Dynamic Mechanical Properties of Selective-laser-melting-processed Ti6Al4V

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Original Article

Keywords: Selective laser melting, Titanium alloy, Triply periodic minimal surface, Split-Hopkinson pressure bar

Posted Date: September 27th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-924004/v1>

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Title page

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ORIGINAL ARTICLE

Dynamic mechanical properties of selective-laser-melting-processed Ti6Al4V

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Abstract: The relative density grading of metal lattice structures becomes a favourable design for bone plants since these structures are suitable for human implantation and have good biological compatibility. The unit cell structure designed using this method is better than that designed by traditional 3D modelling software, especially when using a bionic unit cell design created by a triple periodic minimum surface (TPMS). In this study, the manufacturability of Gyroids was tested by studying three different designs: the relative density of 30%, 20%, and 10% sheet structure. The main purpose is to understand the influence of relative density on the static compression performance of the sheet-like Gyroids structure. This study qualitatively analyses the influence of the relative density of the Gyroids lattice structure prepared by the selective laser melting technology on the compressive strength, elastic modulus, energy absorption and failure mechanism. As the relative density of the sheet structure decreases, the compressive strength decreases. The elastic modulus of the sheet structure of 10% is slightly higher than that of 20%, showing a different trend from the compressive strength. At the same time, the energy absorption per unit volume increases when the relative density decreases and becomes smaller, and the failure modes of the three relative densities all show a 45° fracture failure.

Keywords: Selective laser melting • Titanium alloy • Triply periodic minimal surface • Split-Hopkinson pressure bar

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1 Introduction

A porous structure contains cavities and pillars or sheet-like solid phases. Materials having a porous structure exhibit excellent properties such as high specific strength, low density and excellent sound absorption performance[1, 2], with low relative density being the main feature, which is the ratio of the density of the porous structure to the density of the material. The porous structure is divided into two categories: random and periodic[3]. In the random porous structure, the pores are randomly distributed, such as in the foamed aluminium structure. The pore distribution and pore shape cannot be controlled in the random porous structure. The periodic porous structure contains a controlled unit cell array or a structure with the same surface formed by a periodic function. The mechanical properties of a material with a porous structure primarily depends on the relative density, pore shape and the direction of the geometric defects.

The triply periodic minimal surface (TPMS) contains a periodic porous structure with unit cells and has fixed curvature; TPMS is especially a zero-curvature surface and exhibits excellent transition capabilities. This novel idea aims to obtain a lightweight and energy-absorbing body, and address problems such as implantation[4]. In contrast to other porous structures, the TPMS structure offers a perfect combination of curved surfaces and a predetermined geometric shape[5]. TPMS provides a new type of energy-absorption structure that is more flexible than traditional porous materials. The porous structure is divided into two main types: stretching and bending dominant. The stretching-dominant porous structure is suitable for lightweight structures because of its stiffness, whereas the bending-dominant porous structure is suitable for energy absorption applications because it offers high strain capacity under constant stress[6].

Nature has always inspired people to create new geometries[7]. Additive manufacturing (AM), also known

as 3D printing, has made the development of porous structures with complicated geometries possible[8]. AM allows complex shapes with precise structures to be developed without the needed for complicated processes[9]. Recently, selective laser melting (SLM), a novel AM technology, has been used to produce effective geometrical structures with the best mechanical properties[10, 11].

The TPMS structure is widely known for its energy absorption capacity. Therefore, its mechanical properties and performance under dynamic loading are very important. Ming et al. studied SLM and the structure and properties of the SLM-processed Ti6Al4V. Studies have shown that acicular martensite increases the strength and hardness and reduces the plasticity of the SLM-processed Ti6Al4V. SLM significantly affects the dynamic mechanical properties of the forged Ti6Al4V at high temperature and high strain rate, but the strain rate has no significant effect on the dynamic mechanical properties of forged Ti6Al4V at room temperature [12]. Bar et al. found that the SLM-processed AlSi10Mg showed anisotropy, and its dynamic mechanical properties has no significant sensitivity to the strain rate[13]. Ponnusamy et al. studied the dynamic mechanical properties of the SLM-processed and heat-treated AlSi12 alloy and noted a significant reduction in the dynamic yield strength and ultimate compressive strength of the heat-treated AlSi12 solid cylinders[14]. Xiao et al. studied the dynamic mechanical properties of the rhombic dodecahedral unit cell structure prepared by SLM and electron beam melting, and found that the SLM-processed unit cell is more sensitive to the strain rate, especially when the strain rate is lower than 1000 s⁻¹[15]. Another study found that different gradient modes and loading directions under dynamic load conditions have no effect on the energy absorption capacity[16]. Zhang et al. conducted a split-Hopkinson pressure bar (SHPB) test on the SLM-processed 316L stainless steel lattice structure to determine the effect of strain rate on the impact behaviour of the lattice structure[17]. Jin et al. studied the influence of the structural parameters on the mechanical properties of Pyramidal Kagome lattice materials under dynamic loads[18]. Saremian et al. studied the mechanical properties of three lattice structures under dynamic loads. Studies have shown that the lattice structure has a higher weight ratio and impact resistance[19]. So far, there are limited experimental data on the dynamic stress-strain relationship of the SLM-processed TPMS lattice structure.

