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Виконано порівняльні дослідження триботехнічних характеристик полімерного композитного матеріалу «Moglice» і розробленого матеріалу ДК-6. Випробування виконувалися на парах тертя «чавун – моглайс» і «чавун – ДК-6». Дослідження необхідні для практичного застосування матеріалів ДК-6 або «Moglice» при відновленні зношених поверхонь тертя. Отримано позитивні результати порівняльних випробувань полімерного композитного матеріалу ДК-6 в порівнянні з «Moglice»

Ключові слова: напрямні ковзання верстатів, триботехнічні характеристики, полімерні композитні матеріали, коефіцієнт тертя

Выполнены сравнительные исследования триботехнических характеристик полимерного композитного материала «Moglice» и разработанного материала ДК-6. Испытания выполнялись на парах трения «чугун – моглайс» и «чугун – ДК-6». Исследования необходимы для практического применения материалов ДК-6 или «Moglice» при восстановлении изношенных поверхностей трения. Получены положительные результаты сравнительных испытаний полимерного композитного материала ДК-6 по сравнению с «Moglice»

Ключевые слова: направляющие скольжения станков, триботехнические характеристики, полимерные композитные материалы, коэффициент трения

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TRIBOTECHNICAL RESEARCH INTO FRICTION SURFACES BASED ON POLYMERIC COMPOSITE MATERIALS

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1. Introduction

A decrease in the operation resource of machinery caused by wear is a serious problem. In technically advanced countries the cost of repair and maintenance of machinery makes up 10...15 % (up to 25 %) on average of the cost of equipment per year. For machines operating under particularly difficult conditions, the cost of major repairs reaches 50 % of their price.

A larger part of machine parts (80...85 %) fail due to intensive wear. At the same time, correct application of tribological knowledge allows saving up to 1.6 % of GDP [1]. An analysis of promising research and developments over the past 35 years proves an important role of the application of tribological knowledge during repairing and restoration of friction surfaces [2].

One of the tasks during repair of metal-cutting machine tools and various equipment is to restore the guides of friction surfaces of frames, slides and casings. In recent years, technologies of restoring carriage saddle guides of metal-cutting machine tools that employ the use of two-component composite materials have been increasingly applied [3, 4]. However, their use in repairing practice and in the practice of subsequent operation requires studying of the characteristics of this material, particularly when operating in a friction couple with cast iron guides of a machine tool. It is required to examine such parameters as a coefficient of sliding friction, smoothness of motion, wear resistance and influence of modern lubricants on these parameters.

If the studies involving such known composite materials as Moglice are not conducted, it is not possible to determine the ranges of optimum performance for friction surfaces of metal-cutting machine tools. Moreover, such studies are required for the application of new composite materials that have not been explored previously.

2. Literature review and problem statement

Composite materials are the multicomponent materials consisting of a plastic base – a matrix and fillers [5].

A promising method for restoring damaged or worn surfaces of guides of carriage saddles of metal-cutting machine tools is the use of polymeric material «Moglice». This material on the epoxy-resin base with finely dispersed anti-friction fillers was designed by the German company «Diamant» [4].

Such polymeric composites can be reinforced with fiber; their tribological tests showed good results [5, 6]. Modern composite materials have gained popularity even for repairing damaged parts in aerospace structures [7].

Additives of various finely dispersed structures, which are described in papers [8, 9], somewhat improve tribological characteristics of composite polymers. However, these improvements are not determining in character.

A detailed scientific literature review of mechanical and tribological behavior of polymeric composites based of natural fibers is presented in paper [10]. This paper also examines the impact of such parameters as applied loading, velocity and friction path on the characteristics of friction and wear of polymeric composites.

Article [11] reports experimental estimation of friction and wear properties of the composite material «Moglice», which allowed the manufacturer to recommend it for repair of metal parts. This material was tribologically tested under conditions of dry friction at reciprocating motion.

Tribological research into polymeric material «Moglice», performed in papers [4] and [12], has shown positive results and confirmed characteristics declared by the company «Diamant» (Germany) [13]. Article [14] explored the issues of application of antifriction composite materials in machine tool engineering.

