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EFFECT OF THE TEXTURE OF FERROMAGNETIC Co–Fe COATINGS ON THEIR DAMPING CAPACITY

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ABSTRACT

The effect of the crystallographic texture of Co-Fe coatings produced by the method of electron beam physical vapour deposition (EB PVD) on their damping capacity (DC) has been studied. It is found that the amplitude dependence of DC of a coating with a fiber <111> texture exhibits a prominent maximum, while that of a coating with a multicomponent <100> + <111> + <110> fiber texture shows the blurred maximum which has shifted to the higher amplitude deformations. The effect of both the fiber texture type and the level of internal (residual) stresses in Co–Fe coatings on the amplitude dependence of the DC has been analyzed within the framework of the Smith-Birchak model. It is shown that transition from a single-component to a multicomponent coating texture reduces the maximum value of DC. In contrast, an increase in the internal stresses in the coatings leads to a shift and blurring of the DC maximum. On this basis, it is concluded that the maximum DC for Co–Fe coatings can be achieved provided that they have a fiber <111> texture and a minimum level of internal stresses.

KEYWORDS: EB PVD, coating, Co–Fe alloy, damping capacity, texture, internal stresses

INTRODUCTION

Suppression of resonance vibrations (RV) in products that are exposed to intense vibrations, for example, in blades of gas turbine engines is a prerequisite for preventing their premature failure [1]. The use of highly damping coatings for such products is considered as one of the means of reducing the amplitude of RV in them. The works [2–4] show the possibility of using ferromagnetic coatings that combine high damping capacity (DC) with acceptable mechanical and corrosion properties.

In ferromagnets with BCC lattice, dissipation of mechanical energy is mainly related with the irreversible shift of the boundaries of 90° magnetic domains in the action of dynamic stresses. In [5], a model displaying magnetomechanical attenuation (MMA) of oscillations is proposed, from which it follows that the maximum value of damping is proportional to the magnetostriction of material saturation and the variation of amplitude dependence of DC characteristics is determined by the level and dispersion of residual (internal) stresses, which interfere with the movement of magnetic domain boundaries.

The work [6] shows that the magnitude of magnetostriction in the massive textured material changes depending on the direction of action of external stresses on it. Therefore, it can be expected that DC of coatings of ferromagnetic materials will depend on the type of coatings texture and residual stresses in their volume.

It is known that the microstructure of vacuum condensates is largely affected by the temperature of their deposition, in particular, at deposition temperatures T_d, for which the temperature T_d/T_m = 0.3–0.5, where T_m is the melting point of condensing metal corresponding to the second structural zone [7], which is characterized by a columnar microstructure of the coating. In this case, the thickness of columnar crystallites decreases as the temperature of condensate deposition drops. The example of vacuum condensates of Cu [8] and Ni [9] shows that with a decrease in the thickness of crystallites, their crystallographic texture changes. Moreover, this is accompanied by the transformation of a single-domain structure of the coatings in a multidomain substructure, when columnar crystallites are fragmented as a result of twins' formation in them. Such changes of microstructure in the coatings of ferromagnetic materials can significantly affect the mobility of magnetic domain boundaries and, accordingly, their DC.

The mobility of magnetic domain boundaries is also determined by the dislocation density in the volume of a coating. The work [10] shows that an increase of dislocation density in the Co–20 wt.% Fe coating as a result of sequential plastic deformation by a shock ultrasonic wave leads to shifting the amplitude maximum of a logarithmic decrement of vibrations (LD) and reduction in its height.

Based on the abovementioned, on the example of coatings from Co–Fe alloy, from MMA oscillations obtained under different conditions of their deposition, the effect of texture on the amplitude dependence of DC characteristics of ferromagnetic alloys with BCC lattice was studied.

Ferromagnetic Co–Fe alloy as an object of study was chosen taking into account its high DC in a wide temperature range, which is important in terms of developing damping coatings based on materials of this class and their practical application [11].