This paper mainly studies the mechanical response of a uniform lattice structure under dynamic loads. To obtain complex structures with precise dimensions, SLM was

used to fabricate samples, and the gyroid structure was chosen as a representative. For comparison, a series of gyroid structures with varying relative densities (10%, 20% and 30%) were designed. In this experiment, a Ti6Al4V alloy was used as the raw material to prepare all samples, which were evaluated by the SHPB test. Finally, the effects of strain rate on the dynamic mechanical properties of the gyroid structures were explored.

2 MATERIALS AND DESIGN

2.1 Design method of TPMS gyroid structure

In this study, the TPMS gyroid structure was selected to design the samples. The gyroid structure has a high strength-to-weight ratio, good fluidity and perfect surface area, highlighting its huge potential in biomedical applications. Low stiffness of the gyroid structure is also a key advantage for load-bearing implants. As mentioned previously, the TPMS parameterised equation represents a surface with a constant average curvature, which can be regarded as the boundary between the pore and the solid. By finding the equation, an isosurface is generated with any number of unit cells and the relative density of a matrix phase gyroid structure, which is a method followed by Maskery et al.[20]. In addition, the matrix phase gyroid structure and network phase gyroid structure can be obtained using the TPMS parameterized equations. The network phase gyroid structure contains only one entity and one space. In contrast to the matrix phase gyroid structure, the relative density of the network phase structure can be adjusted by changing the parameters. The matrix phase gyroid structures with any number of unit cells and volume fractions can be obtained through Boolean operations, as shown in Fig 1; these structures are termed as the double gyroid (DG) structures.

$$\varphi_G = \left\{ \begin{aligned} &\cos(\alpha x - \pi/4) \cdot \sin(\beta y - \pi/4) \\ &+ \cos(\beta y - \pi/4) \cdot \sin(\gamma z - \pi/4) \\ &+ \cos(\gamma z - \pi/4) \cdot \sin(\alpha x - \pi/4) \end{aligned} \right\} + 0.08 \cdot \left\{ \begin{aligned} &\cos[2 * (\alpha x - \pi/4)] \cdot \cos[2 * (\beta y - \pi/4)] \\ &+ \cos[2 * (\beta y - \pi/4)] \cdot \cos[2 * (\gamma z - \pi/4)] \\ &+ \cos[2 * (\gamma z - \pi/4)] \cdot \cos[2 * (\alpha x - \pi/4)] \end{aligned} \right\} + R_G \quad (1)$$

The parameters α , β and γ control the cell size in the x, y and z directions, respectively. Larger parameter values result in smaller cells. In the equation, R_G effectively controls the porosity of the structure, so it also effectively controls the relative density ρ^* of the lattice structure. The

relationship between R_G and ρ^* is unique for each TPMS unit cell. For the DG structure, it is found that the linear equation $\rho^* = -0.3193 \cdot R_G + 0.4919$ ($0.1 \leq \rho^* \leq 0.9$) can be used.

Fig 1 TPMS Gyroid structure (a) TPMS Gyroid structure surface; (b) skeleton TPMS Gyroid structure; (c) sheet TPMS Gyroid structure;

2.2 SLM for preparing the DG sample

In this study, an E-Plus-M150 SLM printer was used to manufacture the Ti6Al4V DG samples. Fig 2 shows the photomicrograph of the obtained Ti6Al4V powder and its particle size distribution. The laser power is 180 W, scanning speed is 1000 m/s, scanning pitch is 0.1 mm rotated at 67° , laser spot diameter is 70 μm and layer thickness is 0.03 μm . The DG sample has a diameter of 24 mm and a height of 21 mm. Fig 3 shows the fabricated DG lattice structure along with its CAD model. The relative densities of the DG unit cell samples are 10%, 20% and 30%.

