Досліджено загасання інфразвуку в сталях Х18Н9Т і 12Х18Н10Т із плазмовими покриттями на основі ($NiAl-SiO_2 \cdot Al_2O_3$). Встановлений вплив покриттів складної мікроструктури з наноскладовими у вигляді аеросилів на параметри внутрішнього тертя досліджуваних композицій. На температурному спектрі за наявності покриттів виявлені аномалії у вигляді піків різної фізичної природи. Запропонований критерій демпфування покриттів із наноскладовими

***Ключові слова:** плазмове покриття, внутрішнє тертя, демпфування, наноскладові, аномальні властивості, модуль пружності*

Исследовано затухание инфразвука в сталях Х18Н9Т и 12Х18Н10Т с плазменными покрытиями на основе ($NiAl-SiO_2 \cdot Al_2O_3$). Установлено влияние покрытий сложной микроструктуры с наносоставляющими в виде аэросилов на параметры внутренего трения исследуемых композиций. На температурном спектре при наличии покрытий выявлены аномалии в виде пиков различной физической природы. Предложен критерий демпфирования покрытий с наносоставляющими

***Ключевые слова:** плазменное покрытие, внутреннее трение, демпфирование, наносоставляющие, аномальные свойства, модуль упругости*

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A STUDY OF INTERNAL FRICTION ANOMALIES IN STAINLESS STEEL WITH NANOSTRUCTURED PLASMA COATING

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1. Introduction

In conditions of exposure to temperature fields and deformations, it is important to ensure dynamic strength and vibration reliability of structural elements, which can be achieved by increasing of their damping capacity. Damping, along with other properties, is an independent physico-mechanical property of metals and alloys [1, 2]. The damping capacity of structural materials can be increased by applying an appropriate functional metal coating [3, 4], in particular, by plasma sputtering [5, 6]. Coating materials include powders of different compositions – metallic [4, 7], ceramic [8], nanostructured [9, 10], and plated [11]. The damping capacity of materials can be characterized by means of the parameters of their internal friction (IF) [2, 7, 12].

Analysis of the IF measurements reveals additional information on structural and phase features of various zones along the composition cross section [5, 13, 14]. Research on the temperature and the amplitude dependences of internal friction (TDIF and ADIF) allows formulating the basic provisions of the mechanism of high damping, depending on the composition and structure of the coatings [5, 14, 15]. At the same time, research on the energy dissipation on TDIF and ADIF in coated structural materials reveals a change in the general background and the appearance of new anomalies [13, 14]. Such circumstances necessitate additional research to better understand these phenomena.

In such conditions, the issue of the damping capacity of coatings (DC), that is the issue of the damping criterion, is topical. The issue of compatibility of the damping capacity with other physico-mechanical properties of the “base-coating” system as a whole remains important.

2. Literature review and problem statement

The problem of increasing the dynamic strength and the related damping properties involves various areas of engineering, aerospace engineering, turbine construction, and transportation.

An effective means of combating vibration is the use of damping materials such as cast iron, composite materials, as well as steel based on Fe–Cr and Fe–Cr–V. However, with the exception of cast iron, they all find little use, which is due to low mechanical properties, high cost, or low heat resistance. The application of damping materials such as coatings on structural steel rationally combines the mechanical strength of the base and the damping capacity of the coating. There exist metal antifriction plasma coatings [4] as well as coatings of polymeric materials and composites [7] that are applied to steel to reduce vibrations by means of electroplating [16].

The effect of plasma single and multicomponent coatings on the parameters of IF has been tested on a number of systems, where iron [17] and high-alloy steels [4, 15] were chosen as bases. At the same time, the research has revealed that it is possible to increase the damping properties of the matrix due to coatings, both without treatment and after thermal diffusion treatment.

In aviation turbine construction, for example, the damping capacity of turbine blades that are made of special alloys is commonly increased due to vacuum condensates, including reinforcing nanocomponents [9, 18]. It was found that the damping capacity of coatings alongside the physical and mechanical properties of coated materials depend on the production parameters and the structure of these coatings [18]. At the same time, the available data reveal the fact of the change in energy absorption resulting from a lower grain size and lower thickness of the applied vacuum coating [19].

