Damping Characteristics of Three-dimensional Co-continuous Network Graphite / Cast Steel Composites

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Abstract. The infiltration casting method is used for the preparation of three-dimensional co-continuous network structure of graphite/cast steel composite material in atmospheric pressure. Using modal analysis method, flake graphite cast iron specimen and composite sample are compared about damping factors. The results show that amplitude attenuation of the composite material is more quickly than that of flake graphite cast iron specimens. Supported in two rigid points state, the first step damping ratio of the composite material is 2.1 times of flake graphite cast iron. At the same time, its tensile strength is 1.54 to 1.68 times that of flake graphite cast iron, its hardness reaches more than 86%, and its bulk density is reduced to less than 94%. The composite not only has good vibration damping and anti-friction performance, but also has comprehensive mechanical properties exceeding the level of flake graphite cast iron. It is possible to replace flake graphite cast iron for manufacturing important mechanical equipment castings such as fuselage and guide rail to obtain better anti-wear / vibration damping effect.

1. Introduction
In the field of mechanical equipment, now flake graphite cast iron is commonly used as the material for manufacturing important parts such as all kinds of fuselage and guide rail. Because of the existence of graphite, the flake graphite cast iron has good wear resistance and vibration damping at the same time, its damping attenuation coefficient is 6 to 10 times that of steel. However, with the rapid development of machining technique, all kinds of machine tools are developing towards high precision, high speed and heavy large size. The dynamic load of various important and heavy large mechanical equipment are getting larger and more complex, and related parts produce more and more serious vibration, fatigue and wear, ordinary flake graphite cast iron can no longer meet the requirements of modern machine tools. In order to reduce the harm, materials with high strength, damping and wear resistance should be used[1]. In recent years, non-metal matrix composites such as resin mineral composites, artificial granite composites and epoxy resin concrete filled structure have been developed. Although these non-metal matrix composites have good damping performance, they have low strength and poor thermal expansion property, making it difficult to be extended for the application[2-4]. Metal matrix composite is the main development of low vibration and noise material[5-6].
The three-dimensional continuous network structure metal matrix composite material is a research field of new composite material that has been paid more and more attention by material researchers at home and abroad over the past decade. The composite has a completely different spatial topology from the traditional composite material, that is, the metal matrix phase and the composite phase (or modified phase) are continuous (connected) in the three-dimensional space, and exhibit an interleaving network structure. The structure makes this material have very unique mechanical, physical and chemical properties. It also has isotropic properties, and has the potential to be used as anti-friction/damping material[7-8]. We took the lead in studying the three-dimensional network structure silicon carbide / flake graphite cast iron atmospheric pressure casting composite at home and abroad, hoping that it has excellent wear resistance and good damping property, which can be used to replace flake graphite cast iron to make important castings such as fuselage and guide rails. The relative wear resistance of the three-dimensional network structure silicon carbide/flake graphite cast iron composite we prepared is as high as 4.7 times to 7.9 times of the flake graphite cast iron, its amplitude attenuation is faster than that of flake graphite cast iron, the first-order damping ratio is 2.3 times that of flake graphite cast iron, and its damping effect is obvious. However, mechanical properties such as strength is not as good as flake graphite cast iron, and it is difficult to meet the performance requirements of more and more developed and heavy mechanical equipment[9-10].

For this reason, we first proposed the following conception of research at home and abroad: using cast steel as the metal matrix phase and flake graphite as the composite phase (modified phase), by using the infiltration casting method to prepare the three-dimensional co-continuous network graphite / cast steel composites. The composite has good technical feasibility as a new anti-wear/vibration damping composite.

2. The Test Sample Preparation Method and Basic Performance

The conventional method for preparing the three-dimensional network structure ceramic / metal composite is pressure casting infiltration method at present. The metal liquid overcomes the permeation resistance under pressure, so that the casting infiltration can be completed. The technological process of pressure infiltration method is complicated, it is inconvenient to operate and control, and the production cost is high.

First, we prepare the three-dimensional co-continuous network graphite preform by using foam plastic precursor coating method, then coat the surface of graphite preform skeleton with metal, and prepare the three-dimensional co-continuous network graphite / cast steel composite by using the infiltration casting method. The method for preparing composite material by penetrating metal melt into the porous preform without exterior load under normal pressure can simplify the preparation technology, reduce the production cost, and easy to realize industrialization production.

