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INVESTIGATION OF CHANGES IN THE MODULUS OF ELASTICITY OF THE SURFACE LAYER MATERIAL DURING FRETTING WEAR

BADANIE ZMIAN MODUŁU SPRĘŻYSTOŚCI MATERIAŁU WARSTWY POWIERZCHNIOWEJ PODCZAS FRETTINGU

Key words: fretting wear, material surface layer, elasticity modulus of the material, fatigue endurance limit.

Abstract: The method, the equipment used, and the results of the study are described in relation to the regularity of changes in the modulus of elasticity of the part material surface layer during operation when the part is under conditions of fretting wear of the contacting surfaces. Recommendations for the practical use of the research results are given.

Słowa kluczowe: fretting-zużycie, warstwa powierzchniowa materiału, moduł sprężystości materiału, granica zmęczenia materiału.

Streszczenie: Przedstawiono technikę, zastosowany sprzęt i wyniki badania zmiany modułu sprężystości materiału warstwy powierzchniowej części podczas pracy części w warunkach frettingu-zużycia stykających się powierzchni. Przedstawiono zalecenia dotyczące praktycznego wykorzystania wyników badania.

INTRODUCTION

The modulus of normal elasticity of E part material is one of the main physical and mechanical properties of structural materials determining the strength and performance characteristics of friction pairs. At the same time, it was found that the influence of various externally force factors results in significant changes in the modulus of elasticity, primarily of thin material surface layers E_{SUR}, which are responsible for the characteristics of wear resistance, contact, and fatigue strength of parts, since they experience the greatest loads in the structural behaviour. For instance, in **[L. 1, 2, 5** etc.**]** it has been established that a decrease in E_{SUR} of steel members in moving joints from $2.1 \cdot 10^5$ to $1.5 \cdot 10^5$ MPa, other conditions being equal, can change their wear rate by a factor of 5–6. The authors' own research results also confirm a significant change in E_{SUR} during the plastic deformation of surface layers by abrasive particles. Moreover, this change is periodic, which is a confirmation of the hypothesis of I.V. Kragelskiy on the predominantly fatigue nature of abrasive wear of metals **[L. 3]**.

When studying the kinetics of fretting wear of metals at the stage of steady-state wear, it was found that the main reason for the petal-layer destruction of the material surface layer of the part material is an accumulation of a large number of dislocations at the surface, followed by the development of hairline cracks. Based on the above, it is particularly important to conduct experimental studies to identify patterns of E_{SUR} metal behaviour under fretting wear in order to explain the physical nature of Z-shaped fretting wear mechanism, as well as to establish correlations between the modulus of elasticity and the material properties.

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METHOD OF PROCEDURE

Cylindrical samples (**Fig. 1**) of special design were used that provides a plane contact (cylinder end – plane) when fretting corrosion is reproduced in accordance with GOST 23.211-80: a movable sample of cylindrical shape d = 8 mm and l = 165 mm with a ground area in the middle, as shown in **Fig. 1**, and the stationary sample of cylindrical shape d = 5 mm and l = 45 mm, the ends of which were lapped on a cast-iron disk to surface roughness Ra = 0.8...1.32 µm.