The experimental research has proved a significant effect of plasma powder coatings on the damping properties of structural steels. For example, the application of Ni and Cu coatings on stainless steel 10Cr18Ni9Ti considerably increases damping compared to electrolytic, gas-flame and other coatings. The damping properties of stainless steel 10Cr18Ni9 with plasma coatings based on NiCrAlY, Al_2O_3 and FeCr as well as nanopowder ZrO_2 are described in studies [15, 20]. The research reveals that relaxation effects along the grain boundaries affect the change in the damping properties of the system as well as the ability of a nanostructure to enhance the mechanical properties of composite materials.

The presence of nanocomponents results in the formation of complex-phase and chemical compositions in the coating structures. A new microstructure of the coating encompasses various zones along the cross-section of the composition that are characterized by an appropriate stress state. The measurements of IF record the peaks of relaxation and changes in the physico-mechanical properties of the "base-coating" system that result from the processes occurring at plasma sputtering and additional heat treatment.

In this respect, it is important to study the effect of the coating composition, their physical properties, thermal diffusion processing as well as the structure and composition of the interphase zone on the damping in alloy steels. A number of studies are devoted to the role of the interphase zone in energy absorption [21, 22].

An important task is to determine the damping properties of structures such as thin-walled layered elements [23]. Thin-walled tubes, capillaries, are used as connecting functionals in aerospace engineering, as elements in the parts of shut-off valves, nuclear reactors, in chemical production, and mechanical engineering. The issue is especially interesting when there is a thin coating on the surface of the base [24]. A review of the studies of the damping properties of sandwich type thin-walled elements is given in paper [25]. The reviewed studies consider the influence of an individual damping layer on the overall damping in a package consisting of several thin layers of different thickness. The corresponding calculation schemes are proposed to determine the damping; it is proved that damping can be increased by varying the thickness of the coating.

It is important to carry out parallel comparative studies of solid cylindrical and hollow (tubular) samples, which would allow a differential approach to the effectiveness of surface and volume layers and reveal where the absorption of elastic energy is most complete. It should be noted that few works are devoted to such issues. A well-known fact is the distinction of the dislocation structure by the sample cross section at the early stages of deformation when the dynamics of dislocations changes.

It is known that the presence of individual defects, foreign atoms and phases, including coatings, on the surface of a solid body also contributes to a change in the dislocation structure in the near-surface layers and in the volume of the composition. A quantitative assessment of the dislocation structure is based on the results of measurements of the amplitude dependence of internal friction, according to the Granato-Luque theory [2, 5, 12, 13]. The research on the complex spectrum of energy vibrations in the "base-coating" system has laid the basis for a model that takes into account different zones of influence on the IF – volume and surface layers of the base and the type of coating [14]. However, the analysis of these phenomena and processes is qualitative and, thus, it requires further research.

In general, the damping properties of plasma coatings on various structural steels have not been sufficiently studied. Therefore, studies in this direction are of practical interest, especially depending on the properties of the powder materials, the thickness of the coatings and their heat treatment. This all in combination with mechanical characteristics make up important and promising tasks.

3. The purpose and objectives of the study

The aim of the study was to reveal the effect of plasma sputtering on the emergence of anomalies in the absorption of elastic energy and the damping properties of high-alloy structural steel with multicomponent coatings.

To achieve the goal, we set the following tasks:

– to consider the peculiarities of damping in the energy elastic vibrations through measuring the internal friction of high-alloy steels with nanostructured plasma coatings;

– to consider the effect of preliminary heat treatment of samples and make a comparative assessment of the level of energy absorption of elastic vibrations in samples shaped as solid cylinders and capillaries;

– to assess the damping capacities of multicomponent nanostructured coatings used on steel samples and determine a parameter that could be taken as a damping criterion.

