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Improving fretting resistance of heavily loaded friction machine parts using a modified polymer composition

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Abstract. The application of coatings based on fluorocarbon polymer composition, friction-mechanical brass, fullerene C_{60} and surface treatment of vibrorolling with the regular roughness for the protection of heavily loaded mating parts of machines, working in conditions of fretting-corrosion. Studied the mechanisms of friction of coating, which will considerably reduce the fretting-wear mechanisms of friction in engineering products. It is established that in all studied for the protection of heavily loaded mating parts of machines is a single mechanism of increasing wear resistance when fretting in the area of the contact layer of the fine particles through the use of thin-layer coatings. Their presence may be due to either structural self-organization material, or forming of composite structures with small wear particles when using the polymeric composition. At that the protective coating virtually eliminates component corrosion mechanism of fretting – wear.

Key words: fretting corrosion, fluorocarbon polymeric composition, friction-mechanical brass, vibrorolling, fullerene C_{60}.

INTRODUCTION

Fretting corrosion is a frequent cause of breakdown of a number of critical parts of internal combustion engines, in particular, those of oversize mining trucks, drilling equipment parts and other ones operating under vibration and high subgrade stresses. Fretting is peculiar to nominally fixed structural connections (e.g., part attachment points, etc.). As a rule, it arises under vibrations that cause oscillatory relative movements and deformations of various kinds. Fretting is often accompanied by chemical processes occurring on friction surfaces (fretting corrosion). Wear caused by fretting manifests itself in 'wasting' of material at part fastening points. Unlike other types of sliding friction, a characteristic feature of fretting is small amplitude of counterbodies' relative movements comparable with the distance between tops of microroughnesses on the friction surface; therefore, removal of wear products from the contact zone is protracted. Whereupon wear products begin to act as an abrasive, causing additional wear (Ramesh & Gnanamoorthy, 2006; Kubiak et al., 2010; Huang et al., 2011).

When choosing materials for coatings protecting high-load joint parts from fretting corrosion, one should take into account not only their wear resistance, but also their shift sensitivity, i.e. the ability of a material to take shear deformation without initiating fatigue damage processes. It is known that it is a feature of sufficiently thin coatings. Those coatings have yet another advantage: they do not impede overhaulability of assemblies and permit to retain negative allowances specified during assembly in the process of operation (Drozdov et al., 2010; Garkunov et al., 2013).

Fretting corrosion is a frequent cause of reduced reliability of a number of vital parts of machines, including mining machinery (Gilev, 2011; Ostrovsky, 2011).

The purpose of this work is to study the impact of coatings based on fluorocarbon polymer compound, friction mechanical brass plating, C_{60} fullerene, as well as surface vibration knurling forming a regular microrelief on wear of heavily loaded joints of mining machinery operating under fretting corrosion conditions.

The thin-layer coatings named above, as well as surface vibration knurling, were never examined before as means of protection against fretting corrosion under high loads characteristic of a number of performance units of internal combustion engines and mining machines. The phenomena of fretting corrosion of parts made of such a widely used structural material as cast iron, as well as the prospects of using C_{60} fullerene under extreme friction conditions (including fretting corrosion) were also underexplored in the literature. The result of research performed by us expand the sphere of application of thin-layer coatings, the surface vibration knurling method and allow to obtain new data for studying the mechanisms of fretting corrosion, creating prerequisites for expansion of the range of surface protection methods in use.

MATERIALS AND EXPERIMENTAL PROCEDURE

A number of studies propose various versions of wear-resistant protection coating operating efficiently under the conditions of fretting corrosion, e.g. copper-nickel (Zhang & Xue, 2011), copper-phosphorous (Aslanyan et al., 2011) and other ones, applied electrolythically; C_{60} fullerene coating (Ginzburg et al., 1997), epilam/foleox polymer coatings and silicon-molybdenum based coatings (Potapov, 1996) and others.

In many cases, special kinds of processing, in particular, vibration knurling creating a regular microrelief on the surface prove effective in fretting control (Bulatov et al., 1997; Varenberg et al., 2002; Volcho et al., 2002).