For example, papers [15, 16] report results of research into antifriction polymeric materials, including the material «Moglice», when used as guides in metal-cutting machine tools.

However, the use of the polymeric material «Moglice» implies significant financial expenditures because of its high cost.

It should be noted that there is a lack of new studies and scientific publications at present related to the application of composite polymeric materials for restoring damaged friction surfaces. This is especially true for the research and development of polymeric materials that are cheaper than «Moglice».

3. The aim and objectives of the study

The aim of present research is to conduct comparative studies of tribotechnical characteristics of the polymeric material «Moglice» and the developed new polymeric composite material DC-6. These studies are required to determine the range of optimal performance of friction surfaces of metal-cutting machine tools after restoration.

To accomplish the set goal, the following tasks had to be solved:

– to develop a procedure for controlling friction and temperature coefficients using a tribometer, which excludes misalignment of the sample and the counter sample;

– to estimate applicability of the Euler's formula for the calculation of friction coefficients when operating according to the scheme «shaft – belt» and «shaft – insert»;

– to devise a technique for controlling the mode of friction and lubrication – fluid, semifluid or boundary.

4. Equipment and procedure of research

4. 1. Comparative tests and verification of calculation formulae for the friction schemes «shaft – belt» and «shaft – insert»

To implement the scheme «shaft – belt», we designed the structure of a tribometer (Fig. 1), making it possible to exclude preliminary macro-alignment, to control friction torque, temperature in the friction zone and electric resistance of a lubricating film [18]. The electronic unit of electric drive control allows us to smoothly change friction velocity from $1.25\cdot10^{-2}$ m/s to 3.14 m/s.

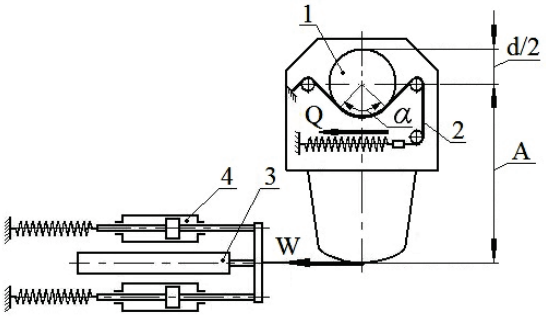


Fig. 1. Schematic of tribometer:
1 — sample; 2 — counter sample in the form of a steel belt;
3 — friction torque sensor; 4 — air dampers

We denoted in Fig. 1 the following: W is the force of springs, opposing friction torque; Q is the force of tension of the counter sample's belt; α is the wrapping angle of the sample by the belt; d is the diameter of the sample; A is the arm of the carriage.

A general view of the tribometer is shown in Fig. 2.

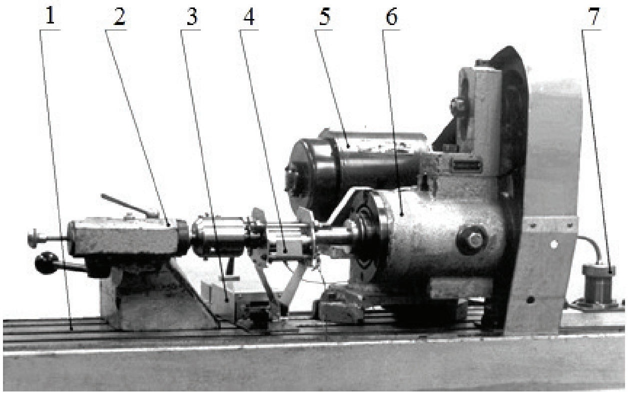


Fig. 2. Tribometer:
1 — frame; 2 — rear center head; 3 — friction torque sensor; 4 — tribometer carriage; 5 — drive motor; 6 — leading center head; 7 — current collector device

Applicability of the Euler's formula for calculating coefficients of friction when operating according to the scheme «shaft – belt» and «shaft – insert» required a validation. For this purpose, we performed experimental comparison of friction coefficients, calculated from the Euler's formula and from classic Amontons – Coulomb formula [16].

