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Increasing the Damping Capability of Titanium Alloys by Deposition of Plasma Coatings Made from Titanium Nickelide

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The article is devoted to solving the scientific and technical problems of increasing the damping capacity of structural materials, in particular, titanium alloys, which is realized by applying plasma coatings of powder of ПН55Т45 brand on a substrate made of titanium ВТ14 (4Al–3Mo–1V) alloy. The research results are presented as the relationship between the structure of hardened plasma coatings and their damping properties. The research stand developed by the authors is based on the method of damped oscillations and used to determine the damping properties of studied coatings. Optical and computer metallography methods are used to study the particle-size distribution, shape, surface condition of source powders, and microstructure of sprayed coatings, using the ММП-2Р metallographic microscope equipped with Delta Optical HDCT-20C digital camera and Scope Image 9.0 image processing software. The phase composition is investigated using x-ray diffraction analysis (XRD) on the ДРОН-3.0. Diffractograms are taken from samples of 0.5 mm thick coatings separated from the substrate. Experimental studies of damping capacity have shown significant benefits of using samples made of ВТ14 with sprayed coating in conditions of vibrations. For example, the layer with a thickness of 0.5 mm, applying the technology of 'plasma spraying–hardening', increases the energy dissipation coefficient by more than 4 times; for the plate

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made of BT14, the value of the energy dissipation coefficient is $\psi = 1.82\%$, and for the same plate with coating, $\psi = 5.6\%$. This effect is explained by the fact that the main phase in the structure of the sprayed coating is titanium nickelide NiTi. Diffraction patterns of studied coatings show the predominant content of titanium mononickelide in the structure of sprayed coatings, the peaks of which for the starting powder are the majority (≅ 95%). In addition to NiTi and Ti_2Ni phases, which are characteristic to the powder, a small number of other phases are formed on the BT14 substrate, namely, Ni_3Ti, Ti_3Ni_4, Ti, but pure Ni lines, which are characteristic to ПН55Т45 powder, are absent on diffractograms taken from samples detached from the substrate. As shown, applying a layer ($\delta = 0.5$ mm) of plasma coating of ПН55Т45 powder on a plate made of BT14 increases the energy dissipation factor by 4 times and more due to the martensitic structure of the hardened coating as well as to the presence of NiTi. The obtained results can be used to study the stress–strain state of aircraft and ship engine parts.

Key words: damping ability, plasma coatings, titanium alloys, titanium nickelide, structural materials, vibrations.

Статтю присвячено вирішенню науково-технічної проблеми підвищення демпфувальної здатности конструкційних матеріялів, зокрема титанових стопів, що реалізовано шляхом нанесення плазмових покриттів із порошку марки ПН55Т45 на підкладинку з ВТ14. Результати досліджень представлено як взаємозв'язок особливостей структури загартованих плазмових покриттів із демпфувальними властивостями; для визначення їх застосовано авторський зразок установки, принцип роботи якої ґрунтується на методі згасних коливань. Для досліджень ґранулометричного складу, форми, стану поверхні вихідних порошків, а також мікроструктури напорошених покриттів застосовано методи оптичної та комп'ютерної металографії з використанням металографічного мікроскопа ММР-2Р, укомплектованого цифровою камерою Delta Optical HDCT-20C і програмним забезпеченням для обробки зображень Scope Image 9.0. Фазовий склад досліджено за допомогою рентґеноструктурної аналізи (РСА) на установці ДРОН-3 у випроміненні молібдену. Зйомку дифрактограм здійснено зі зразків покриттів товщиною у 0,5 мм, відокремлених від підкладинки. Наведена дифракційна картина показує в структурі напорошених покриттів переважний вміст мононікеліду титану, піки якого для вихідного порошку складатимуть більшість (≅ 95%). Крім характерних для порошку фаз NiTi і Ti_2Ni під час формування на підкладинці з ВТ14 щільного шару утворюється невелика кількість інших фаз: Ni_3Ti, Ti_3Ni_4, Ti. Теоретично обґрунтовано й експериментально підтверджено можливість підвищення демпфувальної здатности титанових стопів типу ВТ шляхом нанесення плазмового покриття з нікеліду титану: нанесення шару ($\delta = 0{,}5$ мм) плазмового покриття з порошку ПН55Т45 на пластину з ВТ14 підвищує коефіцієнт розсіяння енергії у понад 4 рази, що пояснюється мартенситною структурою загартованого покриття та наявністю NiTi. Одержані результати можуть бути використані для досліджень напружено-деформованого стану деталів авіяційних і корабельних двигунів.