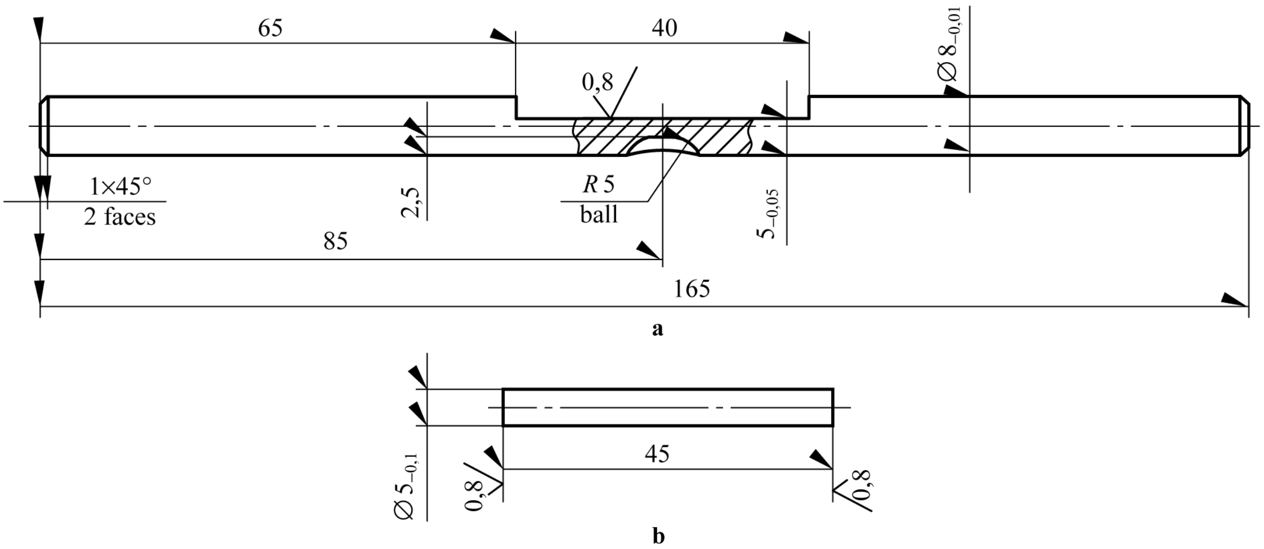

Fig. 1. Outline drawings of a movable sample (a) and a stationary sample (b)
Rys. 1. Szkice próbek ruchomych (a) i stacjonarnych (b)

The following materials were selected for the research:

- Armco iron – carbon content of up to 0.05% – ferrite structure (body-centred cubic (BCC) lattice);
- Steel 60 – carbon content of up to 0.6% – ferrite-pearlite structure (BCC lattice);
- Yellow metal L70 – alloy of copper and zinc with Zn content of up to 30% (face-centred cubic (FCC) lattice); and,
- Alloy VT3-1 – α-titanium with small content of β-titanium (hexagonal (H) lattice).

The choice of these materials is primarily conditioned by the fact that they represent a wide range of the physical and mechanical properties of modern metal engineering materials, including those used for the production of aircraft engines. In addition, these materials have different types of lattices. In this regard, the regularities of the fretting corrosion process obtained for them can be extended to other engineering materials.

The end surfaces of the samples were tested for fretting wear. Fretting wear tests were performed paired up with samples that were used to study internal friction patterns.

The study was conducted in two stages. In the first stage, the fretting wear diagram was taken for each material based on $N = 2 \cdot 10^5$ of vibration displacement cycles, with further analysis and study of the general laws of fretting wear mechanism. The second stage encompassed researching the role of structural damageability processes in the metal surface layers in their under-fretting destruction mechanism.

THE EQUIPMENT AND APPLIANCES USED

As a device for conducting accelerated fretting wear tests that are as close to real conditions as possible, the installation was used as illustrated with the schematic diagram shown in **Fig. 2 [L. 4]**. The installation is based on a planar contact diagram of samples (cylinder end – plane). As the criterion for fretting resistance, the "standard convergence" of samples is accepted, which is the change in the distance between the points of two contacting bodies approaching under fretting wear, which is continuously measured under the applied load (during the entire test time), independent of local deformation.

In most studies, fretting corrosion has not been given sufficient attention to in relation to researching the structural damageability of metals, accompanied by deep changes in the fine crystal structure. It is obvious that additional data on the nature of fretting corrosion can be obtained by careful structural analysis at the dislocation level. Therefore, it is important to develop and apply new methods to study the effect of fretting on the structure and state of surface layers. One of these methods is the method to measure characteristics of elasticity and inelasticity, in particular, the elasticity modulus (Young's modulus) and internal friction, which is characterized by high sensitivity, informative content, and relatively simple interpretations of results and the method of conducting experiments.