4. Materials and methods of research on the "base-plasma coating" system

4. 1. Materials and methods of studying the mechanical properties of coatings

The research used high-alloy steels Cr18Ni9Ti and 12Cr18Ni10Ti as bases; powders such as NiCrBSi (PG-10), NiA1 (with particle diameter of 20–40 μm), mixtures of powders (made of particulates of the composite powder NiA1) and nanocomponents served as coatings. Nanopowders were ultra-fine particles (about 60 nm in diameter) based on aerosil (SiO_2), alumoaerosil ($SiO_2 \cdot Al_2O_3$), and titanaerosil (SiO_2 TiO_2) [8, 13, 17, 26].

In addition, there were used mixtures including alumina powder particles clad with titanium – Al_2O_3/Ti. The cladding was carried out on the ANGA plant by vacuum arc evaporation [11]. Coatings were applied to the surface of samples by plasma sputtering [26]. The strength properties of the coating itself, including cohesive strength, were determined from the results of mechanical tests on a 3-point bending of the specimens shaped as plates, one side of which was coated [26].

4. 2. The calculation and experimental technique for studying the scattering of the energy of elastic vibrations in the composite material

The amplitude and temperature dependences of internal friction (ADIF and TDIF) used to assess the damping properties of the "base-coating" system were measured on a "reverse torsion pendulum" plant [17, 26]. The research on the absorption of infrasound used wire samples of steel Cr18Ni9Ti and tubular samples (capillaries) made of steel

12Cr18Ni10Ti. The wire samples were 100 mm-long and had a 1 mm diameter, whereas the capillaries were 120 mm-long, had a 1.2 mm outer diameter, and a 0.8 mm internal diameter.

The experimental findings and the calculation results, according to [26], allowed determining the amplitude dependences of IF on the coating material. The available characteristics of energy dissipation in the coating, the base and the "base-coating" system allowed calculating the normal modulus of elasticity of the coating E_c, according to the following equation:

$$E_c = E_b \frac{C\sqrt{B}\left(Q_c^{-1} - Q^{-1}\right)}{\sqrt{A}\left(Q^{-1} - Q_b^{-1}\right)}, \qquad (1)$$

where $A=1+(Q_c^{-1})^2$, $B=1+(Q_b^{-1})^2$, and $C=h_c/1-h_c$.

In formula (1), Q^{-1}, Q_b^{-1} and Q_c^{-1} denote energy dissipation (internal friction) in the "base-coating" system, in the base without coating, and in the coating, respectively, and h_c is the coating thickness.

Equation (1) includes a number of components that are found in the direct experiment (Q^{-1} and Q_b^{-1}), or according to the calculation-experimental method (Q_c^{-1}) [17, 26].

5. The findings on internal friction in the samples of plasma-coated high-alloy steel

5. 1. The features of IF in uncoated specimens

In the study of face-centered cubic (cF/fcc) structures, in particular, high-alloy austenitic steels, several anomalies can be obtained on the curves of TDIF, depending on the composition of the material and its structural state, both in the low-temperature and high-temperature spectral areas [27].

Fig. 1 (curves 1–4) shows the dependences of internal friction in the cylindrical samples of steel Cr18Ni9Ti for a wide range of temperatures, whereas Fig. 2 (curves I-IV) shows the dependences of IF in the tubular samples (capillaries) made of steel 12Cr18Ni10Ti. Curves (1, I) and (2, II) in Fig. 1 and Fig. 2 refer to deformed samples (after being drawn through spinnerets). Curves (3, III) and (4, IV) reflect the data for the samples preheated at T=1100 °C for 2 hours. In addition, effects in the range of test temperatures of 20–400 °C are shown on a large scale (Fig. 2, *b*).

The temperature measurements of IF both in the cylindrical and the tubular steel samples Cr18Ni9Ti and 12Cr18Ni12Ti record the effects whose physical nature is known. Fig. 1, 2 show that the effects – the Hashiguchi deformation peaks – are detected on Cr18Ni9Ti (cylinder) steel in the temperature range of 23–127 °C [28]. The temperature range of 320–410 °C demonstrates the Finkelstein-Rosin peaks (FR), the mechanism of which is associated with migration of interstitial atoms in the stress field [29].

