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Mechanical performance of lightweight structures for orthopaedic implants

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Abstract: Lightweight structures (LWS) or cellular structures can be used to tailor the mechanical performances of solid parts, this concept has been applied extensively across the aerospace and biomedical industries. Using advanced additive manufacturing technology, Orthopaedic implants can be designed using LWS to achieve a low Young's modulus while maintaining good bending stiffness and an additional potential benefit of osteoconduction if open lattices are used. In this study, seven patterns of LWS were printed using the selective laser melting method. We aimed to evaluate the effective Young's modulus as well as the bending stiffness of these LWS using tensile and four-points bending tests. The tests were conducted according to the standards of ASTM E8 and F382.

I. Introduction

An ageing global population has led to and increasing demand for Orthopaedic implants. The incidence of elderly patients sustaining fractures continues to increase. This population has specific challenges compared to the young. The main challenge is osteoporosis [1], this leads to weaker and more brittle bone. Current implants do not address this problem sufficiently, leading to high rates of complications in fracture fixation and issues with healing. This has a significant impact on the patient's quality of life and has profound health economic implications.

Stainless steel and titanium are widely used in Orthopaedic implants. The Young's modulus of stainless steel and titanium are 200 GPa and 110 GPa respectively. This is high when compared with the Young's modulus of a cortical bone, 20 GPa [2, 3]. The mismatch causes stress shielding, leading to delayed union or nonunion [4]. In addition to this, failure of fixation is high in osteoporotic bone due to implant stiffness. To address this, we need implants with a low Young's modulus but good strength and fatigue resistance properties.

With the advances in additive manufacturing (AM), implants can now be designed and manufactured with a lower Young's modulus while maintaining sufficient bending stiffness using load-bearing lightweight structures (LWS). Furthermore, the bone in-growth characteristics of LWS implants can be optimized, this could further improve outcomes [5, 6].

The bending stiffness of LWS are rarely discussed. In this study seven LWS were printed via selective laser melting (SLM) and tested using ASTM E8 and F382 standards. The aim is to provide a reference for bending and load-bearing Orthopaedic implant designs.

II. Material and methods

We have designed seven LWS as shown in Fig. 1. Design (1) was a solid tensile bar as a control, (2)-(5) were 2D-planar designs, and (6)-(8) were lattice designs. A Renishaw AM 400 metal printer (Renishaw, United Kingdom) was used to print the designs. Recycled stainless steel 316L powders with sizes between 25-45 µm were used. The following process parameters were used, laser power 200 W, scanning speed 600 mm/s, hatch distance 0.06 mm, layer thickness 0.05 mm and laser focus diameter 0.07 mm. The tensile and bending tests were conducted using Instron 5966 (Instron Corporation, United States), using the test specifications in ASTM E8 and F382.

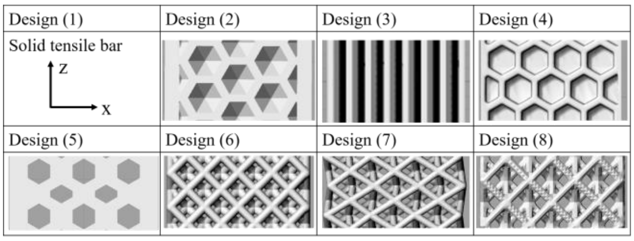

Figure 1: The lightweight structures designed, (1) is a solid tensile bar, (2)-(5) are 2D planar structures and (6)-(8) are lattices.

III. Results and discussion

The load-strain curves of the seven LWS are shown in Fig. 2, the corresponding Young's modulus of each design is summarized in Fig. 3.

The volume fraction of each design is defined using the volume of lightweight structure divided by the volume of the bounding box surrounding the structures, therefore proportionally representing the material usage in LWS compared to a solid part.

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In Fig. 3, the Young's modulus of planar structures (2)-(5) were close to that of the solid reference bar, approximately 140 GPa. This occurred even after a significant reduction of the volume fraction (up to 50 %) in designs (4) and (5). However, using the lattices (7) and (8) designed with a volume fraction between 20% to 30%, the Young's modulus was reduced to 40 GPa, close to that of cortical bone. We have demonstrated a significant reduction in Young's modulus using lattice designs. Furthermore, for lattice designs (7) and (8), the fracture loading was at about 2,900 N and 3,500 N, corresponding to 15% and 18% of the reference bar (19,000 N).

