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Modeling of Magneto-Mechanical Damping in Ferromagnetic Alloys: a Brief Review

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Abstract

This review is devoted to the analysis of three components of magneto-mechanical damping (MMD), namely, macroeddy, microeddy, and hysteresis components, in ferromagnetic alloys. Theoretical models and equations for all three components of the MMD are discussed. The application of the classical theory of micro- and macroeddy MMD to determine the influence of the frequency of cyclic external mechanical load on the damping ability of the material is shown. A discussion on the role of various factors, such as temperature, strain amplitude, vibration frequency, and external magnetic field, on the magnitude of the MMD is provided.

Keywords: Magneto-mechanical damping (MMD); Macroeddy relaxation; Microeddy relaxation; Magnetic hysteresis damping

1. INTRODUCTION

Magneto-mechanical damping (MMD) is a type of damping of mechanical vibrations in magnetic materials associated with the interaction of structural and magnetic subsystems in a solid. This interaction is caused by the phenomenon of magnetostriction, i.e., a change in the size and shape of a crystalline body as a result of magnetization [1]. In some solids, the energy state of the crystal lattice in a magnetic field changes and, as a result, the distances between the lattice nodes also change, i.e., magnetostrictive deformation occurs. The magnetostrictive deformation reaches the greatest values in ferro- and ferrimagnets where the magnetic interactions of atoms are large. The phenomenon being opposite to magnetostriction is the Villari effect [2]. Due to this effect, MMD can be observed even without the action of an external magnetic field.

An important factor affecting MMD is the presence of a domain structure in magnetic materials [3]. The Villari effect can be related to a change in the domain structure of a ferromagnet, which determines its overall magnetization, under the action of mechanical stresses [2]. Like an external magnetic field, an applied mechanical stress can lead to both reversible and irreversible changes in the magnetic structure. An external stress leads to a reorientation of the magnetization vectors in a certain region of the material. As a result, the volume of the selected domain changes due to displacement of domain walls (DWs).

The MMD effect has found a broad application for the materials based on ferro- and ferrimagnetic alloys. The study of MMD and the development of new damping materials have important prospects for using in microelectronic devices [3] and for vibration isolation of precision instruments [4–6]. Acoustomagnetic labels, used for electronic tracking of goods, are one of the first examples of its application [7]; see Fig. 1. The label consists of magnetostrictive strips made of ferromagnetic alloy and a fixed magnetized strip (permanent magnet) in a package made of durable thin plastic. When an alternating magnetic field is applied to such a device, oscillations are excited in the ferromagnetic alloy, which are associated with a reversible displacement of the DWs and reorientation of the magnetization vectors. The secondary field of these oscillations depends on the constant of magneto-mechanical damping and can be registered by a detector.

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Fig. 1. Acoustomagnetic label — an example of the device utilizing the effect of magneto-mechanical damping (MMD).

It is worth noting that a whole class of highly damping materials with the properties controlled by both the atomic-crystal structure and magnetic domains system [8] has been developed on the basis of MMD.

The purpose of this review is to give brief information about the existing theoretical models of the MMD phenomenon and to illustrate their applicability with the experimental data available.

2. MODELS OF MAGNETO-MECHANICAL DAMPING

At the beginning of the 20th century, the experimental techniques became advanced enough to make it possible to mechanically affect a sample in a wide frequency range. The description of obtained experimental data required the development of a theory and adequate models of MMD. As a result, the foundations of the MMD theory were laid in the 1930s to 1940s years [9–11]. Subsequently, the MMD theory was almost completely formed by the end of the 1950s by the works of many prominent scientists (see references in the work [12]).

The total MMD, being described using the decrement of mechanical vibrations δ_{tot}, can be represented as the sum of three main components:

$$\delta_{tot} = \delta_M + \delta_\mu + \delta_h. \quad (1)$$

Part of the macroeddy MMD (δ_M) arises from the volumetric response to a change in the magnetic flux penetrating a sample of ferromagnetic material. Losses due to macroeddy currents appear when the total magnetization of the sample changes under the action of cyclic mechanical stresses σ due to the partial ordering of the magnetic moments of magnetic domains when a magnetic field is applied. The macroeddy component of MMD does not depend on the deformation amplitude but depends on the loading frequency. This is the result of the eddy of currents action induced in an electrically conductive sample in response to a stress-induced change in $d\boldsymbol{B}/d\sigma$ of the total magnetic induction $\boldsymbol{B}$. In 1938, Zener considered attenuation due to macroeddy currents by summing single Debye peaks [9]. For the case of a partially magnetized rod of radius R loaded with a periodic stress σ of frequency ν, the expressions for δ_M were given by Bozorth in 1951 at the lower ($\delta_{M(L\nu)}$) and upper ($\delta_{M(H\nu)}$) frequency limits, respectively, as [2]:

$$\delta_{M(L\nu)} = \frac{\pi}{4}\left(\frac{dB}{d\sigma}\right)^2 \frac{R^2}{\rho} E\nu,$$

$$\delta_{M(H\nu)} = \frac{1}{8\pi^2 \mu_r^{3/2}}\left(\frac{dB}{d\sigma}\right)^2 \left(\frac{R^2}{\rho}\nu\right)^{-1/2}, \quad (2)$$

where ρ is the electrical resistivity, and μ_r is the reversible magnetic permeability, E is material Young's modulus. Several experimental measurements of this MMD component were provided by Berry and Pritchet in the 1970s [13–15] and discussed later by Degauque [16].

Microeddy MMD (δ_μ) is a consequence of reversible displacements of 90° DW or reorientation of magnetization vectors in domains. The associated change in the local magnetization induces microeddy currents, even though the macroscopic magnetization of the sample may not change. This type of MMD depends on the frequency of the mechanical action used in experiments. The currents, in turn, are caused by local changes in the magnetization due to the displacements of the DW under the action of mechanical stresses. In contrast to the case of macroeddy MMD, when significant magnetization is required for the appearance of observable damping, δ_μ has the greatest value near the demagnetized state [17].

Depending on the frequency range and the type of motion assumed for the DW, various expressions were proposed that describe δ_μ [2,18]:

$$\delta_\mu = A\frac{E\lambda^2 M_S^2}{\mu\rho\sigma_i^2}\nu \quad (3a)$$

for the reversible motion of rigid DW at a relatively low frequency, where μ is the magnetic permeability, M_S is the saturation magnetization and A is a parameter depending on the level of internal stresses σ_i with wavelength λ; or

$$\delta_\mu = \frac{GNa^2\bar{l}^2}{12W_\omega}\cdot\frac{m\nu/\beta'}{1+(m\nu/\beta')^2} \quad (3b)$$

for the reversible motion of flexible DW, considered as elastic membranes fixed by dislocations. In Eq. (3b) G is the shear modulus, Na^2 is the area per unit volume of DWs with an effective mass m, $\bar{l}$ is the average distance between pinning dislocations, W_ω is energy of magnetic DW, and β' is a parameter characterizing viscous damping. Another expression for macroscopic MMD was obtained by Mason [19] by summing single frequency peaks of Debye relaxations. We discuss it below in Section 3 together with an experimental example.

The third contribution to total MMD δ_{tot} is the hysteresis MMD (δ_h). This component of MMD arises due to the irreversible DW shift with magnitude comparable to the domain size. Hysteresis type MMD is the most widespread in ferromagnetic materials and is found in practical applications more often than others. That is why the term "MMD" often refers to this component only. This amplitude-dependent component is associated with the motion of DWs. Hysteresis MMD is also associated with such an interesting phenomenon as irreversible Barkhausen jumps on strain-stress (τ-γ) diagrams beyond the critical stress τ_{cr}. For small applied shear stresses τ or shear strains γ, the dissipated hysteresis energy ΔW_h and hysteresis MMD δ_h [2,16]:

$$\Delta W_h = \frac{4}{3}\frac{dG^{-1}}{d\tau}\tau^3, \quad \delta_h = \frac{\Delta W_h}{2\pi W}. \tag{4}$$

As the energy of elastic vibrations W varies with τ^2, this implies a linear amplitude dependence of internal friction. For higher stresses, however, the hysteretic losses ΔW_h no longer increase with τ^3 but with a stress-dependent exponent $0 < n < 3$, and finally reach a saturation level. As a consequence, δ_h shows a maximum depending on the stress or strain amplitude. Degauque [16] related the value of saturation ΔW_h to the value of "effective" internal stresses that oppose the motion of DWs. He pointed out that the position and height of the amplitude-dependent damping peak δ_h can be used to determine the level of these internal stresses and found as an example a value of 7 MPa for high purity iron sample subjected to recrystallization. Accounting for this mechanism of MMD, a variety of high-damping magnetic materials have been developed; see Section 4.

For clarity, one may consider the operation of components of MMD using four 90° magnetic domains as an example. In Fig. 2a the square magnetic material cell schematically demonstrates magnetic domains with different orientations of magnetization designated by the arrows and DWs along diagonals of the square. In Fig. 2b it is shown that mechanism of microeddy relaxation δ_μ is associated with reversible displacements of 90° DWs or reorientation of magnetization vectors. Fig. 2c explains the mechanism of macroeddy relaxation δ_M as the partial ordering of the directions of magnetic moments in the entire cell. Figure 2(d) describes the hysteresis MMD δ_h as the process related to irreversible DW displacements being comparable to the domain size.

