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Fracture Mechanism Analysis of Schoen Gyroid Cellular Structures Manufactured by Selective Laser Melting

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Abstract

Ti-6Al-4V triply periodic minimal surface (TPMS) structures with biomorphics scaffold designs are expected to be the most promising candidates for many biological applications such as bone implants. Fracture is the main failure mode of Ti-6Al-4V cellular structures at room temperature. However, there is currently less investigation on general analysis about the fracture mechanism of Ti-6Al-4V TPMS cellular structures. In this work, a typical TPMS structure, Schoen Gyroid, was designed and porous Ti6Al4V Schoen Gyroid specimens were manufactured using Selective laser melting (SLM). Finite element analysis (FEA) method was employed to calculate the stress distribution under compression. The FEA results are used to predict the fracture positions, fracture zones as well as fracture mode. The uniaxial compression experiments were conducted and compared with the FEA results. The experimental and simulation results show high consistency.

Introduction

Cellular structures have attracted many researchers due to their considerably high performances such as superior energy absorption characteristics, light weight, excellent thermal and acoustic insulation properties and high strength–weight ratio. A clear description of the mechanical properties is necessary before the specified cellular structure are used in biomedical implants [1] and energy absorption or impact mitigation [2] with their tailored porosity, density, strength, and ductility.

Research efforts made in this aspect have been mostly focused on elastic module, yield strength, ultimate tensile strength, which are the main performance parameters of cellular structure materials. Gibson and Ashby are the precursors in this field [3]. They proposed the Gibson-Ashby equations fitted from the experimental data, which show a great potential of predicting these parameters. Maskery [4, 5] investigated the uniaxial compression responses of the functionally graded porous structures of Al-Si10-Mg and Nylon 12.

However, Fracture is the main failure mode of the cellular structures fabricated by SLM. Fractures occurred during the tensile and compression process have a dramatic impact on the mechanical properties of cellular structure. Xiao[6] investigated the compression behaviours of Ti-6Al-4V lattice structures at ambient temperature, 200℃, and 400℃, and 600℃ respectively, and found that there are obvious shear bands observed along the 45° plane. The fractures occurred along the shear bands result in a sharp drop of the stress-strain curve and greatly reduce the energy absorption capacity.

The structure Optimisation by strengthening the weakness will obviously improve the energy absorption capacity of brittle materials. Hence it is necessary to inquire about the fracture mechanism of these structures, and some research has been done. For example, mechanical behaviours of Al-Si10-Mg lattice structures manufactured by selective laser melting were examined by Maskery et al. [4] and fractures were observed almost exclusively at the lattice nodes which are associated with both tensile and shear loading. Mazur et al. [7] investigated the deformation and failure behavior of 6 lattice structures with different cell topologies manufactured by SLM through theoretical prediction and experimental validation, and found that fracture predominately occurs in joints.

However, the existing research on fracture mechanism and position are all focused on lattice cellular structures that are derived from Boolean intersections of geometric primitives and have many straight edges and sharp turns. These straight edges and sharp turns will result in highly stress concentration. M. Smith et al.[8] used finite element models to analyse the stress distribution within the bcc unit cell at increasing levels of crush and found that the formation of plastic hinges in the struts are close to the nodal regions due to the stress concentration. Besides, the horizontal struts in lattice cellular structure will decrease the manufacturability in the additive manufacturing processes[7].

Schoen Gyroid is a triply periodic minimal surface structure with smooth infinite surfaces and uniform curvature radius [9]. Without straight edges and sharp turns, Schoen Gyroid cellular structures are expected to show high manufacturability in the selective laser melting (SLM) additive manufacturing processes and excellent mechanical properties [10]. However, there is currently less investigation on general analysis about the fracture mechanism of Ti-6Al-4V Schoen Gyroid cellular structures.

In this paper, Ti–6Al–4V Gyroid TPMS cellular structures with an interconnected high porosity of 85% and single unit sizes of 4.5mm were manufactured by SLM. The mechanical properties under uniaxial compression were evaluated by both experimental tests and FEA method. FEA results were used to predict the fracture positions, fracture zones as well as fracture mode.

2 Method

2.1 Experiment method

The Gyriod unit cell is mathematically designed by a computational method which is reported in our previous work (Hao et al., 2011). The cellular samples with volume fraction of 15% and size of 25mm×25mm×12.5mm were fabricated by 3T RPD Ltd. UK using DMLS EOSINT-M270 machine supplied by EOS GmbH, Munich, Germany.

Uniaxial compression tests were carried out using an AG-IC100 KN Electronic Universal Testing Machine (SHIMADZU, Japan). Experiments are performed at a constant loading rate of 0.75mm/min which equates to an axial strain rate of about 10-3/s, according to ISO-13314-2009. The compression responses of tested specimens were recorded and used to calculate the stress train curves of each TMPS cellular structure.