In this study, the macro-morphology of the composite material specimen prepared by normal pressure casting infiltration method is shown in Figure 1. The preparation conditions are as follows: the pore size of the foam ceramic preform used is 8ppi, the surface is treated with Cu-Cr-Ti metallization coating, the grade of molten steel is ZG200-400, and the sand casting process of furan resin is used.

![Figure 1. Macro-morphology of three-dimensional network structure of graphite/cast steel composite material and HT150 flake graphite cast iron specimen.](image)

The basic performance of the prepared new three-dimensional network structure graphite / cast steel composite material specimen after heat treatment are shown in Table 1. Its tensile strength exceeds that
of flake graphite cast iron and reaches more than 200MPa, which is 1.54-1.68 times of flake graphite cast iron; Its hardness is close to flake graphite cast iron, reaching more than 86% of it, and the bulk density is 6.7~6.8g / cm³, which is reduced to below 94% of flake graphite cast iron.

Table 1. The base parameters of the composite material and HT150 flake graphite cast iron specimen.

| Material type                  | Composites | Composites | Composites | flake graphite cast iron |
|-------------------------------|------------|------------|------------|--------------------------|
| Metallization process of foam | Untreated  | Ni-Cr-Fe   | Cu-Cr-Ti   | --                       |
| Average tensile strength (MPa)| 192        | 236        | 257        | 153                      |
| Hardness (HBW)                | 147~158    | 154~168    | 158~172    | 178                      |
| Average density (g/cm³)       | 6.70       | 6.78       | 6.78       | 7.22                     |

Note: (1) The diameter of the parallel working section of the tension test specimen is 20 mm, the nominal length is 60 mm, and the corner radius R is 25 mm. (2) The heat treatment of the composite material specimen is normalizing (heating to 850°C for heat preservation for proper time and then air cooling), the purpose is to refine the structure of the steel and improve its strength and hardness. (3) The heat treatment of the flake graphite cast iron specimen is annealing (heating to 500°C for heat preservation for proper time, furnace cooling to 200°C and then air cooling), the purpose is to remove thermal stress and increase strength. But the hardness is reduced.

3. Experimental Method for Vibration

We conducted a vibration comparison experiment on flake graphite cast iron specimen and three-dimensional continuous network graphite/cast steel composite material with the same geometric dimension using modal analysis to identify the modal parameters of the two material under the same support condition. In this way, the damping characteristics of the three-dimensional continuous network graphite/cast steel composites were evaluated preliminarily. The modal analysis is a method of modal analysis of structure by microcomputer, the steps are as follows:

(1) Pulse or steady random simulation test was conducted on the structure to obtain the force signal by the force sensor, and obtain the vibration response signal at each measuring point by the vibration sensor;

(2) The force and the vibration response signal on the measuring point were parallel sampled, and converted into digital signal, which is stored in the microcomputer.

(3) The real part and imaginary part of the transfer function of each measuring point were calculated by the microcomputer, and the amplitude-frequency response curve was obtained;

(4) The amplitude-frequency response of the transfer function of each measuring point should be lumped average, and the frequency point of each peak was used as the estimated value of the modal frequency.

(5) The modal frequency and the modal damping ratio corresponding to the minimum value of the objective function E were found by the optimization method to calculate the modal shape. The basic principle of modal analysis technique is as follows: the mechanical dynamic characteristics H(ω) and the external force Y(ω) and its corresponding response X(ω) have the following relationship:

\[ H(\omega) = Y(\omega) / X(\omega) \]

H(ω) is also called a mechanical transfer function or frequency response function in here. After discretization, the mechanical dynamic characteristics can be described by a n-order matrix differential equation:

\[ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \]  

in which f(t) is the n-dimensional excitation force vector; \( \dot{x}, \ddot{x} \) and \( x \) are the n-dimensional displacement, velocity, and acceleration response vector respectively; M, K, and C are the mass, stiffness, and damping matrix of the mechanical structure respectively. They are usually real symmetric n-order matrices.
According to equation (1), the natural frequency and the corresponding vibration mode of the mechanical structure can be obtained. The vibration mode is arranged in column the mode vectors in matrix form (mode matrix) by column:

\[
\Phi = [\phi_1, \phi_2, \ldots, \phi_n]
\]  \hspace{1cm} (2)

and can be obtained:

\[
\Phi^T M \Phi = [m_r] \hspace{1cm} \Phi^T K \Phi = [k_r] \hspace{1cm} \Phi^T C \Phi = [c_r]
\]  \hspace{1cm} (3)

in which: \(m_r\) is generalized mass, \(k_r\) is generalized rigidity and \(c_r\) is generalized damping.