In one case, friction coefficients were calculated from the formula derived from the Euler equation

$$f = \frac{\ell n\left(\frac{6.66 \cdot W}{Q} + 1\right)}{\alpha}. \qquad (1)$$

In another case, friction coefficients were calculated from the Amontons-Coulomb formula

$$f = \frac{F}{N} = \frac{6.66 \cdot W}{N}, \qquad (2)$$

where W is the power of return springs (reinforcement of springs, opposing friction torque); Q is the belt tension force; **a** is the wrapping angle of the sample by the belt; F is friction force between the sample and the counter sample; N is intensification of sample loading; 6.66 is the magnitude of transmission coefficient, taking into account the ratio of half diameter of sample d and carriage arm A of the tribometer (Fig. 1).

An analysis of the magnitudes of friction coefficients, calculated based on experimental data [16], shows that the formula derived from the Euler equation is true for both schemes «shaft – belt» and «shaft – insert». For both friction schemes, the magnitudes of friction coefficients f, calculated from the Amontons-Coulomb formula for boundary lubrication, are overrated by 2.05 and 1.86 times compared with those indicated in the literature. For fluid lubrication, they are overrated by 3.2 and 2.8 times, which makes it impossible to apply the Amontons-Coulomb formula.

For the friction scheme «shaft – insert», the Euler's formula is applicable while the Amontons-Coulomb formula is not. This is explained by the fact that the intensification of load on the sleeve is created according to the same principle as in the scheme «shaft –belt», that is, through the belt that wraps the sleeve. The wrapping angles of sample α were different, which was taken into account in the calculations.

However, friction coefficients, calculated from the Euler's formula for the case of friction by the scheme «shaft – sleeve», are lower than those for friction by the scheme «shaft – belt» by 8.3...16 %. Apparently, the reason for this is incomplete triggering of the mechanism of additional belt tension due to friction force because of the increased friction in bending places of a steel tape.

4. 2. Control over friction mode and determining sliding velocity

Friction between the carriage saddle and the frame guides of the metal-cutting machine tool occurs in the mode of boundary and semifluid lubrication. To conduct tribotechnical research into composite materials, it is necessary to identify regions of friction velocities characteristic of the boundary and semifluid lubrication.

With a view to defining a friction mode typical of friction between the carriage saddle and the guides of a metal-cutting machine tool, the author examined conditions of occurrence of different friction modes: boundary, semifluid and fluid.

Separation of friction modes into boundary, semifluid and fluid lubrication in experimental studies is possible based on the Guersey diagram or by the character of oscillograms, obtained while measuring electrical resistivity of a lubricating film.

The Guersey diagram shows dependence of friction coefficient f on the Sommerfeld criterion, which includes viscosity of lubricating oil **m**, sliding velocity V and pressure p. This diagram can be obtained by changing one of the parameters, for example, sliding velocity V.

Determining friction mode by the character of oscillograms is possible when controlling electrical resistivity of a lubricant film. At boundary friction, there is a straight line on the oscilloscope screen and at fluid friction, there is a sinusoid. In transient modes from boundary to fluid friction, flickering sinusoids are observed. To control the friction mode by the character of oscillorgams, the method that employs an electronic bridge scheme, was chosen [19].

Measurements of friction torque, sliding velocity, and temperature were conducted by the technique, described in [19]. Friction coefficients were calculated from the formula (1) based on the Euler's formula.

Results of research into friction modes at continuous lubrication of samples are shown in Fig. 3, 4.

Dependence of friction coefficient f on sliding velocity V has a characteristic form of the Guersey curve.

