methods

2.2.1. Relative density

The density of SLM-processed components (including lobster-eye parts and cubic parts) were measured using the Archimedes’ principle. To avoid the trapping of bubble inside the small channels, ethanol was employed as the solution, because of the lower surface tension (0.0223 N/m at 20 °C) than water (0.0728 N/m at 20 °C). The relative density (\(\zeta\)) were calculated by the following equation:

\[
\zeta = \frac{\rho_m \times 100\%}{\rho_T}
\]

where \(\rho_m\) was the measured density of the SLM-processed part and \(\rho_T\) is the theoretical density of AlSi10Mg (2.68 g/cm³).

2.2.2. Dimensional accuracy

For this particular lobster-eye structure, special emphasis was put on the forming accuracy of the cone angle (\(\theta\)) and the thickness of thin walls (\(t\)). SLM-processed components were sliced along the height direction to facilitate the optical microscopic (OM) observation (Olympus PMG3, Japan). The key structure parameters were measured from the OM images by the software of ToupView.

2.2.3. Surface morphology

The surface roughness of SLM-processed parts was measured by the LEXT OLS4100 Laser Confocal Microscope (Olympus, Japan). In addition, the surface morphology was characterized using a JSM-6360LV scanning electron microscope (Jeol, Japan).

3. Results and discussion

3.1. Densification behavior

The relative density of the bulk part and the lobster-eye part exhibited the same trend against the laser power (Fig. 3(a)). The relative density firstly increased with the laser power and reached the highest relative density (99.7% for the lobster-eye part and 99.4% for the bulk part) at the laser power of 400 W, and then a decrease was observed when the laser power further increased to 425 W. From the comparison between the bulk part and the lobster-eye part, it is obvious that the relative density of lobster-eye parts was always higher than that of the bulk parts.

From the cross-sectional OM images shown in Fig. 3(b), it can be seem that when the laser power was low (325 W), the porosity level of the cubic part and lobster-eye part was similar to each other. For the
cubic part, several big pores with the size of about 80 μm can be observed. For the lobster-eye part, instead of big-size pores, many small pores were found. With the increase of laser power, the number of pore significantly reduced, resulting to the increase of relative density. Comparing the cubic part and the lobster-eye part, the porosity level of the former was higher than that of the latter, which was in agreement with the result of relative density shown in Fig. 3(a).

The relation between the laser processing parameters and the densification behavior of SLM-processed AlSi10Mg has been well-investigated. In the work of Chen et al. (2017b), the relative density of SLM-processed AlSi10Mg firstly increases and then decreases with the increase of laser power, which is in agreement with the results of this work (Fig. 3(a)). The underlying reason for this phenomenon could be explained as follows: when increasing the laser power, more energy was introduced to the powder bed, resulting to better fusion of powder, and thus higher relative density; however, when the laser power was too high, the intensive energy input cause the formation of thermal cracks (Gu et al., 2012) or layer delamination (Chen et al., 2017b), leading to the reduction of relative density.

Because of the small-dimension feature of lobster-eye parts, the processing condition was significantly different with that of the bulk parts. During SLM processing, the bulk-to-powder ratio near the molten pool of the bulk part is remarkably larger than that of the thin-wall part (Fig. 4). Alkahari et al. (2012) and Dai and Gu (2015) report that the thermal conductivity of powder is grammatically lower than that of the bulk form of the same material. Therefore, under the same laser power, more heat stayed in the melt pool of the thin-wall part during SLM fabrication, leading to better fusion and consequent higher relative density.

3.2. Dimensional accuracy

For the specific lobster-eye parts, particular emphasis was placed on the forming accuracy of wall thickness (t) and cone angle (θ), which were schematically shown in Fig. 5(a). The trends of wall thickness and cone angle against laser power were presented in Fig. 5(b). For the wall thickness, all values were higher than that of the designed value (0.2 mm), which might be related with the attached balls on the wall.

Fig. 6. (a) The inner surface and outside surface roughness and (b) the SEM surface morphology of SLM-processed lobster-eye parts with different laser power.
surface. The thickness values increased when the laser power increased from 325 W to 350 W, then slightly reduced to a relatively stable value of 0.214 mm when further increased laser power from 375 W to 425 W. In terms of the cone angle, with the increasing of laser power, the cone angle firstly increased and then reduced when the laser power exceeded 375 W.