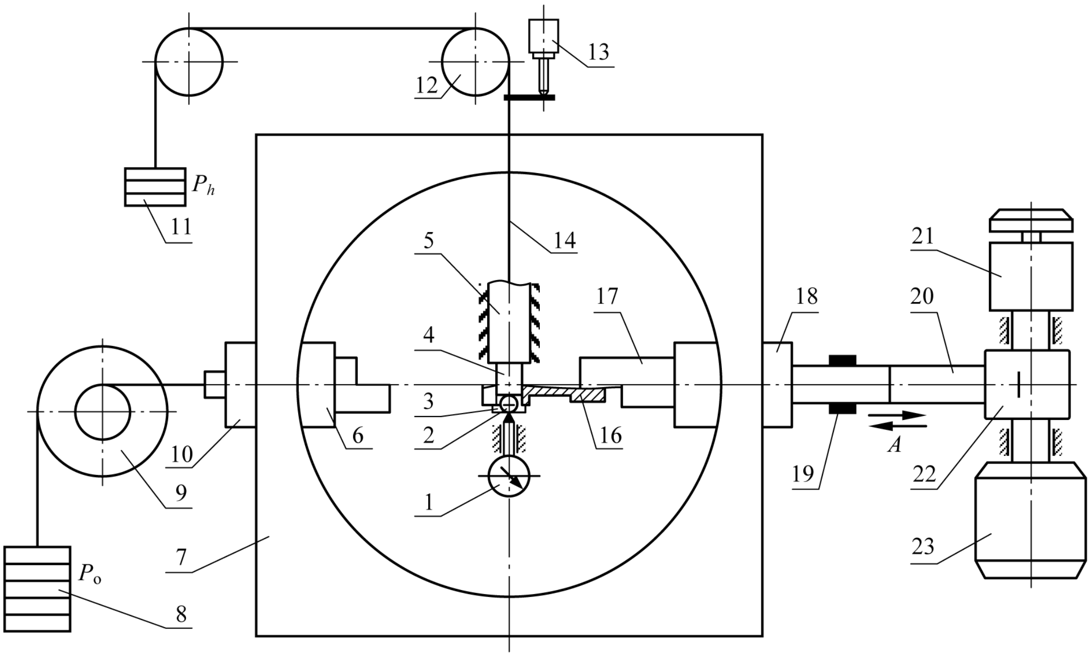

Fig. 2. Schematic diagram of the device for conducting accelerated laboratory tests for fretting wear [4]: 1 – dial test indicator, 2 – bracket, 3 – lever-type clamp, 4 – movable sample, 5 – stationary sample, 6 – sealing, 7 – work chamber housing, 8 – change weight set, 9 – loading system, 10 – movable rod, 11 – change weight set, 12 – loading system, 13 – inductive gage, 14 – metallic cable, 15 – immovable block, 16 – clamping device, 17 – movable rod, 18 – sealing, 19 – strain gage, 20 – slider, 21, 22 – eccentric-type vibrator, 23 – DC motor

Rys. 2. Schemat urządzenia do przyspieszonego badania laboratoryjnego na zużycie frettingowe [4]: 1 – czujnik zegarowy, 2 – wspornik, 3 – wspornik dźwigni, 4 – ruchoma próbka, 5 – nieruchoma próbka, 6 – uszczelnienie, 7 – obudowa komory roboczej, 8 – zestaw wymiennych obciążników, 9 – system obciążający, 10 – ruchomy trzpień, 11 – zestaw wymiennych obciążników, 12 – system obciążników, 13 – czujnik indukcyjny, 14 – metalowa lina, 15 – nieruchoma podkładka, 16 – uchwyt zaciskowy, 17 – ruchomy trzpień, 18 – uszczelnienie, 19 – tensometr, 20 – suwak, 21, 22 – mimośrodowy wibrator, 23 – silnik prądu stałego

Internal friction is generally expressed in decrease in amplitude of free elastic vibrations created in the substance under the appropriate influence. Vibration damping is an extremely sensitive indicator of changes in the properties of metals depending on the temperature and time. Therefore, a method of measuring internal friction is used to study the internal structure of metals and its changes depending on variety of factors. However, this method has not been used before to study structural damageability in thin metal surface layers resulting from fretting.

