Simulation of change in rheological properties of structure of combined materials in tribosystem

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Abstract. The paper presents experimental and theoretical dependences of changes in the rheological properties of the structure of materials of the surface layers of triboelements in the tribosystem during running-in, the methodical approach to definition of such properties with use of transverse ultrasonic waves is substantiated. It has been experimentally established, that the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the surface layer during the period of running-in increases by 32 to 45 % from the initial structure. A parameter for estimating the rheological properties of the structure of conjugate materials in the tribosystem as a function of time is proposed. This is a physical quantity that characterizes the ability of the materials included in the design of the tribosystem, irreversibly convert mechanical energy into thermal energy in the process of deformation of surface layers. Determined by ultrasonic vibrations passing through the material and reduced to a distance of one meter, the dimension 1/m.

1. Introduction

For modeling and forecasting of wear resistance of tribosystems, and also for calculation speed of wear and losses on friction, in mathematical expressions it is necessary to take into account the factor which is the characteristic of materials from which triboelements are made. This factor must be a structurally sensitive characteristic and respond to changes in the surface layers of materials during the running-in process, as well as the magnitude and gradients of temperatures and stresses in the materials during running-in. As proved in the works [1, 2] such a factor may be the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of materials.

During the operation of the tribosystem, mechanical energy, due to the dynamic contact of the triboelements, is transmitted to the material by stress waves, transforming into internal friction. Relaxation of stresses on the spots of actual contact is due to the rheological properties of the structure of the materials of the surface layers, which leads to a more uniform redistribution of stresses by volume and prevents the accumulation of defects that cause stress concentration. Therefore, the greater the proportion of mechanical energy supplied by friction to the moving and stationary triboelements, dissipated in the form of heat, the higher should be the wear resistance of the tribosystem.

2. Analysis of recent studies and publications

The first work, which is set interconnection between the internal friction of the structure of materials and wear resistance, were the works of V.V. Sheveli [3-7]. In the works it is proved that relaxation processes show a higher structural sensitivity to changes in the stress-strain state of the material under
dynamic loading in comparison with the physical and mechanical properties of materials. Based on the analysis of works [3-7] a conclusion can be drawn that rheological properties of structure of materials, from which the tribosystem is made, are function of wear resistance, losses on friction, and also time of running-in.

In works [8-10] the authors carried out research and presented experimental data on the effect of the structure of tribosystem materials on wear resistance. It is shown in the works that the grain size of the structure of conjugated materials are functions of wear resistance and friction loss.

In work [11] the analysis of occurrence of peaks of internal friction in copper at various temperatures, for example, at temperature is presented 175°C and at temperature 230°C. It is shown that with increasing temperature, the maxima of internal friction caused by relaxation along the grain boundaries are observed. These data allow us to conclude about the significant effect of temperature on the amount of internal friction of the structure of materials. Similar studies and conclusions are presented in work [12].

During the operation of the tribosystem there is an increase in the temperature of the surface layers of triboelements, which will cause changes in the rheological properties and thus affect the wear resistance of the tribosystem. We can assume that such processes will be active during the running-in, which is confirmed in the work [4]. In the specified work dependences of increase in a logarithmic decrement of attenuation of ultrasonic vibrations in structure of materials of triboelements during running-in are presented. It is established that the increase in internal friction during the running-in period can reach to 30%.

In the works [1, 2] experimental dependences of change of rheological properties of structure of materials of surface layers of triboelements in tribosystem during running-in are presented, the methodical approach to definition of such properties with use of cross ultrasonic waves is substantiated. It is experimentally established that the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the surface layer material during the running-in period increases by 32…45 % depending on the initial structure of the materials. On the basis of experimental data the mathematical expression which allows to define increase in rheological properties of structure of materials of triboelements for the period of running-in is received. The use of such dependences will increase the accuracy of modeling the processes of friction and wear.

3. Statement of the objective and tasks of the study
To carry out modeling of change of rheological properties of structure of the connected materials in a tribosystem during running-in, obtain mathematical expressions for their approximation and perform experimental studies to confirm the adequacy of their approximation.

4. Development of mathematical model
In work [1] obtained an expression that characterizes the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material and is a structurally sensitive characteristic of this material:

$$\delta = \frac{20 \lg(A_o / A_1) - 20 \lg(A_o / A_2)}{2H} \cdot \cos a,$$

where $\delta$ is logarithmic decrement of attenuation of ultrasonic vibrations in the structure of the material, dB/m; $A_o$ – the magnitude of the amplitude of the initial pulse generated by the flaw detector is not measured during the experiment; $A_1$ – the magnitude of the amplitude of the first, single reflected pulse of the flaw detector, mV; $A_2$ – the magnitude of the amplitude of the second, twice reflected pulse of the flaw detector, mV; $H$ – material thickness, m; $a$ – the angle of introduction of the ultrasonic wave into the material, degree.

