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Research on the damping mechanisms of composite materials

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Abstract. Traditional researches concerning the damping mechanisms of materials are limited to the phases and structures of materials, ignore the damping-related characteristics of the vibration source and of the materials themselves, and thus have great one-sidedness. This paper combines vibration science and material science on the basis of the models of mechanical vibration. Based on summarizing existing damping mechanisms, it proposes three mechanisms of damping: wave-type, particle-type and molecular force-type. By considering the macroscopic morphology of materials and the structures of molecules composing materials, it provides a guideline for preparing damping materials and studying their performance. Drawing on various research results, it also presents some inference based on available theories, creates a new perspective for researching damping mechanisms, and thus it is of high reference value for future research.

1. Introduction

The damping characteristics of materials serve to improve fatigue resistance and vibration-and-noise reduction of materials since damping converts mechanical energy into other forms of energy. Therefore, damping capacities is classified as one of three major functions of modern materials (the other two are shape memory and superplasticity)^[1-5].

Researching into materials' damping characteristics entails studying material's damping mechanisms on which Chinese and foreign researchers have done considerable relevant researches and gained several research data and results. Nevertheless, these researches mainly focus on the impact on materials' damping capacities of the microstructures of materials including the matrix of materials, the type and fraction of intensifiers added into materials, and interfaces between the matrix and intensifiers, as well as second phase particles. They fails to take into account the relations between the characteristics of vibration waves generated in damping and the damping itself, simply considering grain boundaries and material organization. Therefore, they are not comprehensive; especially, researches on metal foams and extruded powder materials are highly limited.

According to material science, the properties of solid materials depend on their crystalline structures and composition. Thus, familiarity with and even control of their structures constitutes a precondition for properly selecting a material that meets a set of predetermined performance requirements and for developing a new material of better performance. Therefore, researches on the damping capacity of materials must consider the effects on damping of the characteristics of the vibration waves generated in damping, the material structures and the properties of materials themselves.

This paper discusses the damping mechanisms of materials in a systematic and from-macro-to-micro way via introducing the characteristics of vibration waves into its research scope.

2. Damping capacity

Applying an alternating stress σ onto a material sample generates a stress-strain hysteresis loop (as shown in Figure 1) due to the strain ε generated in the sample lagging behind the stress. The area of the loop represents the energy consumption per unit volume of the sample in a loading and unloading circle. Thus the damping capacity of the sample can be defined as ^[6-7].



Figure 1. Delay loop of stress-strain of material

$$\psi = \Delta W / W \tag{1}$$

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(2)

Where

 Ψ is the specific damping capacity of the sample material;

 ΔW is the energy consumed by a unit volume of the sample in a vibration circle;

W is the energy supplied externally to the unit volume of the sample in a vibration circle.

3. Damping model^[8]

When an object is sliding along a lubricated surface at a low relative velocity, the resistance of the object due to friction with the surface can be assumed as approximately proportional to the speed. Figure 2

shows a damped vibrating system: a spring k, a mass m and a damper c. The system can be seen as a simplification of the following system where a piston moves along a cylinder. The relative movement between the piston and cylinder causes a fluid resistance that is proportional to the relative speed and has a direction contrary to the direction of the velocity. The mass of the damper can be neglected.



Figure 2. The damping model

Assume the downward vertical direction as the positive x axis and the static equilibrium position of the object as the origin. When the object moves downwards, it has a positive displacement. Thus, the damping force can be expressed as

$$F_d = -c\dot{x}$$

where c is the viscous damping coefficient. According to Newton's laws of motion,

$$m x = -c x - k x$$
$$\ddot{x} + \frac{c}{m} \dot{x} + \frac{k}{m} x = 0$$

Eq. (2) is the differential equation governing the free vibration of the damped vibrating system. For obtaining the solutions of Eq. (2), suppose

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$$x = e^{st} \tag{3}$$

where s is an undermined coefficient. Substituting s into Eq.(2), the following can be acquired:

$$\left(s^2 + \frac{c}{m}s + \frac{k}{m}\right)e^{st} = 0$$

It can be seen that Eq.(3) satisfies Eq.(2), namely Eq.(3) being a solution of Eq.(2).

