zone for the welding parameters under consideration is determined by the depth of penetration of temperature T_{cr} in the zone of a maximal initial depth of the defect, a_0, i.e. approximately 5 mm above the curves in Figure 3, respectively: for curve *1* (δ = 20 mm) the minimal values of thickness within the defect zone will be δ_{min} = 9 mm at S_0 = 50 mm and δ_{min} = 16 mm at S_0 = 150 mm; for curve *2* (δ = 15 mm) it will be δ_{min} = 9.5 mm at S_0 = 50 mm and δ_{min} = 14 mm at S_0 = 150 mm. For δ = 10 mm, this welding sequence is inadmissible in terms of the accepted safety requirements.

Note the possibility of decreasing pressure in the pipeline as a method of improving safety of welding repair of defects of the type of thinning. Figure 4 shows the curves demonstrating the efficiency of this method for a case of large sizes of thinning.

CONCLUSIONS

1. In repair of thinning defects in main pipelines by arc welding, the minimum admissible thickness within the defect zone according to the safety requirements under operating pressures depends upon size S of the defect along the generating line, to a much lesser degree upon size c on the circumference, as well as upon the thermal parameters of welding and accepted sequence of welding-up of the defect.

2. In terms of the safety requirements, the best way of welding repair of defects is to deposit beads on the circumference, starting from the end regions located along the generating line, which allows decreasing the length of a defect in the indicated direction.

3. Worthy of notice from the practical standpoint is development of nomograms to evaluate the possibility of using welding with specific process parameters to repair the considered thinning defects, depending upon the geometric dimensions of the defect, such as S_0, c_0 and a_0, wall thickness δ, pipe diameter D and internal pressure in a pipeline.

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POSSIBILITIES FOR LOWERING DYNAMIC STRESS IN STRUCTURAL ELEMENTS OF MACHINES USING NANOSTRUCTURED COATINGS*

A.I. USTINOV[1], **A.P. ZINKOVSKY**[2], **I.G. TOKAR**[2] and **V.S. SKORODZIEVSKY**[3]

[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

[2]G.S. Pisarenko Institute for Problems of Strength, NASU, Kiev, Ukraine

[3]G.V. Kurdyumov Institute for Metal Physics, NASU, Kiev, Ukraine

The paper gives the results of experimental studies of the influence of structural characteristics on physico-mechanical properties of coating materials and damping capacity of coated structural elements allowing for such factors as temperature, frequency and amplitude of stress.

Keywords: *coating, material nanostructure, temperature, structural element, vibration frequency, logarithmic damping decrement, dynamic stress*

Progress of modern mechanical engineering leads to high requirements made of the reliability and fatigue life of both individual structural elements and machines as a whole. As most of them are operating under the conditions of a broad spectrum of dynamic loads, which may lead to failure and breaking up of structural elements, and can have catastrophic consequences, ensuring their dynamic strength is one of the key problems in achievement of reliable functioning during the required service life. This is particularly urgent for aviation gas turbine engines (AGTE), most of the defects in which (more than 60 %) detected during design, development and operation, are due to insufficient strength of the components and structural elements, and, primarily, blades. About 70 % of the defects are of vibration-related origin.

One of the most important technico-economic quality indices of mechanical engineering products is ensuring their vibration reliability. In most of the cases, however, it is impossible to eliminate hazardous resonance modes as a result of a considerable density of

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frequencies of natural and forced vibrations in operation of the considered objects. Therefore, various design-technological methods are used, lowering the risk of their consequences, among which the determinant factor is increase of damping capacity as a means of limitation of maximum resonance stresses of the most stressed structural elements.

In the case of AGTE compressor blades made of high-strength titanium alloys with low values of dissipative properties, one of the effective methods to improve the vibration reliability is deposition of highly-damping coatings on the airfoil [1]. As these alloys are sensitive to surface damage, coatings should also have the required set of physico-mechanical characteristics, namely high values of hardness, fatigue limit, corrosion resistance, etc., i.e. they should simultaneously provide reliable resistance to operating conditions of the structural elements.

Extensive experience has now been accumulated in development of such coatings, which satisfy the conditions of AGTE manufacturing and operation to varying degrees [2]. One the other hand, it should be noted that the parameters of the above characteristics of materials, which can be used as high-damping coatings, are insufficient, and their increase by alloying or thermomechanical treatment as a rule leads to deterioration of the dissipative properties.