Applying transverse oscillations excited by an inclined piezoelectric transducer (PET) and measuring with an ultrasonic flaw detector UD2-12 the magnitude of the first and second pulses in dB according to the formula (1) the value $\delta$, dB/m, can be calculated which characterizes the rheological
properties of the material structure.

Figure 1. The scheme of application of transverse waves in determining the internal friction of the structure of materials in the tribosystem during running-in: PET is piezoelectric transducer; 1 – fixed triboelement; 2 - movable triboelement; 3 – contact area; $A_0$ is the magnitude of the amplitude of the initial pulse of the flaw detector, during the experiment, is not measured; $A_1$ is single wave reflection; $A_2$ is double wave reflection; $\alpha$ is the angle of introduction of the ultrasonic wave into the material; $H$ is thickness of the material.

The study of the dependences of the change in the logarithmic decrement of attenuation during the running-in of the tribosystem was performed according to the scheme «disk–pad» by friction machine SMT-1. A flat sample size 10*10 mm and length 35 mm was used as a “pad”. PET was installed on the flat face of the sample, as shown in Figure 1. Movable triboelement – a roller – was made of steel 40H (HRC 58). Fixed triboelements – flat samples – were made of steel 40H (HRC 58); bronze Br.AZh 9-4 (HB 110); brass LMcSKA 58-2-2-1-1 (HB 125).

As used lubricating medium transmission oil GL-4, $E_u=3.6*10^{14}$ J/m$^3$; which was applied to the friction zone by drip. Sliding speed 0.5 m/s, loading 400 – 1600 N, depending on the connected materials in the tribosystem.

The initial values of the logarithmic decrement of attenuation, which is denoted by $\delta_0$, take from work [1]:

- steel 40H (HRC 58), $\delta_0=443.6$ dB/m;
- Br.AZh 9-4 (HB 110), $\delta_0=784.0$ dB/m;
- LMcSKA 58-2-2-1-1 (HB 125), $\delta_0=840.5$ dB/m.

Combinations of materials in the tribosystem that is in the works [3, 4] called compatibility of materials, will affect the tribological characteristics. The main conclusion of the work [1, 2] is that in the process of running the rheological properties of the structure of the materials of the surface layers of the mobile and fixed triboelements increase, which is reflected in the change logarithmic decrement of the attenuation of ultrasonic vibrations as they pass through the material from $\delta_0$ to $\delta_{\text{max}}$. This dependence is approximated by the expression presented in the paper [2]:

$$\delta_{\text{max}} = \delta_0 + \delta_0 \cdot \left( \frac{W_{TR,f}}{f_{fr\,(\text{max})} \cdot N \cdot v_{sl}} \right) \cdot \sin \left( \frac{t}{t_{\text{com}}} \right),$$

(2)

where $W_{TR,f}$ is the rate of dissipation in the fixed triboelement of the tribosystem is calculated according to the work [13], dimension J/s; $f_{fr\,(\text{max})}$ is the maximum value of the coefficient of friction during the running-in of the tribosystem; $N$ is load on the tribosystem, N; $v_{sl}$ is sliding speed, m/s; $t_i$ is time in the process of running-in, s; $t_{\text{com}}$ is time of completion of running-in, s.

Using this expression, it is possible to perform modeling of changes in the rheological properties of
the structure of materials of movable and fixed elements of the tribosystem.

The formula is used for a fixed triboelement:

\[ \delta_{f(\text{max})} = \delta_{f(0)} + \delta_{f(0)} \cdot \left( \frac{W_{TR,f}}{f_{r(\text{max})} \cdot N \cdot v_0} \right) \cdot \text{th} \left( \frac{t_i}{t_{\text{com}}} \right) \]

where \( \delta_{f(\text{max})} \) is the maximum value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the fixed triboelement after completion of running-in, the dimension dB/m; \( \delta_{f(0)} \) is value of logarithmic decrement of attenuation of ultrasonic oscillations of initial structure of material of fixed triboelement, dimension dB/m.

The formula is used for the movable triboelement:

\[ \delta_{\text{mov(\text{max})}} = \delta_{\text{mov}(0)} + \delta_{\text{mov}(0)} \cdot \left( \frac{W_{TR,mov}}{f_{r(\text{max})} \cdot N \cdot v_0} \right) \cdot \text{th} \left( \frac{t_i}{t_{\text{com}}} \right) \]

where \( \delta_{\text{mov(\text{max})}} \) is the maximum value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the movable triboelement after completion of running-in, dimension dB/m; \( \delta_{\text{mov}(0)} \) is the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the original structure of the material of the movable triboelement, dimension dB/m; \( W_{TR,mov} \) is the rate of dissipation in the movable triboelement of the tribosystem, calculated according to the work [13], dimension J/s.