It is known that the FR peak in a number of moments is accompanied by the appearance of one or two additional peaks on either side of the main one. As follows from the obtained data, when the vibration frequency is low (1 Hz), the temperatures of the peak development are lower in comparison with the known ones. The peak in the temperature range of 600–700 °C) is associated with grain-boundary relaxation. According to some researchers, it may generally coincide with the phase peak at 730 °C [27, 29]. The findings indicate that the grain-boundary peak (GBP) is separated and slightly shifted toward higher temperatures (T_{max}~717 °C).

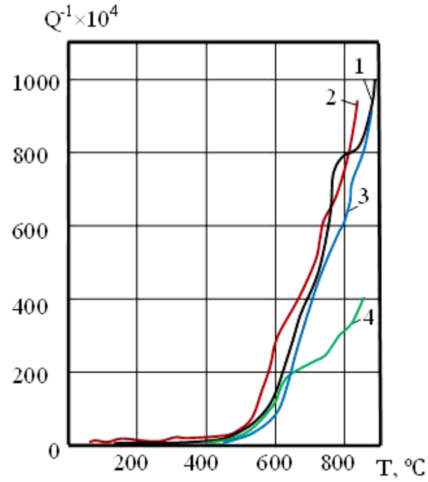
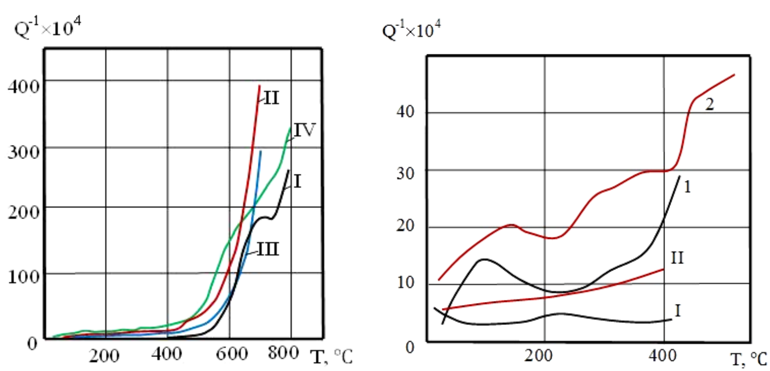


Fig. 1. Temperature dependence of internal friction in the samples of steel Cr18Ni9Ti: 1 and 3 – uncoated; 2 and 4 – plasma-coated (the coating is based on $NiA1-SiO_2 \cdot Al_2O_3$); samples 1 and 2 are in the deformed state; samples 3 and 4 are preannealed before sputtering for 2 h at T=1100 °C

The results of measurements on the preannealed samples show the following. It is evident that the overall background of the IF for steel 12Cr18Ni10Ti (Fig. 2, curve I) is much lower in comparison with the IF spectrum for steel CrI8Ni9Ti (Fig. 1). Meanwhile, the temperature spectrum of elastic energy absorption is shifted to lower temperatures, especially in the range of 20–400 °C. Thus, the deformation peak that was earlier observed at 100–150 °C is shifted and revealed in the area of 0 °C. Respectively, the FR peaks is shifted; in addition, the initial state is characterized by a small peak at 242 °C.



a *b*

Fig. 2. Temperature dependence of IF in the capillary samples of steel 12Cr18Ni10Ti: *a* – I, III – uncoated; II, IV – plasma-coated (the coating is based on $NiA1-SiO_2\ Al_2O_3$); curves I and II – deformed; III and IV – preannealed for 2 hours at T=1100 °C before sputtering; *b* – the findings correspond to Fig. 1, 2, and on a large scale – to the temperature range of T=20–400 °C

In the area of high temperatures, the steel sample 12Cr18Ni10Ti in the initial state (Fig. 2, curve I) exhibits the effect of absorbing elastic energy at 677–687 °C. This peak corresponds to the phenomenon of grain-boundary slippage that is characteristic of austenitic steel. The phase effect in the steel samples 12Cr18Ni10Ti is also displaced compared to the sample of steel Cr18Ni9Ti; thus, it is natural that the GBP is less pronounced.

5. 2. The effect of the coating system ($NiA1–SiO_2 \times Al_2O_3$) on internal friction

According to the findings, a plasma coating based on the powder mixture $NiA1–SiO_2·Al_2O_3$ leads to changes in the type and level of the TDIF in the composition under study (Fig. 1, curve 2 and Fig. 2, curve II). The temperature spectrum of the coated samples proves to be higher than that of the uncoated bases, both in the low-temperature and high-temperature ranges.