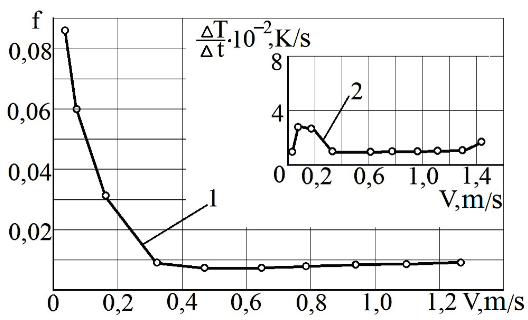


Fig. 3. Dependence of friction coefficient f (1) and temperature change rate $\Delta T/\Delta t$ (2) on sliding velocity V

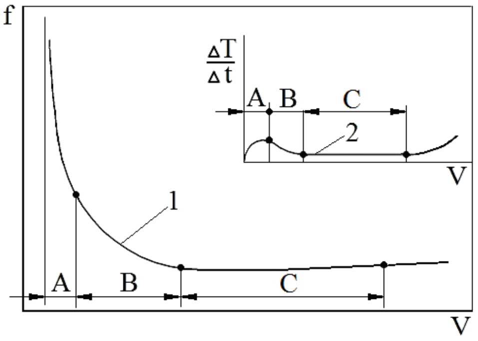
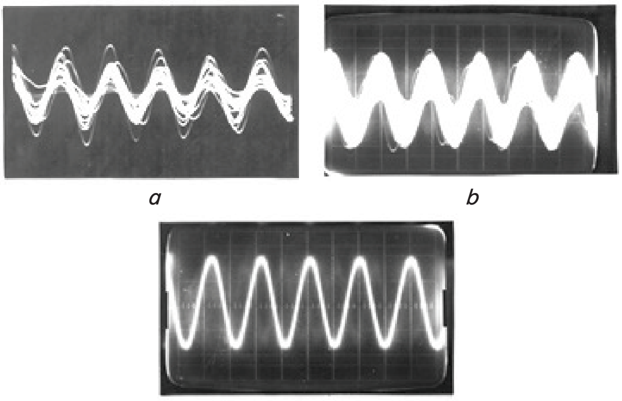


Fig. 4. Velocity ranges corresponding to different friction modes: 1 — dependence of friction coefficient on sliding velocity *V*; 2 — dependence of temperature change rate $\Delta T/\Delta t$ on sliding velocity *V*

Thanks to measurements of temperature change rate $\Delta T/\Delta t$, it became possible to determine more precisely the region of boundary friction. This is the range of small velocities on the initial section of the Guersey curve, on which at an increase in sliding velocity *V*, temperature increase rate $\Delta T/\Delta t$ elevates (section *A* in Fig. 4).

Boundary lubrication in this velocity range (section *A*) was proved by the character of oscillograms – a straight slightly flickering line was visible on the oscilloscope screen. At an increase in velocity *V* (Fig. 3), weak sinusoid spikes appeared on the screen (Fig. 5, *a*).



a *b*

c

Fig. 5. Oscillograms of friction modes: *a* — transient mode from boundary to semifluid lubrication; *b* —transient mode from semifluid to fluid lubrication; *c* — fluid lubrication

In section *B* (Fig. 4), a decrease in friction coefficient *f* and temperature change rate $\Delta T/\Delta t$ is observed, which is associated with the further rise in thickness of a lubricating film. Flickering sinusoids are observed in oscillograms, which proves the semifluid friction mode (Fig. 5, *b*).

With subsequent increase in sliding velocity *V* (section *C*), thickness of a lubricating film increases even more. At friction in range *C,* oscillograms have the form that is closer to the fluid one. At these velocities, metal contact between friction surfaces remains. This is evidenced by faint flickering lines and blurred image of the sinusoid on the oscilloscope screen.

As a result of determining of friction mode by the character of oscillograms and due to measurements of temperature change rate $\Delta T/\Delta t$, it became possible to determine the region of boundary friction. This is the range of small velocities in the initial section of the Guersey curve of up to 0.1 m/s, at which at an increase in sliding velocity *V*, temperature increase rate $\Delta T/\Delta t$ grows as well (section *A* in Fig. 4). Boundary lubrication in this velocity range was proved by the character of oscillograms – a straight slightly flickering line was visible on the oscilloscope screen.

4. 3. Comparative experimental research into friction of the polymer «Moglice» and DC-6

The objective of this research is to compare friction coefficients of the polymeric material «Moglice» and polymeric material «DC-6» at friction with cast iron.

The polymeric material «DC-6» is produced in Ukraine and it is cheaper compared with the polymer «Moglice».

