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Kinetics of boundary layers in non-conformal contact under non-stationary conditions

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Abstract

In this work, the conditions for the formation of adsorbed boundary layers on friction surfaces under rolling with sliding were studied. The tests were carried out according to the roller-on-roller scheme on an SMC-2 rig, the specimens being cylindrical rollers of steel 45 with hardness HRC 32. The studies were performed in the mode of frequent starts and stops: acceleration 4 s, stop 3.5 s, the cycles following one another without pauses. The total rolling speed was 1.91 m/s, the slip 20 %, the contact stress 550 MPa, the total number of operating cycles N = 2350. The lubricant layer thickness was determined by the voltage drop method in the normal glow discharge mode. For the base oil, over the first $N \leq 250$ operating cycles a breakdown of the lubricant layer was recorded in 75 % of the cycles. At $250 \leq N \leq 1000$ an adsorbed boundary layer 0.036 – 1.056 µm thick is formed, and at $N \geq 1280$ the film thickness is 0.150 – 1.524 µm and the frequency of breakdowns decreases on average to 10 % of the cycles. The suspension forms boundary layers more intensively, however their stability is lower: repeated adaptation occurs only at $N \geq 2100$ cycles, the layer thickness in this case being h = 0.130 – 1.620 µm. On 55 % of the contact area chemisorbed films 0.051 – 0.186 µm thick were recorded. A mechanism of the formation and adaptation of boundary adsorption layers on friction surfaces under conditions of frequent starts and stops has been revealed, which consists in the fact that activation of the metal surfaces under multi-cycle action and polarization of hydrocarbon molecules by the electric field of the solid phase initiate the formation of the layer, while its subsequent failure exposes the nascent metal surface, and the escape of electrons from it (exoelectron emission) creates conditions for the formation of anions and radicals and the growth of chemisorbed films. The obtained dependences of the boundary layer thickness on the number of operating cycles make it possible to predict the lubrication regime of non-conformal friction units under conditions of frequent starts and stops and to choose the concentration of the fullerene additive in a justified way.

Key words: friction, lubrication, boundary adsorption layer, chemisorbed film, fullerene C_{60}, lubrication regime, non-stationary conditions, durability.

Introduction

The durability of contacting surfaces in a non-conformal friction unit is to a considerable extent determined by the lubricating film [1].

Its thickness must be greater than the root-mean-square sum of the highest asperities of the friction surfaces. The most favorable conditions occur when a hydrodynamic or elastohydrodynamic film is realized in the contact, at the same time between these two states there lies a transition region with intermediate properties.

It is important to note that the service life of non-conformal friction units in real operating conditions never covers the whole active friction surface of the mating parts, since manufacturing errors, shaft misalignment and initial roughness leave only a third or a half of the nominal area in work. Because of this the actual contact stress can exceed the calculated one, which is able to cause failure of the tribosystem. Therefore the service life of such a friction unit is determined not by a calculation from nominal parameters, but by the ability to maintain the required lubricant layer thickness in the contact.

Literature Review

In unsteady operating regimes boundary friction prevails. The boundary, mixed and hydrodynamic regimes are distinguished by the mechanism of friction in the contact [2]. Under boundary lubrication the elastic and plastic deformation of the substrate is decisive, under mixed lubrication the adsorbed layer of liquid dominates, and under the hydrodynamic regime shear of the lubricant layer takes place between the surface and the asperity.

Under such conditions the interaction of metal surfaces in a lubricating medium is determined by a complex of mechano-physicochemical processes which depend on the composition and properties of the medium [3]. The wear resistance of a polymolecular boundary layer is determined by molecular-kinetic factors, whereas for a monomolecular adsorption layer the strength of the adsorption bond and the kinetics of its restoration on the nascent surface become decisive.

An additive operating under boundary friction conditions must consist of a mixture of different substances. Their molecules must exhibit effective adsorption capacity, which ensures the formation of an adaptive boundary film, at the same time such a film protects the friction pairs from direct contact. Chemisorption provides a stronger interaction with the surface than physical adsorption, and therefore better protects the film from abrasion [4].

In the crystal, fullerene C_{60} molecules are bound by weak van der Waals forces. A calculation by the molecular orbital method shows that the face-centered cubic lattice of fullerite is described by a series of bands which do not overlap. The band width is 1.5 – 1.8 eV, which makes fullerite a semiconductor. The valence band is able to accept no more than six doped electrons.

At $0 < x < 3$, where x is the number of doped electrons, the conductivity of the sample increases with increasing x, while at $x = 6$ the conduction band is filled completely, and the properties of the sample are determined by the structure of the next free band.