The anomalous influence of coatings on the material, which manifests itself in changes in both the initial and the general levels of IF, is obvious. The effect of coatings is also manifested in the change, and in many cases, in the appearance of new effects in the energy absorption spectrum, in particular, in the area of grain-boundary relaxation [13, 14]. In addition to the main grain-boundary peak (GBP), in most cases, in the temperature range of 550–800 °C, there appear additional peak effects that shift along the temperature scale depending on the coating composition.

The samples of steel Cr18Ni9Ti that are subjected to sputtering in the vibration spectrum of elastic energy $Q^{-1}(T)$ without preheating manifest the deformation peak at 100–150 °C and the FR peaks (curve 2), similarly to uncoated samples (Fig. 1). There is also observed a broad GBP that contains several components.

Plasma coating made of $NiA1–SiO_2·Al_2O_3$ applied on the outer surface of the tubular samples of steel 12Cr18Ni10Ti exerts an even greater influence on the TDIF, which is shown in Fig. 2, curve II. Application of the coating on the capillary samples enhances the GBP, as in the case of solid samples, with the overall level of IF decreasing.

The preheating of the samples significantly affects the IF parameters (Fig. 1, 2, curves 3, III, 4, IV). The application of the plasma coating ($NiA1–SiO_2·Al_2O_3$) onto the preannealed matrix (1100 °C, 2 h) made of the steels Cr18Ni9Ti and 12Cr18Ni10Ti changes the spectrum of elastic energy absorption. Compared to the results for the samples in the delivery condition, as seen in Fig. 1, 2, the overall IF level decreases; therefore, the FR peaks and the peaks caused by the matrix deformation at 100–150 °C almost disappear; the high-temperature peaks at 600 °C and 720 °C have also changed. The internal friction in the preannealed samples, in the spectrum of the grain-boundary relaxation, has a value that differs significantly from the values of the samples without preliminary annealing. The grain boundary peak (GBP) changes its shape and varies both in width and in magnitude.

In addition to the TDIF measurements, Fig. 3 shows the data on the ADIF for the coated samples. The application of the plasma coating ($NiA1–SiO_2·Al_2O_3$) increases the damping in the mechanical vibration energy (curves 2, 4). The ADIF anomalies are observed to a greater extent in the deformed cylindrical samples.

The anomalous behavior of the ADIF and TDIF as well as the peak effects in the coated samples are reflected in a certain relaxation of the effective shear modulus ($\Delta G/G$)≈ ≈(f^2) on the curves (f^2–T). The application of coatings increases the shear modulus $G \sim f^2$ (Fig. 4), to a greater extent in the preannealed samples (curve 4).

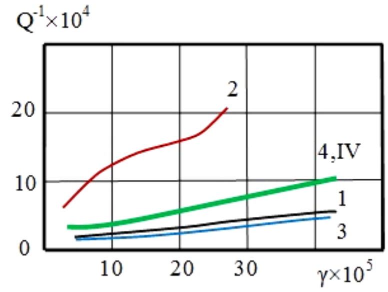


Fig. 3. Amplitude dependence of the internal friction in the samples of steel Cr18Ni10Ti: 1, 3 — uncoated; 2, 4 — coated; 1, 2 — deformed; 3, 4 — preannealed; IV — the tubular coated preannealed sample of steel 12Cr18Ni10Ti

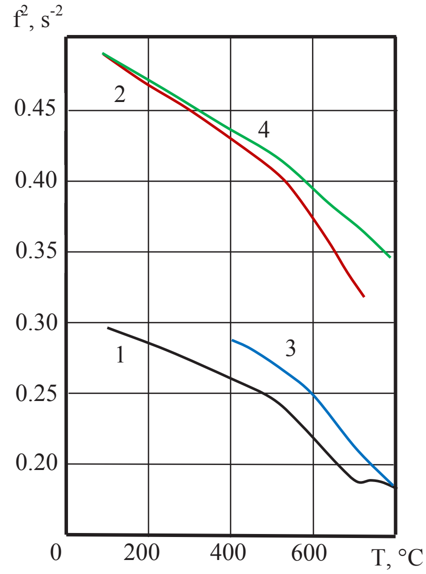


Fig. 4. Temperature dependence of the quadratic vibration frequency of the samples of steel Cr18Ni10Ti: 1, 3 — uncoated; 2, 4 — coated; 1, 2 — deformed; 3, 4 — preannealed