Considering the tendencies in development of modern aviation engine construction, manifested in increase of gas temperature and dynamic stress amplitudes, and widening of the external load frequency spectrum, there arises the need to create new materials for coatings. Regarded as the latter can be nanostructured vacuum condensates developed at PWI (further on referred to as condensates) [3], which are deposited on structural elements from the vapour phase by the technology given in [4].

An urgent task from the view point of applicability of such coating materials in manufacture of compressor blades of modern AGTE, is determination of optimum parameters of their material structure and deposition conditions to improve the damping capacity of blades in operation, which is the purpose of this work.

Coating materials and method to produce them. In this work quasicrystalline alloy Al–Cu–Fe characterized by increased values of hardness (10–11 GPa) and corrosion resistance [5, 6], as well as pure copper and with iron additives (up to 4 %) were selected as the main coating material. The latter two materials can be used as a bond coat having a high level of adhesion with the structural element and coating material. In addition, copper presence in the coating composition results in an increase of energy dissipation in the vibration system, as it belongs to highly damping materials in the nanostructured state [7].

Coatings 50–150 μm thick from the selected materials were produced by the technology of electron beam evaporation and deposition in vacuum [4]. The latter was performed on pin samples from VT1-0 titanium alloy characterized by low dissipative properties at up to 450 °C temperature [8]. Initial materials for coatings were copper and iron ingots, as well as tablets of a compacted mixture of aluminium, copper and iron powders. At deposition of Cu–Fe coatings metal was evaporated from two targets simultaneously. Sample surface was first cleaned in a vacuum furnace by an argon ion beam. Coating deposition rate was 2–3 μm/min, and their structural condition was changed by variation of sample temperature in the range from 160 up to 600 °C.

Coating deposition on AGTE compressor blades was performed in the mode of their rotation to ensure coating uniformity. For this purpose the blades were attached to a horizontal shaft, rotating during the process of coating formation.

Coating structure was studied by the methods of scanning and electron microscopy (CanScan4 instrument), and their microhardness was measured on transverse microsections of the samples by Vickers method using PolyvarMet optical microscope at 0.05 N load for 10 s.

Main principles of the procedures of investigation of coating material dissipative properties and structural element damping capacity. Energy dissipation characteristics of coating material were determined by calculation-experimental method. First the amplitude dependencies of the logarithmic damping decrement were derived by the results of testing coated samples supported in cantilever in the damped vibration mode in a unit described in [9]. Then they were used as the basis to determine by the calculation procedure of [10] the amplitude dependencies of the true logarithmic decrement for the coating material, i.e. its energy dissipation characteristics in a uniform stressed state.

Damping capacity of the structural elements was determined using experimental devices developed at G.S. Pisarenko Institute for Problems of Strength of NASU to study the dissipative properties of materials and structural elements both at room and elevated temperature [11], minimizing the energy losses in the articulations, not related to hysteresis losses in materials of the test object or in coatings. Logarithmic damping decrement was determined by the resonance curve method [1].

A cantilever sample of a rectangular cross-section ($h \times b \times 1 = 4 \times 12 \times 150$ mm) was selected as the test object. Coating was deposited only on one surface of the sample test portion across its entire width b, starting from the root section. It had a constant length of 50 mm. Sample was tested at constant thickness $h = 4$ mm and reduction of length l of its test portion from 150 to 50 mm to achieve the required vibration frequency.

In keeping with problem definition, the following range of test parameter variation was established: vibration frequency 150–1000 Hz, temperature 20–400 °C (which, on the whole, corresponds to the main operating modes of AGTE compressor blades).

Structure and properties of coating materials. Structure of copper coatings was changed by variation of deposition temperature T_c in the range of 160–600 °C, which resulted in the size of the columnar