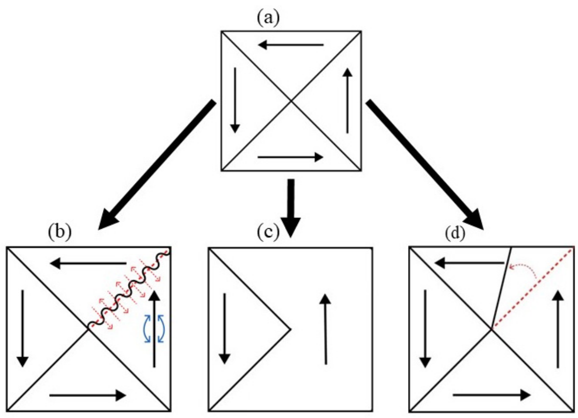

Fig. 2. Components of magneto-mechanical damping on the example of four 90° domains in a square cell of a ferromagnetic sample.

More information on the theory and modeling of MMD including complex cases of domain structure rearrangement under the influence of various external factors can be found in monographs by Nowick and Berry [12] and Blanter and Pigusov [20].

3. DEPENDENCE OF MICRO- AND MACROEDDY COMPONENTS OF MMD ON FREQUENCY AND MAGNETIC FIELD

The main feature of micro- and macroeddy damping is the presence of characteristic relaxation frequencies. Classical static methods of mechanoscopy or common methods of dynamic mechanical spectroscopy operate in the range from 0.01 Hz to 100 Hz and are far from the region in which these relaxations affect MMD. However, in the frequency range up to several kHz, both relaxation processes make a considerable contribution.

Consider the frequency dependence of micro- and macroeddy MMDs based on theoretical concept of Mason and Zener [9,12,21] and the data obtained in internal friction experiments performed by the composite piezoelectric oscillator method [22,23]. In the frequency range up to several kHz, both relaxation processes make a comparable contribution.

Accounting only for the first term of the spectrum in the Debye equation for oscillation damping, the main relations for the characteristic damping frequencies of macro- and micro-vortices have the following form [24]:

$$\delta_{M,\mu} = \pi\left(\frac{E_u - E_r}{E_r}\right)\frac{\nu/\nu_{M,\mu}}{1+(\nu/\nu_{M,\mu})^2}, \tag{5}$$

where E_u is the effective Young's modulus in the saturated state, E_r is the Young's modulus during relaxation under the action of macro- or microeddy MMD, $\nu_{M,\mu}$ are the characteristic frequencies of macro- and microeddy damping. Having found the values of Young's modulus during the experiment, one can obtain a qualitative scheme of the effect of the used frequency on the MMD components (Fig. 3).

It follows from Fig. 3 that there is no micro- and macroeddy relaxation in the saturating magnetic field. The macroeddy damping also vanishes at zero magnetic field, where the damping of microeddy part of MMD has maximum values (for instance, for Ni_2MnGa at an experimental frequency of ~7 MHz [24]). The value of the magnetic field at which the MMD component has a maximum value is denoted as H_m. For the Ni_2MnGa alloy, the maximum macroeddy damping is achieved at an experimental frequency of ~10 kHz. Separately, we note that the attenuation of the microeddy currents decreases with increasing magnetic field, and the macroeddy currents reach its maximum value at half value of the saturating field [24].

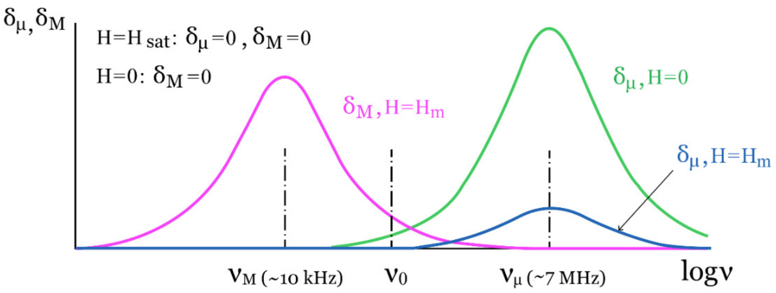

Fig. 3. Scheme of the influence of the frequency ν on the components of the microeddy and macroeddy MMD with characteristic frequencies for Ni_2MnGa. Adapted from Ref. [24].

