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Prediction of Compressibility and Mechanical Properties of Porous Structures based on Gibson-Ashby Model

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Abstract

Porous structure has become one of the most popular materials in various research fields, and has been widely used in aerospace devices, biomedical devices and other fields due to the good specific strength, energy absorption and other characteristics. Based on Gibson-Ashby model, the relationship between mechanical properties of porous structures with AlSi10Mg as the base material and the volume fraction was established. By adjusting the volume fraction, the mechanical properties of Dodeca and Octa porous materials could be predicted and designed more accurately. The porous structures with 80% and 90% porosity were prepared by SLM technology. Gibson-Ashby mathematical model with ASi10Mg as the matrix material was established by quasi-static compression test and numerical simulation techniques for different porous material structures, which is convenient for data prediction of mechanical behavior of porous materials with different volume fractions.

Keywords

Porous Structure; Gibson-Ashby Model; Dodeca and Octa Material; ASi10Mg.

1. Introduction

The porous structures designed based on 3D Voronoi method have good parameter controllability and mechanical properties, and have broad application prospects in energy absorption devices, medical implants and other fields. In order to evaluate the mechanical properties of porous structures manufactured by selective laser melting (SLM), most researchers use mechanical tests and numerical simulations. The mechanical properties of porous materials can be predicted using mathematical models and verified by a small number of tests, which will be very helpful for the use of porous materials in specific environments. Over the years, many scholars have studied the mechanical characteristics of porous materials, among which the model developed by Gibson and Ashby is the most commonly used, which can accurately predict the mechanical behavior of porous materials. Kornievsky et al. [3], using effective modulus and finite element method, based on the regular porous structure model composed of Gibson-Ashby cells(Figure 1), the elastic modulus of porous structures was studied, and it was found that for the same porosity, the cells with thicker edges have greater stiffness than those with thinner edges. In addition, anisotropy increases with increasing porosity, and the degree of anisotropy is greater for monocytes with thick edges. Their research results prove the applicability of Gibson-Ashby model.

Figure 1. Gibson-Ashby cells

2. Experiment and Method

Generally, the mechanical properties of porous structures are controlled by their relative density, cell structure and cell anisotropy. Gibson and Ashby studied the relationship between elastic modulus and relative density, yield strength and relative density of randomly distributed porosity and open pore structures with smooth surfaces as:

$$\frac{E}{E_S} = (\frac{\rho}{\rho_S})^2 \tag{1}$$

$$\frac{\sigma}{\sigma_S} = 0.3 \times (\frac{\rho}{\rho_S})^{1.5} \tag{2}$$

Where, Es, ρ_S and σs are elastic modulus, relative density and yield strength of dense solid materials, respectively. E, ρ and σ are the elastic modulus, relative density and yield strength of porous structures, respectively. The Es of fully densified AlSi10Mg is assumed to be 25804 Mpa. For many metals, σs is about one-third of the Vickers hardness. In this paper, the porous structure of the support rod Vickers hardness is 860 Mpa, so σs is 287 Mpa.