The regularities of the formation of boundary layers under lubrication with a fullerene C_{60} suspension in conditions of frequent starts and stops remain unclarified. Among the mechanisms of action of nanoscale additives, the formation of a tribofilm, the rolling effect of spherical particles, the healing of microdefects, surface polishing and a synergistic effect are named [5]. It has not been established how the additive concentration affects the thickness of the adsorption layers and the lubrication regime in a non-conformal contact of point form.

Purpose

To investigate the mechanism of the formation and adaptation of boundary adsorption layers on contacting surfaces under lubrication with I-20 mineral oil and an 18 % fullerene C_{60} suspension in unsteady operating regimes.

To evaluate the role of the activated metal surface and the temperature factor in the formation of boundary films.

Methods

The lubricant layer thickness was determined by the voltage drop method in the normal glow discharge mode. A voltage close to zero corresponds to direct metal-to-metal contact, and its rise corresponds to the presence of an insulating film [6]; electrical methods for assessing the state of the lubricant layer are systematized in the review [7].

In order to establish the lubrication regime in the contact, the dimensionless criterion λ was used, which is determined by the ratio of the lubricant layer thickness to the height of the asperities of the contacting surfaces. The proportion of cycles with breakdown of the layer at standstill was recorded separately.

The tests were performed according to the roller-on-roller scheme on the SMC-2 laboratory rig, the specimens being cylindrical rollers of steel 45 with hardness HRC 32.

The studies were carried out in the mode of frequent starts and stops. The total rolling speed of the test specimens reached 1.91 m/s with a subsequent instantaneous stop.

The recording of the lubricant layer thickness was performed during the start-up period, at the maximum friction torque, under conditions of rolling with 20 % sliding. The duration of one cycle was 7.5 s: 4 s of acceleration and 3.5 s of stop. The cycles were repeated continuously. The total number of operating cycles in the experiment amounted to $N = 2350$ at a contact stress of 550 MPa.

Within the operating cycles up to $N = 1000$ the bulk temperature of the oil was 20 °C, subsequently it gradually increased and at $N \leq 2350$ reached 66 °C.

Results

Formation of boundary layers under lubrication with the base oil I-20

Over the first 250 operating cycles a loss of layer continuity at stop was recorded in 75 % of the cases, which caused the appearance of direct contact without lubricant.

It was established that an increase in the rotational speed of the test specimens leads to an increment of the oil film thickness within 0.360 – 0.420 μm, which is practically independent of the bulk temperature in the contact.

Within the experiment it was recorded that the formation of the boundary layer is ensured by the acquisition of polarity by hydrocarbon molecules in the field of the solid phase and by the activation of the contacting surfaces under cyclic loading. In work [8] it was established that the thickness of the boundary layer, like the distance of interaction of the molecules with the surface, is determined by the field strength of the surface and the energy of thermal vibrations.

In the range of operating cycles $250 \leq N \leq 1000$ the lubricant layer thickness is 0.036 – 1.056 μm. The layer adapts to the variable load, which makes it possible to reduce the proportion of direct contact of the surfaces to 25 % of the starts and stops.

In work [9] it was established that the accumulation and ordering of adsorbed molecules occurs under the action of repeated rolling.

Heating of the oil shifts the balance between the energy of thermal vibrations and the energy of retention of the molecules on the surface. With the predominance of the former, the ordering of the layer is lost, and the proportion of cycles in which the layer was not recorded at standstill increases.

At $N \geq 1280$ operating cycles a repeated restoration of the layer to 0.150 – 1.524 μm is observed, and ruptures of the lubricant film are recorded within 10 % of the starts and stops.

Heating is accompanied by an intensification of the oxidation processes in the friction pair. The joint action of the activated metal surface and the oxidized hydrocarbons causes polymerization reactions, the products of which are fixed on the metal chemisorptively; the thickness of the formed films is 0.059 – 0.148 μm.

The serviceability of the I-20 oil under non-stationary conditions is determined not by viscosity but by the ability to retain the boundary layer (Fig. 1). Up to $N \leq 250$ the boundary regime is realized in the contact; with the growth of the layer it changes to mixed, which is maintained up to $N \leq 1000$.

As a result of heating of the lubricant, the boundary lubrication regime is established. The subsequent restoration of the adsorption films at t = 50 – 66 °C ensures the mixed regime until the end of the experiment.