The modal parameters are used to express the frequency response function of the mechanical structure:

\[
H(\omega) = \sum_{r=1}^{n} \frac{\phi_r^T \phi_r}{m_r \left((\omega_r^2 - \omega^2) + j^2 \xi_r \omega \omega\right)}
\]  \hspace{1cm} (4)

Then the element of the \(i^{th}\) row and \(j^{th}\) column of the \(H(\omega)\) matrix are:

\[
H_{ij}(\omega) = \sum_{r=1}^{n} \frac{\phi_r \phi_j}{m_r \left((\omega_r^2 - \omega^2) + j^2 \xi_r \omega \omega\right)}
\]  \hspace{1cm} (5)

In which: \(\omega_r^2 = k_r/m_r\) is the \(r^{th}\) modal frequency, \(\xi_r = c_r/2m_r \omega_r\) is the \(r^{th}\) modal damping ratio and \(\phi_r\) is the \(r^{th}\) vibration mode.

From the above analysis, it can be seen that a frequency response function of a mechanical structure \(H_{ij}(\omega)\) contains its information on the modal frequency and damping ratio. Therefore, if a typical frequency response function of a mechanical structure is measured, its modal frequency and damping ratio can be obtained from the frequency response function. The damping ratio refers to the ratio of the damping coefficient to the critical damping coefficient.

In this experiment, three supporting methods were used to test the damping characteristics of the material: the specimen state of supported over two rigid points (see Figure 2), the specimen state of supported over level soft foam (see Figure 3), and the specimen state of two points handining (see Figure 4).

**Figure 2.** The specimen state of supported over two rigid points.

**Figure 3.** The specimen state of supported over level soft foam.

The principle block diagram of the vibration testing system is shown in Figure 5.

The frequency response function testing process is as follows: use a force hammer to excite the vibration at point A, and the force sensor on the hammer feels the force signal, which is amplified by the amplifier and input to channel 1 of the UT3316FS-ICP. At the same time, the acceleration sensor is used to measure the acceleration response at point B. The signal is amplified by the amplifier and input to channel 2 of UT3316FS-ICP, and then collected and analyzed by UT3316FS-ICP to obtain the
frequency response function from point B to point A. Finally, UT3316FS-ICP is used to curve fit the frequency response function to obtain the damping ratio.

Figure 4. The specimen state of two points handing.  

Figure 5. The principle block diagram of the vibration testing system.

4. The Experimental Results of Vibration

The measured damping ratio of the three-dimensional continuous network graphite/cast steel composites and flake graphite cast iron specimen is shown in table 2. The ratio of the damping ratio of the specimen is shown in Table 3.

Table 2. The modal frequency and damping ratio of the specimen.

| Test status                  | Material type          | The first step | The second step | The third step |
|------------------------------|------------------------|----------------|-----------------|---------------|
| supported over two points    | Composites             | 0.2108         | 1.4324          | 0.7630        |
|                              | Flake graphite cast iron | 0.1004       | 1.4290          | 0.1004        |
| supported over foam          | Composites             | 0.1411         | 2.2789          | 0.3524        |
|                              | Flake graphite cast iron | 0.1176       | 1.8991          | 0.3204        |
| two points handing           | Composites             | 0.1807         | 1.0996          | 0.3366        |
|                              | Flake graphite cast iron | 0.1004       | 0.2972          | 0.1683        |

Table 3. The ratio of damping ratio (composite materials / flake graphite cast iron).

| Test status                  | The first step | The second step | The third step |
|------------------------------|----------------|-----------------|---------------|
| supported over two points    | 2.1            | 1.0             | 7.6           |
|                              | 1.2            | 1.2             | 1.1           |
| two points handing           | 1.8            | 3.7             | 2.0           |

It can be seen from Table 2 and Table 3: under different supporting states, the damping ratio of the three-dimensional network structure graphite/cast steel composites specimen is larger than that of flake graphite cast iron.