3. Results and discussion

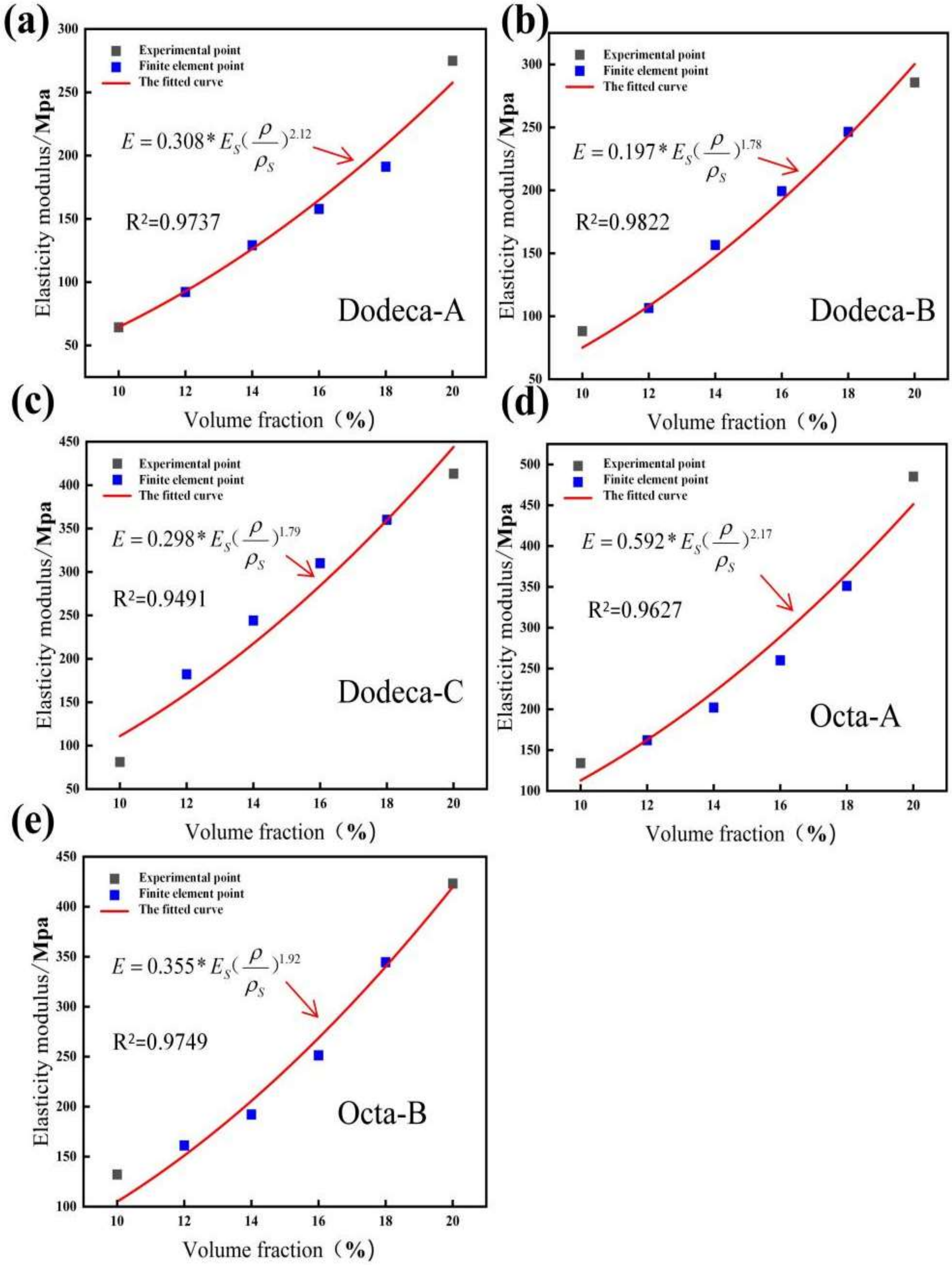

Figure 2. Elastic modulus-volume fraction curves of porous structure under compression test and finite element analysis: (a) Dodeca-A structure; (b) Dodeca-B structure; (c) Dodeca-C structure; (d) Octa-A structure; (e) Octa-B structure