$$s^{2} + \frac{c}{m}s + \frac{k}{m} = 0$$
 (4)

This algebraic equation Eq.(4) is the characteristic equation of Eq. (2), and Eq. (4) has two roots S_1 and S_2 :

$$s_{1,2} = -\frac{c}{2m} \pm \sqrt{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}}$$
(5)

Thus, the general solution of Eq. (2) is

 $x = B e^{s_1 t} + D e^{s_2 t}$ (6)

where B and D are arbitrary constants depending on the initial conditions of the motion. The solution Eq. (6) is determined by the nature of s_1 and s_2 . Since it can be seen from Eq. (5) that the value of the term under the radical sign in Eq.(5) can be greater than, equal to or less than zero depending on the value of the damping coefficient c, the roots s_1 and s_2 can be different negative real roots, equal negative real roots or complex roots. The value of c enabling that the term under the radical sign in Eq.(5) has a value of zero, namely that s_1 and s_2 are equal negative real roots, is called the critical damping coefficient, denoted c_c , i.e.:

$$c_c = 2m\sqrt{\frac{k}{m}} = 2m\omega_n = 2\sqrt{km}$$
⁽⁷⁾

where ω_n is the natural frequency of the undamped vibration system and ζ is a dimensionless constant called the damping ratio.

$$\xi = \frac{c}{c_c} \tag{8}$$

The damping ratio ζ characterizes the amount of damping of the vibrating system:

When $\zeta > 1$, overdamping happens;

When $\zeta = 1$, critical damping occurs;

When $\zeta < 1$, underdamping takes place.

$$\frac{c}{m} = \frac{c}{c_c} \frac{c_c}{m} = 2\xi\omega_n$$

Since ζ is dimensionless, Eq. (2) and (5) can be rewritten as:

$$\ddot{x} + 2\xi \omega_n \dot{x} + \omega_n^2 x = 0 \tag{9}$$

$$s_{1,2} = \left(-\xi \pm \sqrt{\xi^2 - 1}\right)\omega_n \tag{10}$$

The following several paragraphs are dedicated to proving that the vibration system cannot be in a state of free vibration when $\xi > 1$ or $\xi = 1$, and that the vibration system is in a state of attenuating vibration when $\xi < 1$.

When $\xi > 1$, it can be seen from Eq. (10) that s_1 and s_2 are different negative real roots.

Substituting them into Eq. (6) leads to:

$$x = B e^{\left(-\xi + \sqrt{\xi^2 - 1}\right)\omega_n t} + D e^{\left(-\xi - \sqrt{\xi^2 - 1}\right)\omega_n t}$$
(11)

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The two terms on the right-hand side of Eq.(11) are of absolute values decreasing exponentially with time. This means that the object will eventually return to the position of equilibrium after moving away from it, which may happens in one of the three cases. The first case is that x_0 first increases to an extreme value and then gradually reduces to zero; in the second case, x_0 decreases monotonously; in the third case, the object may cross the equilibrium position and x_0 reaches an extreme value in the opposite direction of the initial displacement of the object, and then x_0 drops to zero finally. It can be proved that the object goes beyond the equilibrium position at most one time. Thus, under the action of overdamping the free motion of the vibrating system is not vibration.

When $\xi > 1$, it can be seen from Eq.(10) that s_1 and s_2 both equate $-\xi \omega_n$, under which it can be proved that $x = te^{-\omega_n t}$ and $x = te^{-\omega_n t}$ both satisfy Eq.(9). Therefore, the general solution to Eq.(9) is: $x = (B + Dt)e^{-\omega_n t}$ (12)

It can be seen that under critical damping the distance of the object from the position of equilibrium also reduces to zero exponentially with time after reaching an extreme value. It's obvious that this kind of free motion is not vibration.

Only under the condition of underdamping $\xi < 1$, the vibrating system can be in a state of free vibration.

Therefore, based on the vibration model proposed by Yu Dejie^[8] it can be inferred that the damping effects of materials under $\xi > 1$ or $\xi = 1$ are achieved by forces and that the damping effects of materials under $\xi < 1$ are attained via vibration waves.