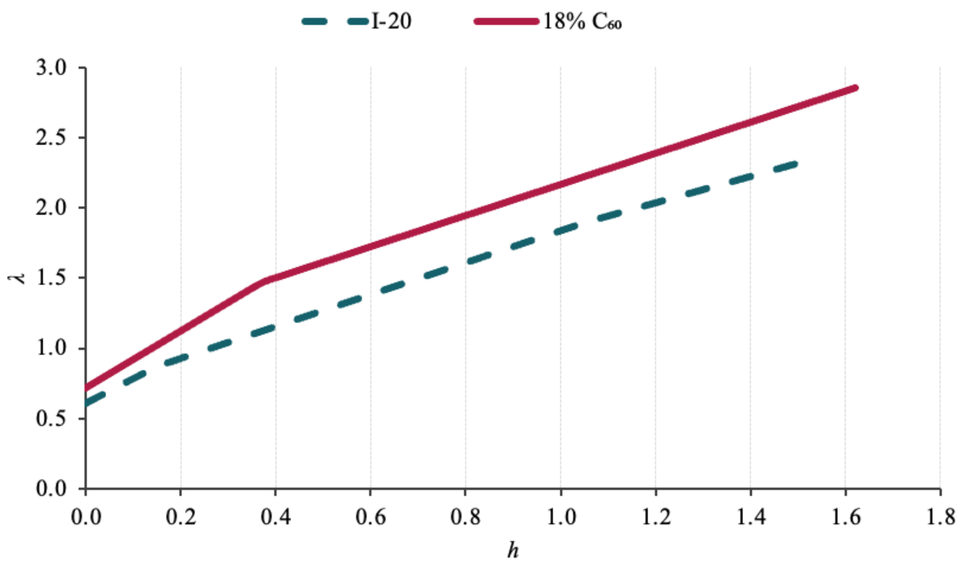

Fig. 1 Dependence of the lubrication regime criterion λ on the thickness of the adsorbed boundary layer h, μm: dashed line – I-20 oil, solid line – 18 % fullerene C_{60} suspension

Effect of the 18 % fullerene C_{60} suspension on the kinetics of the adsorption layers

It was found that the 18 % suspension based on fullerene C_{60} forms boundary adsorption layers more effectively than the base mineral oil I-20 at t = 20 °C. It was experimentally established that at $N \leq 190$ the thickness of the boundary films is 0.063 – 0.371 μm. During the stop, a breakdown of the lubricant layer was found in only 10 % of the cycles.

With an increase in the number of operating cycles of the tribosystem it was established that in 35 % of the cycles the thickness of the layers reaches 0.700 – 1.400 μm, however the formed boundary layers are unstable, which leads to their gradual failure.

The thermal effect in combination with frequent starts and stops causes a disturbance of the stability of the boundary lubricating film and its gradual removal from the contacting areas of the surfaces. Repeated adaptation of the layer occurs at $N \geq 2100$, its thickness in this case being h = 0.130 – 1.620 μm. The low stability of the formed layers is associated with the weak adhesive interaction with the metal surface, as a result of which they are easily removed. A breakdown of the lubricant layer was recorded in 40 % of the cycles.

Fig. 2 shows the state of the contact zone after the formation of the lubricant layer. According to the experimental results, the formation of a chemisorbed film with a thickness of h = 0.051 – 0.186 μm was established, extending over 55 % of the area of interaction of the surfaces.

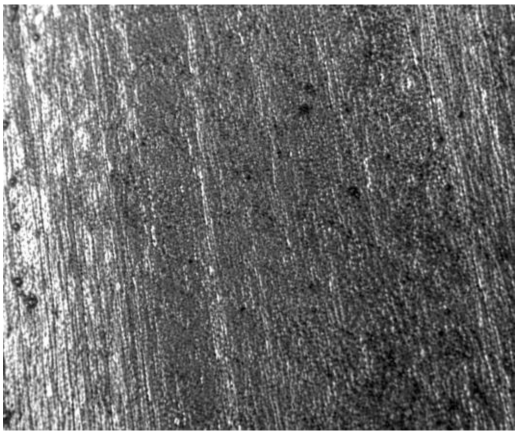

Fig. 2 Friction surface after lubrication with the 18 % fullerene C60 suspension

Lubrication regime and the mechanism of formation of chemisorbed films

With an increase in the number of operating cycles the mixed lubrication regime is realized in 25 % of the cycles ($\lambda \geq 2.860$), whereas at the initial stage of operation of the contact the boundary regime prevails ($\lambda = 0.845 - 1.471$). The established regularities were obtained for multi-cycle dynamic loading in the presence of the fullerene C_{60} additive, Fig. 1.

Chemisorbed films are formed on the friction surfaces, which include resinous products, friction polymers and oxidation products. Their formation is caused by the attachment of activated anions and radicals to positively charged microsurfaces.