Because the orientation of thin walls is not parallel to the SLM building direction, all the thin walls were downfacing structures with various declined angle to the building direction. With the increase of laser power, the size of melt pool and the volume of liquid metal increased. Song et al. (2015) claim that the fully melted liquid tended to flow downward under the influence of gravity, leading to the increase of cone angle and the increase of thin wall thickness. Yu et al. (2016a) claim that when the laser energy is too high, excessive liquid formed and developed into “self-balling”. Therefore, when further increased the laser power, the liquid metal trended to form balls rather than flow downward, leading to the reduction of cone angle.

3.3. Surface roughness

The surface roughness of the inner surface and outside surface of the SLM-processed lobster-eye parts was presented in Fig. 6(a). It is obvious that the roughness of inner surface was always higher than that of the outside surface. For the outside surface, the roughness increased
slightly from 325 W to 350 W, and then decreased with the increasing of laser power from 350 W to 425 W. The relation between outside surface roughness and laser parameters was in agreement with the study of Liu et al. (2018) and Mumtaz and Hopkinson (2009). However, the surface roughness of the inner surface exhibited completely different trend comparing with the outside surface. With the increase of laser power, the roughness of inner surface sharply increased from 325 W to 350 W and then slightly increased from 350 W to 425 W.

The representative low magnification SEM surface morphologies of SLM-processed lobster-eye parts were illustrated in Fig. 6(b). Many ball-like features can be observed on the outside surface of the 325 W sample, which might be related to the balling-effect or the attached unmelted powder particles. With the increase of laser power to 425 W, less amount of ball-like features was observed on the outside surface than that of the 325 W sample, and the proportion of smooth area (dark area) increased, contributing to the reducing surface roughness value (Fig. 6(a)). For the inner surface, with the increase of laser power, more big size balls can be found, and balls tended to form clusters rather than single balls. All these contributed to the remarkable increase of inner surface roughness (Fig. 6(a)).

When the laser power was low, due to the lack of fusion, the laser scan track tended to break into discontinuous dots and consequently led to the formation of roughed surface. With the increase of laser power, smooth laser scan tracks formed and the surface roughness reduced. However, a completely opposite response to laser power was witnessed for the inner surface roughness. This anomaly can be explained by the particular structure of the lobster-eye. The lobster-eye structure consists of many small channels, because of the layer-wise feature of the SLM process, a square box was scanned for each layer. Therefore, the powder, locating in this square box, suffered more thermal cycles than the powder outside the lobster-eye structure. As a consequence, the powder near the inner surface tend to gather together and form clusters (Fig. 6d) on the surface, resulting in the higher roughness of inner surface.

The inner surface roughness of different positions of the channel (laser power 425 W) was measured and listed in Fig. 7. The roughness of the middle part of the channel was the highest, and the roughness of the top part and bottom part was close to each other. From SEM images of surface morphologies on different positions (Fig. 7b–d), it is obvious that more ball-like features and more clusters of balls can be observed from the middle position surface. The surface roughness of thin-wall parts is greatly influenced by the local temperature of part during SLM processing. Xiong et al. (2018) find that decreasing the local temperature is associated with the decrease of surface roughness of thin-wall parts. Gu et al. (2018) report that the local temperature varied significantly during the SLM processing, especially along the building direction. At the bottom position, the portion being fabricated was close to the bulky substrate plate, which
absorbed a large amount of heat during processing, contributing to the lower local temperature of the portion and thus lower surface roughness (Fig. 8(a)). With the increase of building height, the molten pool moved away from the bulky substrate plate and the heat conduction to the substrate plate was weakened (Fig. 8(a)). As a consequence, the local temperature was relatively higher than that of the bottom position, resulting in the increase of surface roughness. However, the surface roughness at the top position was lower than that of the middle position. This anomaly can also be explained by the particular structure of the lobster-eye. Because all the channels are arranged over a spherical surface, the cross-section dimension of the channel increases from bottom to top. In other words, the distance between two parallel thin walls increase with the building height. When a thin wall was under fabrication, the thermal effect to the previous fabricated thin wall was weaker at the top position than that of the bottom position (Fig. 8(b)), leading to the reduction of roughness at the top position. Under the combined influence of those two factors, the inner surface roughness exhibited the unique behavior at different positions.

