Mechanisms of vibration damping in heat power engineering structural materials

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Abstract. This article explores two models of internal friction in porous materials and ultrafine-grain composite materials. The high-temperature background is described by two straight sections based on the dependence of the internal friction value on the reverse temperature or frequency of vibrations.

1. Introduction

Structural materials used in the design and manufacture of thermal power equipment often work in difficult conditions. They are caused by simultaneous exposure to chemically aggressive media, high temperatures and pressures, as well as a significant level of vibration. The increased level of noise and vibration leads to premature wear of mechanisms and machines, as well as has an adverse effect on the health of service personnel. Harmful effects of acoustic noise and vibrations on the environment are referred to as noise pollution. Reducing noise pollution is an urgent problem in the design and operation of power equipment.

Damping undesirable oscillatory processes inherent in the operation of power machines can be carried out in two fundamentally different ways. The first of them is constructive and consists in the use of specially designed damping devices in the design stage of the equipment. These devices include various types of dampers in the form of nodes with a viscous resistance to vibrations, elastic elements that connect nodes with different sources of vibration and provide resistance for their mutual transmission. The disadvantage of this method is that it cannot be used on existing equipment, since this requires changes to its design. The second method, which has a more universal character, can be used both in the design and at the stage of using the equipment. It consists in the use of materials with high damping properties in the manufacture or replacement of structural elements. The damping properties of metals and alloys are determined by their chemical composition, microstructure, and preparation methods. The physical cause of damping is the conversion of vibration energy into internal energy due to internal friction. Special materials include alloys with thermoelastic martensite, with a magnetic component in the structure, and with significant heterogeneity of the defect and phase structure. The working conditions of structural materials with the first two elements of the structure often have restrictions on temperature and the amount of external DC voltage. Materials that are characterized by the presence of the third of the listed structure elements have a wider area of use. Widely distributed classes are porous and composite materials. The purpose of this paper is to describe the damping mechanisms in them.

2. Damping mechanisms in porous metals.

A lot of research has been devoted to the study of internal friction in porous materials. This applies to both bulk samples [1, 2] and films [3]. The main parameter that characterizes the state of porous systems is the relative density \( P = \rho^*/\rho_s \), where the numerator is the mass density of the porous...
material, and the denominator is the density of the material in the limit state without pores. The level of vibration damping depends on this parameter. Recently, foam metals have become famous, the relative density of which is very small. Their structure consists of empty or gas-filled cells that are interfaced with common faces. This porous structure is called closed. If only edges are common to neighboring pores, then the structure with pores is of the open type. If \( P > 0.3 \), then the sample is a solid matrix with individual pores included in it. In such systems, the pore energy located at the grain boundary is always less than the pore energy in the grain volume [4]. In addition, most existing models of void formation associate this process with the participation of grain boundaries. Therefore, the pores at the grain boundaries seem to play a major role in the physical properties of porous materials.

Arbitrary orientation of the grain boundary segments in relation to the applied forces leads to the fact that there are shear and normal mechanical stresses in the boundary plane. Under their influence, the boundary segments located between the supports are effective sources of excess vacancies. Generated vacancies relax diffusely on pairs. This process is non-conservative and leads to the addition or removal of a substance in the boundary area. This causes a mutual displacement of the mating grains. The effect is more pronounced in samples with a relatively large proportion of the material belonging to the boundary, such as ultra-fine-grained or nanostructured metals.

The grain boundary with an open porous structure containing evenly spaced Islands of conjugation in the form of circles of radius \( R \) is chosen as the model boundary. Such areas under the action of an variable voltage applied to the boundary become periodically active sources and sinks of vacancies of the frequency \( \omega \). We solve the nonstationary diffusion equation for vacancies

\[
\frac{\partial C}{\partial t} = D \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial C}{\partial r} \right) + A \exp(\imath \omega t)
\]  

(1)

with boundary conditions in the form \( C(R,t) = 0 \), \( \frac{\partial C(0,t)}{\partial r} = 0 \) with the Fourier method. Here \( C \) – excess compared to equilibrium concentration of vacancies at the boundary, \( D \) – the grain boundary diffusion coefficient of vacancies, \( r \) – the polar radius, \( A \) – the density of the source positions. The solution of equation (1) has the form:

\[
C(\rho,t) = \frac{2A}{\omega} \exp(\imath \omega t) \sum_n \frac{Z \exp(-i\varphi_n)}{\mu_n J_1(\mu_n\rho)} J_0(\mu_n \rho), \quad Z = \frac{\omega R^2}{D}.
\]  