Ключові слова: демпфувальна здатність, плазмові покриття, титанові стопи, нікелід титану, конструкційні матеріяли, вібрації.

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1. INTRODUCTION

Increasing the damping capacity of structural materials is an urgent problem of materials science, the solution of which significantly expands the possibilities of operation of machine-building structures in conditions of vibrations. Modern technical solutions for the manufacture of supports, frames, shock absorbers include the use of high damping alloys (manganese–copper, nickel–titanium, magnesium, *etc.*) [1], the use of bimetallic compounds [2], methods of heat treatment of structural parts [3], application of functional damping and vibration-absorbing coatings on the surface of structures [4]. The formation of the coating layer on the products will contribute to the additional dissipation of vibration energy and, in addition, can perform the functions of protection against elevated temperatures, corrosion processes and other negative operational factors. The prospects of application of coatings with the effect of shape memory are determined in [4–7]. Nanostructured coatings of Cu and Cu–Fe condensates deposited on BT-1 (Grade 2) titanium alloy [7] are among the prospective ones. Their application is efficient due to the formation of a nanotube substructure and a significant weakening of the role of intragranular dislocations in mechanical energy dissipation.

Alloys and coatings based on titanium nickelide, in which intermetallic compounds such as NiTi, $NiTi_2$ and Ni_3Ti have a strengthening effect, have high heat resistance and corrosion resistance [5, 8]. Unlike other intermetallic, titanium mononickelide (NiTi) has a high ductility and damping ability with the effect of shape memory, which is also characteristic to nitinols—double alloys based on it. An increase in their damping capacity (by about 9%) is achieved after quenching, which results in the formation of thermoelastic martensite. This effect can be explained by the mechanisms of energy scattering, which occurs due to the shift of the interfacial boundaries between martensite and the initial phase and between individual martensite crystals and the boundaries of the twins.

Nitinols are solid solutions based on the titanium mononickelide intermetallic compound in a percentage of from 48% Ti to 54% Ni. The initial structure of titanium nickelide is a stable face-centred lattice of the CsCl type, which undergoes thermoelastic martensitic transformation during deformation with the formation of a low symmetry phase. The set of valuable properties, such as low density

(ρ = 6450 kg/m^3), high melting point (t = 1240–1310°C) in combination with the unique effect of shape memory, determine the need for its use in medical, military, missile technics. However, the high cost of nitinol significantly limits its widespread use, which makes coating deposition technologies development relevant.

Results of studies of the formation of gradient layers with nanoscale structure by plasma sputtering of mechanically activated ПН55Т45 powder, combining plasma sputtering technologies with thermal deformation methods that provide high tribological characteristics of structural steels (1044 (45), 5135 (40Х), 30ХГСА steel, AISI 321 (12Х18Н5Т), are shown in Refs. [9, 10]. However, in modern engine building there is a need for wear-resistant and damping coatings of titanium nickelide on titanium alloys of ВТ type (GOST 19807–91). Specific operating conditions, adaptation to the production base, reducing the cost of parts for their widespread implementation require additional studies to identify features of the structure and properties.

Therefore, the goal of study is identifying the possibility of increasing the damping capacity of titanium alloys of the ВТ type by applying a plasma coating of titanium nickelide as well as finding the relationships between structure and properties of such coatings.

2. EXPERIMENTAL DETAILS

The coatings were formed by plasma technology on the 'Kyiv-7' installation using deposition modes, substantiated by the authors of [11]. Table 1 shows the characteristics of materials, used for studies.

Optical and computer metallography methods were used to study the particle size distribution, shape, surface condition of source powders, and microstructure of sprayed coatings, using a ММП-2Р metallographic microscope equipped with a Delta Optical HDCT-20C digital camera and Scope Image 9.0 image processing software. Sample preparation involved making cross sections and their etching with Kroll's reagent (1–3 ml HCl, 4–5 ml HNO_3, 95 ml H_2O). The phase composition was investigated using x-ray diffraction analysis (XRD) on the ДРОН-3.0 device in MoK_α = 0.7126 Å radiation with phase identification using ASTM tables [12]. Diffractograms were taken from samples of 0.5 mm thick coatings separated from the substrate.

In order to form a martensitic structure of the coatings, the samples were quenched at the temperature of 820°C for 1 h with subsequent cooling in water, for which СНОЛ–1.6.2.08/9-М1 laboratory furnace was used.