EXPERIMENT PROCEDURE

Co–20 % Fe coating of 90–120 μm thickness was deposited by the method of EB PVD on 1.8 mm thick substrates, produced in the form of an elongated trapezoid from the sheet of Ti-6-4 alloy (Figure 1). The coating was produced in the stationary and nonstationary conditions at substrate temperatures of 350–500 °C. In the first case, the substrate was fixed over the evaporator, in the second case it rotated around its longitudinal axis at a speed of 80 rpm in the process of coating formation.

Characteristics of DC of coating material (amplitude dependences of LD) were investigated in the laboratory installation described in [12]. The initial values of LD of the substrate-coating system were measured in the mode of freely attenuated bending oscillations with a frequency of 130–150 Hz. The intrinsic of LD of the coating material were determined by the procedure described in [13], based on the initial data for the specimens with coatings and without them. Such approach allows eliminating nonuniform distribution of deformation on the surface of the specimen, i.e., it represents deformation of the coating material in the approximation of pure bending, and also makes it possible to eliminate the effect of coating thickness on its DC.

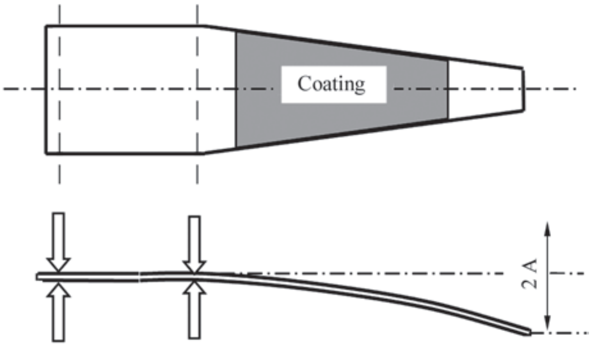

Figure 1. General appearance of substrate of a trapezoidal shape with the Co–20 % Fe coating for the study of DC characteristics of the substrate-coating system

Examination of the coating microstructure was carried out on witness specimens produced in identical conditions of deposition. For this purpose, plates of 5×10 mm of Ti-6-4 alloy were used, which were fixed near the substrate on its holder. Further, these witness specimens were mechanically cut into two parts, from which specimens for electron microscopic and X-ray examinations were made. Trapezoidal substrates with coating were not subjected to any treatment and were used further to determine the characteristics of their DC.

Figure 2 presents the overall appearance of the microstructure and the distribution of chemical elements over the thickness of the witness specimen cross-section. It is seen that the microstructure of the material is homogeneous, and there are no defects on the interface of the substrate with coating that contribute to the reduction of adhesion between them.

For X-ray structural analysis of Co–Fe coatings, the DRON-4M diffractometer in the radiation of the copper anode was used. Figure 3 presents the diffraction patterns of coatings, deposited under different conditions. It is seen that on both diffraction patterns, only maxima of BCC structure are present. Such a fact draws attention, that the ratio of intensities of diffraction peaks changes during the transition from