Fig 2 Ti6Al4V powder (a) powder morphology (b) particle size distribution

Fig 3 Double Gyroid model (a) Relative density 10%; (b) Relative density 20%; (c) Relative density 30%;

The dynamic compression experiment is performed based on an SHPB test, which has been commonly used to test the dynamic behaviour of materials. The dynamic impact test of the DG lattice sample is conducted using an SHPB test with a sensor. The loading direction is equivalent to the construction direction. As shown in Fig 4, in the SHPB test device, the incident, transmission, absorption and impact rods are all high-strength steel rods with a diameter of 37 mm. The test sample is sandwiched between the incident and transmission rods. Before the start of the experiment, petroleum jelly is applied between the end faces of the sample, incident rod and transmission rod to reduce friction. When the incident rod is impacted by the impact rod, a compressive stress pulse is generated at the interface, which propagates through both the rods. When the compressive stress pulse reaches the sample, both the incident and impact rods undergo elastic deformation. The sample undergoes plastic deformation. The strain gauge is located at the centre of the incident and transmission rods, and it transmits and records the corresponding stress pulse. The stress pulse signal is processed, amplified and recorded by an oscilloscope. In the experiment, nitrogen was used as the gas source to provide the power for launching the impactor rod.

The mechanical properties were predicted based on the Ashby theory, which has been widely used in previous study[21]. The Gibson–Ashby equation is as follows:

$$E/E_s = C_E \cdot (\rho/\rho_s)^{m_E} \quad (2)$$

$$\sigma/\sigma_s = C_\sigma \cdot (\rho/\rho_s)^{m_\sigma} \quad (3)$$

where ρ , E and σ are the density, relative Young's modulus and strength of the TPMS structure, respectively, and ρ_s , E_s and σ_s are the density, relative Young's modulus, and strength of the Ti6Al4V bulk sample, respectively. C_E , m_E , C_σ and m_σ are constants that are specific to the material and its geometric shape.

In this study, different air source pressures were used to conduct the impact experiments on the DG samples with different volume fractions. The energy absorption is calculated as follows:

$$W = \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon \quad (4)$$

where W is the energy absorption per unit volume, ε is the strain and $\sigma(\varepsilon)$ is the stress corresponding to the strain ε .

Fig 4 Schematic diagram of SHPB device

3 Experimental results

Fig 5 shows the stress–strain curve of the DG sample measured by the SHPB test. The dynamic experiments were conducted at different bullet speeds. The sample was not compacted after the first pulse duration, which is due to the large sample size and confirms its excellent resistance to deformation. However, it was observed that the dynamic response is similar to that under quasi-static loading. They consist of an elastic phase, followed by strain hardening until the peak stress begins to drop and the sample breaks. Compared with the quasi-static compression mechanical properties, the dynamic mechanical properties show higher strength and elastic modulus. In addition, the strain hardening area after the elastic phase shows many oscillations in the dynamic curve, which may be due to defects in the sample. All samples with relative densities of 10%, 20% and 30% show that the fluctuation phase is shorter at high strain rates, and the closer the strain rate to the fracture strain rate, the longer the fluctuation phase will be. The strength of the sample decreases with strain rate by about 3%–10%. In summary, the closer the strain rate is to the fracture strain rate, the better the dynamic mechanical properties will be.

Fig 5 SHPB experimental stress-strain curve: (a) 30% relative density; (b) 20% relative density; (c) 10% relative density;

Fig 6 shows the results between the impact velocity, strength and relative Young's modulus. All the DG samples with the three different relative densities show Impact velocity sensitivity and strain rate sensitivity. The strain of the material with respect to time is the strain rate, and the impact velocity change is essentially the change in the strain rate. The strengths of the sample with a relative density of 30% at strain rates of 260 s⁻¹ and 360 s⁻¹ are 228 MPa and 237 MPa, respectively. The strengths of the sample with a relative density of 20% at strain rates of 252 s⁻¹ and 305 s⁻¹ are 137 MPa and 144 MPa, respectively. The strengths of sample with relative density of 10% at strain rates of 193 s⁻¹ and 270 s⁻¹ are 89 MPa and 91 MPa, respectively. The results show that as the relative density increases, the strength and strain rate of the sample when it breaks also increase. In addition, the samples with relative densities of 30% and 20% seem to be more sensitive to the strain rate than the sample with relative density of 10%. The results also revealed that the relative Young's modulus of samples with a relative densities 20% and 30% changed significantly, while the relative Young's modulus of sample with a relative density of 10% remained mostly unchanged.