Fig. 4 shows that in the high-temperature area (600 °C and 730 °C), the temperature dependence of the quadratic frequency (f^2) is anomalous, which proves the phase origin of the effects and is in compliance with the TDIF data (Fig. 1). The effect of the coating itself is anomalous. At the same time, an increase in the internal friction corresponds to an increase in the shear modulus ($\Delta G/G$) in the range of +2.1–+5.6 % for a broad temperature interval (473–1033 K).

In general, as the research shows, the shear modulus G is a less sensitive characteristic than the TDIF and ADIF parameters.

6. Discussion of the effect of plasma sputtering on the absorption of elastic vibration energy and assessment of the damping capacities of nanostructured coatings

The research shows that the damping mechanism of the elastic vibration energy for coated samples is more complex than for the base uncoated material. In the case of plasma sputtering, the formation of coating and of the contact interphase zone is accompanied by their saturation with a large number of point and linear defects. Coatings that are made of deformed powder particles contain a large number of both intragranular and intergranular boundaries. In plasma coatings, these interfaces include a macro-boundary between the coating and the base, and the interfaces between lamellas in the coating layer are characterized by the presence of pores and other microdefects.

Coating affects the dynamics of mobile dislocations, both in the base and in the coating; the overall density of loose dislocations is much higher than in the uncoated samples.

As Fig. 3 shows, the samples coated with NiA1–SiO_2×Al_2O_3, which include nanocomponents (such as aerosil), manifest an increase in the slope of the ADIF curves (tgα–$\Delta Q^{-1}/\Delta\gamma$). The slope of the curves characterizes the energy scattered by the motion of dislocations in the microplastic deformation zone of the material. An abrupt increase in the ADIF at the initial stage is due to the detachment of the dislocations from the pinning points in the alloys. Further deformation causes the second critical strain γ''_{cr}, which may be due to the detachment of the dislocations from the pinning points in the coating.

When strain amplitudes are higher than the critical value γ''_{cr}, mobility of the dislocations is high; as a result, there appear local deformations inside individual grains and the vibrations continue to decrement. When applied shear stresses are increased, a new decrement is observed in macro-scale deformations that involve several neighboring grains. Relaxation mechanisms work at the interfaces of individual grains and particles, as well as at the interphase boundaries in the "coating-base" system. In this case, the deformation field as well as the relaxation effects $Q^{-1}(\gamma)$ affected by vibration loads improve the damping capacity of the structure. This situation can serve as a basis for obtaining composite materials that have high damping characteristics [15].

The measurements of IF show that when the samples are twisted, their outer layers such as the relatively thin coating (50–70 μm), interphase zones in the coating and the base, and the surface layers of the base are subject to deformation. Parallel studies of solid and hollow samples allow obtaining comparative information on the role of surface layers of the base material in absorbing the energy of elastic vibrations. Fig. 1, 2 show that in the solid cylindrical samples elastic energy is absorbed as well as in the tubular samples with 0.2 mm-thick walls. The course of these processes is determined by the structure and composition, especially of the surface (rather thin) layers of the sample, including the coating and the interphase zone between the coating and the matrix.

The energy decay can be explained by the commensurability of the thickness of the applied layer and the capillary (tube) wall. Thus, the above concerns the layers with the most pronounced effects. Meanwhile, the damping effects occurring in the coating and in the thin layers of the matrix itself can be superimposed, which is proved by the ADIF results (Fig. 3) for the cylindrical samples (curve 4) and the capillaries (curve IV). Fig. 3 shows the data for the samples annealed before the coating (NiA1–$SiO_2{\cdot}Al_2O_3$) deposition at 1100 °C for 2 hours. There is a practical coincidence of the curves, which indicates the prevailing influence of the coating itself and the near-surface layers of the base.