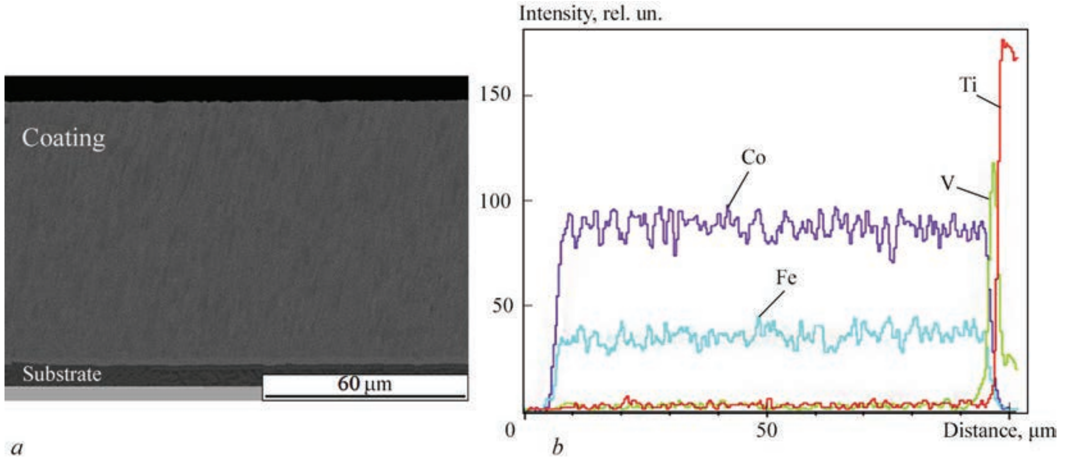

Figure 2. General appearance of microstructure (*a*) and distribution of chemical elements (*b*) according to the thickness of witness specimen cross-section with the Co–20 % Fe coating

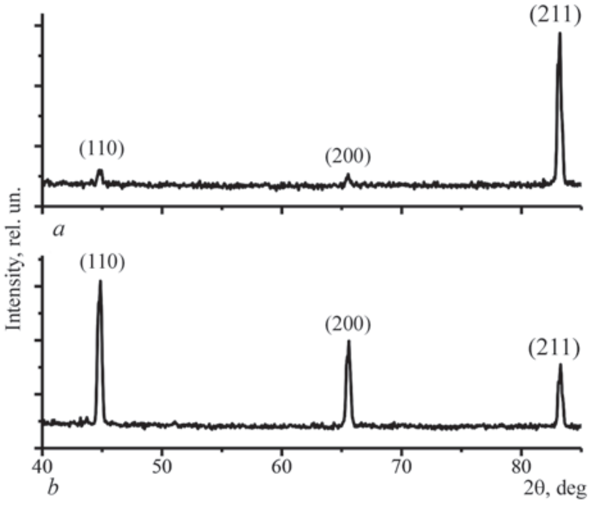

Figure 3. Diffraction pattern of Co–20 % Fe coatings deposited in the stationary conditions (*a*) and during substrate rotation (*b*)

the coatings produced in the stationary conditions and during substrate rotation.

The analysis of the crystallographic texture of the coatings was performed using an X-ray diffractometer DRON-3, equipped with a textured attached device, in CuK_α radiation. The measurements were carried out using a parallel beam geometry at scanning angles from 0 to 80° and from 0 to 360° for α and β, respectively. The data obtained on a nontextual $BaTiO_3$ specimen were used to record the defocusing effect. The analysis of crystallographic texture was carried out by constructing straight and reverse pole figures (PF) by means of the MTEX Matlab software package [14].

DAMPING PROPERTIES OF COATINGS

Figure 4 presents amplitude dependences of LD reflecting DC of substrate-coating systems, obtained in the conditions of stationary and nonstationary deposition of coatings. It is seen that DC of both oscillating systems is several times higher than that of the substrate without coating. Moreover, in the case of coating deposited with a stationary substrate, the level of DC is significantly higher compared to the coating deposited on a rotating substrate.

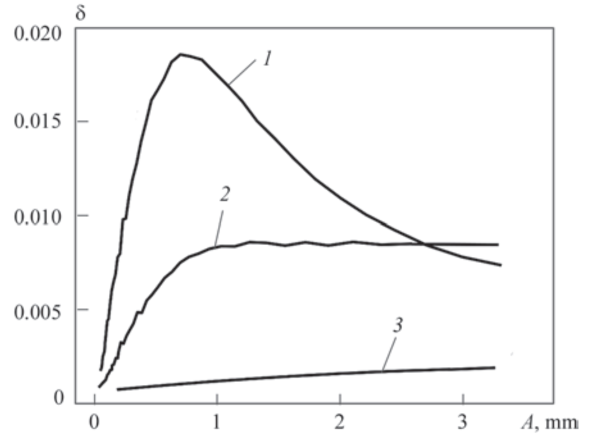

Figure 4. Amplitude dependences of LD for substrates with Co–20 % Fe coatings deposited on a stationary substrate (*1*), substrate during rotation (*2*) and for a substrate without coating (*3*)

Figure 5 presents the calculated amplitude dependences of intrinsic of DC for the coating material produced in the stationary and nonstationary conditions of deposition. It can be noted that the level of DC of the coating produced in the stationary conditions is almost twice higher than that of the coating deposited in the nonstationary conditions. From the comparison of the shape of the curves of amplitude dependences, it is seen that for the coating deposited in the stationary conditions, the rate of decrease of the curve for the descending part of the maximum is sharper.