### 3.4. Forming defects

The low-magnification SEM images of different positions inside the channel with different SLM laser power were compared in Fig. 9. When the laser power was 325 W, many interlayer pores can be detected from all positions. Most of those pores were located near the junction of two perpendicular thin walls. Comparing the three different position, it can be found that the amount of interlayer pores in the middle position was the highest among the three positions. For the 400 W processed part,
through more ball-like features can be seen from the inner surface than that of the 325 W part, almost no interlayer pore can be found from the three positions. The top-view SEM images of the 325 W and 400 W SLM-processed lobster-eye parts were presented in Fig. 10. All the thin walls, whether parallel or perpendicular to the recoating direction, exhibited regular shape. The 325 W parts showed many discontinuous scan tracks on the top of thin walls, especially at the junction positions (marked by arrows in Fig. 10(a)). Apart from that, several pores can also be detected at the junction positions (marked by arrows in Fig. 10(b)), which might be related with lack of fusion during SLM processing. For the 400 W sample (Fig. 10(c)), the scan track was more continuous and smooth. Instead of pores, some balls can be found on the top of thin walls (marked by arrow in Fig. 10(d)), which might be related with the “self-balling” effect (Yu et al., 2016b) caused by high laser power.

3.5. Optimal laser processing parameters

From the results presented above, none of the laser power could deliver the best outcome in all aspects, namely densification behavior, dimensional accuracy, surface roughness and forming defects. To determine the optimal laser power for the SLM-processed lobster-eye component, those aspects should be ranked in order of importance. The surface roughness of the lobster-eye part, especially the inner surface roughness is important for the optical application. However, due to the nature of SLM process, the side surface roughness of thin-wall structures is difficult to be controlled at a low level. Post-processing, such as electro-chemical polishing, abrasive flow machining or surface coating, must be conducted to obtain the required surface finishing. The key structural parameters, namely the cone-angle and the thickness of thin-wall, directly affect the optical performance of lobster-eye structure. Between these two structural parameters, the wall thickness can be further modified by post-processing. While, the cone-angle is difficult to change after SLM-processing. Therefore, the dimensional accuracy of cone-angle (θ) is more important than that of wall thickness (t). The level of densification behavior directly governs the forming defect. The pore formed within parts significantly influences the mechanical behavior, especially fatigue property, which is harmful for long-term service of SLM-processed components. The pore located on the surface, which is difficult to be eliminated by post-processing, might trap light and greatly diminish the optical performance. Based on the above discussion, the ranking of aspects in order of importance was drawn as follows: densification behavior > dimensional accuracy (cone-angle) > dimensional accuracy (wall thickness) > surface roughness.

According to the order of importance, the laser power of 400 W, which delivered the highest relative density and relatively high dimensional accuracy of cone-angle, was determined as the optimal laser power. Using the optimal laser parameters, a demo component of full-size lobster-eye was fabricated and presented in Fig. 11.

4. Conclusion

Lobster-eye thin-wall components were fabricated by SLM with AlSi10Mg powder. The influence of key laser processing parameter, namely laser power, on the densification behavior, dimensional accuracy, surface roughness and forming defect was systematically investigated. Based on the results and discussion, several key conclusions are highlighted as follows:

- The relative density of SLM-processed lobster-eye parts firstly increased with the laser power and reached the highest relative density at the laser power of 400 W, and then decreased when the laser power further increased to 425 W. Under the identical laser processing parameters, the relative density of the lobster-eye part was higher than that of the bulk parts, thanks to the small dimension feature of thin-wall structures.
- The roughness of inner surface and outside surface showed completely different responds to the laser power. With the increase of laser power, the outside surface roughness gradually reduced, however, an increase of roughness was witnessed for the inner surface. In addition, the inner surface morphology behaved differently along the building direction. All these phenomena were related with the particular geometry of the lobster-eye structure.
- Considering the function and post-processing of lobster-eye parts, a ranking of aspects in order of importance was proposed, which was densification behavior > dimensional accuracy > surface roughness. According to this ranking, 400 W was the optimal laser power for the SLM-processed lobster-eye parts.

An important finding of this work was that not only the laser parameters, but also the structural features influenced the formability of SLM-processed components. Therefore, when employing SLM technology to fabricate parts with complex and fine geometries, the influence of structural features must be considered at the stage of structure design and SLM parameter design.

Acknowledgments

The authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (No. 51735005).

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