4. Damping mechanisms for materials

It can be seen from the damping model described above that the damping mechanisms of material have to do with the frequency of the mechanical wave:

 ωv ----- the frequency of the vibration imposed on the material;

 ω n ----- the natural frequency of the vibrating system; the values of ω n can be derived by the model mentioned above;

ωc ----- the critical frequency of the material, depending on the type of the material.

When $\omega v > \omega n$, materials consume vibrational energy mainly through the reflection, diffuse reflection and mutual interference, which reflects a wave-type damping mechanism. In this case, the damping performance of a material is closely tied with its size.

When $\omega n < \omega v \le \omega c$, materials consumes vibrational energy mainly by dislocations, grain boundary friction, pinning, and second phases, which reflects a particle-type damping mechanism. This mechanism is the focus of current research.

When $\omega v \leq \omega c$, the vibration imposed onto a material is mainly absorbed by the matrix forming the material. In this case, the damping performance has a strong relationship with the type of the material.

The following points should be noted:

a) When a material is subjected to vibration, the three cases specified above may not occur simultaneously. It's possible that only one or two of the three cases may happen. The key to determine which case or cases occurs or occur is the mutual relationship among ωv , ωc and ωn .

b) If the vibration applied a material reaches to a certain extent, the material will be damaged. Although the consequences are the same, the first case differs from the third case in the mechanism by which the material is damaged. In the first case, the damage of the material leads to the damage of the forces among the molecules forming the material. In the third case, the collapse of the forces among

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the molecules forming the material causes the damage of the material. In short, the first case is an outside-in process while the third case is an inside-out process.

c) The first and second damping mechanisms of a material have close links with the preparation processes of the material. When the process pressure is not very high and the particles of the material matrix and the pores inside the material are relatively big, the probability of the first damping mechanism is relatively high. When damping occurs by the first mechanism, the material displays a wave-type damping; when damping occurs by the second mechanism, the material displays a particle-type damping

d) The first type of damping of materials is realized by wave while the second and third types of damping are achieve by the transferring of forces. Specifically, the second type is achieved mainly through the interaction among crystals while the third type the force is achieved by intermolecular forces. Thus, the third type of damping has nothing to do with the preparation processes of materials. It mainly involves the characteristics of the molecules composing the materials. When the composition of a material is set, the effects of the third type of damping for the material are basically determined.

4.1. Wave-type damping

The morphological characteristics of composite materials are similar to that of metal forms. As shown in Figure 3, there are numerous bubbles and tiny pores inside composite materials. According to Huygens's Principle^[9], vibration causes wave and wave transmits mainly by the interaction of medium molecules.

Composite's absorption of vibration waves is similar to its absorption of sound waves. As shown in Figure 4, when a vibration wave strikes the surface of a composite material, reflection, diffuse reflection and interference occur. The following presents the details of what happen when the vibration wave meets the walls of the holes on the surface of the matrix of the composite:

a) Some part of the vibration wave is reflected by diffuse reflection while some part of it is scattered. The reflected wave interacts with the scattered wave via interference, thus attenuating the original vibration wave.

b) Another part of the vibration wave travels through the holes and attenuates due to diffusion and expansion. When it meets adjacent bubbles, it repeats the processes of attenuation via diffusion and expansion;

c) There is a part of the wave diffracted into the tiny pores inside the material. The diffracted wave attenuates mainly in two ways, either by interference with other part of the wave or by diffusion and expansion;

d) In addition, the friction and heat exchange between the vibration wave and the hole wall also generates a damping effect;

The wave property of damping is substantiated by early reteaches. As for low-frequency vibration waves, the vibration absorption coefficients of materials are usually low while materials usually have high vibration absorption coefficients for high-frequency vibration waves. The wave-type damping of a material has to do with the vibrational frequency of the source of the vibration wave, the sizes of tiny pores inside the material and the structure of the material.