The process of friction between the cylindrical sample of diameter d=30 mm and a cast iron sleeve – the counter sample – was studied. The sleeve mounting scheme is shown in Fig. 6. The temperature in the friction zone was measured using a chromel-copel thermocouple of 0.2 mm in diameter. Loading force of the sample N=490 N, sleeve wrapping angle α=116°.

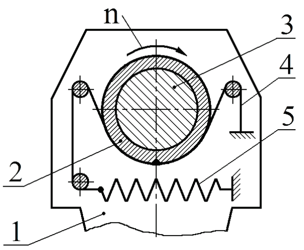


Fig. 6. Schematic of mounting of the cast iron sleeve: 1 — tribometer carriage; 2 — sleeve; 3- sample; 4 — steel belt; 5 — belt tension springs

Choice of friction velocity during conducting of the experiment was performed, taking into account the need to provide boundary friction.

The main objective of the research was to apply the polymeric material «Moglice» and the developed polymer composite material DC-6 to restore the damaged or worn surfaces of the guides of the carriage saddle of metal-cutting machine tools. That is why sliding velocity in the process of research was consistent with average velocity of rapid motion of carriages and table of machines, which was equal to 3.4 m/min=0.056 m/s. The tests were conducted at rotation rates of 10, 20, 30, 40, 50 rpm (Table 1).

Table 1

Friction velocities *V* at the assigned rotation frequencies of sample *n*

n, rpm	*V*, m/s
10	0.0157
20	0.0314
30	0.0471
40	0.0628
50	0.0785

All samples were made with diameter D=30 mm and height H=40 mm. The samples with the polymeric coating «Moglice» and polymeric material coating «DC-6» were used for the experiments.

Cast iron sleeves, made with a gap of not larger than 10 μm between the sample and the sleeve as an assembly, served as counter samples.

5. Results of research into friction of the polymers «Moglice» and DC-6

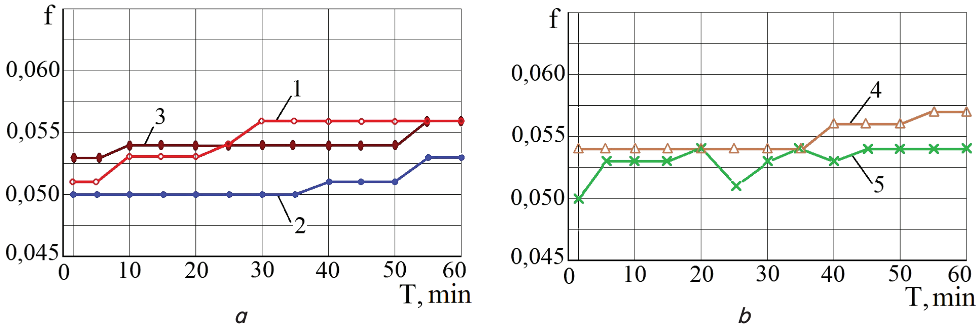
A cast iron counter sample – a sleeve and a sample from the polymeric material «Moglice» were tested at rates of 10, 20, 30, 40, 50 rpm.

At various sliding velocities, the same sample with the «Moglice» coating was used, as well as for DC-6. Cast iron sleeves for research into friction of «Moglice» or DC-6 were different, but they were the same at various sliding velocities.

Test results are shown in Fig. 7, 8.

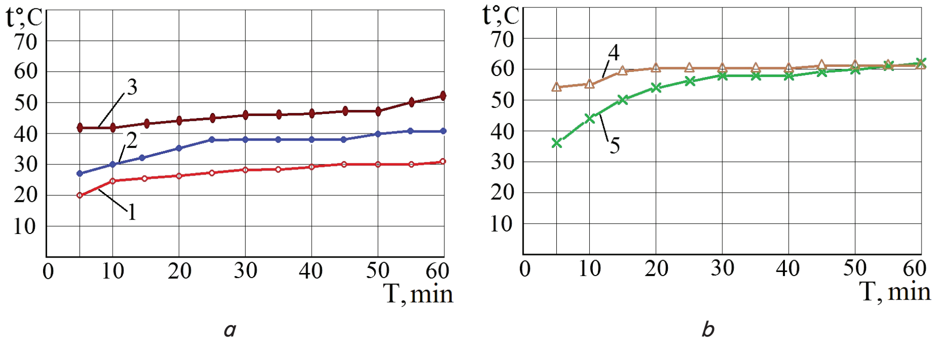
Test results for the cast iron counter sample – «sleeve» and the sample from the polymeric material «DC-6» at rates 10, 20, 30, 40, 50 rpm are shown in Fig. 9, 10.