This work studies thin-layer coatings based on fluorocarbon polymer compound, friction mechanical brass plating, C_{60} fullerene-containing additives to lubrication oil and grease, as well as using vibration knurling creating a regular microrelief when exposed to heavy contact loads peculiar of large-size joints of locomotive and marine diesel engines, mine trucks and a number of heavily loaded joints of mining machinery.

Samples were tested according to the procedure meeting GOST 23.211-80 on a special FK testing facility using the principle of a standard friction machine (Fig. 1, a & b). In all cases, coatings were applied to fixed samples and mobile counter-samples were not coated.

Fixed sample (1) was a disk 35 mm in diameter and 7.5 mm thick. Moving counter-sample (2) was a hollow cylinder whose internal and external diameters were equal, respectively, to 25 and 20 mm. Its end (ring) surface contacted with the flat surface of the sample, creating a ring contact 0.5 cm^2 in area. Eccentric (7) with eccentricity equal to 0.1 mm and rocker arm (5) caused the cylinder to execute reciprocating rotary oscillations around its own axis. Axial loads applied to it created preset pressures acting at right angle at the contact surfaces. This research plant allowed to vary fretting amplitude at contact surfaces from 40 to 200 μm, to change pressure applied at right angles from 10 to 85 MPa and to create oscillation frequency from 200 to 1,000 cycles per minute thanks to using a friction machine drive. An eccentric was used as the top roller in the standard ‘roller to roller’ test procedure. This design allowed us to obtain reciprocating rotary oscillations of moving countersamples and to use measuring capabilities of the friction machine (friction moment and coefficient).

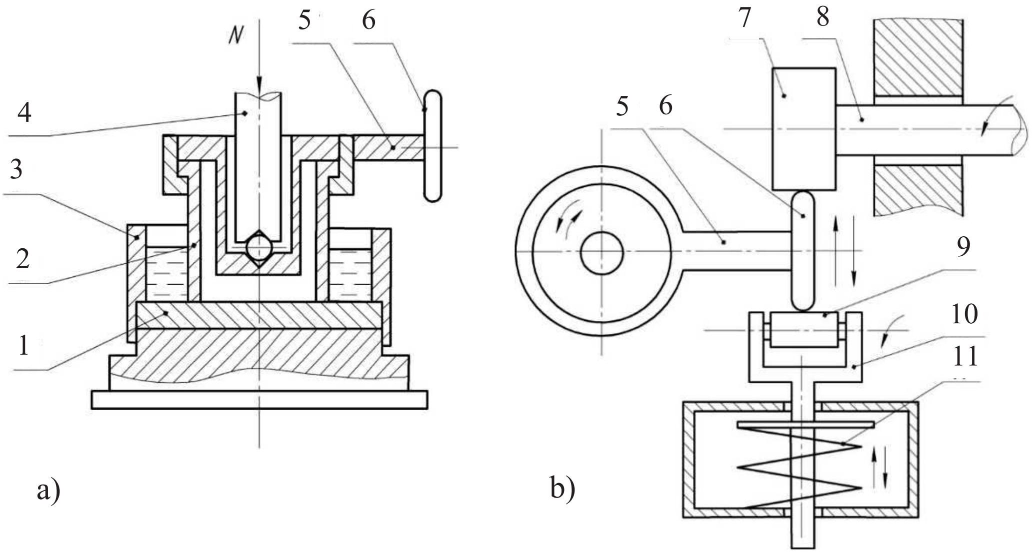

Figure 1. Friction machine FC: a) cross-section, b) top view: 1 – fixed sample, 2 – mobile sample, 3 – liquid process medium cell, 4 – thrust rod, 5 – rocker arm, 6 – roller; 7 – eccentric, 8 – drive shaft, 9 – pressure roller, 10 – fork, 11 – spring.

The linear wear of samples was measued by processing friction track profilograms otained on a standard profilograph-profilometer, mass wear was evaluated by weighing on electronic scales with an accuracy to 0.1 mg before and after tests.