(2)

Here \( \rho = r/R \), \( J_0, J_1 \) – zero and first order Bessel functions, \( \mu_n \) – roots of the \( J_0 \) function, \( \tan \varphi_n = \omega R^2 \sqrt{D} / \mu_n \). Taking into account the effect of stress adjustment [5] gives the expression for \( A \):

\[
A = \frac{C_0 \sigma_0 \omega}{4kT} \sum_n \frac{Z \exp(-i\varphi_n)}{\mu_n \sqrt{Z^2 + \mu_n^2}}.
\]  

(3)

Here \( \sigma_0 \) – stress amplitude, \( \Omega \) – atomic volume, \( C_0 \) – equilibrium concentration of vacancies in the boundary, \( k \) – Boltzmann constant, \( T \) – thermodynamic temperature. The rate of mutual normal displacement of grains is determined by the amount of outgoing substance from the boundary segment under consideration.

\[
v = \frac{J}{\pi R^2},
\]  

(4)

where \( J \) – the full flow of vacancies across the interface segment boundary. Finding it from (2), we get

\[
v = \frac{4AD\delta \exp(\imath \omega t)}{\omega R^2} \sum_n \frac{Z \exp(-i\varphi_n)}{\sqrt{Z^2 + \mu_n^2}},
\]  

(5)

where \( \delta \) – the diffusive thickness of the boundary.

The damping capacity or internal friction can be found from the expression
Q^{-1} = \frac{\Delta W}{2\pi W}, \quad (6)
where the numerator is the amount of energy scattered over the period, and the denominator is the maximum stored elastic energy.

Substituting the previously found expressions in (6), we finally get [6]:
\[ Q^{-1} = \frac{\pi \beta E \varepsilon \Omega R^2 C_0}{kTV} \left( S_2 + Z^2 S_1 \right), \quad (7) \]
\[ S_1 = \sum_n \frac{1}{Z^2 + \mu_n^2}, \quad S_2 = \sum_n \frac{\mu_n^2}{Z^2 + \mu_n^2}, \quad S_3 = \sum_n \frac{1}{\mu_n^2 (Z^2 + \mu_n^2)}. \]
Here \( V \) – the volume of grain per unit area of the boundary, and \( E \) – the Jungs modulus. The geometric coefficient \( \beta \) takes into account the number of crystallite interface regions in the boundary and their orientation with respect to the external stress.

If the structure of the boundary with closed pores is taken as a model, then the pore regions and the conjugacy of the material of neighboring grains change places in comparison with the ones described above. A similar calculation results in the expression for internal friction:
\[ Q^{-1} = \frac{4\pi^3 \beta \varepsilon \Omega E (1 - (1 - \Delta)^2)}{V k T} \left( S_1 S_2 + S_3 S_1 \right) \frac{1}{Z} \left( S_1 S_2 + S_2 S_3 \right). \quad (8) \]

The sums \( S_1, S_2, S_3 \) and \( S_4 \) are defined by the expressions:
\[ S_1 = \sum_n \frac{\lambda_n^4 l_n^2 Z}{(1 - G_n) (Z^2 + \lambda_n^4)}, \quad S_2 = \sum_n \frac{\lambda_n^4 l_n^2 Z^2}{(1 - G_n) (Z^2 + \lambda_n^4)}, \quad S_3 = \sum_n \frac{\lambda_n^4 l_n^2 Z}{(1 - G_n) (Z^2 + \lambda_n^4)}, \quad S_4 = \sum_n \frac{\lambda_n^4 l_n^2 Z^2}{(1 - G_n) (Z^2 + \lambda_n^4)}, \quad G_n = \frac{J_0^2 (\lambda_n)}{J_0^2 (\lambda_n (1 - \Delta))}, \]
\[ I_n = \int_{1-\Delta}^{1+\Delta} \mu_n (\rho) d\rho = \frac{1}{\lambda_n} [N_0 (\lambda_n) J_1 (\lambda_n) - J_0 (\lambda_n) N_1 (\lambda_n (1 - \Delta)) - J_0 (\lambda_n (1 - \Delta) N_1 (\lambda_n (1 - \Delta))]. \]

Here \( \Delta = 1 - \sqrt{\kappa} \), \( \kappa \) – percentage of boundary area without pores, \( \lambda_k \) – roots of the equation \( J_0 (\lambda (1 - \Delta)) N_0 (\lambda) - J_0 (\lambda) N_0 (\lambda (1 - \Delta)) = 0 \). In these expressions \( J_i (p) \) and \( N_i (p) \) are the \( i \)-order Bessel and Neumann functions.

