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Analysis of Temperature Fields at High-Speed Friction of Inorganic Materials to Control their Friction-Induced Thermal Fatigue

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Temperature distribution in thin surface layers of rubbing bodies has been studied experimentally at high sliding velocities. The material of the surface layers is shown to undergo severe thermal loading. Temperature distribution comprising two portions, which differ in temperature gradients, is typical for the mated materials having substantially different hardnesses and for similar materials with strong adhesion at the interface. The existence of a subsurface heat source has been proved. Temperature distribution having a maximum under the friction surface of one of the pair's elements has been registered for the silica glass – steel pair. Optical-electron scanning technique has been modified and used for the experimental study of temperature distribution in depth of thin surface layers of rubbing bodies at high sliding velocities. A method for determining temperature fields in the zone of machining of hard inorganic materials has been developed and used.

Keywords: friction, friction-induced thermal fatigue, temperature, temperature distribution, surface layers, thermal properties, plastic deformation, adhesion.

1. INTRODUCTION

The repeated simultaneous thermal and mechanical loading of mated materials at friction and machining causes friction-induced thermal fatigue. The latter appears as cracks on the material surfaces due to the accumulation of irreversible transformations occurring in the materials. When machining such inorganic materials such as diamond, silicon, and ceramics thermal phenomena play a leading role in their failure, which results mainly from thermal cracking. So, the lack of data on temperature fields in the zone of cutting of natural diamond monocrystals increases rejects by 5 – 7 %. Therefore, information on temperature fields in the zone of contact between a tool and a material being cut is necessary to use effectively such materials and to improve the quality of articles made of them.

Thermal processes in the zone of cutting of hard inorganic materials deserve comprehensive study. Experimental investigations carried out using thermocouples [1] and thermography methods [2, 3] give data for estimating average surface temperature of the material being cut. However, the most share of liberated heat is localized within the surface layers adjacent to contact spots. It is the share, which governs the mode and rate of material failure. So, the study of temperature distribution in depth of surface layers of mated materials is of practical importance. These studies are also vital for theoretical research in friction heat problems whose background is an assumption of the location of a heat source. To calculate correctly a friction unit it is necessary to know heat partition factor. This implies the study of the distribution of heat between the friction parts.

So, the study of processes of heat energy generation and distribution in thin surface layers of rubbing bodies at high sliding velocities is a challenging task to be solved to refine our understanding of the wear of the materials susceptible to thermal cracking and to improve their wear resistance as well as to propose methods of control of thermal conditions at high-speed operation of friction units.

The aim of the present study is to find regularities of thermal processes in thin surface layers of inorganic materials at high-speed friction to reduce their friction-induced thermal fatigue.

2. EXPERIMENTAL TECHNIQUE

Steel, titanium, aluminum, silica, aluminum-boron silicate, and sodium-boron silicate glasses were used to make a rotating member of a friction pair. The stationary member was made of sapphire, silica glass, and steel. Sapphire and glass were selected for their different structure and thermal properties hence different resistance to friction-induced thermal fatigue. Mechanical and thermal characteristics of the materials under testing are listed in the Table 1.

The pin-on-disc geometry was used to study temperature distribution in depth of rubbing bodies.

P, *V* – conditions were as follows: sliding velocity was varied from 0 to 80 m/s, nominal pressure ranges from 0.06 to 0.1 MPa.

Thermal processes were studied using the system incorporating an objective lens, an optical scanner, a monitoring device, a video tape-recorder, an amplifier, a device to form oscillograms of image brightness, and a digital oscillograph. Both IR-scanner "Thermovision-470" equipped with an additional optical system and TV camera served to investigate temperature field in the friction zone.

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Table 1. Mechanical and thermal characteristics of the materials being tested

Material	Hardness, MPa	Elasticity modulus, 10^5 MPa	Melting point, K	Heat conductivity Wt/(m·K)
Steel	1300	2	1807	73
Titanium	1900	1.3	1943	30
Aluminum	270	0.62	933	217
Sapphire	20140	3.8	2323	27
Aluminum-boron silicate glass	73	0.5	1595	0.79
Sodium-boron silicate glass	68	0.47	1673	0.87
Silica glass	83	0.7	2073	0.69

Temperature distribution across a single hot spot was obtained by selecting a line on the monitor which corresponded to the required section (by the "stopframe" mode) forming a signal oscillogramm of the line with respect to the zero-level of the line synchropulse. Temperature distribution along the spot length was obtained by an oscillogramm formed as a result of selecting instantaneous values of the signal of each line corresponding to a preset synchropulse duration. The measuring system was calibrated before and after each experiment in order to monitor the error introduced into temperature readings by the transfer film on the counterbody.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Temperature distribution in depth of rubbing bodies

Distribution of temperature in depth of friction member surface layers and the position of the distribution curve maximum are governed by the properties of mated materials and load and velocity conditions. So, when a silica glass stationary specimen rubs against titanium rotating one the dependencies of the temperature under the glass friction surface on the depth are represented as monotonous curves (Fig. 1, curve 1). This proves that heat is generated within a very thin (a few micrometers thick) surface layer of glass.

The pair silica glass – aluminum alloy also demonstrates the dependencies without subsurface temperature maxima within the whole load and velocity range being tested.