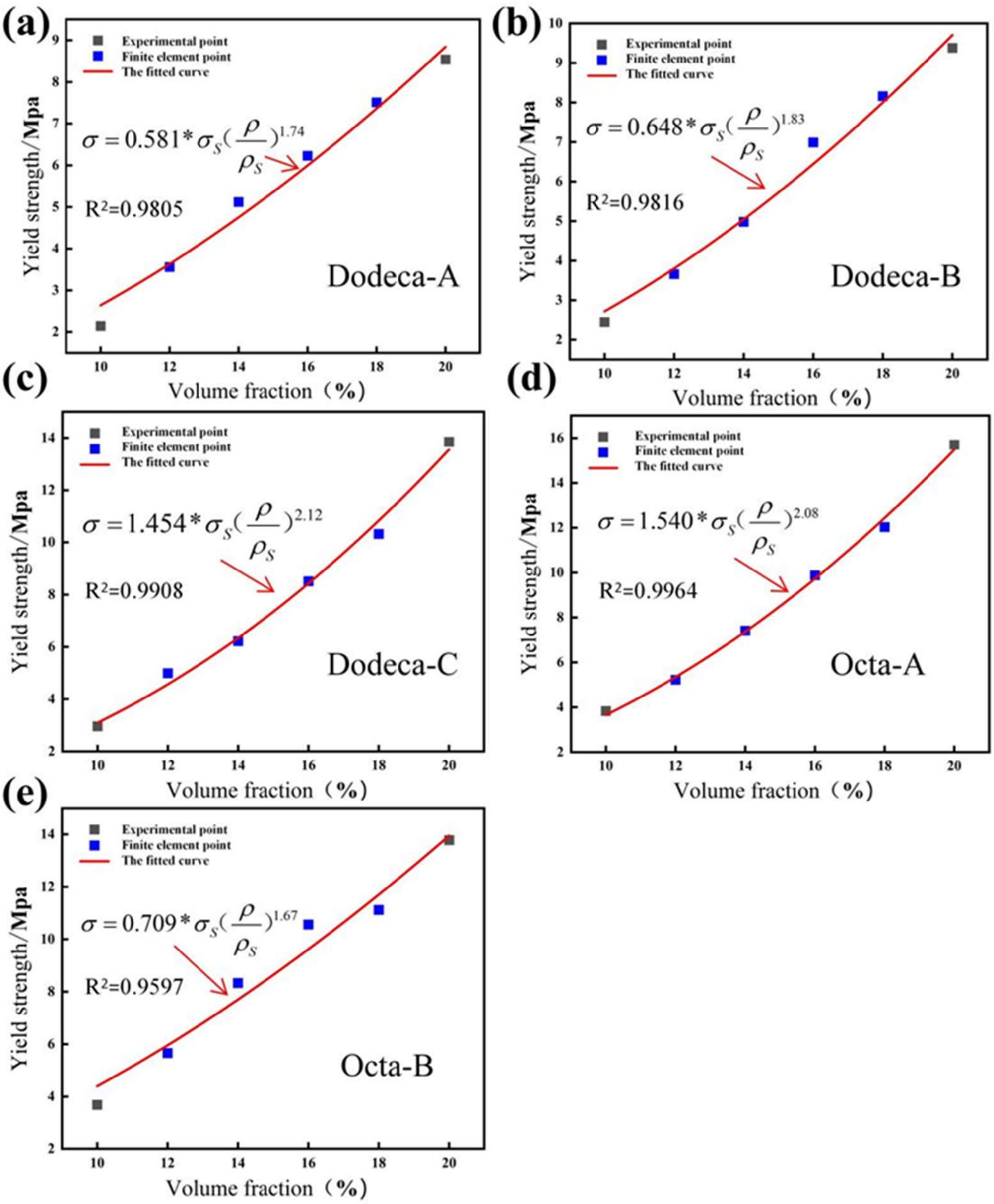

Figure 3. Yield strength-volume fraction curves of porous structure under compression test and finite element analysis: (a) Dodeca-A structure; (b) Dodeca-B structure; (c) Dodeca-C structure; (d) Octa-A structure; (e) Octa-B structure

The experimental results and the finite element simulation results are fitted to the nonlinear equation. 10% and 20% of the volume fractions are obtained through the test, 12%, 14%, 16%, 18% are obtained through the finite element calculation, which can be used to predict the mechanical properties of Dodeca and Octa structures with any volume fraction. As shown in Figure 3, in order to fit the functional relationship between elastic modulus and volume fraction through compression test and finite element analysis data, and in the formula represents the density of porous structure and the density of matrix material.