Average velocity of fast auxiliary motions of carriage and tables of machine tools is equal to 0.056 m/s. This corresponds to rotation frequency of the sample during the studies in the range of 30...40 rpm (Table 1). A wider range of rotation frequencies of the sample was selected for a more complete picture of research results. Wear of the saddle guides occurs both at auxiliary motions and at working feeds.



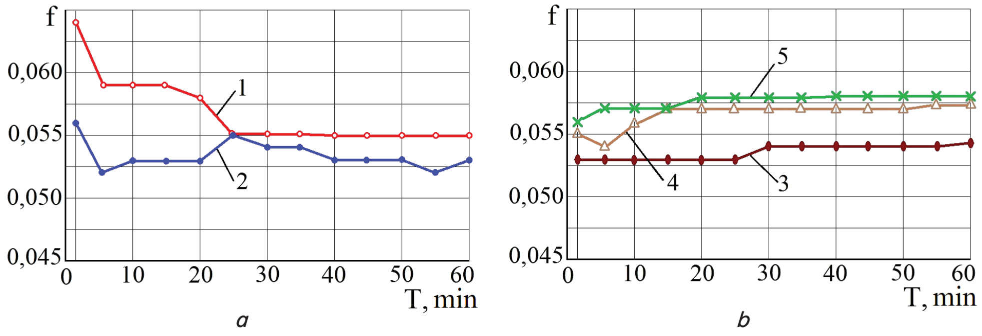
a *b*

Fig. 7. Dependence of friction coefficient *f* on operation time *T* of friction couple «cast iron — moglice»: *a* — 1 — 10, 2 — 20, 3 — 30 rpm; *b* — 4 — 40; 5 — 50 rpm



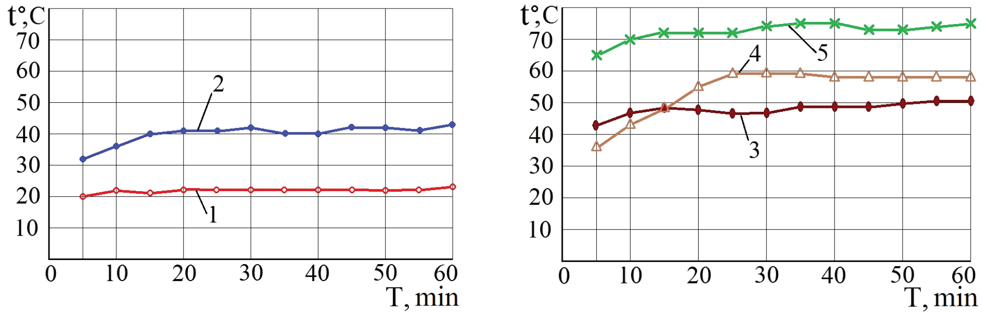
a *b*

Fig. 8. Temperature change *t* depending on operation time *T* for friction couple «cast iron — moglice»: *a* — 1 — 10, 2 — 20, 3 — 30 rpm; *b* — 4 — 40; 5 — 50 rpm



a *b*

Fig. 9. Dependence of friction coefficient *f* on operation time *T* of friction couple «cast iron — DC-6»: *a* — 1 — 10, 2 — 20, 3 — 30 rpm; *b* — 4 — 40; 5 — 50 rpm



a *b*

Fig. 10. Temperature change *t* depending on operation time *T* for friction couple «cast iron — DC-6»: *a* — 1 — 10, 2 — 20, 3 — 30 rpm; *b* — 4 — 40; 5 — 50 rpm

6. Discussion of results of comparative experiments

Design of the applied tribometer allowed us to exclude preliminary macro-alignment, control friction torque, temperature in the friction zone and electrical resistance of a lubricating film.