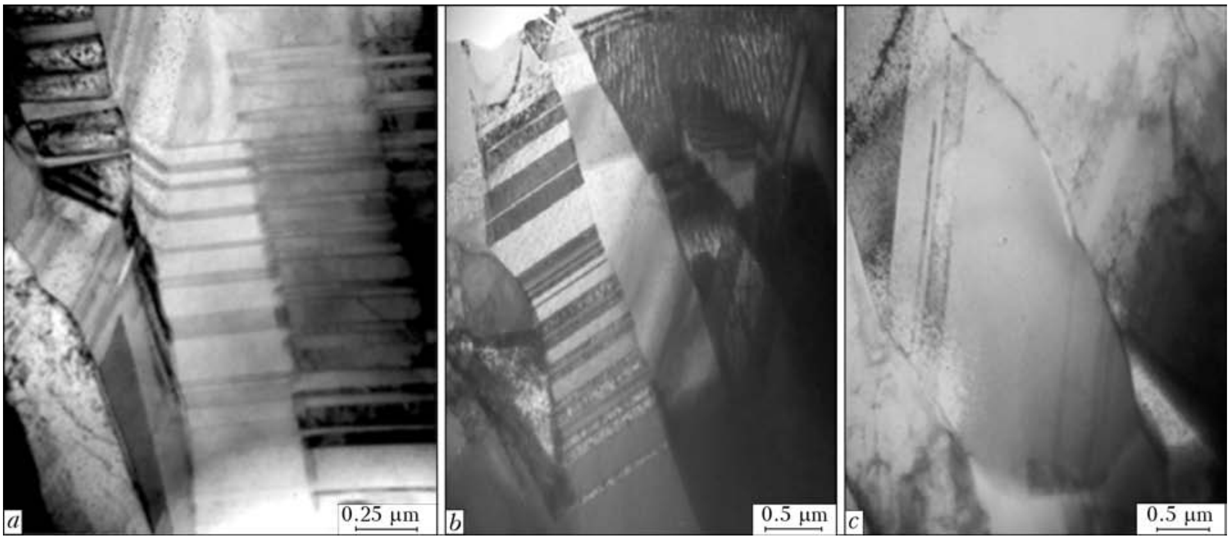


Figure 1. Microstructure of copper condensates (cross-section) deposited on a sample at the temperature of 170 (*a*), 230 (*b*) and 350 (*c*) °C

grain D (of the crystallite) decreasing from 4–5 μm (T_c = 600 °C) to 0.3–04 μm (T_c = 160 °C). A qualitative change of crystallite substructure was found.

From Figure 1 it is seen that the internal structure of the crystallites changes with lowering of deposition temperature, which is manifested in formation of an interlayer of twin domains, located predominantly in parallel to the crystallite growth front (Table). Number of such twins rises abruptly with lowering of the deposition temperature starting from $T_c \approx 350$ °C [7]. At further temperature lowering their quantity rises so much that it leads to formation of a polydomain nanotwinned substructure in the crystallites (Figure 1, *a*).

Transition to a nanotwinned structural state of the copper coatings leads to an abrupt increase of their microhardness from 0.8 up to 1.5 GPa [7], as well as qualitative change of energy dissipation characteristics, which is manifested in an essential weakening of amplitude dependence of the logarithmic damping decrement, inherent to coarse-grained copper with preservation of high values at heating (Figure 2). More over, unlike coarse-grained copper, the energy dissipation characteristics of these coatings are preserved after multiple cyclic deformation.

Additional increase of coating microhardness (up to 2 GPa) is achieved as a result of adding 2–4 % of iron to copper. Energy dissipation characteristics of such a Cu–Fe coating in this case decrease at high deformation amplitudes. On the other hand, they remain quite high and cyclically stable at testing temperature of 20–350 °C. Here an almost complete coincidence of the curves obtained during cyclic deformation of samples at the temperature of 250 °C with the initial curve was registered.

Change of mechanical and dissipative properties of coatings from condensates of copper and Cu–Fe at formation of a nanotwinned substructure in them is due to an essential weakening of the role of intergranular dislocations, both in the process of plastic deformation, and at mechanical energy dissipation.

At approximately 100 nm dimensions of structure components, generation of «fresh» dislocations in metals becomes impossible [12]. On the other hand, the role of grain-boundary surface rises with reduction of grain size, resulting in domination of energy dissipation mechanisms related to thermally activated transformation of atomic configurations on grain boundaries in nanostructured materials.