The source of these particles is the hydrocarbon components of the oil, which are converted into anions, radical anions and radicals. Under variable loading the adsorption layers are destroyed, and the exposure of nascent areas is accompanied by exoelectron emission. The exoelectrons react with the molecules desorbed from the boundary film, whose reactivity, in view of their activated state, should be the highest.

It can be assumed that two interrelated processes develop in the contact zone. Electrons pass from the metal surface into the conduction band of the semiconductor, whereas polarized hydrocarbon molecules accept them from the valence band. Because of the frequent renewal of the physically adsorbed layers the second of them prevails, and the hydrocarbon molecules play the role of p-type dopants.

The absence of the lubricant layer observed in the stationary state is probably associated with the presence of a fullerene layer as a semiconductor phase, which is retained on the contact surface. Under optical magnification this layer becomes noticeable. The experimentally confirmed ability of the I-20 oil to form chemisorbed films is consistent with known data. The polarization of aromatic hydrocarbons by the electric field of the solid phase with the subsequent formation of friction polymers was described earlier [1]. The layer of spherical fullerene C_{60} molecules polymerized on the surface reduces the shear resistance of the crystallites in the tangential direction. Together with the intensity with which the hydrocarbon components of the oil form the film, this determines the stability of the boundary layers upon the introduction of an additive with a layered structure of the crystal lattice.

With a significant cohesive component of the interaction of the polarized molecules, failure of the adsorption layer becomes less probable.

Conclusions

It has been established that the start-stop mode leads to activation of the friction surfaces, which initiates the formation of boundary adsorption layers and their subsequent adaptation to the variable load. The mechanism of this process is the polymerization of the hydrocarbon components, characteristic both of I-20 and of the 18 % fullerene suspension.

A comparison of the lubricating media showed that at the initial stage of the operating cycles the suspension provides a substantially more stable boundary layer: a breakdown was recorded in 10 % of the cycles against 75 % for the base oil. With further operating cycles the ratio changes to the opposite, and a breakdown of the suspension layer is observed in 40 % of the cycles against 10 % for the oil, which indicates the predominantly physical nature of the layers formed by it.

It follows from this that the concentration of the fullerene additive is a means of controlling the composition of the boundary layer, and the maintenance of a stable lubrication regime under unsteady operating conditions ensures the durability and reliability of non-conformal friction units.

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Турица Ю., Ахматов В. Кінетика граничних шарів у неконформному контакті в умовах нестаціонарного режиму

У роботі досліджено умови утворення адсорбційних граничних шарів на поверхнях тертя в умовах кочення з проковзуванням. Випробування проводили за схемою ролик-ролик на установці СМЦ-2, зразками слугували циліндричні ролики зі сталі 45 твердістю HRC 32. Дослідження виконували в режимі частих пусків-зупинок: розгін 4 с, зупинка 3.5 с, цикли слідували один за одним без пауз. Сумарна швидкість кочення становила 1.91 м/с, проковзування 20 %, контактна напруга 550 МПа, загальне напрацювання N = 2350 циклів. Товщину змащувального шару визначали методом падіння напруги в режимі нормального тліючого розряду. Для базової оливи на перших $N \leq 250$ циклах напрацювання зафіксовано зрив змащувального шару в 75 % циклів. При $250 \leq N \leq 1000$ формується адсорбційний граничний шар завтовшки 0.036 – 1.056 мкм, а при $N \geq 1280$ товщина плівки складає 0.150 – 1.524 мкм і частота зривів знижується в середньому до 10 % циклів. Суспензія формує граничні шари інтенсивніше, проте їх стійкість нижча: повторна адаптація настає лише при $N \geq 2100$ циклів, товщина шару при цьому складає h = 0.130 – 1.620 мкм. На 55 % площі контакту зафіксовано хемосорбційні плівки завтовшки 0.051 – 0.186 мкм. Виявлено механізм утворення й адаптації граничних адсорбційних шарів на поверхнях тертя за умов частих пусків-зупинок, який полягає в тому, що активація поверхонь металу при багатоциклових діях і поляризація вуглеводневих молекул електричним полем твердої фази запускають формування шару, а подальше його руйнування оголює ювенільну поверхню металу, і вихід електронів з неї (екзоелектронна емісія) створює умови для утворення аніонів і радикалів та наростання хемосорбційних плівок. Одержані залежності товщини граничного шару від напрацювання дозволяють прогнозувати режим мащення неконформних вузлів тертя в умовах частих пусків-зупинок та обґрунтовано обирати концентрацію фулеренової присадки.

Ключові слова: тертя, мащення, граничний адсорбційний шар, хемосорбційна плівка, фулерен C_{60}, режим мащення, нестаціонарні умови, довговічність.

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