The friction scheme, which uses a flexible, self-adjusting metal belt, solved the problem of misalignment of the counter sample – an insert or a sleeve. In the known tribometer, misalignment of the counter sample is inevitable, which leads to the necessity of macro-alignment. This, in turn, increases the time of the experiment, changes the gap in a friction couple, and distorts results of the experiment. The macro-alignment, when equilibrium roughness and new physical and mechanical properties of the tension surface are established, is inevitable in all cases.

Comparative tests of friction by the scheme «shaft – belt» and «shaft – insert» proved that for the friction scheme «shaft – insert», Euler's formula is applicable. Friction coefficients, calculated from Euler's formula, are lower than those at friction by the scheme «shaft – belt» by 8.3...16 %, which is not essential for comparative tests.

The developed technique of controlling the friction mode and temperature change rate $\Delta T/\Delta t$ helped determine the region of boundary friction. Determining of friction mode by the character of the oscillogram proved the region of boundary friction. This is the range of small velocities in the initial section of the Guersey curve of up to 0.1 m/s, at which at an increase of sliding velocity V, temperature increase rate $\Delta T/\Delta t$ grows as well (section *A* in Fig. 3).

Approximately after 25–30 minutes of operation at velocity of 0.015 m/s (10 rpm), friction coefficients stabilized in the experiments, which indicates the end of macro-alignment of the sample and the counter sample. At other velocities, as they increase, friction coefficients varied slightly depending on operation time both for the friction of polymer «Moglice» and for DC-6.

Discussion of results of research into friction of the polymer «Moglice»

Studies of friction of the polymer «Moglice» by the scheme «shaft – sleeve» «cast iron-moglice» at sliding velocity of 0.015 m/s (10 rpm) showed the values of friction coefficients $f=0.056$ after the macro-alignment. Low values of friction coefficients for the scheme «shaft – sleeve» are explained by the fact that there is more lubricant in the gap between the sleeve and the shaft (sample). That is why the friction mode is closer to semifluid that at friction by the scheme «shaft – belt».

At 20 rpm at the initial friction moment, friction coefficient was slightly lower, but it increased over time. With an increase in velocity, temperature had higher indicators. This can be explained by the fact that at velocity of 10 rpm, there was a macro-alignment of the sample and roughness smoothed. When tests were carried out at the rate of 20 rpm, the sample already had a smoother surface, which could contribute to a decrease in the friction coefficient.

With a further increase in sliding velocity for friction couple «cast iron – moglice», friction coefficient changed slightly and temperature in the friction area increased. Observations in the course of the experiment showed that an increase in sliding velocity leads to a faster temperature increase for friction couples with polymers than for metal friction pairs. It can be explained by worse heat conductivity of polymers in comparison with metals and softening of the polymer even at slightly elevated temperatures.

Jumps in the obtained values of friction coefficients are caused by high sensitivity of the friction torque sensor of the tribometer and periodic renewal of lubricating oil in the operation process.

Discussion of results of research into friction of polymer DC-6

Micro-alignment of friction couple «cast iron – DC-6» by the scheme «shaft – sleeve» at sliding velocity of 0.015 m/s (10 rpm) led to a decrease in friction coefficient to the value close to f for the couple «cast iron–moglice». Higher f for DC-6 at the starting moment of operation is due to higher original roughness of the sample, which is associated with worse machinability of DC-6 by cutting.

For other friction velocities, values f, approximately coincide with f for polymer «Moglice».

Friction temperature for DC-6 at sliding velocity of 0.015 m/s (10 rpm) is lower than for «Moglice» by 10 °C. Polymer DC-6, which is more viscous in its original state, at applying the coating and at solidification has a more porous structure, which increases oil absorption of the friction surface. Apparently, this decreases temperature at friction.

At friction at velocities of 20, 30, 40 rpm, temperature corresponded to friction temperature for «Moglice». The exception was friction at velocity of 50 rpm and was higher by 15 °C than for «Moglice», which may be due to slight softening of DC-6. Friction coefficient was also higher than for «Moglice».