Fig 6 The results between impact velocity and strength and relative Young's modulus under dynamic load: (a) Relative density 30%; (b) Relative density 20%; (c) Relative density 10%;

Ti6Al4V alloys have the advantages of high strength and being lightweight. The energy absorption law of a porous structure under dynamic load is still unclear. Because the laboratory SHPB test is simple, there are too many uncontrollable factors. Only the energy absorption at the first fracture is studied here. The cumulative energy absorption and strain curve of the DG samples is shown in Fig 7. When the DG sample can break, as the impact velocity increases, the absorbed energy decreases. In

addition, the closer to the impact velocity at break, the higher the energy absorption will be. This indicates that the impact velocity just before fracture makes the sample have good dynamic mechanical properties. This finding is of great significance to the application of porous structures.

Fig 7 Energy absorption per unit volume: (a) 30% relative density; (b) 20% relative density; (c) 10% relative density

The relation between the mechanical properties (relative Young's modulus and strength) and relative density of the DG samples is shown in Fig 8. According to the formula in the second part, E_s and σ_s are obtained to be 108.09 GPa and 1188.4 MPa, respectively. According to the literature[22], $m_E=1$ and $m_\sigma=1$ represent the standard tensile-dominant structure, and $m_E=2$ and $m_\sigma=1.5$ represent the standard bending-dominant structure. Fan et al. found that the elastic modulus and strength of gyroid, Neovius and Schwarz P structures under quasi-static compression conditions show tensile-dominant behaviour[23]. Due to the different loading methods of the force, the same structure exhibits different dynamic mechanical properties. All in all, the elastic modulus and strength of the gyroid structure under dynamic load conditions are close to the bending-dominant behaviour. The stress-strain curve of the bending-dominant porous structure shows that the porous structure has a tendency of strain hardening, which can withstand high impact and energy. This shows that the gyroid structure has excellent mechanical properties under dynamic loads. In addition, the fitting line of the elastic modulus density and strength density helps determine the volume fraction of the gyroid structure design in practical applications.

Figure 8 (a) The relative modulus-density fitting line of the Double Gyroid structure; (b) The relative strength-density fitting line of the Double Gyroid structure

4 Conclusions

In this study, the changes in the relative Young's modulus, strength and strain rate of the DG structure under dynamic loads were analysed. The energy absorption equation is used to analyse the relation between the relative density of the DG structure, impact velocity and energy absorption per unit volume. The following conclusions can be drawn from this work:

- (1) The DG structure is a sheet-like TPMS structure obtained through Boolean operations for different relative densities.
- (2) The fracture strain rate and strength of the DG structure with different relative densities under dynamic load have been analysed. Under dynamic loads, the DG structure exhibits strain rate effect.
- (3) Compared with the mechanical properties obtained under the quasi-static compression conditions, the strength and relative Young's modulus under dynamic load are improved.
- (4) The closer the DG structure is to the impact velocity when fracture occurs, the higher is the energy absorption, and the DG structure has good dynamic mechanical properties under this condition.
- (5) Under dynamic load, the relative Young's modulus and strength of the DG structure are close to the performance of the bending-dominated structure, which is different from the quasi-static mechanical properties.

This study mainly analyses the impact of dynamic loads on the mechanical properties of TPMS structures. As there are only few studies on the structure of SLM-processed TPMS under dynamic loads, the dynamic performance of the porous structure is of great significance to the structural design in practical applications. Porous structures are particularly used in implants and impact-resistant designs, for which the dynamic mechanical properties are particularly important.

5 Declaration

Acknowledgements

The authors sincerely thanks to Professor North University of China for his critical discussion and reading during manuscript preparation.

Funding

This research was funded by the National Natural Science Foundation of China (Grant No. 52075502, No. 51905497), the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (No. 2019L0559), the Support Program for Young Academic Leaders of North University of China (No. QX201902) and Science and Technology Project of North University of China (No.20201705).

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: Zhong-Hua Li: Writing - Original Draft. Zhi-Cheng Yang: Formal analysis. Bin Liu: Conceptualization. Jia-Xin Li: Writing - Review & Editing. Ze-Zhou Kuai: Investigation. Huo-Dong Li: Investigation. Yan-Lei Chen: Supervision

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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