The first series of samples and counter-samples made of grade 15 steel were tested by rotating and reciprocating motion with 100 μm amplitude under 25 MPa pressure and at 900 cycles min^{-1} frequency. The second series of tests was performed on samples made of SCh 25 grade cast iron and grade 15 steel counter-samples with 20 μm displacement amplitude and at 250 cycles min^{-1} frequency under 85 MPa pressure. The number of load cycles for each pair of samples amounted to 5 x 10^5, at least 4 samples with each type of coating have been tested. Wear after tests were assessed by mass change of the samples within the accuracy of 0.1 mg. Linear wear was assessed by friction tracks profile diagram. Friction coefficient was determined by calibration graphs according to resistive strain gauge readings.

The third series of tests compared steel and cast iron samples machined by vibration knurling that created a regular microrelief and processed by grinding. Samples and counter-samples made of grade 20 steel were tested at 20 MPa load and 100 μm oscillation amplitude and 900 Hz oscillation frequency. Samples made of grey cast iron and counter-samples made of grade 20 steel were tested at 87 MPa load and 50 μm oscillation amplitude and 500 Hz oscillation frequency.

The fourth series of tests compared impact of C_{60} fullerene added to lubricating oil and grease in the form of powder containing 2.5% of C_{60} fullerene on fretting wear of steel and brass samples with steel counter-samples during intense mechanical agitation. Brass samples were coated with fullerene as well. Test conditions were as follows: oscillation amplitude 150 μm, oscillation frequency 500 cycles min^{-1}, normal load during tests with lubrication 4.2 MPa, during tests without lubrication 3.2 MPa.

RESULTS AND DISCUSSION

The results of tests of metal samples coated with fluorocarbon polymer compound and friction mechanical brass plating are shown in Fig. 2 in comparison with the uncoated samples data. In Fig. 2, a one can see the results of fretting wear tests of metal samples (where U_l is linear wear, μm; U_m is wear measured by a sample mass change, mg), in Fig. 2, b, the wear of counter-samples, and in Fig. 2, c, the values of established friction coefficients μ. Steel samples were used for tests Nos. 1–3 inclusive, whereupon No. 1 is an uncoated sample, No. 2 is a sample coated with 3–5 μm thick friction mechanical brass plating, No. 3 is a sample coated with 5 μm thick fluorocarbon polymer compound. Samples Nos. 4–6 inclusive were made of cast iron, whereupon sample No. 4 was uncoated, sample No. 5 was coated with friction mechanical brass plating and sample No. 6, with fluorocarbon polymer compound.

As can be seen in Fig. 2, mass wear U_m and linear wear U_l under fretting conditions is reduced several times by all types of coatings under study. Whereupon the fretting friction coefficient values obtained during tests do not correlate to the samples wear data. In the cases under consideration, friction coefficient is even higher than the one of the reference sample. This may be caused by both specific character of strain affecting friction joints under high basic loads under fretting conditions as compared to ordinary sliding friction and the nature of microstructural changes in surface layers of the joint parts. Besides, during model tests under actual loads and displacement amplitudes relatively small contact area of samples (0.5 cm^2) brings about harder fretting conditions than in real joints. This also may increase friction coefficient several times as compared to sliding friction coefficient.

A raster electronic microscopic examination of friction surfaces has been carried out in order to detect the phenomena that reduce fretting wear when effective coatings are used (Bulatov et al., 1994; Krasnyy et al., 2013; Maksarov et al., 2015).