After completion of running-in time of operation of a tribosystem \( t_i \) is equal to the time of completion of running-in \( t_{\text{com}} \), i.e., the stationary process of operation of the tribosystem is considered.

5. The results of the calculation and their discussion

Dependences of change of logarithmic decrement of attenuation of various constructional materials, in combination with a mobile sample from steel 40H, as functions of time of running-in, are shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** Dependences of change of logarithmic decrement of attenuation of ultrasonic oscillations in structure of materials in tribosystem \( \delta_{\text{c}} \), as a function of running time \( t_i \) for various materials of a fixed triboelement: 1- LMcSKA 58-2-2-1-1; 2 - Br.AZh 9-4; 3 - steel 40H.

The analysis of the presented experimental dependences allows to draw a conclusion that in the course of running-in rheological properties of structure of materials increase. For example, for steel 40H the logarithmic decrement of attenuation increases with values \( \delta_{0} = 374 \) dB/m to values \( \delta_{\text{max}} = 584 \) dB/m, which is 31.8 %. For bronze Br.AZh 9-4 the logarithmic decrement of attenuation increases with values \( \delta_{0} = 679 \) dB/m to values \( \delta_{\text{max}} = 984 \) dB/m, which is 44.9 %. For brass LMcSKA 58-2-2-1-1
the logarithmic decrement of attenuation increases with values $\delta_0 = 840 \, \text{dB/m}$ to values $\delta_{\text{max}} = 1218 \, \text{dB/m}$, which is 45.0%.

To evaluate the rheological properties of the structure of conjugate materials in a tribosystem consisting of movable and fixed triboelements, on the basis of works [14], let’s use the expression:

$$RS\, _{\text{TS(max)}} = \frac{\delta_{\text{mov(max)}} \cdot \delta_{\text{f(max)}}}{\pi} \, 1/\text{m},$$

where $RS\, _{\text{TS(max)}}$ is maximum value of rheological properties of bonded materials in the tribosystem after completion of running-in, dimension 1/m.

Using formulas (3) – (4) and substituting them into a formula (5) changes in the rheological properties of the structure of the materials of the tribosystem $RS\, _{\text{TS(max)}}$ are simulated depending on their combination in the design. Simulation will be performed for the established mode of operation. The results of the simulation are summarized in Table 1.

**Table 1.** - The results of changes in the rheological properties of different structures of tribosystems

| Tribosystem design          | Initial value $RS\, _{\text{TS(0)}}$ | Maximum value $RS\, _{\text{TS(max)}}$ | % increase during running-in time |
|-----------------------------|--------------------------------------|---------------------------------------|----------------------------------|
| steel 45+steel 40H         | 229.7                                | 318.2                                 | 38.5                             |
| steel 20H+steel ShH15      | 230.8                                | 319.0                                 | 38.2                             |
| steel 40H+steel 40H        | 249.9                                | 346.7                                 | 38.7                             |
| steel 40H+cast iron VCh70  | 309.7                                | 431.9                                 | 39.4                             |
| steel 40H+Br.AZh 9-4       | 332.5                                | 479.0                                 | 44.0                             |
| steel 40H+LMcSKA 58-2-2-1-1| 344.2                                | 494.9                                 | 43.7                             |
| cast iron CCh15+LMcSKA 58-2-2-1-1 | 406.9                           | 586.2                                 | 44.0                             |
| cast iron VCh70+Br.AZh 9-4 | 412.0                                | 593.0                                 | 43.9                             |

Analysis of the results that are presented in the table 1, allows us to conclude that in the process of running-in, the change in the rheological properties of the structure of conjugated materials in the tribosystem reaches the value 38.2 to 44.0% in the direction of increase.

It should be noted that the results are given in the table 1, obtained for tribosystems with the following parameters: $K_f = 12.5 \, \text{1/m}; K_{ov} = 0.5; \text{ lubricating medium GL-4, } E_u = 3.6 \times 10^{14} \, \text{J/m}^3; \text{ load } N=2000 \, \text{N}; \text{ sliding speed } v_{sl} = 0.5 \, \text{m/s. Variable factors are combinations of conjugate materials in the tribosystem.}$

To evaluate the rheological properties of the structure of conjugated materials in the tribosystem during running-in [15], when $t_i$ varies from zero to $t_{\text{com}}$, let’s use the expression:

$$RS\, _{\text{TS}}(t_i) = \sqrt{\frac{\delta_{\text{mov}}(t_i) \cdot \delta_{\text{f}}(t_i)}{\pi}} \, 1/\text{m},$$

where $RS\, _{\text{TS(0)}}$ - values of rheological properties of connected materials in the tribosystem, as a function of running-in time, dimension 1/m; $\delta_{\text{mov}}(t_i)$ is the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the movable triboelement, as a function of the running-in time, the dimension dB/m, calculated by expression (4); $\delta_{\text{f}}(t_i)$ is the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the fixed triboelement, as a function of the running-in time, the dimension dB/m, calculated by expression (3).