The height and profile of the MMA maximum are determined by saturation magnetostriction and residual stresses [5]. Taking into account that the magnitude of the magnetostriction of the material depends on its texture [6], it was assumed that the differences in the amplitude dependence curves of DC of Co–Fe coating materials produced under different conditions of their deposition (Figure 5) are predetermined by their different texture.

MICROSTRUCTURE OF COATINGS

The characteristic microstructure of the Co–20 % Fe coating is shown in Figure 6. It is seen that the coating

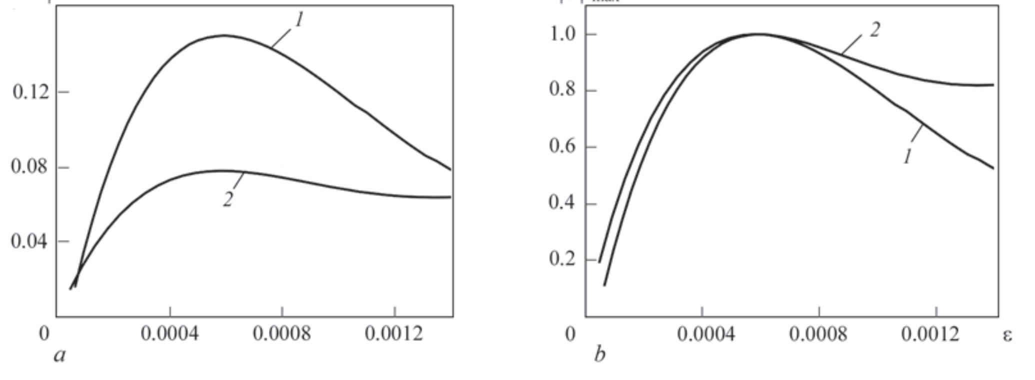

Figure 5. Amplitude dependences of energy loss coefficient ($\psi = 2\delta$, where δ is the intrinsic of LD) of intrinsic (*a*) and values normalized to the maximum (ψ_{max}) (*b*) for Co–20 % Fe coatings deposited in the stationary (*1*) and nonstationary (*2*) conditions

consists of columnar grains oriented perpendicular to the surface of the substrate.

It turned out that such coatings are characterized not only by the elongation of grains in the direction of their growth, but also by the presence of a certain predominant crystallographic orientation. In Figure 7, *a*, PF (110), (100) and (211) are presented, built for the Co–20 % Fe coating, deposited in the stationary conditions. It is seen that the distribution of density of the poles (110) and (100) has a circumferential character. Taking into account the angular distance of the circumferential distributions, it was concluded that this type of pole density distribution can be obtained in the case of fiber texture with a predominant orientation of crystallites in the <111> direction. Figure 7, *b* presents PF of the Co–20 % Fe coating deposited in the nonstationary conditions. It is seen that also in this case, a fiber texture is formed. However, the grains are mainly oriented along the <100> axis, where the maximum pole density is observed in the center of PF.

To evaluate the volume fraction of crystallites characterized by different orientations based on the obtained results on the distribution of pole density, inverse PF were built. Figure 8 presents inverse PF built for the Co–20 % Fe coatings deposited in the stationary and nonstationary conditions. It is seen that in the case of coating deposited in the stationary conditions, the fiber texture is a single-component of <111> type,