Generalization of research results.

On average, friction coefficients for materials «Moglice» and «DC-6» are comparable.

Friction temperature of materials «Moglice» and «DC-6» increases at an increase in sliding velocity. For polymer «Moglice», friction temperature increases over time, in contrast to «DC-6». Apparently, it is due to porosity and oil absorption of «DC-6».

Friction coefficient is influenced by surface roughness, since micro-alignment of the material takes place. We obtain rougher surface on the polymer «DC-6» at handling by cutting, which can be easily avoided by the micro-alignment.

At high sliding velocities, the polymers «Moglice» and «DC-6» are heated, softened and set.

For more complete assessment of applicability of the composite polymeric materials «DC-6» in repairs of friction surfaces of metal-cutting machine tools, it is necessary to carry out comparative experimental studies of wear resistance of «DC-6» and the polymer «Moglice».

7. Conclusions

1. The technique of controlling coefficients of friction and temperature was developed. As a result of application of a tribometer, which excludes misalignment of the sample and the counter sample, it was possible to avoid the macro-alignment. The counter sample in this tribometer is capable of self-adjustment by the sample.

2. Applicability of the Euler formula for calculating friction coefficients was proved both when operating by the scheme «shaft – sleeve» and when operating with a flexible steel belt – the counter sample.

3. The developed technique for controlling the mode of friction and lubrication by character of oscillograms and by measuring temperature change rate $\Delta T/\Delta t$ allowed determining the region of boundary friction. This is the range of small velocities of up to 0.1 m/s

4. Comparative research into tribotechnical characteristics of the polymeric material «Moglice» and the developed new polymeric composite material DC-6 showed that coefficients of sliding friction and heat resistance of the couples «cast iron – DC-6» and «cast iron – moglice» are close in magnitude. Thus, to restore damaged or worn friction surfaces of metal-cutting machine tools, it is possible to apply such polymeric materials as «Moglice» and «DC-6».

The composite polymeric material «DC-6» can replace the more expensive repair material «Moglice», which will allow less costly repairs of metal-cutting machine tools.

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STUDY INTO FORMATION OF COBALT-CONTAINING PEO-COATINGS ON AK12M2MGN FROM A PYROPHOSPHATE ELECTROLYTE

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Досліджено формування кобальтовмісних оксидних покривів методом плазмово-електролітичного оксидування силуміну АК12М2МгН у пірофосфатних електролітах. Показано, що варіювання концентрації кобальту сульфату в розчині впливає на робочі параметри ПЕО. Встановлено, що склад та морфологія сформованих оксидних шарів залежать від співвідношення компонентів електроліту. Це дозволяє керувати процесом інкорпорації допанта в матрицю оксиду алюмінію. Обґрунтовано склад пірофосфатного електроліту для одержання оксидних покривів, збагачених каталітичним компонентом

Ключові слова: оксидний покрив, силумін, АК12М2МгН, плазмово-електролітичне оксидування, пірофосфатний електроліт, морфологія поверхні

Исследовано формирование кобальтосодержащих оксидных покрытий методом плазменно-электролитического оксидирования силумина АК12М2МгН в пирофосфатных электролитах. Показано, что варьирование концентрации кобальта сульфата в растворе влияет на рабочие параметры ПЭО. Установлено, что состав и морфология сформированных оксидных слоев зависят от соотношения компонентов электролита. Это позволяет управлять процессом инкорпорации допанта в матрицу оксида алюминия. Обоснован состав пирофосфатного электролита для получения оксидных покрытий, обогащенных каталитическим компонентом

Ключевые слова: оксидное покрытие, силумин, АК12М2МгН, плазменно-электролитическое оксидирование, пирофосфатный электролит, морфология поверхности

1. Introduction

The alloys of aluminum with silicon are demanded structural materials. Due to their unique physical-mechanical properties and high treatment manufacturability, they are widely used in various industries: automotive and motor engineering, heating and water supply systems, consumer goods.

High silicon content provides silumins with enhanced casting properties, higher corrosion resistance, strength and durability. At the same time, coarse-needle eutectics and primary deposition of silicon in the structure of silumins cause