Construction of Three-dimensional Co-continuous Composites with Controllable Volume Fraction

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Abstract. Efficient and low-cost manufacturing methods and adjustable properties are an important way to further promote the application of co-continuous composites. In this paper, a three-dimensional co-continuous composites model with controllable volume fraction is designed. The model uses triply periodic minimal surface (TPMS) as the internal structure and spatial segmentation strategy to accurately control the volume proportion of each phase, which enriches the three-dimensional modeling method of co-continuous composites and provides new ideas and methods for the wide application of co-continuous composites with adjustable characteristics. Finally, samples are manufactured through efficient and low-cost 3D printing technology.

1. Introduction

With the development of modern industry, the demand for co-continuous composites is also growing rapidly, but the high manufacturing cost has become the main bottleneck for the wide application of co-continuous composites. Low cost co-continuous composites manufacturing technology is one of the core issues in the field of co-continuous composites in the world. Through the improvement and development of traditional assembly and maintenance and raw materials, the cost performance of co-continuous composites can be improved, and more importantly, the manufacturing cost of co-continuous composites can be reduced. In recent years, it has been found that adjusting the volume fraction of each component of co-continuous composites can affect the properties of co-continuous composites.

Kun Qiu [1] used the finite element method to analyze that the toughness and strength characteristics of new Amorphous Composites (i.e. metal glass composites, MGCs) are affected by particle volume and particle spacing. The experimental results show that the toughness and plasticity of metal glass composites have been significantly improved due to the increase of particle volume fraction and the reduction of particle spacing, especially when the volume fraction is 45%. The optimized design of volume fraction is conducive to the manufacture of composites with better toughness.

Wenge Chen [2] explored the effect of carbon fiber volume fraction on the properties of carbon fiber reinforced copper matrix composites. The experiment shows that with the increase of carbon fiber volume fraction, the density of the composite becomes lower, and the density of the composite increases after re-pressing and re-firing. When the volume fraction of carbon fiber reaches 1%, the material density will increase to the highest value (8.6409g/cm3). The hardness of the composite increases first and then decreases. When the volume fraction of carbon fiber reaches 5% after re-pressing and re-firing, the hardness of the composite will increase to the highest value (50.6hv). As the
volume fraction increases to 15%, the conductivity of the material will decrease to 75.8% IACS. It can be seen that the change of carbon fiber volume fraction affects the hardness and conductivity of carbon fiber reinforced copper matrix composites.

Min Wang [3] prepared CF/Al2O3-20%Ni cermet composites with different carbon fiber volume fractions, which were 0%, 5%, 10% and 15% respectively. By controlling the volume fraction of carbon fiber, the changes of hardness, flexural strength and fracture toughness of CF/Al2O3-20%Ni composites were studied. The experiment shows that with the increase of carbon fiber volume fraction, the hardness of the composite will decrease, while the fracture toughness and flexural strength of the composite first increase and then decrease. When the carbon fiber volume fraction reaches 10%, the fracture toughness and flexural strength show the maximum value, which are increased by 79% and 134% respectively compared with the sample with carbon fiber volume fraction of 0%. This shows that the toughness and strength properties of CF/Al2O3-20%Ni composites are more perfect after adding carbon fiber. The results show that the change of the volume fraction of each component in the composite has a great impact on the toughness, strength, energy absorption and rigidity of the composite.

Three dimensional co-continuous composites have more advantages than traditional composites in improving mechanical properties. Through the designed method, the proportion of each component can be adjusted simply and efficiently, and the optimal combination of various properties can be realized to meet different engineering needs. At present, most researchers studied the preparation methods of co-continuous composites and analyzed the mechanical properties under different volume fraction, and there is no research on building a three-dimensional co-continuous composite digital model with controllable volume fraction. In this paper, the three-dimensional co-continuous composites model with controllable volume fraction is designed. The model uses triple periodic minimal surface (TPMS) as the internal structure, and uses spatial segmentation strategy to accurately control the volume proportion of each phase. The design algorithm for constructing three-dimensional co-continuous composites and the design algorithm for controllable volume fraction are studied, an efficient and low-cost co-continuous composite sample is manufactured by 3D printing technology.

2. Three dimensional co-continuous composites model with TPMS structure

In recent years, due to the limitation of pore making structure geometry in the construction of bone scaffold model, biologists, physicists, material scientists and medical scientists have found that the triply periodic minimal surface (TPMS) structure with high-quality continuity and optimization is suitable for pore making structure, so they try to apply this surface structure to the design of bone scaffold model. Zhitong Li [4] analyzed the performance simulation of artificial bone scaffold based on TPMS unit, and selected P unit and I-WP unit of TPMS structure as biological scaffold unit cells, respectively. Then the three-dimensional modeling method is used to establish the unit models of P unit and I-WP unit. Based on this parameterized element model, the relationship between thickness and configuration parameters (i.e. s and k) and the porosity and specific surface area of two different structural units is studied. The results show that the P unit is most affected by the configuration parameters during degradation. In the reconstruction of bone scaffold, the P unit is greatly affected by stress, the I-WP unit is greatly affected by permeability in the pre-growth stage, and I-WP unit is greatly affected by stress in the post-growth stage. Wenying Zhao [5] analyzed the mechanics and permeability of bone scaffolds based on TPMS. Because the bone scaffolds constructed by TPMS have bionic morphology closer to natural bones, five common TPMS surface structures (i.e. D unit, G unit, Schwarz P unit, F-RD unit and Fischer-Koch S unit) and three lattice structures (i.e. cube lattice, FD cube lattice and octa lattice) were selected. Eight kinds of bone scaffold models with different internal structures were designed, and the mechanical and permeability were analyzed. Through numerical simulation analysis, the results show that the porosity of TPMS increases, and the permeability of bone scaffold is better.