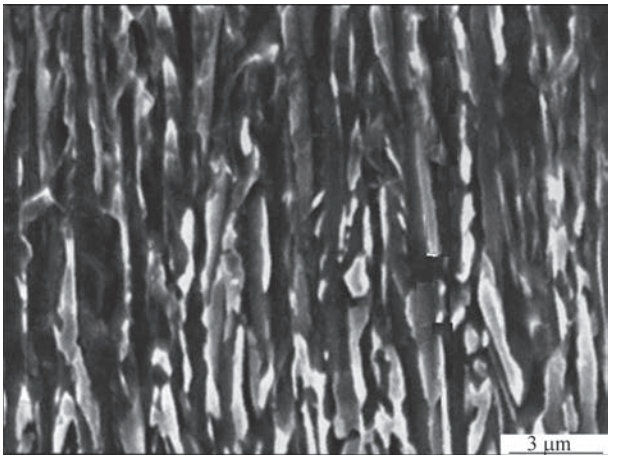

Figure 6. Cross-sectional microstructure of Co–20 % Fe coating etched to reveal grain boundaries

and in a coating produced in the nonstationary conditions, it is a multicomponent <100> + <111> + <110>. Moreover, the volume fractions of the components differ. The largest volume fraction is characteristic of the component of the fiber texture of <100> type and the smallest is typical of <110> component (Table 1).

It is seen that, despite the presence of <111> and <110> components, the <100> texture component is dominant in the multicomponent texture of a coating deposited in the nonstationary conditions. A coating deposited in the stationary conditions has a one-component fiber texture <111>.