The effectiveness of the coating is also illustrated by Fig. 5 that shows the results of the TDIF measurements for the samples of steel Cr18Ni10Ti. Curve 1 in Fig. 5 shows the IF in the uncoated sample, whereas and curve 2 – in the one coated with NiA1–$SiO_2{\cdot}Al_2O_3$. In Fig. 5, curve 3 corresponds to the damping of energy Q^{-1} (T) in the coating after processing the measurement results in accordance with the proposed methods [26]. The revealed regularities that are shown in Fig. 1, 2 prove an increased role of the deposited coating (NiA1–$SiO_2{\cdot}Al_2O_3$) in the damping in the elastic vibration energy. This applies equally to both solid cylindrical specimens and tubular ones (capillaries).

Thus, an increase in the damping in the elastic vibration energy, an increase in the GBP height, and the appearance of new peak effects is a consequence of an increase in the number of mobile dislocations in case with a specific plasma coating.

At the same time, the coating has a strengthening effect due to the fixation of mobile dislocations. The effect is accompanied by a decrease in the overall level of energy damping, a decrease or total suppression of the peak heights, and an increase in the critical strain γ_{cr} [13, 14, 17].

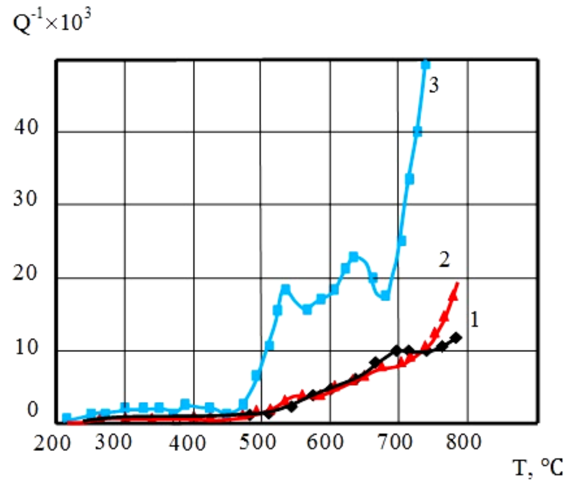


Fig. 5. Temperature dependence of the internal friction in the "steel-coating" system: 1 – the uncoated base of Cr18Ni10Ti; 2 – the base of Cr18Ni10Ti with the plasma coating (NiA1–$SiO_2{\cdot}Al_2O_3$); 3 – the absorption of energy in the coating

The complex peaks shown in Fig. 1, 2, 5 in some cases are a consequence of the superposition of several peak effects, which to a certain extent indicates a nonlinear relationship between the coating and the base.

Preannealing (Fig. 1, curves 3 and 4) also helps to secure dislocations, reduce energy dissipation, and achieve a more stable state.

In general, an increase or decrease in the level (background) of energy decay (or peak height) in the presence of a specific coating with an appropriate modulus of elasticity is characterized by the ratio of the opposite factors of influence, i. e. there is observed an increase in the density of mobile dislocations, and, in contrast, in the degree of their fixation.

Consequently, when the dislocation structure of the layers adjacent to the interphase zone changes, boundary dislocations appear due to plasma deposition and form a complex multiphase structure of the coating with specific strength and cohesive characteristics (Table 1). The resulting structure also influences such a basic physical characteristic of the coating material as the modulus of elasticity (Fig. 4).

On the other hand, when vibration loads are applied, the formed complex coating structures can be a source of high damping capacities.

The effect of coatings on the metal base can be assessed by means of the proposed damping criterion based on the following considerations. There is observed an opposite character of the influence of such factors as an abnormal increase in the level of IF, on the one hand, and an increase in the modulus of elasticity due to fixation of mobile structural elements, on the other hand. Based on this fact, as well as data from the previous studies [1, 21], it is possible to assess the effect of the coating with its damping capacities on the metal base. There is proposed a damping criterion as a product of the elastic modulus E_c and the coefficient of internal friction Q_c^{-1} of the coating under a specific deformation, namely:

$$D_{damp}=E_c\,Q_c^{-1}. \qquad (2)$$

The coating elasticity modulus E_c is obtained from measurements of the IF in the "base-coating" system, according to the procedure outlined above (1). As an example, the results of distinction of the specific coating spectrum are shown in Fig. 5.