### 3. The damping mechanisms in metal composites

Composites are very promising structural materials due to the fact that they have unique physical and mechanical properties. For example, their specific strength and modulus of elasticity can be several times higher than similar characteristics of traditional materials, such as steel and metal alloys. In addition, they in many cases have high heat resistance and corrosion resistance. Of particular interest are the damping properties of composite materials. Various classes of composites [7], in particular metal-metal [8], have an increased damping ability or a high level of high-temperature internal friction background. The increase in internal friction during the transition from conventional composites to composites with ultra-small inclusions and grains is associated with both the concentration of the reinforcing component and its dispersion. The latter circumstance means an increase in the total area of interphase boundaries.

The modular structure of the composite material will be represented as simple polyhedra arranged in a matrix. These polyhedra can form an infinite cluster if the proportion of the reinforcing component exceeds the percolation threshold. In the simplest case, the reinforcing component can be considered as having the form of fibers. In this case, the model can be reduced to solving a one-dimensional diffusion problem. Here we present a two-dimensional model in which the shape of the granules is assumed to be cubic for simplicity. Tangent and normal tensile and compressive stress
variables occur on \( L \)-side square faces that are differently oriented in space. The presence of the latter changes the chemical potential of vacancies at the interfacial boundaries, which leads to the appearance of diffusion flows between neighboring faces, and to the deformation of the material as a whole.

The diffusion equation for the excess compared to the equilibrium concentration of vacancies \( C(x, y, t) \) with a periodically active distributed power source \( A \) has the form

\[
\frac{\partial C(x, y, t)}{\partial t} = DV^2 C(x, y, t) + A \exp(i\omega t)
\]  

(9)

Here \( V^2 \) — two-dimensional Laplace operator, the other notation is the same. By placing the \( x \) and \( y \) coordinate axes along the sides of the segment and solving equation (9) with zero boundary conditions on its sides by the Fourier method, we obtain:

\[
C(x, y, t) = \frac{16AL^2}{\pi^4D} \exp(i\omega t) \sum_{m,l} \exp(-i\phi_{ml}) \sin \frac{\pi m x}{L} \sin \frac{\pi l y}{L},
\]

(10)

\[
Z = \frac{\omega L^2}{\pi^2D}, \quad \tan \phi_{ml} = \frac{\omega L^2}{D\pi^2(m^2 + l^2)}, \quad m, l = 1, 3, 5, ...
\]

To calculate the rate of mutual normal displacement of grains of neighboring phases, we use an expression similar to (4). The total flow of vacancies across the entire boundary of the square segment has the form:

\[
J = DL \left[ \int_0^t \left( \frac{\partial C(x, 0, t)}{\partial y} \right) \left( \frac{\partial C(x, L, t)}{\partial y} \right) dx + \int_0^t \left( \frac{\partial C(0, y, t)}{\partial x} - \frac{\partial C(L, y, t)}{\partial x} \right) dy \right].
\]

(11)

The effect of stress adjustment is taken into account in the same way as in section 2. This gives the expression for the value \( A \)

\[
A = \frac{\beta \pi^6 D \sigma_0 C_0 \Omega}{64L^2 kT} \sum_{0}^{-\frac{1}{2}}
\]

(12)

\[
\sum_{m,l} = \sum_{m,l} \frac{m^2 + l^2}{m^2 + l^2 + Z^2} \left( \frac{Z}{m^2 + l^2 + Z^2} \right)
\]

The value of internal friction is found [9] according to the expression (6).

\[
Q_0^{-1} = \frac{\pi^4 \beta^2 C_0 \Omega^2 \delta G}{32kTL} F(Z),
\]

(13)

where

\[
F(Z) = \frac{1}{Z \sum_{m,l} \frac{m^2 + l^2}{m^2 + l^2 + Z^2}}
\]

Here \( G \) — the shift modulus, and the coefficient \( \delta \) takes into account the actual geometry of the structure.

4. Discussion of results

Expressions (7), (8) and (13) describe the temperature-frequency dependence of the internal friction or damping capacity. This dependence contains two straight sections with tangents of angles of inclination equal to -1 and -0.6 in the case of formula (8). This means that the effective activation energy of the internal friction background is equal to \( 0.6U_\mu \) at low temperatures and high frequencies,
or \( U_m \) in the area of high temperatures and low frequencies. Here \( U_m \) – the energy of grain boundary migration vacancy. In the dependencies described by expressions (7) and (13), the tangent of the angle of inclination of a rectilinear section in the high – frequency region is the values enclosed in the range 0.5-0.6. The exact value is determined by the deviation of the geometry of the pores or inclusions of the second phase from the one accepted in the models.