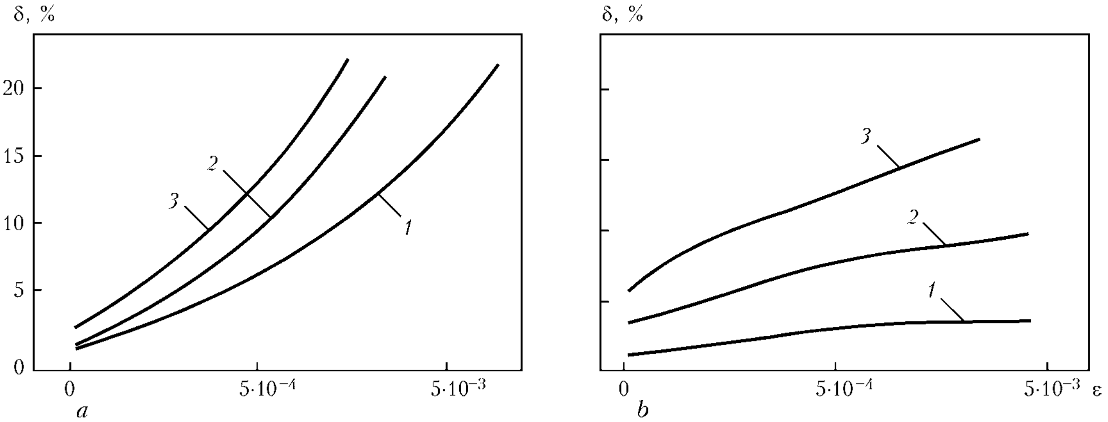


Figure 2. Amplitude dependencies of the logarithmic damping decrement of sample derived for copper condensates with 2.5 μm grain size (*a*) and polydomain nanotwinned substructure (*b*) at the temperature of 20 (*1*), 250 (*2*) and 350 (*3*) °C

Figure 3 gives the results of investigation of the influence of grain size on energy dissipation characteristics for coatings from Al–Cu–Fe composite alloy. In coatings deposited at T_c = 650 °C, average grain size D was equal to 580 nm. At lowering of deposition temperature to 350 and 270 °C, it was reduced to 270 and 30 nm, respectively. For coatings with grain size of 580 and 270 nm the parameters of energy dissipation characteristics in the temperature range of 20–400 °C turned out to be low. However, with grain size reduction to 30 nm, an abrupt increase of the logarithmic damping decrement at 250–400 °C was registered (see Figure 3).

A feature of the considered nanostructured coatings is their amplitude-independent nature right up to relative deformation amplitudes $\varepsilon = 1.2\cdot10^{-3}$, which is important from a practical viewpoint. Note also the high hardness of such coatings (15 GPa) and lower value of the modulus of elasticity (177 MPa), compared to a coating of the same composition with grain size equal to 270 and 580 nm, and modulus of elasticity of 207 and 210 MPa, respectively.

Thus, from the results of the above-described investigations it follows that selection of the respective modes of electron beam deposition on the structural element surface allows forming nanostructured coatings with an increased level of dissipative and mechanical properties.

Results of determination of damping capacity of coated structural elements and their analysis. Three kinds of coatings, the characteristics of which are given in the Table, were selected for analysis.

The obtained amplitude-frequency characteristics of the samples were used to determine the values of their logarithmic damping decrement and its respective dependence on maximum stress amplitude σ_{max} at variation of vibration frequency and testing temperature at different values of coating parameters. Note that at resonance testing it is impossible to ensure the same frequency of sample oscillations. As this discrepancy is minor, it did not have any essential influence on test result analysis.

Coating composition and characteristics

Sample #	Coating composition	Deposition temperature T_c, °C	Grain size D/d, nm	Coating thickness h_c, μm
1	Copper	605	3000	97
2	Same	345–350	1400/160	150
3	»	240–245	780/65	170
4	»	600	2800	33
5	»	600	2800	100
6	»	300	1100/105	87
7	»	300	105	72
8	Iron	700	2500	110
9	Same	340	70	102
10	Al–Cu–Fe	500	430	53
11	Same	500	430	62
12	»	300	110	55
13	»	300	110	58

Note. d — twin thickness in copper condensates.

To perform comparative analysis of the influence of particular factors on the damping capacity of samples with the selected coatings, first the amplitude dependencies of the logarithmic damping decrement were determined for an uncoated sample in the specified range of vibration frequencies at room temperature (20 °C), given in Figure 4, *a*. Presented results show that the above dependencies are of a linear nature, while the influence of vibration frequency on the value of the logarithmic damping decrement is negligibly small at small stress amplitudes, and somewhat rises at their increase.