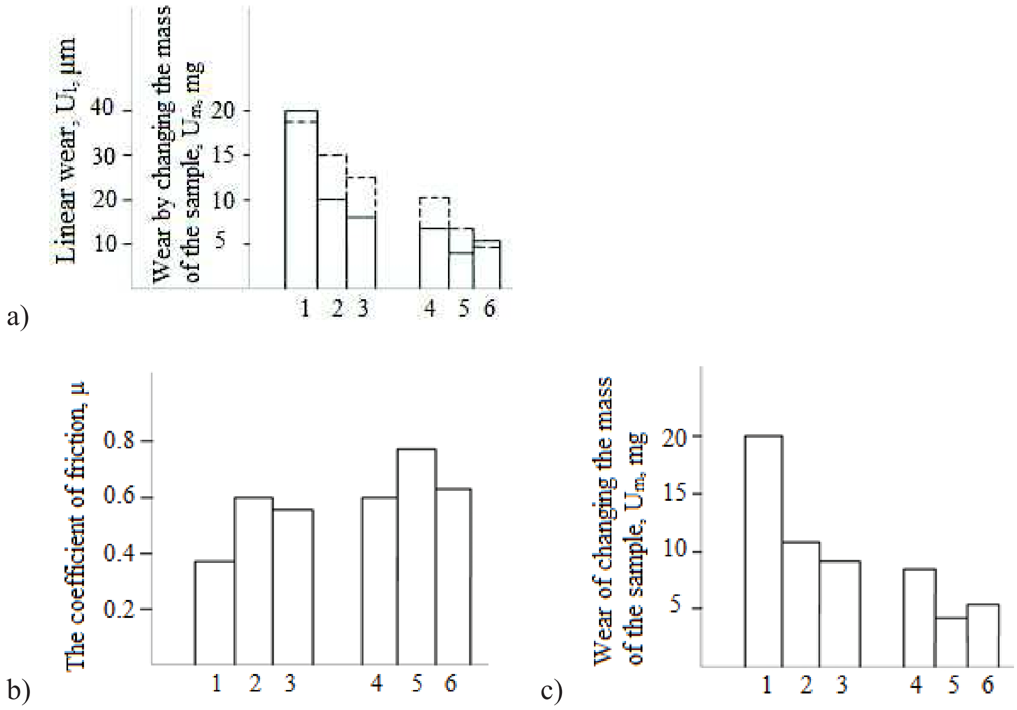

Figure 2. Fretting test results: a) – wear of samples (contour line – mass, dashed line – linear); b) – counter–samples wear; c) – established friction coefficient values; 1–3 – steel specimens: 1 – uncoated; 2 – friction mechanical brass plating, thickness 3–5 µm; 3 – fluorocarbon polymer compound, thickness 5 µm; 4–6 – cast iron samples: 4 – uncoated; 5 – friction mechanical brass plating; 6 – fluorocarbon polymer compound.

Caverns filled with oxidized wear particles observed on friction surfaces of reference steel samples are typical of fretting wear. Oxidization is evidenced by a specific effect of electric charge accumulation on low-conductivity surface of oxidized particles that reduces image contrast and creates an impression of 'fluorescence' under the impact of electron beam. Since such an effect is not observed on the rest of the friction surface, it is believed that wear particles are oxidized after they are formed as a result of interaction between oxygen and the surface of small particles that was activated in the process of friction. I.e. probably the process of corrosion is not related directly to the mechanics of fretting wear, moreover the areas with oxidized particles (Fig. 3, a) occupy a comparatively small part of the total friction area. Areas covered with particles several microns in size without oxidization traces (Fig. 3, b) are also encountered rather often on the 15 grade steel fretting wear tracks; brittle fracture cracks are clearly visible on them. Apparently, those particles are carbide or other inclusions characteristic of steel resulting from perlite interlayers fracture in the process of friction, etc.

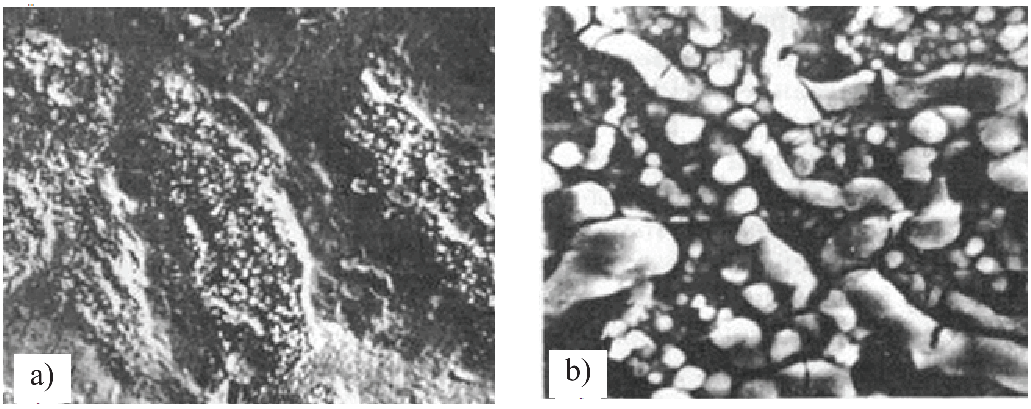

Figure 3. Fretting wear surface (steel): a) – caverns with wear particles, (x 160); b) – particles on the friction surface, (x 2,000).