In connection with the above, an effective way to simultaneously determine the internal friction and Young's modulus E in studies of under-fretting fatigue-corrosion processes is the installation shown in **Fig. 3 [L. 6]**.

The operating principle is to excite frequency of natural bending vibrations of the sample (10), which has a certain geometric shape, i.e. a cylinder with diameter d = 6...8 mm and length l = 150...200 mm. Electrical vibrations coming from the tone oscillator (2) are converted into mechanical vibrations by the converter (3) and fed to the sample (10) using a thin tungsten wire. Through the same wire, mechanical vibrations are fed from the sample to the electromagnetic converter (4), where they are converted into the electrical ones. The resulting electrical vibrations are fed to the vertical plates of the oscilloscope (6). The maximum amplitude of vibrations (resonance) is used to judge the coincidence of the frequencies of induced and natural oscillations of the sample. The value of the natural oscillation frequency obtained in this way is plugged into the formula for determining the modulus of elasticity. For the accepted shape and type of the suspension of the sample, the modulus of elasticity is determined by the following formula:

$$E = 1.6388 \cdot 10^{-7} \left(\frac{l}{d} \right)^4 \cdot \frac{P}{l} \cdot f_l^2 ,$$

where E is the sample material elastic modulus, MPa; l is the sample length, cm; d is the sample diameter, cm; P is the sample weight, g·s; f_l is the frequency of natural bending vibrations, Hz.

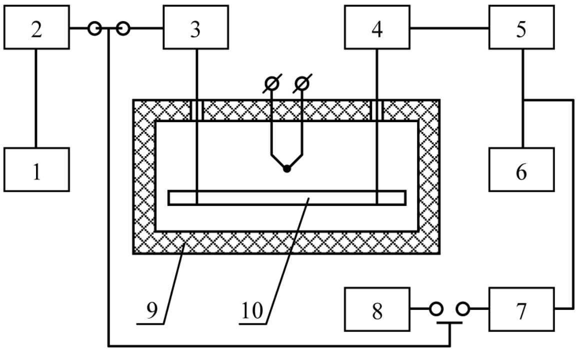

Fig. 3 Block diagram of the device for simultaneous determination of Young's modulus and internal friction of materials over the temperature range: 1 – frequency meter, 2 – tone oscillator, 3 – electromagnetic converter of electric vibrations, 4 – electromagnetic converter of mechanical vibrations, 5 – voltage amplifier, 6 – electronic oscilloscope, 7 – millivoltmeter, 8 – electronic scaler, 9 – electric furnace, 10 – sample

Rys. 3. Schemat blokowy urządzenia do równoczesnego wyznaczania modułu Younga i tarcia wewnętrznego materiałów w zależności od temperatury: 1 – licznik częstotliwości, 2 – generator dźwięku, 3 – elektromagnetyczny przetwornik drgań elektrycznych, 4 – elektromagnetyczny przetwornik drgań mechanicznych, 5 – wzmacniacz napięcia, 6 – oscyloskop, 7 – miliwoltomierz, 8 – elektroniczne urządzenie przetwarzające, 9 – piec elektryczny, 10 – próbka