Co-continuous composites are composed of two or more different materials, and the phases are continuous and connected [6]. TPMS structure is a triple periodic minimal surface with continuity,
connectivity and volume fraction controllability. Because we need to design the internal structure of three-dimensional co-continuous composites that can meet the basic functions, TPMS structure is the best choice for the internal structure of co-continuous composite [7].

The TPMS structure is a triple periodic structure, which means that the microstructure is repeated in three dimensions. Similar to other periodic structures, TPMS structure is also composed of multiple periodic units. By consulting literature [8-9], it is found that there are many coordinate algorithms that can generate TPMS structure. Weierstrass function is a kind of real valued function that is continuous everywhere and non-differentiable everywhere, which can represent the coordinates of TPMS structure in an accurate parametric form.

\[
x = Re \int_{\omega_0}^{\omega} e^{i\theta} (1 - \tau^2)R(\tau)d\tau
\]

\[
y = Re \int_{\omega_0}^{\omega} e^{i\theta} (1 + \tau^2)R(\tau)d\tau
\]

\[
z = Re \int_{\omega_0}^{\omega} e^{i\theta} 2\tau R(\tau)d\tau
\]

Three TPMS equations [10-13] can be obtained by accurately parameterized TPMS structure coordinates, as follows:

P surface:
\[
\phi_p(x, y, z) = \cos(X) + \cos(Y) + \cos(Z) + C
\]

G surface:
\[
\phi_g(x, y, z) = \sin(X)\cos(Y) + \sin(Z)\cos(X) + \sin(Y)\cos(Z) + C
\]

D surface:
\[
\phi_d(x, y, z) = \cos(X)\cos(Y)\cos(Z) - \sin(X)\sin(Y)\sin(Z) + C
\]

Figure 1. TPMS unit structure diagram. (a) P-type surface; (b) G-shaped surface; (c) D-shaped surface.

The proposed model design method uses TPMS structure as the internal core structure, and makes the internal structure based on TPMS conformal with the complex external shape. Finally, a three-dimensional co-continuous composites model with complex external shape and TPMS internal structure is constructed, as shown in Figure 2.
3. Study on controllability of volume fraction

Compared with traditional continuous composites, an important advantage of continuous composite models based on TPMS structure is that they can control the volume fraction of the model very simply and accurately.

Figure 3 (a) shows the P surface of TPMS structure when the surface isosurface is zero. If we adjust the value of the medium value surface in the TPMS level set approximation equation, that is, the value of C in the equation, we can obtain the P surface structure with different volume proportions when the surface isosurface is equal to 0.5, 0, -0.5, respectively. As shown in Figure 3 (a) and Figure 3 (c).

As shown in Figure 3 (a) and Figure 3 (c), we find that two independent spaces are segmented by using surface isosurface. When the equivalent value C changes, the size of the two independent spaces separated by the equivalent surface of the TPMS structure changes. By using the characteristics of TPMS, we propose the controllability strategy of co-continuous composites volume fraction [7]. Firstly, for two independent spaces separated by isosurface, we can consider one space as A phase in co-continuous composites and the other space as B phase. Then, by adjusting the equivalent face value C, the A phase space of the co-continuous composites becomes smaller (or larger) and the B phase space becomes larger (or smaller), so that the volume fraction of each constituent phase in the co-continuous composites can be accurately and simply controlled, as shown in Figures 4-6.
Figure 4. Schematic diagram of spatial distribution of each phase. A: High volume fraction; B: High volume fraction; C: Low volume fraction; D: Low volume fraction.

Figure 5. Accurate control of volume fraction of each phase. (a) A phase volume fraction 76%, B phase volume fraction 24%; (b) A phase volume fraction 63%, B phase volume fraction 37%; (c) A phase volume fraction 37%, B phase volume fraction 63%.

Figure 6. Schematic diagram of controllable volume fraction.
4. Sample manufacturing based on 3D printing technology
In the manufacturing mode of co-continuous composite materials, the emergence of 3D (three dimension) is a new idea in industrial manufacturing. 3D printing technology has also become additive manufacturing. It is a technology to gradually generate solid models through continuous layer by layer stacking of materials based on the slice data of 3D models. 3D printing technology is a comprehensive and systematic emerging technology in the fields of mechanical engineering, computer programming and material engineering [14].

The 3D printing method of additive manufacturing is different from the traditional equal material manufacturing and reduced material manufacturing. It can quickly manufacture the co-continuous composite model with complex structure and maximize the use of raw materials [15].

Finally, co-continuous composite samples with controllable volume fraction were manufactured by 3D printing technology, as shown in Figure 7.

Figure 7. 3D print sample.

5. Conclusion
The characteristics of co-continuous composites with controllable volume fraction of each component manufactured by 3D printing technology have been significantly improved compared with traditional composites. Using this characteristic, the co-continuous composites model with high-quality characteristics can be designed. By simply adjusting the equivalent face value C in the TPMS level set approximation equation, we can easily and accurately construct various three-dimensional co-continuous composite models with controllable volume fraction suitable for specific application requirements.

The outstanding feature of the proposed design is that it can construct co-continuous composites in three-dimensional space. At the same time, through the advantage of controllable volume fraction, it enriches the three-dimensional co-continuous composite model and provides a new idea and method for a wide range of practical applications of co-continuous composites with adjustable properties.

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