The values of the elasticity moduli of a number of coatings made of powder mixtures that were obtained earlier and the damping criterion are presented in Table 1. Table 1 also shows the results on the cohesive strength of the coatings in question that have been determined experimentally, i. e. by calculations for the corresponding strain values and the damping coefficient Q^{-1}. The data on cohesive strength are borrowed from the results of earlier studies [26].

Table 1

The values of physical and mechanical properties of plasma coatings

Sr. No.	Coating	The elasticity modulus of the coating, E_c, GPa	Cohesive strength σ_{coh}, MPa	Damping coefficient D_{damp}, GPa
1	AlNi	105	284	0.22
2	Mo	89	136	0.134
3	NiA1 – ($SiO_2{\cdot}Al_2O_3$)	157	374	0.345
4	AlNi – Al_2O_3/Ti	88	125	1.02
5	NiCr – ($SiO_2{\cdot}Al_2O_3$)	194	472	0.772
6	NiCr –($SiO_2{\cdot}TiO_2$)	217	125	0.92

In Table 1, nanocomponets are presented as nanoparticles, i. e. aerosils (lines 3, 5, 6), and also as a vacuum-arc clad Ti-shell on Al_2O_3 particles (line 4).

The ability of materials to dissipate the stored elastic energy happens after the deposition of plasma coatings, to a greater extent, if the coating structure has long interphase boundaries. This is illustrated by the example of multicomponent coatings containing nanoparticles in the form of nanopowders ($SiO_2{\cdot}Al_2O_3$, $SiO_2{\cdot}TiO_2$) or coated powders (Al_2O_3/Ti).

7. Conclusions

1. The study of high-alloy steels Cr18Ni9Ti and 12Cr18Ni10Ti with plasma coatings based on NiA1–$SiO_2{\times}Al_2O_3$ has proved a significant effect of the nanostructured coatings on the internal friction. In a wide temperature and amplitude ranges of measurements, the damping coefficient of the elastic energy in the coated samples is higher than in the uncoated base. The TDIF curves represent changes in the overall levels of the IF, as well as changes in the anomalies shown as deformation peaks, the Finkelstein-Rosin effects, GBP, and phase peaks. The maxima of IF emerge due to admixture atoms and dispersed particles in the form of aerosils.

2. The comparative assessment of the absorption rates of the elastic vibration energy has revealed that the plasma coating based on NiA1–$SiO_2{\cdot}Al_2O_3$ that is deposited on the surface of the tubular samples of steel 12Cr18Ni10Ti exerts a greater effect on the TDIF compared to the solid samples of steel Cr18Ni9Ti. The coating deposited on the surface of capillaries enhances the GBP, and the overall level of the IF decreases. The coating of the annealed matrix of steels Cr18Ni9Ti and 12Cr18Ni10Ti, in comparison with samples in the delivery condition, is characterized by a decrease in the overall level of the IF and practical disappearance of the FR peaks and peak effects that result from the matrix deformation at 100–150 °C. It is found that high-temperature peaks change at 600 °C and 720 °C. The internal friction in the preannealed samples in the area of grain-boundary relaxation has a value that differs significantly from the value of the samples without preannealing. The grain boundary peak (GBP) changes its shape and varies both in width and in magnitude. The experiments prove that the plasma coating (NiA1–$SiO_2{\cdot}Al_2O_3$) increases the shear modulus (to a greater extent in the preannealed samples).

3. The research shows that the damping level of the energy of elastic vibrations $Q^{-1}(T, \gamma)$, and, consequently, the damping capacity of the plasma coating is characterized by the ratio of the opposite factors of influence, namely, an increase in the dislocation density, on the one hand, and the degree of their fixation, on the other hand. The criterion $D_{damp}=E_cQ_c^{-1}$ is proposed as a quantitative measure of the damping efficiency of the composite material. A complex coating based on coated powders and nanostructured mixtures has the highest damping properties.

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