One of the ways to determine the elastic modulus of the part surface layer material is the collision method, which consists in measuring the contact time of two bodies τ (the flat sample and the spherical indenter) in the course of their impact interaction. According to the known dependence found by Hertz, the measured value τ is related to the Young's modulus of the material surface layers by the following dependence:

$$E_{SUR} = \frac{1}{\left(\frac{\tau}{3.3} \right)^{5/2} \cdot \sqrt{R\text{v}} \cdot \left(\frac{m_1 + m_2}{m_1 \cdot m_2} \right) \cdot \frac{1}{2\left(1 - \mu^2\right)} - \frac{1}{E_1}} \quad (1)$$

where E_1 and E_{SUR} are the elasticity moduli of the indenter and the sample materials, respectively, daN/mm^2; μ is the Poisson ratio ($\mu = 0.33$); $\text{v} = \sqrt{2gH}$ is the indenter speed at the moment of collision (H is the indenter drop height, mm; $g = 9810$ mm/s^2); R is the indenter radius, mm; m_1 and m_2 are the sample and the indenter mass, respectively, kg; τ is the measured time of the contact, s.

The appearance of the device for determining the elastic modulus of metallic material surface layers by the collision method is shown in **Fig. 4**, and the schematic diagram is shown in **Fig. 5 [L. 7]**. The device consists of a massive base (1) to which the clamping device (2) is attached. The clamping device has the base in-plane displacement ability for the fine adjustment of the contact between the sample and the indenter in the equilibrium position. The spherical indenter (4) is suspended on the copper or nichrome wire with a thickness of 0.1–0.3 mm to the rod rigidly connected to the base 1. The design of the suspension unit provides electrical isolation of the wire with the indenter from the "ground" of the device. As indenters, the balls made of high-carbon steel of the SHX15 type used in the hardened and low-sintered state with elasticity modulus $E_0 = 2.1 \cdot 10^5$ MPa. In the initial state (at height H), the indenter is held by an electromagnet (5). The unit is powered by direct current from two independent power supplies with voltages of 5 V and 15 V.

The experiment is as follows: From the measured values of length of the wire with the indenter l and the angle of deviation of the indenter from the equilibrium position φ, value H is calculated in accordance with the following formula:

$$H = 2l \cdot \left(\sin \frac{\phi}{2} \right)^2$$

The flat sample (3) is fixed in the clamping device and brought into contact with the indenter in the equilibrium position. Then the indenter rises to the height H and is held in this state by the electromagnet (5). At the same time, a voltage of 15 V is applied to the measuring circuit of the installation. When the circuit of the electromagnet is opened, the indenter is released and falls freely until it collides with the sample surface. Contact time τ at the collision is recorded by the frequency counter-timer (6) of type F 5041. The experiment is repeated 25...30 times at different points on the sample surface. Next, statistical processing of the measurement results is performed and the value of the average arithmetic contact time is determined by the value of the elastic modulus of the sample material surface layer. If there is a rigid connection between the sample (3) and bearing large-sized base (1), the mass of the sample is much larger than the mass of the indenter ball and can be assumed to be infinite, then Formula (1) can be simplified. For example, when determining E_{SUR} of the steel sample, this relationship will be as follows **[L. 6]**:

$$E_{SUR} = \frac{25.3\, m}{R^{0.5} \cdot \text{v}^{0.5} \cdot \tau^{2.5}}$$

where m is the mass of the ball-indenter, kg.