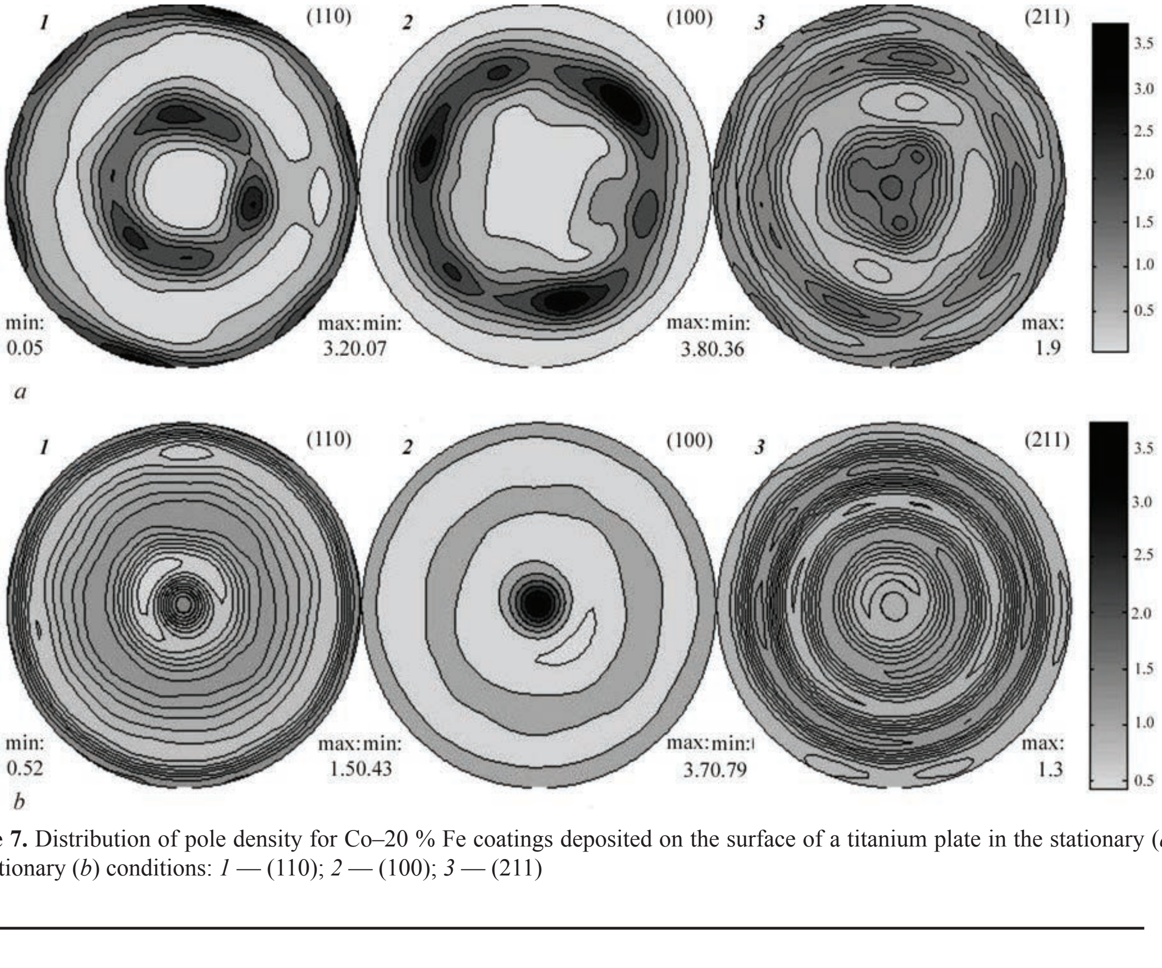

Figure 7. Distribution of pole density for Co–20 % Fe coatings deposited on the surface of a titanium plate in the stationary (*a*) and nonstationary (*b*) conditions: *1* — (110); *2* — (100); *3* — (211)

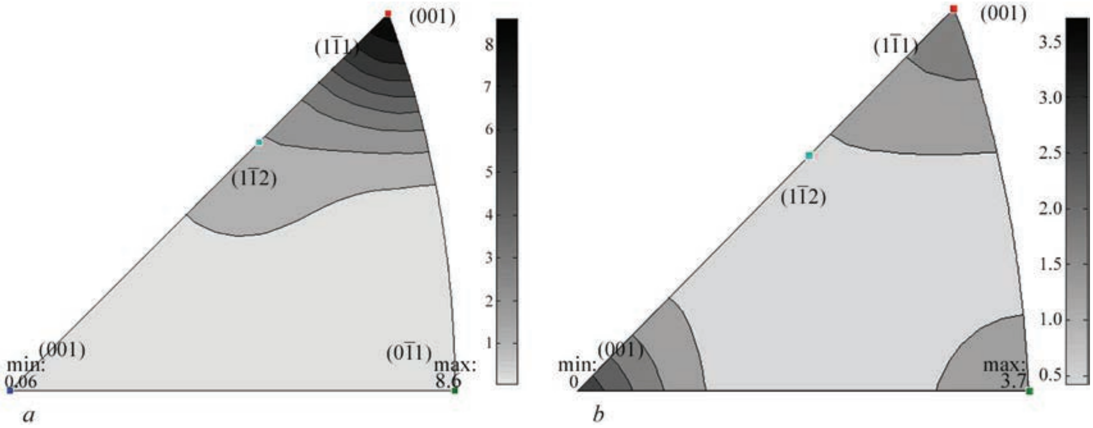

Figure 8. Inverse PF built in the direction perpendicular to the surface of Co–20 % Fe coating deposited in the stationary (*a*) and nonstationary (*b*) conditions

EFFECT OF TEXTURE ON THE DC AMPLITUDE DEPENDENCE OF COATINGS

According to the Smith–Birchak model [5], the height of the MMA maximum in the materials with BCC lattice is determined by the dependence:

$$\left(\frac{\Delta U}{U}\right)_{\max} = \frac{3KE\lambda_s}{2\Delta\sigma_i}\times \left\{1-\left[\left(1-\frac{\Delta\sigma_i}{\sigma_i}\right)\Big/\left(1+\frac{\Delta\sigma_i}{\sigma_i}\right)\right]^{2/3}\right\}, \qquad (1)$$

where K is the constant that depends on the shape of the hysteresis loop; E is the modulus of elasticity; λ_s is the saturation magnetostriction; $\Delta\sigma_i$ is the dispersion of value of internal stresses; σ_i is the average value of internal stresses.

In [6] it was shown that the value of λ_s is determined by the type of fiber texture of the material and the direction of application of alternating deformations. Based on the obtained data on the texture of the coatings and taking into account the direction of their deformation during oscillations of flat specimens, the values of λ_s for the coatings with different texture (Table 2) were calculated, using the procedure [6] and experimental values of magnetostriction for Co–Fe alloy along the crystallographic <100> and <111> directions [15].