Modeling, according to formula (6), the theoretical dependences of the change in the rheological properties of conjugated materials in the tribosystem during running-in were obtained, which are
presented in figure 3. From the analysis of the obtained dependences it follows that the rheological properties of conjugate materials in the tribosystem $R_{S_{TS}}$ increase from the original value, at $t_i = 0$, to values that characterize the changes in the structure of the materials of the surface layers of the mobile and fixed triboelements during the running-in $t_i = t_{пр}$.

![Figure 3](image)

Figure 3. Dependences of change of rheological properties of structure of connected materials in tribosystem $R_{S_{TS}}$, as a function of running time $t_i$ for various bonded materials: 1 - steel 40H+ LMcSKA 58-2-2-1-1; 2 - steel 40H+ Br.AZh 9-4; 3 - steel 40H+steel 40H

Time $t_i$, upon reaching which the value is stabilized $R_{S_{TS}}$, corresponds to the time of completion of running-in. This fact was verified experimentally on various tribosystems with parameters: $K_f = 12.5 \text{ 1/m}$; $K_{ov} = 0.5$; lubricating medium GL-4; $E_u = 3.6 \times 10^{14} \text{ J/m}^3$; load $N = 2000 \text{ H}$; sliding speed $v_{sl} = 0.5 \text{ m/s}$. Variable factors are combinations of conjugate materials in the tribosystem.

For the tribosystem “steel 40H+steel 40H” stabilization of the moment of friction and temperature of a fixed triboelement occurred at $t_i = 2200 \text{ s}$, that can be considered as time of completion of running-in.

For the tribosystem “steel 40H+ Br.AZh 9-4” stabilization of the moment of friction and temperature of a fixed triboelement occurred at $t_i = 1600 \text{ s}$, that can be considered as time of completion of running-in. For the tribosystem “steel 40H+ LMcSKA 58-2-2-1-1” stabilization of the moment of friction and temperature of a fixed triboelement occurred at $t_i = 1200 \text{ s}$, that can be considered as time of completion of running-in.

The completion time, which was obtained theoretically, was verified experimentally. The sample size during the experimental studies was checked for compliance with the normal distribution law. Analysis of the obtained results allows us to conclude that the experimental sample size corresponds to the normal distribution law.

The results of experimental studies to determine the stabilization time of the value $R_{S_{TS}}$ were tested for homogeneity and reproducibility from experience to experience by the Cochran’s test. The analysis of the obtained results allows concluding that the results are homogeneous and reproducible.

Rheological properties of the structure of conjugated materials in the tribosystem $R_{S_{TS}}$ is a physical quantity that characterizes the ability of materials included in the structure of the tribosystem to irreversibly convert mechanical energy into thermal energy in the process of deformation of surface layers. The dimension 1/m was determined by ultrasonic vibrations passing through the material and reduced to a distance of one meter.

Rheological properties of the structure of bonded materials in the tribosystem should be used in modeling and forecasting the wear resistance of tribosystems, as well as to calculate the wear rate and friction losses. Parameter $R_{S_{TS}}$, which is a structurally sensitive characteristic of the materials from which the triboelements are made. As follows from the results of table 1 and dependencies, figure 3,
this parameter responds to changes in the surface layers of triboelements in the process of running-in, as well as to the magnitude and gradients of temperatures and stresses in the process of running-in.

6. Conclusions
1. The paper presents experimental and theoretical dependences of changes in the rheological properties of the surface layers of triboelements in the tribosystem during running-in, substantiates a methodical approach to determining such properties using transverse ultrasonic waves. It is experimentally established that the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the surface layer material during the running-in period increases by 32 to 45% from the initial structure of the materials.
2. A parameter for estimating the rheological properties of the structure of conjugate materials in the tribosystem as a function of time is proposed. This is a physical quantity that characterizes the ability of materials included in the structure of the tribosystem to irreversibly convert mechanical energy into thermal energy in the process of deformation of surface layers. The dimension 1/m was determined by ultrasonic vibrations passing through the material and reduced to a distance of one meter.

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