The elastic modulus model can be expressed as:

$$\frac{E}{E_S} = C_1 (\frac{\rho}{\rho_S})^m \tag{3}$$

In formula (3), the value of m is generally between 1.8 and 2.2, and the specific value is determined by the tensile dominant shape, bending dominant shape or combined deformation in the deformation process of the single cell. The obtained test results were fitted with the finite element results, and the fitted coefficient R2 values were 0.9737, 0.9822, 0.9491, 0.9627 and 0.9749, respectively. The index of fitting curves of Dodeca-A, Octa-A and Octa-B structures and finite element results are 2.12, 2.17 and 1.92, respectively, in the range of 1.8-2.2, while the results of Dodeca-B and Dodeca-C structures are 1.78 and 1.79, which are slightly out of the range.

In the Gibson-Ashby model, C1 represents a constant, which has a value of 1. In the process of fitting test points and finite element points, variable C1 will give better fitting coefficient and fitting accuracy to the fitting curve. The C1 values obtained from the test results and the finite element results are 0.308, 0.197, 0.298, 0.592 and 0.355.

The yield strength of porous structures can also be predicted by the Gibson-Ashby model:

$$\frac{\sigma}{\sigma_S} = C_2 \times (\frac{\rho}{\rho_S})^m \tag{4}$$

In formula (4), and represents the yield strength of the matrix material with porous structure; The value of C2 is generally in the range of 0.1 to 1.5. FIG. 3 shows the relationship between the yield strength and the volume fraction obtained by the test results and the finite element analysis results. The fitting coefficients R2 of the fitted exponential equations are all greater than 0.9, indicating that the fitting is good. It is worth noting that the C2 value is also slightly out of range.

This reason may be due to the deviation between the finite element results and the test results. Due to its geometric characteristics, porous structures can produce relatively large adhesive powders and micro-molten pools. First, in the SLM process, when the laser scans the metal powder, there are many heat-affected zones around it, resulting in the metal powder being melted or sintered around the molten pool. Moreover, compared with solid blocky structures, porous structures have significantly larger specific surface area (surface area divided by volume), which allows more metal powder to adhere to their surfaces. When a high laser is scanned on a thin rod with a porous structure, the temperature of the molten pool and the heat affected zone will be very high, which will greatly increase the density after solidification, and also increase the probability of adhesion of loose powder to the surface. Secondly, when the laser moves at high speed, there will be a process of acceleration and deceleration of each scanned track, which requires a lot of excess energy input. In summary, porous structures manufactured by SLM will have a larger melt pool, especially at the boundary. The larger molten pool increases the size, weight and volume fraction of the single rod, which affects its mechanical properties.

At the same time, there are defects and residual stress in the porous structure manufactured by SLM, which is also a factor affecting its mechanical properties. In the finite element model, the definition of the material is continuous and uniform, while in the actual additive manufacturing process, there are cracks, unmelted particles, impurities and other internal defects, which cannot be fully reflected by the finite element simulation, so some differences are caused. In addition, the existing temperature gradient and cooling rate in the SLM process will cause large inherent residual thermal stress, resulting in the reduction of the stiffness of SLM materials. Moreover, crack nucleation and propagation in SLM process are related to the internal residual stress, which will accelerate the formation of micro-cracks.

4. Conclusion

In general, the prediction model established in this section based on test data and finite element data has a good fitting index. The mechanical properties of Dodeca and Octa porous structures can be accurately predicted and designed by adjusting their volume fraction. The deviation of exponent and coefficient in Gibson-Ashby model may come from the deviation of finite element results and test results. At the same time, elastic modulus and yield strength are interdependent for specific structural design.

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