Application of fluorocarbon polymer compound solution with subsequent drying creates a thin polymer film on the surface. This film protects friction surfaces from oxidization and caving (Fig. 4), a) and somewhat increases the fineness of the particles visible on the surface, preventing their brittle fracture (Fig. 4, a & b).

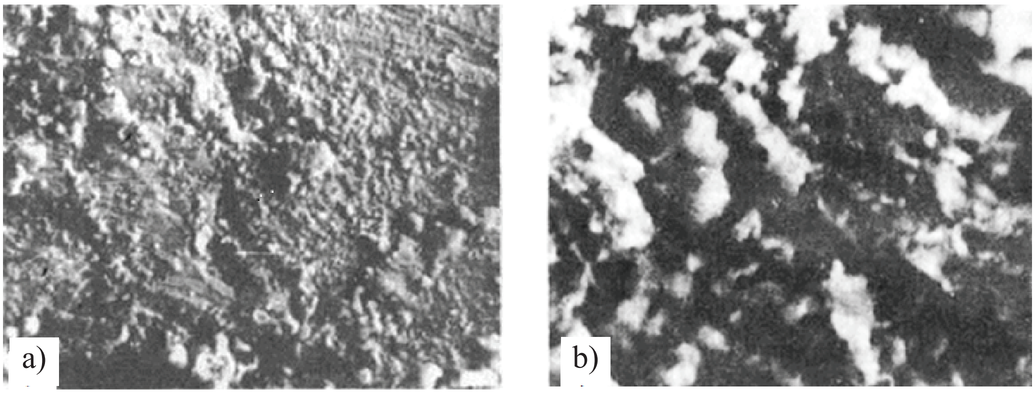

Figure 4. Fretting wear surface (fluorocarbon coated steel): a) – friction surface patch (x 200); b) – dispersed particles on friction surface, (x 2,000).

In this case, microparticles embedded in the polymer film created by the modifying agent may probably act as a fine aggregate in the polymer matrix, forming a composite coating film. Composite polymer materials have shown themselves to advantage as antiwear and antifriction coatings. It is composite coatings with a soft matrix and harder aggregate particles that reduce wear most efficiently, this phenomenon is implemented in the case under consideration as well.

Friction surfaces of friction brass plated samples look somewhat differently. Brass plating creates very smooth layers of brass on the surface of a steel sample. Their adhesion to the surface is poor in some places; there they flake on the friction track during fretting (Fig. 5, a). But more frequently their adhesion is so good that even alligatoring does not bring about flaking and chipping of the brass coating (Fig. 5, b);

this is probably the cause of its efficiency. In Fig. 5, b steel base grains are visible on the fracture surface; they are covered with a plastic, highly porous layer of brass several microns thick. One can see at high magnification that the structure of such a layer consists of separate spherical particles approximately 1 μm large and smaller (Fig. 5, d). Whereupon the highly dispersed structure of the layer created as a result of friction coating application under the impact of high tensions and sliding velocities ensure deformation under the impact of shear stress during fretting by means of mutual rotation and slipping of fine structural elements. Probably, this permits to deform thin subsurface layers of materials without dislocation causing fracture and wear. Implementation of such friction mechanics even at some areas of the contact surface may reduce total wear.