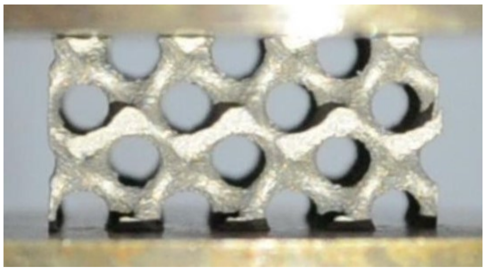

Fig 1 Experiment schematic of the uniaxial compression test

2.2 Finite element analysis modeling

The finite element analysis was carried out with commercial software, DEFORM-3D. A full size model of 25mm×25mm×12.5mm was used to investigate the mechanical properties. The TPMS cellular structure models were placed between two parallel plates, which are regarded as rigid materials. The bottom plate remained stationary while the top plate moved downward at a constant speed (0.0125mm/s) to compact the specimen.

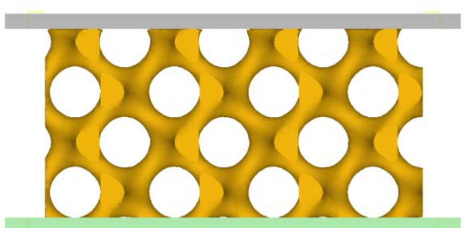

Fig 2 FEA model of the uniaxial compression test

In this work, the Elastic-plastic model was used, and the flow stress at zero strain represents the yield stress for the material. The yield stress increases with the accumulated effective plastic strain. The strengthening mechanism was considered as Johnson-Cook (JC) model, which is commonly used in the dynamic response analysis of materials.

Results and Discussion

3.1 Finite element analysis results

Failure under compression testing is highly related with the stress distribution on the surfaces of the specimens. In order to illustrate failure mechanisms of porous structures, it is essential to analyze stress distribution under compression. As mentioned above, the straight edges and sharp turns in lattice cellular structure will result in highly stress concentration[8]. Compared with the existing lattice cellular structures (BCC, BCCZ, FCC, diamond et al.), triply periodic minimal surface structures have smooth infinite surfaces and uniform curvature radius.

In this work, Fig.3 (A) shows the Von Mises stress distribution of the Gyriod structure at 5% overall deformation. The plot shows that the stress distribution is similar in each unit cell and the stress on the surface of each strut is uniform, while the 45°struts concentrate more stress than the horizontal struts. As many researchers reported [7, 11], for both bulk and porous structure materials, failures occur along 45° direction, which is the biggest shear stress direction. Figure 3 (B) shows the shear stress distribution of Gyriod structure at 5% overall deformation. In this figure, it is clear that the shear stress concentrates on the 45° struts, and the level of shear stress is highest at the center of the struts, which is because the strut center has the minimum cross-sectional area.

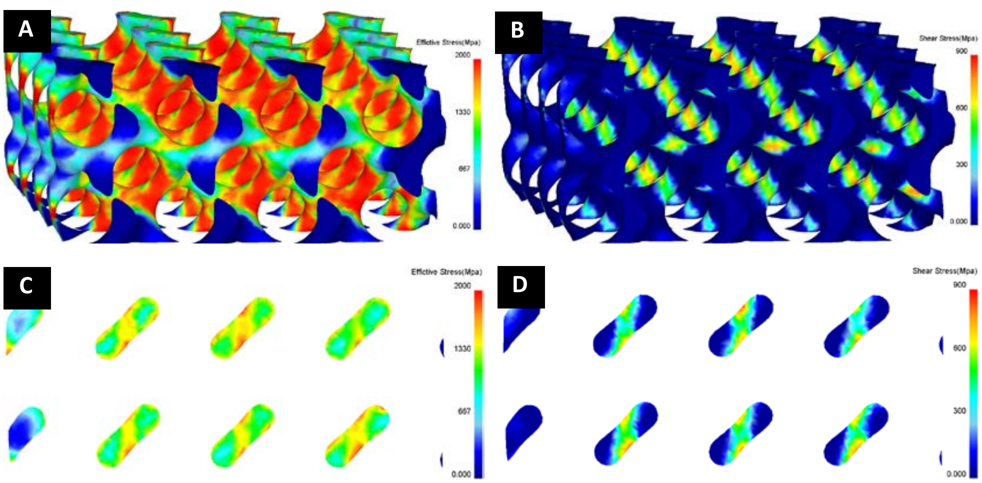

Fig.3 Stress distribution of the Gyriod cellular structure at 5% overall deformation: (A) Von Mises effective stress distribution,(B) 45°shear stress distribution,(C) Von Mises effective stress distribution on the vertical plane, and(D) 45°shear stress distribution on the vertical plane.