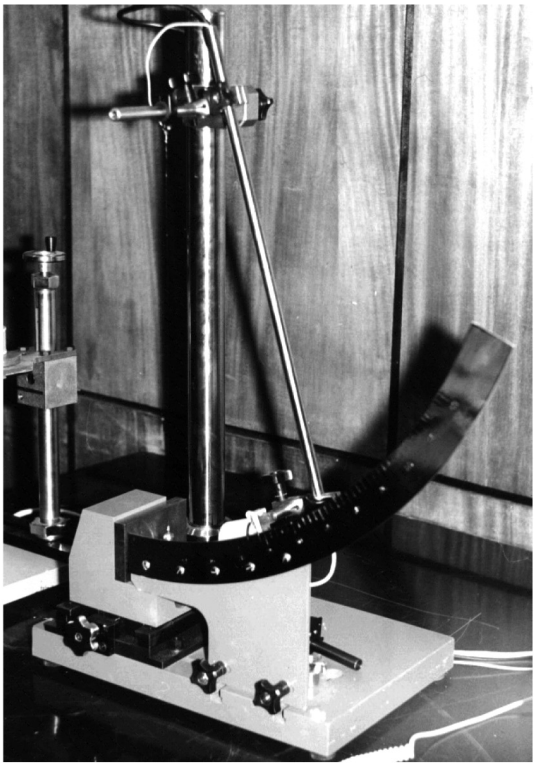

Fig. 4. Appearance of the device for definition modulus of elasticity of metal surface layers

Rys. 4. Wygląd urządzenia do wyznaczania modułu sprężystości powierzchniowych warstw metali

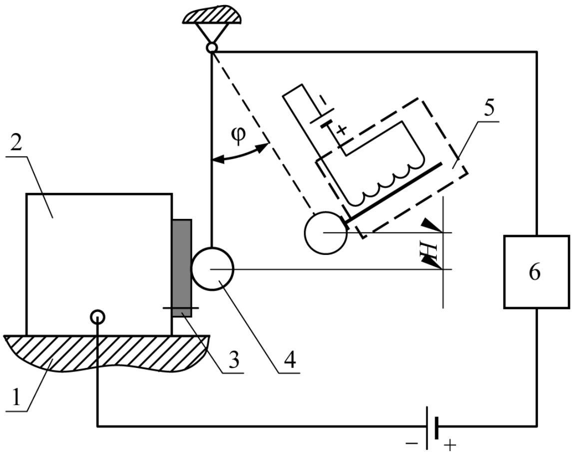

Fig. 5. Schematic diagram of the device for determination of the elastic modulus of metal material surface layers by the impact interaction method: 1 – base, 2 – clamping device, 3 – sample, 4 – ball-indenter, 5 – electromagnet, 6 – frequency counter-timer

Rys. 5. Schemat urządzenia do określenia modułu sprężystości warstw powierzchniowych materiałów metalowych metodą oddziaływania udarowego: 1 – podstawa, 2 – uchwyt zaciskowy, 3 – próbka, 4 – kulka-wgłębnik, 5 – elektromagnes, 6 – miernik częstotliwości-chronometr

When the measurement τ error is ≈ 1%, the relative error in determining the modulus of elasticity is 1...3% with a confidence probability ρ = 0.95. The calculated value of E_{SUR} can also be used to determine the depth of the elastic penetration of the indenter into the surface of the sample material δ using the following formula:

$$\delta = \frac{1.24\, m^{0.4} \cdot v^{0.8}}{R^{0.2} \cdot E_{SUR}^{0.4}}$$

THE BODY OF RESEARCH

Using the type of equipment described above, studies were performed on the effect of surface layers of metal materials on the Young's module of external force action caused by the fretting process. The module was periodically changed depending on the duration of exposure. In addition, it was found that the minimum value of the modulus of metal materials due to the influence of external force factors and the associated increase in the density of dislocations is $E_{\min} \approx 0.7\, E_0$ **[L. 1]**.