This type of internal friction dependence can be understood for evaluation reasons. For example, for composites, the flow of vacancies \( J \) from a segment is determined by their concentration gradient, which is proportional to

\[
J \sim \frac{DC}{l} \sim \frac{D\sigma_0}{lT},
\]

where \( l \) – diffusion length of vacancies, \( \sigma_0 \) – the amplitude of the variable stress. Energy loss \( \Delta W \) for the period of vibrations \( T_0 \) is proportional

\[
\Delta W \sim J\sigma_0 T_0 \sim \frac{DT_0\sigma_0^2}{lT}.
\]

Elastic energy \( W \sim \sigma_0^2 \). Therefore,

\[
Q^{-1} \sim \frac{DT_0}{lT}.
\]

At low frequencies or high temperatures, the diffusion has time to pass over the entire segment, so the size \( L \) can be taken as the diffusion length. It does not depend on the period of fluctuations. Then

\[
Q^{-1} \cdot T \sim DT_0 \sim D/l \sim Z^{-1}.
\]

In the region of high frequencies or low temperatures the main role in diffusion processes is played by the regions near the boundaries of the segment length

\[
l \sim \sqrt{2DT_0}.
\]

In this case

\[
Q^{-1} \cdot T \sim \sqrt{DT_0} \sim \sqrt{\frac{D}{\omega}} \sim Z^{-1/2}.
\]

Many materials of heat power engineering are used in the area of elevated temperatures. Vibration damping by such materials is described by the high-temperature part of the \( Q^1 \) dependence on the reverse temperature. At this site, the activation energy coincides with the energy of migration of vacancies along the grain boundary or interphase boundary. The amount of internal friction in this area increases rapidly with an increase in temperature or a decrease in the frequency of vibration. Therefore, the use of such materials in this temperature-frequency domain is most effective for parts of steam pipelines, steam generators and other units operating at high temperatures.

5. Conclusion

Increased noise and vibration of power equipment adversely affects its performance and durability, the state of the environment and has a negative impact on the health of personnel. One of the ways to reduce vibration energy is the use of metals and alloys with increased damping capacity. The ability of a material to dampen vibrations is related to internal friction processes occurring in a solid. They convert the energy of vibrations into the internal energy of the body.

The internal friction spectrum of ultra-fine grain composites and porous materials with pores at the grain boundaries is monotonous, depending on frequency and temperature. The spectrum consists of two linear regions with different activation energies. The damping efficiency increases with increasing temperature and decreasing frequency.

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References

[1] Golovin I S and Sinning H-R 2004 Internal friction in metallic foams and some related cellular structures Materials Science and Engineering: A 370, I 1–2 P 504
[2] Ota K, Ohashi K and Nakajima H 2003 Internal friction in lotus-structured porous copper with hydrogen pores Materials Science and Engineering: A 341 I 1–2 P 139
[3] Du G, Tan Z, Li Z, Liu K, Lin Z, Ba Ya and Ba D 2018 Microscopic damping mechanism of micro-porous metal films Current Applied Physics 18 I 11 P 1388
[4] Hartland P, Crocker A G and Tucker M O 1988 Grain growth with boundary pores Journal of Nuclear Materials 152 I 2–3 P 310
[5] Kul'kov V G 2007 Diffusion Model of Internal Friction in Nanocrystalline Materials *Technical Physics* **52** № 3 P 333

[6] Kul'kov V G and Syshchikov A A 2020 Contribution of Porous Grain Boundaries to the High-Temperature Background of Internal Friction *Russian Metallurgy (Metally)* **2020** No 4 P 277

[7] Deodati P, Donnini R, Montanari R and Testani C 2009 High temperature damping behavior of Ti₆Al₄V–SiC₅ composite *Materials Science and Engineering: A* **521–522** P 318

[8] Trojanová Z, Riehemann W, Ferkel H and Lukáč P. 2000 Internal friction in microcrystalline magnesium reinforced by alumina particles *Journal of Alloys and Compounds* **310**, 1–2 P 396

[9] Deshevyh V V, Kul'kov V G, Korotkov L N and Tarasov D P 2012 High-temperature internal friction background in nanocomposite material *Composites and nanostructures* № 2 P 24 [in Russian]