Clearly, in the unaxial compressive test process, failures are easy to first occur at the 45° struts of the Gyriod structure, especially at the center of these struts. Hence, the direction of fracture zones is approximately 45 degrees to the horizontal plane. Furthermore, to investigate the failure mechanism, the Von Mises stress and shear stress distributions of a vertical cross-section of the whole model are showed in Fig.3(C) and (D), respectively. Then, the stresses at different locations in the struts are observed and it is found that the stress level on the strut surface is higher than that inside of the strut.

Therefore, plastic strain firstly occurs on the surface of the struts. Since the actual surfaces of the SLM-manufactured objects exist a large number of defects (such as adherent unmelted powder particles, micro-cracks and micro-pores)[10, 12, 13], macro cracks are easy to be initiated and propagate along these defects induced by high level stress. So, it is more likely to produce cleavage fracture.

3.2 Experimental results

Figure 4 shows the actual failure position and fractured zone directions at the compression tests after 30% deformation. In this work, failure position mostly occurred at the center of the struts, while there were still some failures at the positions near the joint regions mainly due to the surface defects of these regions. Nearly all the failures happened on the inclined struts and few failures on the horizontal struts. The fractured zone directions in Fig. 4(B) and Fig. 4(C) are all about 45 degrees to the horizontal plane.

The fracture morphologies of the compression sample are shown in Fig. 5. The smooth shell and river patterns appear in Fig. 5(A) being the characteristics of cleavage fracture. However the small and irregular dimples in Fig. 5(B) are also distributed around the cleavage fracture shells. Therefore, the fracture mode of the Ti-6Al-4V Gyriod structure is a mixed style based on brittle fracture. Similar conclusion for the fracture mode of the Ti-6Al-4V BCC porous structure fabricated by SLM was made by[14].

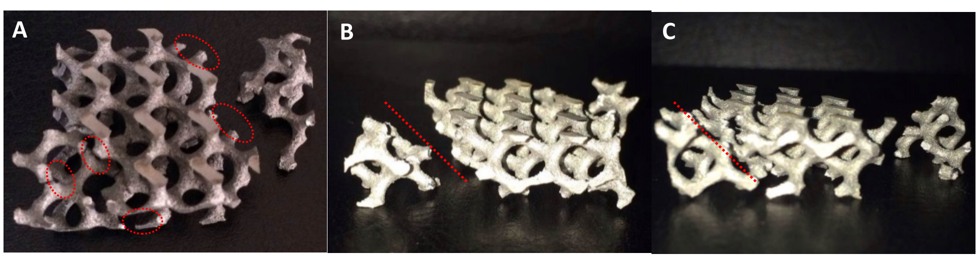

Fig.4 Observations from different perspectives after 30% deformation: (A) Fracture positions observed from the top view, (B) Fracture zone direction observed from the front view, and(C) Fracture zone direction observed from the back view.

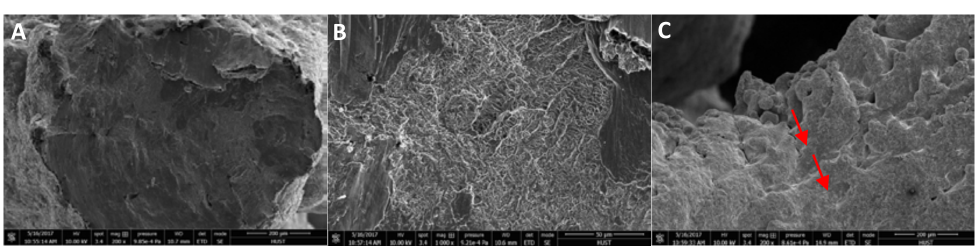

Fig.5 Fracture and surface morphologies of the test sample after 30% deformation: (A) Smooth river and shell patterns, (B) Small and irregular dimples, and(C) Surface

crack initiation and propagation

The surface morphology of the SLM-made lattice structure in Fig. 6(C) shows the crack initiation and propagation. The fractured surface of the SLM-manufactured specimen is rough with many pores and unmelted powder particles. The cracks initiate at the defect positions and propagate perpendicularly to the surface, which is in agreement with the FEA analysis results mentioned above.

Conclusion

Failure of porous structures occurring in the uniaxial compression process is highly related with the stress distribution. In this paper, both finite element analysis and experimental methods are employed to investigate the failure mechanism of the SLM-manufactured Gyriod cellular structure under uniaxial compression, and stress distributions are also plotted in color contour. Both the finite element analysis and experimental results show that the 45°struts concentrate more stress than the horizontal struts, and the level of shear stress is highest at the center of the struts, which results in the fact that the fracture zones all own 45° angle with horizon plane. Failures occur mostly at the center of the struts, which are opposite to the fracture mode of other porous structures having many straight edges and sharp turns.

Acknowledgements

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