The results of microstructural and x-ray diffraction studies were

TABLE 1. Characteristics of used materials.

Characteristic	Substrate	Powder
Brand	BT14 (4Al-3Mo-1V, GOST 26492-85)	ПН55Т45 (GOST 28844-90)
Usage	Parts for the chemical industry, aircraft, and rocketry, which operate for a long time at temperatures up to 400°C	Wear-resistant coatings that can work in sea water, alkalis, in the air at temperatures up to 600°C
Supplied as	High-quality and flat rolled metal	A fraction of 40–100 μm is used for plasma spraying
Chemical composition, mass %	Ti—86.82–92.8% Fe—up to 0.25% C—up to 0.01%	Nickel-based powder with a content of 45% Ti, 0.07% C
Structure	Belongs to (α+β) alloys of martensitic class	Consists of an austenitic phase (≅ 95%) with a small amount (≅ 5%) of the martensitic phase
Preliminary preparation before spraying	Degreasing and shot blasting	Drying of the powder at a temperature of 60–80°C

compared with the state diagram of Ti–Ni [13] and supported by measuring the microhardness of the phases (GOST 9450-76) using ПМТ-3 microhardness tester.

The basis of the experimental research is the physical and mechanical essence of the phenomenon of vibration energy absorption: structural elements absorb the mechanical energy of vibrations, converting it into heat, which is then dissipated. This effect determines the damping properties of materials, and the method of free transverse damping oscillations of console-mounted specimens is the most effective for studies of these properties [4, 6].

The research stand, developed by authors (see Fig. 1) was applied for experimental researches in laboratory conditions.

The experimental stand consists of the base *1*, the table *7*, props *2*, *6*, and *8*, the rigid bar *3* and the indicator *5*. A sample *10* with a hole for fixing the ferromagnetic rod *11* and an additional weight is attached to the prop *2* by using special clamps *4*. The end of the rod is lowered into the inductor *9*, which is fixed by props *8* to the table.

If necessary, the stand can be connected to a personal computer with automatic recording of vibrograms of damped oscillations (see Fig. 2), which can be used to calculate the logarithmic decrement δ (dimensionless physical quantity, inverse of the number of oscilla-

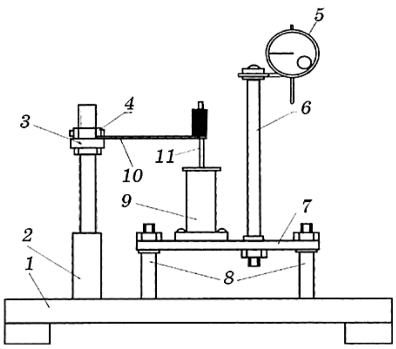

Fig. 1. Experimental stand for studies of dampening properties: *1*—base; *2*, *6*, *8*—props; *3*—rigid bar; *4*—clamp; *5*—indicator; *7*—table; *9*—inductance coil; *10*—studied sample; *11*—ferromagnetic rod with weight.

tions, after which the amplitude decreases exponentially) and scattering coefficient energy $\psi = 2\delta$ (ratio of scattered energy per cycle of established oscillations to the amplitude value of the potential energy of the elastic medium).

The developed stand allows conducting experiments in the frequency range of 10–40 Hz, which, although related to low frequencies of dynamic oscillations, is typical for the operation of certain