Let us consider the results of the performed testing from the viewpoint of the influence of vibration frequency on damping capacity of samples with the selected coatings.

Analysis of amplitude dependencies of the logarithmic damping decrement of samples with single-component coatings (samples *1*–*9* were made at room temperature), corresponding to their certain structural condition (Figure 4, *b, c*) showed that in this

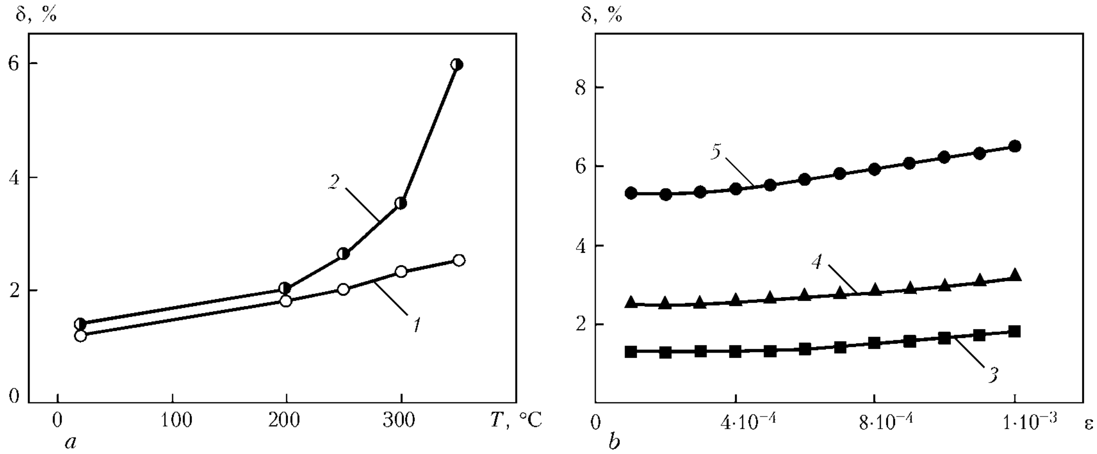
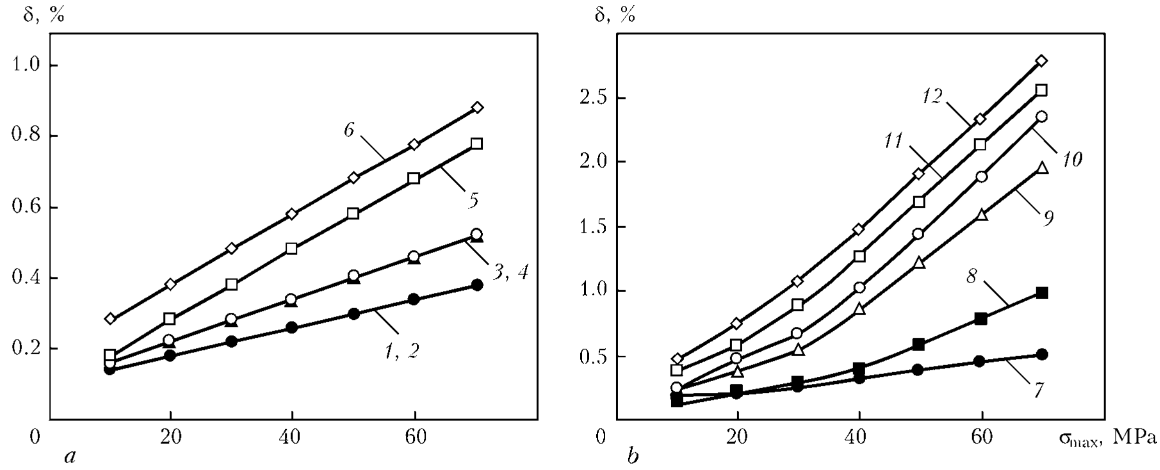


Figure 3. Dependence of logarithmic damping decrement of a sample with Al–Cu–Fe alloy coating on temperature (*a*) at relative deformation amplitude $\varepsilon = 5\cdot10^{-4}$ for grains of 580 (*1*) and 30 nm size (*2*) and on relative deformation amplitude (*b*) at grain size of 30 nm and temperature of 20 (*3*), 300 (*4*) and 350 (*5*) °C