Figure 6 shows the experimental dependences of the change in contact time for samples from the materials under study on the duration of fretting wear tests (at the steady-state wear stage). Moreover, the value of time measurement $\bar{\tau}_{\text{MEASUR}}$ corresponds to the average measured contact time of the sample and indenter during the test for the fretting wear; the value of time measurement $\bar{\tau}_{\text{MEASUR}}$ is after recrystallization annealing of the sample; value $\bar{\tau}_0$ is the time before the experiment (without sample damage). From **Fig. 6**, it can be seen that the force frictional interaction of metal materials during fretting is accompanied by intensive change $\bar{\tau}_{\text{MEASUR}}$, and the same is recorded for E_{SUR}. This change has the clearly cyclical character, frequency, and amplitude which depends on the type of contacting materials (including the initial value of Young's modulus – E_0) ($6{\cdot}10^3$ cycles), and the smallest in the pair of titanium alloy VT3-1 ($15{\cdot}10^3$ cycles).Thus, the largest period and amplitude of cyclic changes $\bar{\tau}_{\text{MEASUR}}$ are observed in pairs of Armco-iron and yellow metal L70 ($6{\cdot}10^3$ cycles), and the smallest is in the pair of titanium alloy VT3-1 ($1.5{\cdot}10^3$ cycles).

As a result, the value $(\Delta E/E_0)^{\text{DEF}}$ made up on average: 18.1%; 15.5%; 17.8%; 11.2% for Armco iron, steel 60, L70 and VT3-1, respectively. Taking into account the linear nature of change in the degree of plastic deformation and Young's modulus of a thin surface layer of metals, it is possible to determine the relative change in the modulus directly on the surface of the material $(\Delta E/E_0)^{\text{SUR}}$. Values $(\Delta E/E_0)^{\text{SUR}}$ made up: 36.2%; 31%; 35.6%; and 22.4% for Armco iron, steel 60, L70 and VT3-1, respectively.

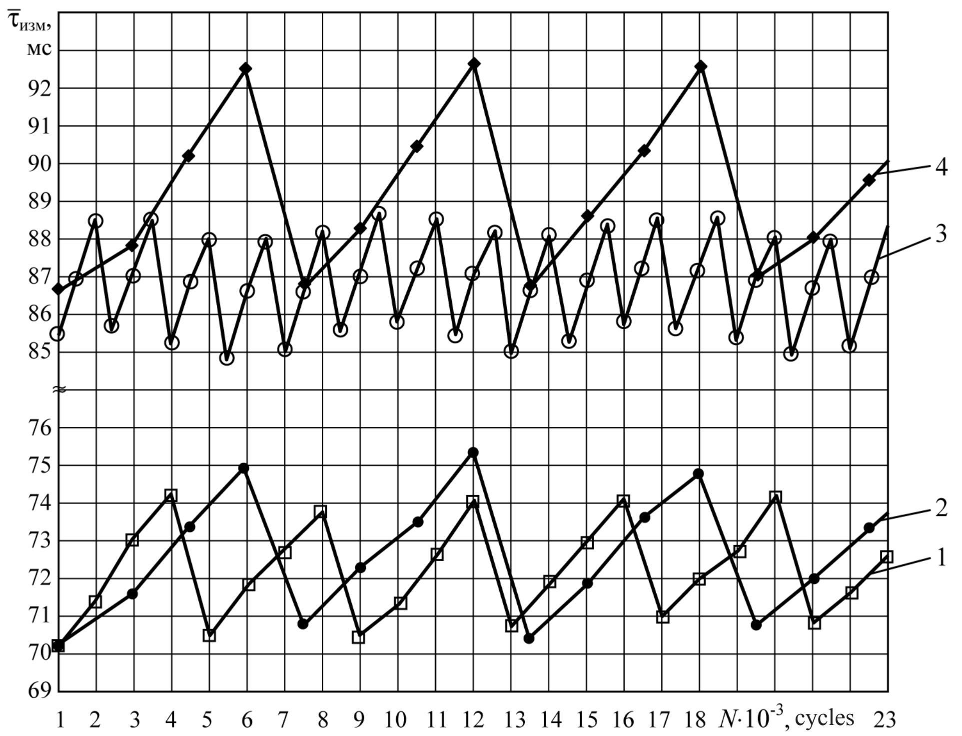

Fig. 6. Experimental dependences of the measured contact time on the duration fretting wear tests for pairs of samples: 1 – steel 60; 2 – armco iron; 3 – VT3-1; 4 – L70