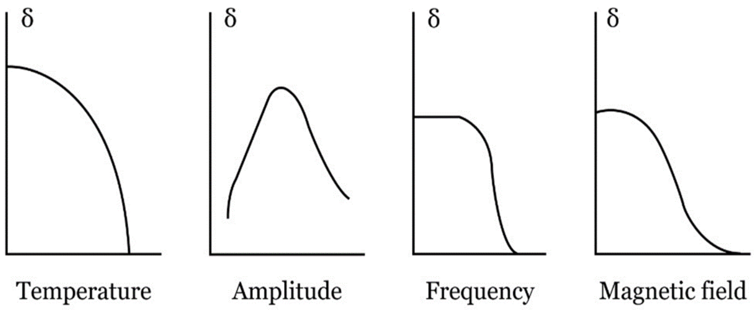

Fig. 4. Qualitative dependences of magneto-mechanical damping (MMD) on temperature, strain amplitude, loading frequency, and external magnetic field. Adapted from Ref. [25].

The characteristic frequencies at which the maximum values of macro- and microeddy MMD are observed can be estimated by the relations:

$$\nu_M \approx \frac{\rho}{\mu_0 \mu_r a^2}, \quad \nu_\mu \approx \frac{\rho}{\mu_0 \mu_r b^2}, \tag{6}$$

where μ_0 is the magnetic constant, a is the characteristic size of the sample cross section, and b is the size of the magnetic domains. These formulas are universal and are suitable for any ferro- and ferrimagnets. The presence of the sample size in the first equation and the domain size in the second one is the key difference between the relaxation processes under consideration. These equations are analyzed in more detail in works [12,24,25].

4. DEPENDENCE OF MMD ON EXTERNAL PARAMETERS AND MATERIAL CHARACTERISTICS

The damping ability of ferromagnetic materials is affected by many parameters that are associated with their intrinsic properties, e.g., crystal and magnetic structures, grain size and the presence of defects [26]. In addition, MMD depends on the frequency and amplitude of cyclic strain used in the experiment, the magnitude of the external magnetic field, and temperature [26,27]. Some of the dependences of MMD on external parameters are schematically shown in Fig. 4.

The damping capacity of a single-crystal sample is several times greater than that of a polycrystalline sample. This shows a strong negative role of grain boundaries on damping [28]. For example, in work [29] the effect of grain size on mechanical attenuation in Fe-Al ferromagnetic alloy with 5 wt.% aluminum, was studied at frequency of 120 Hz. With the decrease in the average grain size (from 845 to 130 μm), the value of the magnetostriction saturation increased, but simultaneously the surface area of the DWs decreased. The balance of these two mechanisms determined the maximum damping capacity for this material at a grain size of about 196 μm. The presence of the optimal grain size, which corresponds to the maximum damping properties at different frequencies, has also been confirmed in works [30–32]. A decrease in the damping capacity due to macro- and microeddy losses is also observed with strong grain refinement by methods of severe plastic deformation [33]. On the contrary, the grain size has little effect on the mobility of DWs and does not change the hysteresis losses [34]. During heat treatment of materials below a certain critical temperature, a decrease in local internal stresses and structural defects leads to easier movement of magnetic domains [35]. As a result, similar to nonferromagnetic materials [36], during primary annealing, damping increases due to diminishing in the density of dislocations and diffusion of point defects. However, when the alloy is annealed above the critical temperature, the dimensions of the magnetic domains become so large that the area of the DWs decreases that leads to a decrease in the damping capacity. As can be seen, the influence of external parameters on the damping characteristics of alloys with MMD is complex and diverse, because their action is associated with the work of various elements of the magnetic and crystalline structure.

5. CONCLUDING REMARKS

The review provides a concise explanation of the presence and the role of three components of magneto-mechanical damping (MMD) in ferromagnetic materials and discusses the features of these types of damping. The application of the classical theory of micro- and macroeddy MMD to determine the influence of the frequency of external mechanical loading on the damping value, has been shown. A discussion of the influence of various external factors on the magnitude of the MMD has been given. Despite the fact that most of the MMD models were formulated more than half a century ago, their application in the development of new magnetic materials is still relevant.

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Моделирование магнитомеханического затухания в ферромагнитных сплавах: краткий обзор

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Аннотация. Настоящий обзор посвящен анализу трех составляющих магнитомеханического затухания (ММЗ) в ферромагнитных сплавах: макровихревой, микровихревой и гистерезисной. В работе рассмотрены теоретические модели и уравнения для всех трех компонент ММЗ. Показано применение классической теории для определения влияния частоты циклического внешнего механического воздействия на демпфирующую способность материала при микро- и макровихревом ММЗ. Обсуждается зависимость величины ММЗ от различных факторов, таких как температура, амплитуда деформации, частота воздействия и внешнее магнитное поле.

Ключевые слова: магнитомеханическое затухание (ММЗ); макровихревая релаксация; микровихревая релаксация; магнитомеханическое гистерезисное затухание