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material SiC/Al



Figure 3. The morphological characteristics Figure 4. Schematic diagram of the wave of the composite property of a vibration

1. Vibration wave 2. Reflected wave 3. Bubble wall 4 .Incident wave 5.Hole 6. Material matrix

4.2. Particle-type damping

Particle-type damping consumes energy mainly through interactions among microscopic particles. Current researches on it include dislocation damping^[10], interface damping^[11], grain boundary damping, twin-boundary damping and magnetic domain wall damping, etc. These types of damping share a major feature that they dissipate energy via the relative motion among microscopic particles which follows Newton's laws of motion.

Particle-type damping is the focus of current research. One of the recognized research results is Ginzburg-Landau (GL) Theory^[12]:

$$Q^{-1} = \Lambda B L^4 / (36 G b^2)$$
 (13)

Where

 Λ represents the dislocation density;

B stands for the damping factor;

L for the pinning length

G is the shear modulus;

b is the Brandt vector

Researchers have used the rule of mixtures (ROM) to predict the damping performance of a composite material according to the damping performance of the composting units of the material. Hashin^[13] derived the longitudinal damping capacity of the unidirectional continuous fiber reinforced composite material as:

$$\psi_c = \psi_m V_m E_m / E_c + \psi_f V_f E_f / E_c \tag{14}$$

Where ψ represents the damping capacity of composite material;

V is the volume fraction;

E stands for the modulus of elasticity;

Subscripts m, f and c denote the matrix alloy, fiber and composite materials, respectively.

Eq. (14) fails to consider the interface layer that exists practically. Therefore, Wolfenden and Wolla^[14] proposed a new ROM to calculate the damping capacity of composite materials:

$$\psi_c = \psi_r V_r + \psi_m V_m + \psi_i V_i \tag{15}$$

where i represents the interface layer.

4.3. Molecular force type damping

Molecular force type damping mainly refers to damping generated by interaction among molecules. It can be put under two major categories: metallic molecular force damping and polymer molecular force damping.

Metallic-molecular-force damping consumes energy mainly through intermolecular forces. Since molecules and crystals are composed by several or a large number of atoms^[15-17], the study of metallic-molecular-force damping involves complex problems of systems including a number of nuclei and electrons; these problems are called multiple body problems in wave mechanics. The starting point

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to analyzing these problems is the Schrodinger equation and Pauli Exclusion Principle. When a material is subjected to a vibration with a frequency higher than on, these high-frequency energy is absorbed by the molecules in the material, either through consumption of vibrational energy by intermolecular forces, either through converting vibrational energy into exchange energy, namely consumption of vibrational energy by setting two electrons in a position between the involved two atoms.

Polymer-molecular-force damping (also called viscous damping) dissipates energy mainly by transforming vibration energy into heat via the relative motion of and between molecules. Polymer materials are usually composed by numerous soft, long and curly intertwining molecules with an aspect ratio about 1/10000, (as shown in Figure 5 where the schematic structure of a common polymer chain is displayed). According to the mechanical properties of polymer materials in various transition regions (as shown in Figure 6), polymer materials in the glass transition region, namely at a temperature around Tg, have good damping performance ^[18-19]. When a polymer material is subjected to vibration, its molecules tend to move against one another, causing relative motion within the material. Meanwhile, the chemical units composting its molecules will also rotate freely. In short, when the material is subjected to vibration, its molecular chains will not only slip and rotate again one another but also be pulled and bended, thus consuming vibration energy imposed on the material.



Figure 5. Schematic diagram of a common polymer chain



Figure 6. Variety of dynamic mechanical property of polymers with temperature

5. Conclusion

The damping mechanisms proposed above not only systemize existing damping theories but also explain various damping behaviors of materials, thus offering guidance for developing damping materials and their preparation processes. When the type of a material is determined, the material's damping capacity and its preparation processes is conflicting because the preparation of the high-strength and high-hardness material calls for maximized process pressure while excessive pressure leads to a decrease in the material's wave-type damping capacity.

Although this study has considered the structure and composition of materials as well as the frequencies of vibration waves, it is still limited in that damping is influenced not only by the frequency of the vibration wave, but also by the frequency of the vibration involved in the vibration wave, thus requiring further research.

Although temperature has a major impact on the practical damping capacity of materials, it has nothing to do with the damping mechanisms of materials. In fact, the impact of temperature on practical damping capacity of materials can be explained by the damping mechanisms proposed.

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