Rys. 6. Eksperymentalne zależności zmierzonego czasu kontaktu od czasu zużywania frettingowego dla par próbek: 1 – stal 60; 2 – żelazo armco; 3 – VT3-1; 4 – L70

So, the average value $(\Delta E/E_0)^{\mathrm{SUR}}$ for the group of material under study makes up ≈ 30%, which corresponds to relation $E_{\mathrm{SUR}} \approx 0.7E_0$, respectively. The latter ratio corresponds to the extremely deformed state of the surface layer material preceding its brittle destruction in accordance with modern dislocation concepts of the fatigue nature of friction and wear of metals. The established regularity of periodic reduction in the elastic modulus of the surface layer to its critical value of $E_{\mathrm{SUR}} \approx 0.7E_0$ in the process of fretting wear of metal materials is direct confirmation of the Z-shaped mechanism, as well as the low-cycle fatigue model of wear in this type of friction interaction.

It should be noted that, for Armco iron and yellow metal L70, the obtained values $(\Delta E/E_0)^{\mathrm{SUR}}$ are considerably higher than those for steel 60 and even more so for alloy VT3-1. This may be directly related to the structure of the lattice of the materials under study (the number of sliding planes of dislocations), which, other things being equal, determines the thickness of the extremely deformed surface layer of the material in the process of external force action.

The above results of experimental studies of metal fretting wear are of scientific novelty for further study of physical processes and phenomena occurring on the friction contact, but they also have a certain practical value.

One of the directions of practical use of the obtained data is to refine the design calculations of the main operational characteristics of the friction pair parts. For example, in the works of Professor Kolokoltsev V.M. **[L. 8]** in the course of long-term experimental studies, the dependence of the endurance limit on the elastic modulus of technically pure metals is established as follows:

$$\sigma_{-1} = 20.4 + 1.81E - 6\cdot10^{-3}E^2 + 1\cdot10^{-4}E^3\,,$$

where σ_{-1} is the fatigue limit of the material under study.

In practice, the Manson equation is widely used to calculate the cyclic durability of GTE critical parts (disks, blades etc.), which also encompass the Young's modulus. The equation has the following form:

$$\Delta\varepsilon = \frac{3.5\cdot\left[\sigma_2(t) - \sigma_m\right]}{E(t)}\cdot N^{-0.12} + \left[\ln\frac{100}{100\cdot\Psi(t)}\right]^{0.6}\cdot N^{-0.6}$$

where $\Delta\varepsilon$ is the material relative deformation increment during 1 cycle; N is the cyclic durability, cycles; σ_m is the average cycle stress, MPa; $\sigma_{\text{в}}(t)$ is the material stress limit at working temperature t, MPa; $\Psi(t)$ is the hardening degree of the material at temperature t,%;

and, $E(t)$ is the elasticity modulus of the material at temperature t, MPa.

Analysing the above equation, it is plain to see that the physical and mechanical properties of the material included in it are represented as the function of the operating temperature t.

At the same time, our studies of the kinetics of fretting wear of metals revealed the qualitative and quantitative dependence of the material surface layer elastic modulus on the duration of frictional action during fretting. The obtained data indicate that, when calculating the cyclic durability of mating parts operating under vibration conditions and the existing risk of fretting corrosion on contact surfaces, it is necessary to take into account the change in the modulus not only from the temperature, but also from the duration of continuous working time of the part.

Thus, at present, a significant change in E_{SUR} of parts and elements of constructions is almost not taken into consideration during the work process, while it is the physical state of the material surface layer that is a decisive factor to ensure the above performance properties.

CONCLUSION

In view of the foregoing considerations, the data obtained as to the change of the part material surface layer modulus of elasticity under fretting-wear can be considered as a theoretical and methodological foundation for the control of the technological process of parts manufacturing, and the forecasting of performance properties of parts, in particular, fretting wear of the material surface layer.

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