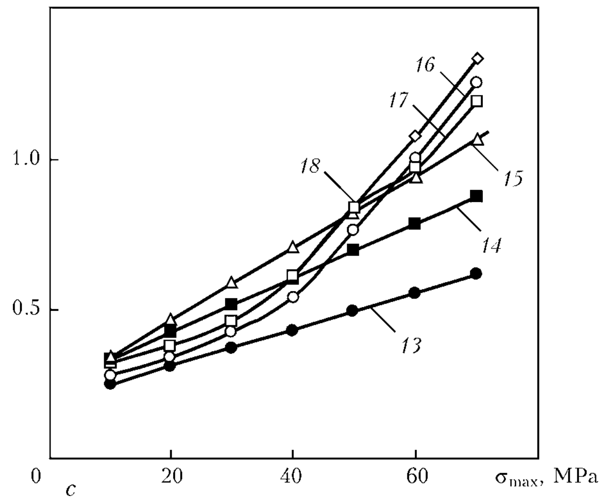


Figure 4. Dependencies of logarithmic damping decrement of a sample without coating (*a*) and with single-component coatings of copper (T_c = 605 °C, h_c = 97 μm) (*b*) and iron (T_c = 700 °C, h_c = 110 μm) (*c*) on maximum stress amplitude at variation of resonance vibration frequency, Hz: *1* — f = 143; *2* — 312; *3* — 507; *4* — 614; *5* — 744; *6* — 881; *7* — 143; *8* — 328; *9* — 492; *10* — 620; *11* — 712; *12* — 792; *13* — 147; *14* — 328; *15* — 519; *16* — 624; *17* — 732; *18* — 868

case the influence of vibration frequency on the value of logarithmic decrement depends on coating type. So, the most significant frequency dependence of the logarithmic damping decrement is characteristic for copper coating, particularly, at increased amplitudes of maximum stresses. It is less pronounced for samples with an iron coating.

The influence of frequency on sample damping decrement is visually demonstrated by its frequency dependencies, which for the maximum stress amplitude (σ_{max} = 50 MPa) are given in Figure 5, where the average vibration frequency is plotted along the abscissa axis, allowing for the impossibility of ensuring its constant value during testing.

It follows from the presented test results that damping capacity of the samples essentially depends on their microstructural characteristics.

On the whole, the obtained data lead to the conclusion that frequency dependence of the logarithmic damping decrement of a sample is more characteristic at deposition of a copper coating. The degree of its growth is the most pronounced in coatings with coarse grains and higher values of maximum stress amplitude. For samples with an iron coating the above dependence of the logarithmic decrement on vibration frequency is practically not registered, particularly at lowering of maximum stress amplitude.

In keeping with the problem definition, we will analyze the results of investigations on determination of the joint influence of vibration frequency and operating temperature on the damping capacity of coated samples. Let us consider problem solution in the case of a coating from quasi-crystalline Al–Cu–Fe alloy (more probable) compared to single-component coatings for practical applications, particularly for AGTE compressor blades.

Samples were tested at variation of the same technological and operating parameters, considered for single-component coatings, as well as of the operating temperature. Similar to homogeneous coatings, amplitude dependencies of the logarithmic damping decrement on the maximum stress amplitude were obtained. Their analysis showed that damping capacity of samples with the considered coating at elevated temperature can rise three and more times.

Obtained amplitude dependencies of the logarithmic damping decrement were used to plot the diagram of its variation, depending on the frequency of resonance vibrations of the sample (Figure 6). As follows from the presented data, vibration frequency practically has no influence on damping capacity of a sample with multicomponent coating from quasicrystalline Al–Cu–Fe alloy.

Assessment of cyclic strength of titanium blades with coatings from nanostructured copper. High level and cyclic stability characteristics of energy dissipation by copper-based nanostructured condensates, as well as their good adhesion to titanium alloys allow