To evaluate the influence of the texture type, let us calculate the amplitude dependence of the energy loss coefficient ψ for the coatings with different fiber textures. According to the Smith–Birchak model, this dependence is determined by the expression:

$$\psi = (2KE\lambda_s/\sigma_i)\{[1 - \exp(-2x)\times(1 + 2x + 2x^2)]/x^2\}, \qquad (2)$$

where $x = \sigma/\sigma_i$; σ is the amplitude of alternating stresses of the oscillating specimen.

In [2] it is shown that a satisfactory correspondence between the experimentally measured values of DC of the specimen for different oscillation amplitudes and values calculated by the formula (2) can be obtained in the condition that the value of the internal stresses is $\sigma_i = 17.5$ MPa.

In Figure 9, *a*, the amplitude dependences of the energy loss coefficient of the coating material with different types of texture are given. It is seen that when the type of fiber texture changes, the height of the DC maximum changes: the largest value is observed in the case of the fiber texture of <111> type, and the smallest value is <100>. However, the shape of the amplitude dependence of DC for the coatings with different texture remains unchanged (Figure 9, *b*).

Comparing these dependencies with the experimental results obtained for the coatings with different types of fiber texture (Figure 5), it can be assumed that a change in the type of fiber texture of the coating can only lead to a decrease in the level of DC. At the same time, the experimental amplitude dependences of the energy loss coefficient for the coatings produced under different conditions show not only a decrease in the value of the DC maximum, but also

Table 1. Characteristics of fiber textures of specimens produced in the process of deposition of Co–20 % Fe alloy on titanium substrates

Conditions of coating deposition	Volume fraction of texture components		
	<110>	<100>	<111>
Stationary	0.0	0.0	1.0
Nonstationary	0.16	0.6	0.24

Table 2. Magnitude of magnetostriction of Co–20 % Fe coating saturation with different types of fiber texture under its tension/compression

Type of fiber texture of coating	<100>	<110>	<111>
Magnitude of saturation magnetostriction, 10^{-6}	93.9	119.1	127.5

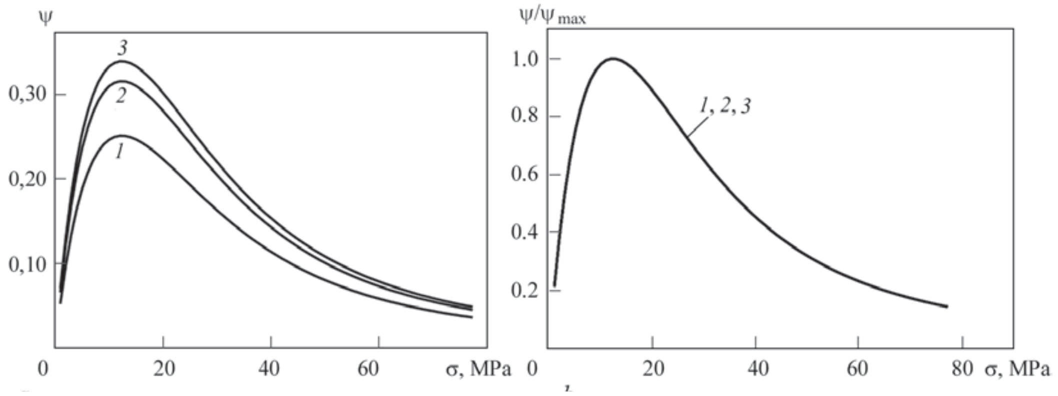

Figure 9. Amplitude dependences of energy loss coefficient of coatings with fiber textures of <100> (*1*), <110> (*2*) and <111> (*3*) type at the same level of internal stresses (*a*) and normalized to the maximum value ψ_{max} (*b*)