By printing the lattice structures using medical grade titanium alloys (Ti-6Al-4V), we believe that the Young's modulus can be further reduced and may approach that of the cortical bone.

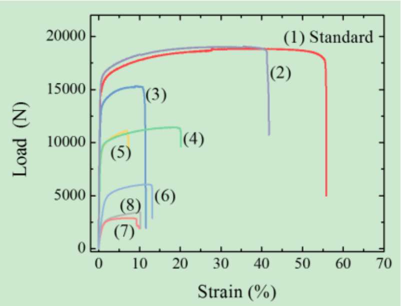

Figure 2: The load-strain curves obtained from tensile tests for lightweight designs (1)-(8) as indicated.

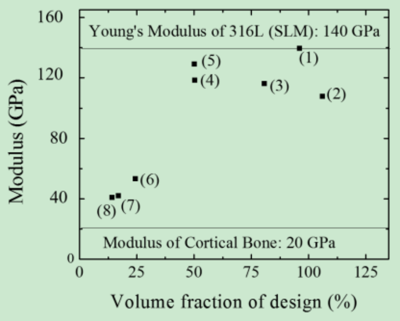

Figure 3: Young's modulus for designs (1)-(8) compared to the volume fraction.

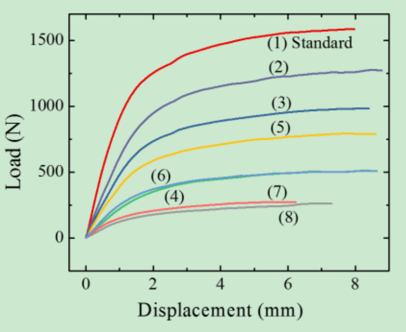

Figure 4: The load-displacement curves from four-point bending tests for designs (1)-(8).

The load-displacement curves from the four-point bending tests are shown in Fig. 4. The bending stiffness *(El_e)* of the LWS were calculated using the *equation (1)*:

$$EI_e = \frac{(2h+3a)Kh^2}{12} \qquad (1).$$

Wherein, E is the modulus of the structures (N/mm^2); I is the moment of inertia (mm^4); a is the center span distance (20 mm); h is the loading span distance (20 mm); and K is the plate's modulus (N/mm), this represents the slope of the elastic region of the bending load-displacement curve.

The bending stiffness *(El_e)* of the seven LWS were calculated using *equation (1)*. The bending stiffness for each were (1) 3.27 $N\text{-}m^2$, (2) 1.88 $N\text{-}m^2$, (3) 1.56 $N\text{-}m^2$, (4) 0.69 $N\text{-}m^2$, (5) 1.27 $N\text{-}m^2$, (6) 0.87 $N\text{-}m^2$, (7) 0.60 $N\text{-}m^2$, and (8) 0.46 $N\text{-}m^2$.

To reduce the stress shielding effect, lattice designs (7) and (8) having a Young's modulus (E) close to that of cortical bone are preferred. However, the corresponding bending stiffness *(El_e)* of those lattice designs were comparably lower than those of planar designs. Integrated or combined lattice and planar designs may provide superior functionality while maintaining a low Young's modulus but sufficient bending stiffness for load-bearing implants. Furthermore, open lattices with pore diameters in excess of 100 µm may facilitate cell penetration and tissue ingrowth, this may further improve the healing process [5, 6].

IV. Conclusion

The stainless steel 316L lattice structures designed had a low Young's modulus, much closer to cortical bone than conventional implants with good bending stiffness. This study has demonstrated that the modulus and bending stiffness of SS316L can be manipulated by applying different lightweight designs. The next stage is to combine the different designs and structures to further improve the strength of the implant while maintaining a low Young's modulus. These lightweight structures can be applied in the design of future Orthopaedic implants with a view to promote functional customized devices in biomedical field.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: not required.

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