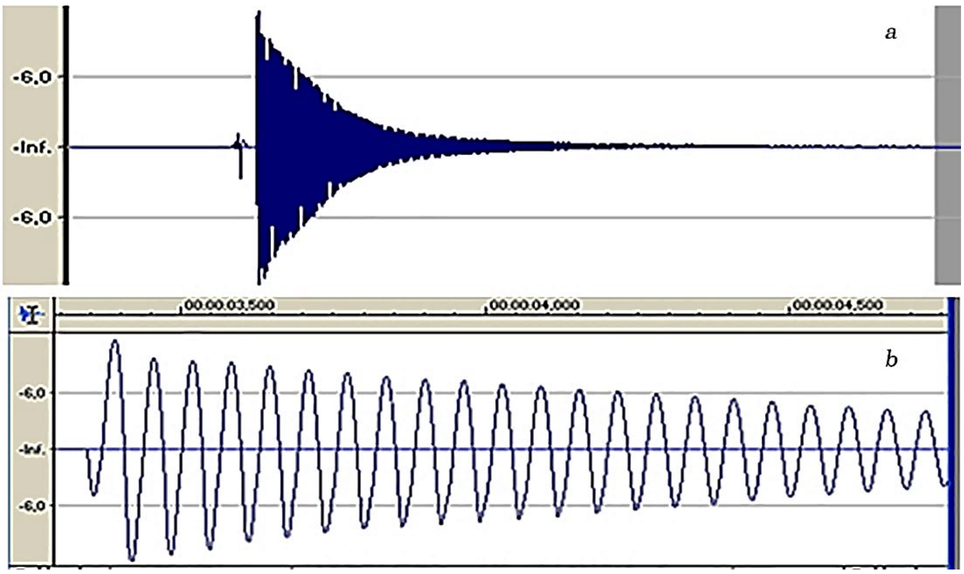

Fig. 2. Vibrogram of damped oscillations of the sample of BT14 (4Al–3Mo–1V) alloy with plasma coating: *a*—general view (data from research stand); *b*—estimated form.

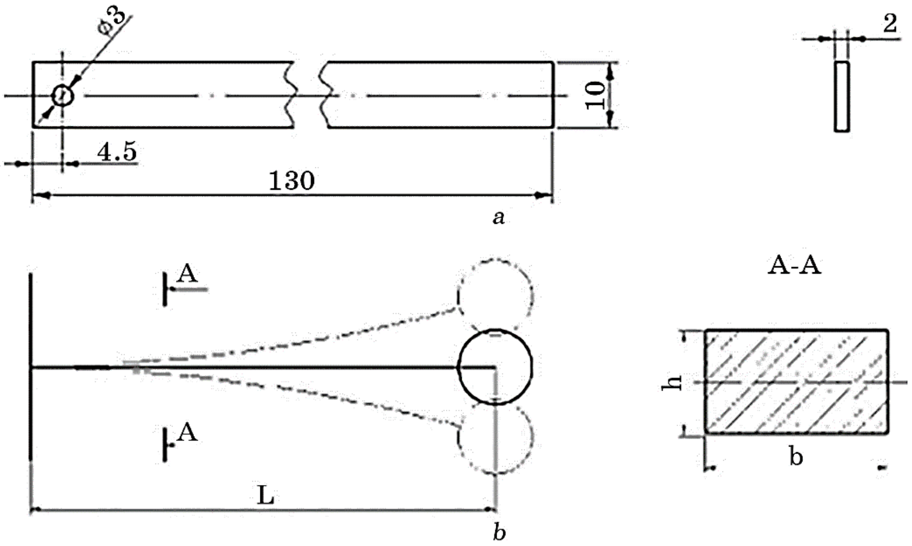

Fig. 3. Samples for damping ability tests: *a*—the sketch of a sample; *b*—testing scheme.

technical equipment and facilities.

Samples in the form of plates measuring 140×10×1.5 mm (see Fig. 3), on which plasma coatings 0.5 mm thick were applied on one side, were used for research. Experiments were performed at oscillation frequency of 40 Hz.

The formulation of the experiments also included comparative studies of the damping ability of plates of BT14 (4Al–3Mo–1V) alloy without coatings, which reveal the effect of plasma coating deposition.

3. RESULTS AND DISCUSSION

The results of microstructure studies are presented in the form of optical micrographs of powder (see Fig. 4, *a*) and sprayed coating before (see Fig. 4, *b*) and after heat treatment (see Fig. 4, *c*), which together with the results of x-ray diffraction (see Fig. 5) give an idea of structural features and are theoretical substantiation of the increase of the damping capacity of plates made from BT14 (4Al–3Mo–1V) alloy by applying a layer of plasma coating of titanium nickelide.

The above diffraction pattern shows the predominant content of titanium mononickelide in the structure of sprayed coatings, the peaks of which for the starting powder (see Fig. 5, *a*) are the majority (≅ 95%). In addition to NiTi and Ti_2Ni phases, which are characteristic to the powder, a small number of other phases are formed