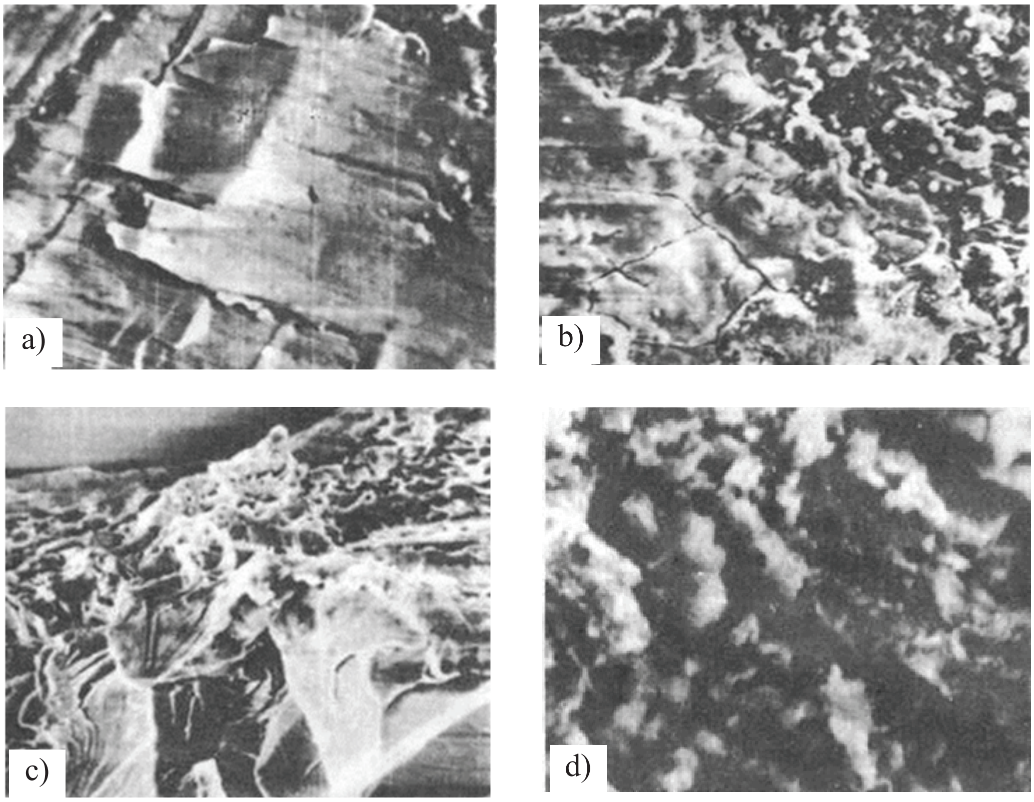

Figure 5. Fretting wear surface (friction mechanical brass plated steel): a) – a layer of brass plating on the friction surface (x 150); b) – alligatored brass plating after fretting (x 300); c) – transverse fracture surface of a plated sample in liquid nitrogen – loose porous brass coating on coarse grain steel base (x 400); d) – a fragment of low-temperature fracture of brass plating with a finely dispersed structure (x 7,000).

Comparative results of tests of vibration knurled and ground samples (in respect of mass and volume wear) after 500,000 cycles are shown in Fig. 6 (1, 2 – steel/steel couple; 3, 4 – cast iron/steel couple; 1, 3 – grinding, 2, 4 – vibration knurling). Vibration knurled samples have shown 30–35% less fretting wear resistance than the ground ones, after lubrication this difference amounts to 25–30% (Bulatov et al., 1994).

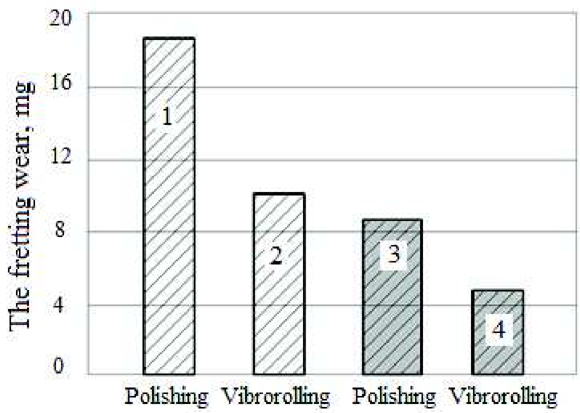

Figure 6. Fretting wear dependence on processing type: 1, 2 – steel samples and counter-samples; 3, 4 – cast iron samples, steel counter-samples; 1, 3 – after grinding; 2, 4 – after vibration knurling.