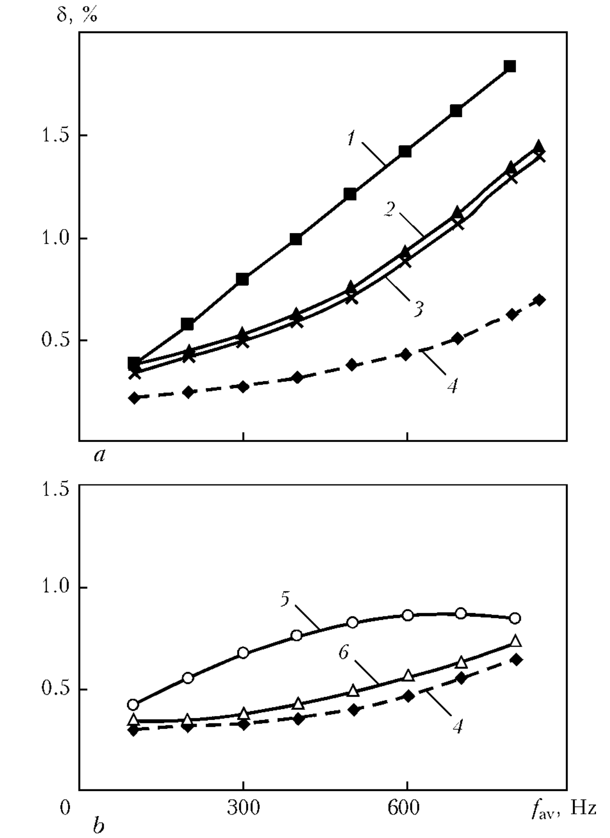


Figure 5. Dependence of logarithmic damping decrement at maximum stress amplitude of 50 MPa for samples with single-component coatings from copper (*a*) and iron (*b*) on average frequency f_{av} of resonance vibrations at different coating parameters: *1* — T_c = = 605 °C, h_c = 97 μm; *2* — T_c = 350 °C, h_c = 150 μm; *3* — T_c = = 245 °C, h_c = 170 μm; *4* — uncoated sample; *5* — T_c = 700 °C, h_c = 110 μm; *6* — T_c = 340 °C, h_c = 102 μm

regarding these condensates as a possible component of the intermediate layer of composite protective coatings for AGTE blades.

Conducted testing was used as the base to establish the technological modes of copper coating deposition on titanium blades, which ensured the coating nanostructured state. The influence of such coatings 5–10 μm thick on fracture strength of titanium blades from VT3-1 alloy was studied. For comparison coatings from copper with microsized grains were deposited on another part of the blade. Testing was conducted at the temperature of 20 °C and vibration frequency of 530 Hz. Cyclic fatigue of the blades was assessed by an accelerated procedure under the conditions of a discrete increase of stress amplitude after every $5\cdot10^6$ vibration cycles [13].

Positive influence on vibration stability of blades with coatings with micron-sized grains was noted in 50 % of the samples. Now, in the case of nanostructured coatings positive result was obtained for all the samples, 50 % of them not failing right up to the end of testing.

The given results confirm the assumption that condensates based on nanostructured copper can be used as the components of composite coatings, for instance bond coats between the structural element and the main part of the coating.

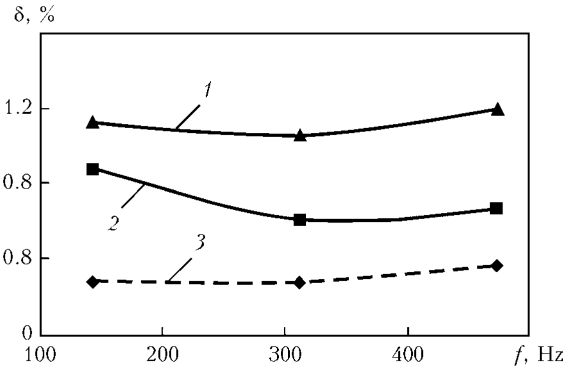


Figure 6. Diagram of variation of the logarithmic damping decrement of a sample with Al–Cu–Fe coating (T_c = 500 °C, h_c = 62 μm) depending on the frequency of resonance vibrations at maximum stress amplitude 45 MPa and testing temperature 350 (*1*) and 20 (*2*) °C and of an uncoated sample (*3*)

CONCLUSIONS

1. It is shown that damping capacity of coated samples essentially depends on their structure and production parameters, primarily coating deposition temperature, as well as vibration frequency.

2. It is established that the logarithmic damping decrement of a sample with a nanostructured coating at elevated temperature can increase by three and more times compared to the room temperature value.

3. A search for further optimum coating nanostructures and their production parameters is necessary to ensure the maximum damping capacity of the structural elements of machines of the type of AGTE compressor blades under service conditions.

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