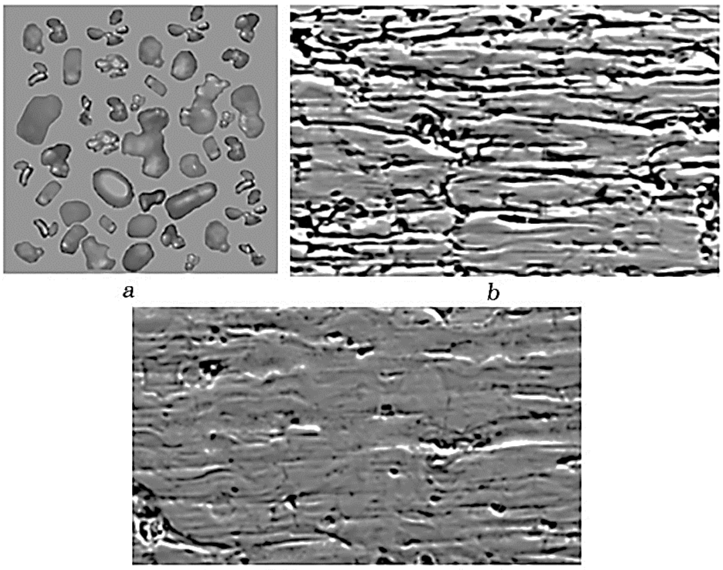

Fig. 4. Optical microphotographs: *a*—ПН55Т45 powder (Ч 650); *b*—microstructure of sprayed coating (×400); *c*—microstructure of sprayed coating (×400) after quenching (t = 820°C, τ = 1 hour).

on the ВТ14 substrate, namely Ni_3Ti, Ti_3Ni4, Ti, but pure Ni lines, which are characteristic to ПН55Т45 powder, are absent on diffractograms taken from samples detached from the substrate. The sprayed layer is homogeneous on the surface and has no notable chips or cracks. This layer has a lamellar structure (see Fig. 4, *b*) with a lamella thickness of 20–30 μm. After hardening to martensite, this structure turns into a dense fine-grained (see Fig. 4, *c*) with high hardness ($H\mu_{200}$ = 8334 MPa). After heat treatment, the phase composition of the coatings does not change.

Experimental studies of damping capacity have shown significant benefits of using samples, made from ВТ14 with sprayed coating in conditions of vibrations. For example, a layer with a thickness of 0.5 mm, applied by the technology of 'plasma spraying–hardening' increases the energy dissipation coefficient by more than 4 times: for the plate made from ВТ14 the value of the energy dissipation coefficient is $\psi = 1.82\%$, and for the same plate with coating $\psi = 5.6\%$. This effect is explained by the fact that the main phase in the structure of the sprayed coating is titanium nickelide NiTi. High mechanical properties of this compound [14] in combination with its functional properties allow to use these materials for parts that undergo long operation under cyclic and shock loads, heavy wear, corrosive environments.

The results, obtained in this work, expand the scientific ideas

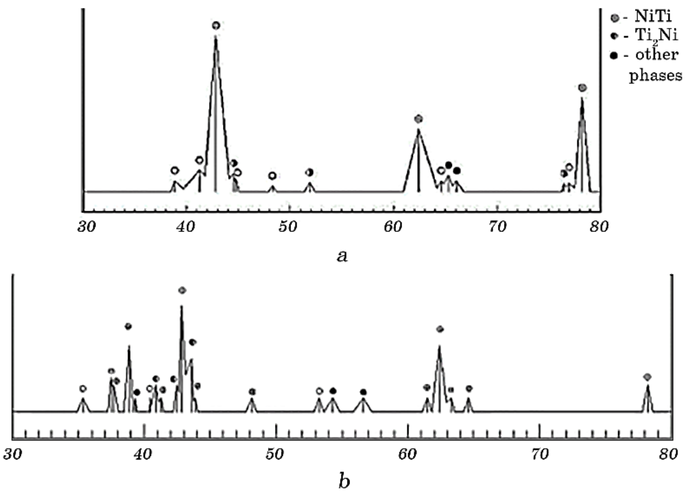

Fig. 5. X-ray diffractograms: *a*—ПН55Т45 powder (initial state); *b*—plasma sprayed coating.

about increasing the damping capacity of titanium alloys by applying a plasma coating of ПН55Т45 powder with a predominant effect of martensitic structure in the phase composition.

4. CONCLUSIONS

The possibility of increasing the damping capacity of titanium alloys of the ВТ type by applying a plasma coating of titanium nickelide is theoretically substantiated and experimentally confirmed. Applying a layer ($\delta = 0.5$ mm) of plasma coating of ПН55Т45 powder on a plate made from ВТ14 increases the energy dissipation factor by 4 times and more due to the martensitic structure of the hardened coating as well as to the presence of NiTi.

The obtained results can be used to study the stress–strain state of aircraft and ship engine parts.

Prospects for further research are related to the approbation of the results obtained on a large scale as well as to the development of practical recommendations for the operation of plasma coatings of titanium nickelide with the definition of boundary conditions.

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