Under free condition, the impulse response time history of each specimen is shown in Fig. 6. Under the two points rigid supporting state, the amplitude attenuation of the composites is faster than that of the flake graphite cast iron specimen. The first step damping ratio is 2.1 times that of the flake graphite cast iron and the damping effect is more significant than the two points handing and foam supporting state. Since the modal frequency difference between the composites and the flake graphite cast iron is small, the difference in weight is not large, and the difference in stiffness is not large, so it
can be concluded that the damping ratio increase of the composite material is mainly due to the material damping coefficient increase.

![Graph](image1)

**Figure 6.** The impulse response time history chart of composite materials and flake graphite cast iron. The picture above—composite materials, the picture below—flake graphite cast iron.

5. Mechanism Analysis of Damping

Flake graphite cast iron has good damping performance because the flake graphite in the flake graphite cast iron cuts the metal matrix apart (see Figure 7), and when subjected to vibration, it will produce small plastic deformation to consume vibration energy. Moreover, the stiffness and elastic modulus of graphite are both smaller than that of metal, the interface of internal graphite and graphite/metal matrix causes sliding during vibration, and causes internal friction, which converts the vibration energy into heat energy, thereby consuming vibration energy. The factors affecting the damping size include the carbon content of cast iron and the shape of graphite, etc. The higher the carbon content, the longer and more coarse the flake graphite, the better the damping performance.[11-12]

![Graph](image2)

**Figure 7.** Graphite content and morphology in flake graphite cast iron (matrix is not corroded).

The internal structure of the three-dimensional co-continuous network graphite/cast steel composite material has the following two characteristics:

1. The material has a three-dimensional continuous network structure formed by graphite network (see Figure 8). Its volume ratio is more than two times of flake graphite in flake graphite cast iron, and its graphite skeleton is longer and more coarse than flake graphite in flake graphite cast iron;
2. The network graphite skeleton generates channels due to the ablation of the plastic precursor during molten steel pouring (see Figure 9).
Figure 8. The fracture surface morphology of composite.

Figure 9. Morphology of the core channels of network graphite skeleton in composite.

The separation of the metal matrix caused by the graphite network, and the channels of the graphite skeleton caused by the ablation of the plastic precursor, can make the composite material easier to produce small plastic deformation when subjected to vibration, the interface of the interior of graphite and the graphite/metal matrix interface are easier to slip, which significantly hinders the propagation of vibration waves, making the three-dimensional co-continuous network structure graphite/cast steel composites absorb more vibration energy, thus showing a higher damping ratio.

6. Conclusion

(1) The damping ratio of the three-dimensional co-continuous network structure graphite/cast steel composite material is greater than that of gray cast iron. Supported in two rigid points state, amplitude attenuation of the composite material is more quickly than that of flake graphite cast iron specimens, the first step damping ratio of the composite material is 2.1 times of flake graphite cast iron, the damping effect is more significant than the two points handing and foam supporting state.

(2) The damping mechanism of the three-dimensional co-continuous network structure graphite/cast steel composite material is: the separation of the metal matrix caused by the graphite network in the composite material, and the channels of the network graphite skeleton caused by the ablation of the plastic precursor, can both effectively hinder the propagation of vibration waves.

(3) The tensile strength of the three-dimensional co-continuous network graphite/cast steel composite material is 1.54 to 1.68 times that of flake graphite cast iron, the hardness reaches 86% or more of flake graphite cast iron, and the bulk density reduces to 94% or less. It not only has good vibration and friction reduction performance, but also has comprehensive mechanical properties that exceed the level of gray cast iron. It not only has good vibration damping and anti-friction performance, but also has comprehensive mechanical properties exceeding the level of flake graphite cast iron. It is possible to replace flake graphite cast iron for manufacturing important mechanical equipment castings such as fuselage and guide rail to obtain better anti-wear / vibration damping effect.

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