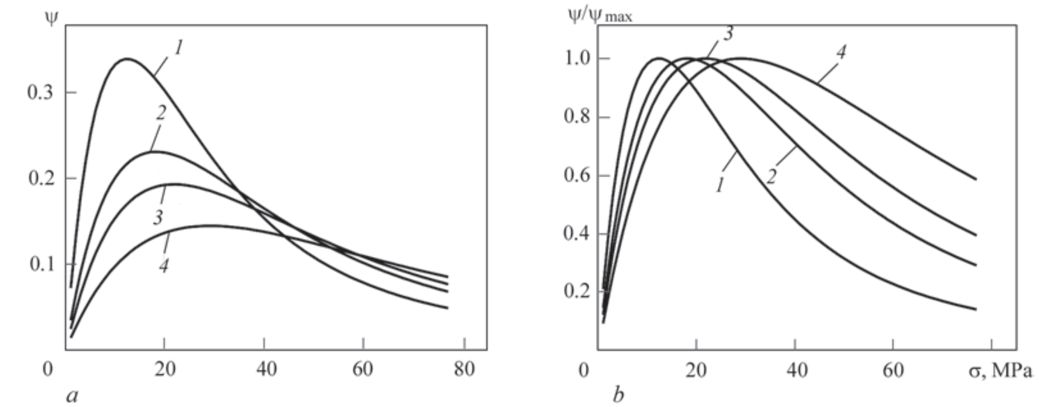

Figure 10. Amplitude dependences of the energy loss coefficient of coatings with a fiber texture of <111> type at different levels of internal stress σ_i, MPa: *1* — 17.5; *2* — 25; *3* — 30; *4* — 40 (*a*) and normalized to the maximum value ψ_{max} (*b*)

its shape (the maximum is blurred towards larger deformation amplitudes). Therefore, it was assumed that such a phenomenon may be associated with a change in internal stresses in the coatings produced under different conditions. To find out this possibility, the amplitude dependences of the energy loss coefficient of the coating material with different levels of internal stresses were calculated.

From the calculated amplitude dependences of the energy loss coefficient of the coating material with the same type of fiber texture, but with different levels of internal stresses presented in Figure 10, it is seen that when the internal stresses grow, the height of the peak decreases, shifts and expands towards larger stress amplitudes during a alternating deformation.

According to the obtained modeling results, it can be assumed that when the conditions for coating production change, variation in their amplitude dependence of DC is mainly predetermined by the change in the fiber texture of the coatings from a single-component one of <111> type, which is formed in the stationary conditions of deposition, to a multicomponent <100> + <111> + <110>, formed in the nonstationary conditions of deposition. However, since, as is seen from Figure 5, for the coatings deposited in the nonstationary conditions, not only a decrease in the height of the maximum on the amplitude dependence of DC is observed, but also its blurring, it can be assumed that such changes are predetermined by an increase in the level of internal stresses in the coatings with a multicomponent texture.

CONCLUSIONS

1. DC of titanium plates with the coatings of ferromagnetic Co–20 % Fe alloy changes depending on the conditions of coating deposition. In the stationary conditions of their deposition, the characteristics of DC of the substrate-coating system are described by a curve with a maximum, and in the nonstationary conditions, they are described by a curve with the saturation on the side of large amplitudes of oscillations.

2. Intrinsic of DC of the Co–20 % Fe coatings formed in the stationary conditions are approximately twice as large as those of the coatings produced in the nonstationary conditions.

3. It was determined that the conditions of deposition of the Co–20 % Fe coatings affect the characteristics of the coating material texture. In the stationary conditions of deposition, a fiber texture of <111> type is formed, and in the nonstationary conditions, a multicomponent texture of <100> + <111> + <110> type is formed.

4. The level of DC of the Co–20 % Fe coatings with a fiber texture of <111> type is predetermined by a high value of the magnetostriction magnitude, which is consistent with the Smith-Birchak model for magnetomechanical damping.

5. A decrease in the level of damping in the Co–20 % Fe coatings with a multicomponent fiber texture of <100> + <111> + <110> type can be a consequence of both a decrease in the average value of the magnetostriction magnitude as well as an increase in the level of internal stresses.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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