Vibration knurled samples with a regular microrelief surface have a different wear resistance improvement mechanics. In Fig. 7, b one can see that the friction track surface is broken down into separate facets whose dimensions are comparable with fretting displacement amplitude. No specific surface layers with a structure different from the original steel structure are visible within the borders of single facets, except usual grooves in the sliding direction. Probably, such a faceted nature of the friction tracks bears record to the process of splitting of strain and deformation waves on the surface with a regular microrelief. This process contributes significantly to the fretting effects hardening.

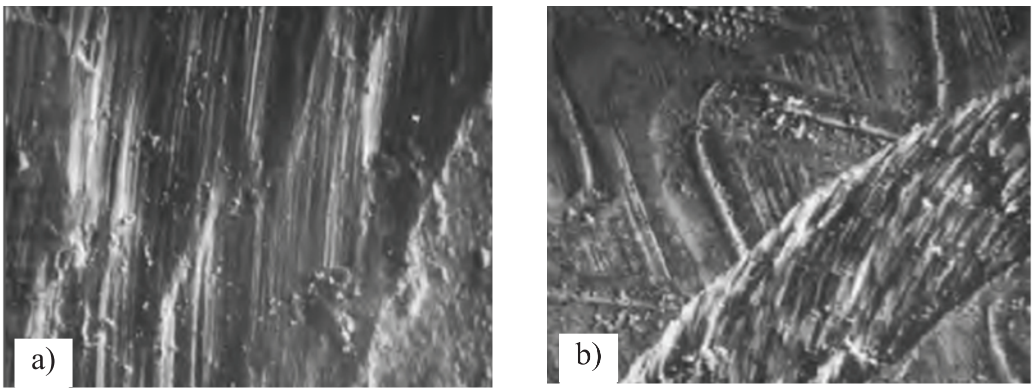

Figure 7. Fretting friction track on steel surface: a) – grinding; b) – vibration knurling.

A combination of the above describe method with application of thin-layer coatings capable of reducing fretting wear even more may be of interest.

The results of tests of C_{60} fullerene additive to lubricating oil and grease presented in Fig. 8 (steel samples and counter-samples) and in Fig. 9 (brass samples and steel counter-samples) demonstrate that introduction of 2.5% powder into lubricating oil reduces fretting wear significantly.

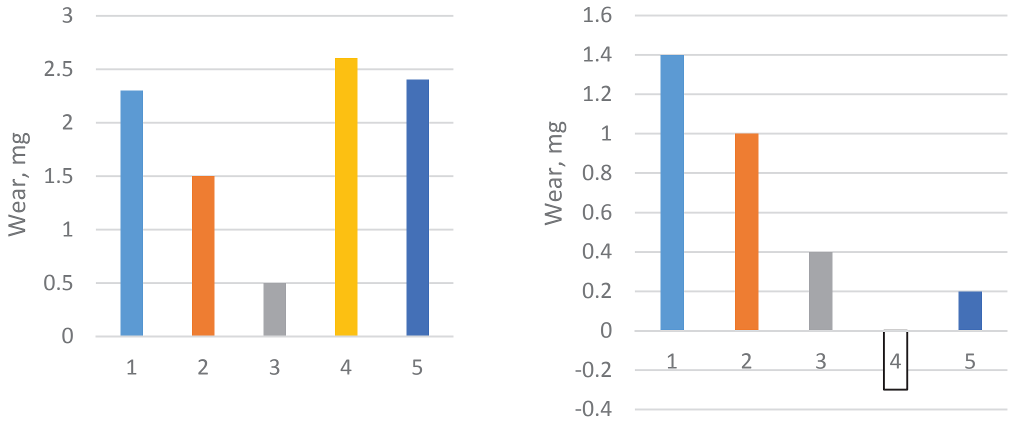

Figure 8. Wear of steel samples and counter-samples: 1 – unlubricated; 2 – VITREA 68 (SCHELL) oil; 3 – VITREA 68 (SCHELL) oil with 2.5% C_{60}; 4 – ALVANIA EP2 (SCHELL) grease; 5 – ALVANIA EP2 (SCHELL) grease with 2.5% C_{60}.

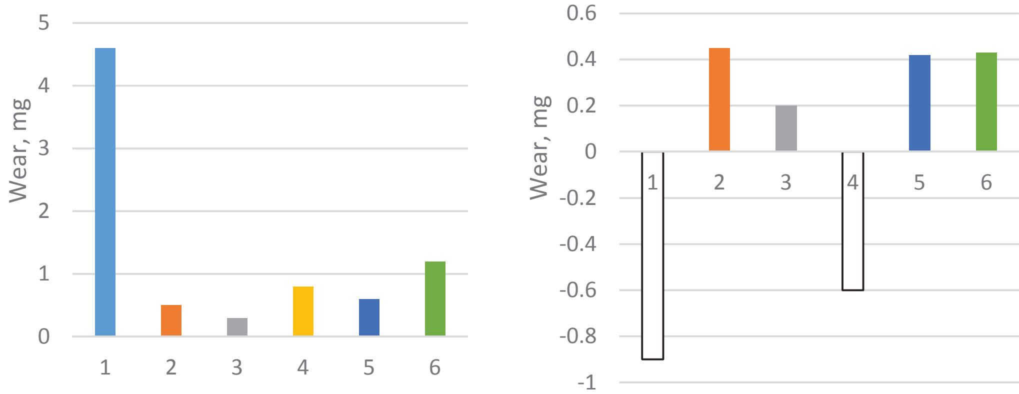

Figure 9. Wear of brass samples and counter-samples: 1 – unlubricated; 2 – VITREA 68 (SCHELL) oil; 3 – VITREA 68 (SCHELL) oil with 2.5% C_{60}; 4 – ALVANIA EP2 (SCHELL) grease; 5 – ALVANIA EP2 (SCHELL) grease with 2.5% C_{60}; 6 – C_{60} coating on a brass sample, dry friction.

Whereupon introduction of analogous powder to lubricating grease proved to be effective only in respect of a combination of brass and steel samples, this is probably caused by high viscosity of grease and its insufficient mechanical stability under shear deformations. In a number of cases wear particles were transferred to the counter-body under study; negative wear values bear witness to that. However, even for such type of lubrication introduction of C_{60} reduced wear as compared to oil without additives (Ginzburg et al., 1997).

Tests of brass samples coated with C_{60} demonstrated that under normal pressure amounting to 4.2 MPa uncoated and unlubricated samples seized and the counter-sample rotation visibly slowed down. Therefore, it was required to reduce load to 3.2 MPa. Rotation slowdown was not observed when a coated brass sample was used. The wear of a coated brass sample was 3 times less than that of an uncoated and unlubricated one, there was no transfer of copper onto the counter-sample. Therefore, it is possible to make a preliminary conclusion that it is effective to use such kind of coatings as a solid lubricant, especially when supplying the friction unit with a liquid lubricant is structurally complex.

CONCLUSIONS

1. As a result of studies of heavily loaded machine part mating protection by fluorocarbon polymer compound, friction mechanical brass plating, it was established that such coatings have the same mechanics of fretting wear resistance improvement in the zone of contact layer of finely dispersed particles thanks to using thin-layer coatings. The presence of such particles may be caused either by structural self-organization of the coating material in the process of friction brass plating, or by creation of a composite polymer coating with fine wear particles when a polymer compound is used. Whereupon the protective coatings considered above virtually exclude the corrosion component of fretting wear.

2. The presence of a regular microrelief improves load-bearing capacity of the surface, facilitates preservation of lubricant in the contact area and removal of wear products. Under the conditions of fretting, regular microrelief facilitates splitting of strain and deformation waves on the surface, improving shear sensitivity and preventing fatigue damage development.

3. Using F_{60} as an additive to lubricating oil and grease, as well as for coating samples facilitates reduction of fretting wear of steel and brass samples, although its use under high contact loads may be only limited.

4. The research performed by us established additional areas of application of thin-layer coatings, including modified polymer compounds and surface vibration knurling method as means of protection against fretting of high-load friction assemblies of machinery. The results of the research may be widely used in production and repair of internal combustion engines, mining machinery, farm equipment and a number of other areas.

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