At $V \leq 45$ m/s the temperature distribution in depth can be conventionally divided into two portions (Fig. 1, curve 2); temperature gradients for the portions can differ several times. The thickness of the intensively heated and deformed surface layer can be roughly estimated by the position of the conventional boundary between the steeper and more flat portions of the curve. The thickness decreases with decreasing nominal pressure and increasing sliding velocity. This can be attributed to the less deep penetration of counterface asperities into the glass surface layer and shorter lifetime of friction junctions.

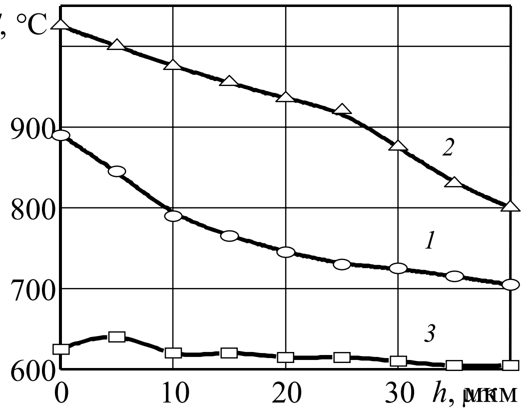

Fig. 1. Temperature distribution in depth of the silica glass stationary specimen rubbing against titanium (1 – $V = 18$ m/s), aluminum (2 – $V = 22$ m/s), and steel (3 – $V = 20$ m/s); $p_a = 0.1$ MPa

At $V > 45$ m/s the flat length of the distribution curve is not registered because plastic deformation is localized within very thin surface layers of glass.

In this friction pair silica glass contacts mainly with an alumina film whose microasperities deform the surface layer of much softer glass. Therefore, deep layers are involved in the process of deformation and heat is generated within the whole volume being deformed. So, we can conclude than both surface and volume heat sources exist in this case; the latter source is located within a softer material and has the surface temperature maximum.

The volume heat source also acts when both mated materials have approximately the same hardness, i.e. when the stationary specimen is made of silica glass and the rotating one is made of silica, aluminosilicate or sodium-silicate glasses. The dependencies of the temperature on the depth for these pairs also contain two portions with substantially different temperature gradients. Because of strong adhesion in these pairs the fracture of friction junctions occurs predominantly beneath the interface, in the bulk of one of the bodies. This is proved by the presence of crater-like dimples on the glass friction surface. Hence, the heat generated at junction fracture is registered in the region, which lies under the interface. The length of the flat portion of the distribution curve increases as the pressure rises and the velocity decreases.

Temperature distribution having a subsurface maximum is typical for the silica glass – steel pair. So, the maximum is located approximately 5 μm beneath the glass friction surface (Fig. 1, curve *3*). At $V \leq 20$ m/s the friction coefficient f for this pair is below 0.25. Saverin's theoretical studies show that in this case the zone of maximal tangential stresses lies under the surface, at a depth of 10 – 12 μm taking into account that the average diameter of a contact spot equals 25 – 30 μm within the tested load and velocity ranges. Therefore, we can suppose that maximum heat generation runs under the glass surface, in the zone where tangential stresses are maximal.

The friction coefficient rises with increasing velocity and the zone of maximal tangential stresses approaches the glass friction surface. Because of this heat is generated within a very thin surface layer of the material at higher velocities and the dependence of the temperature on the depth becomes monotonically decreasing.

When the pressure is increased the difference between the surface and the subsurface temperatures rises. This proves a higher share of subsurface heat generation. The point where the temperature is maximal shifts inward the glass specimen. Further pressure increase causes the rise of the friction coefficient; the temperature decreases monotonically.

3.2. Influence of heat transfer into friction parts and environment on temperature field

Temperature distribution in depth of the stationary (plate) and rotating (disc) members of the friction pair (Fig. 2) made of silica glass has been studied at various velocities and pressures. Distribution curves *T*(*h*) for both the disc and the plate are similar despite the fact that conditions of cooling of the mated materials differ. Since similar materials are in contact, both the disc and plate materials are deformed plastically before single adhesion bonds rupture. Therefore, in both parts heat is generated in a volume beneath the material friction surface and temperature distribution in depth is divided into two portions with different temperature gradients along the normal to the surface (Fig. 2, *b*). As the sliding velocity increases the material volumes being deformed adjacent to adhesion bonds apparently decrease in size and the flat portion of the *T*(*h*) curve is not registered (Fig. 2, *a*).

Values of the temperature gradient along the normal to the friction surface for the rotating disc may exceed by 50% the values for the stationary specimen despite the fact that both materials have equal heat conductivity. The reason is that the disc material near the friction surface is “cool” when entering the contact zone while the plate material is continuously heated.

Comparison of experimental data on the flash temperature and those calculated by Blok formula for a circular heat source sliding over a hemi-space at a high velocity (Peclet number $Pe > 8$) has shown that experimental values exceed calculated ones. Probably, the reason is that Blok theory [4] does not take into account some factors which may influence significantly the flash temperature, viz.: the dependence of material thermal properties on temperature; the elliptical shape of contact spots; the presence of films on friction surfaces whose heat conductivity is less than that of the base material; occurring of tribochemical reactions at contact spots activated by mechanical stresses and temperature.

To account for the elliptical shape of the spots the flash temperature was calculated by D. Kuhlmann-Wilsdorf formula [5]. The more elliptical are the contact spots (the ellipticity rises in the following order: silica glass – titanium, silica glass – steel, and silica glass – aluminum) the more pronounced is the effect of the shape on the flash temperature.

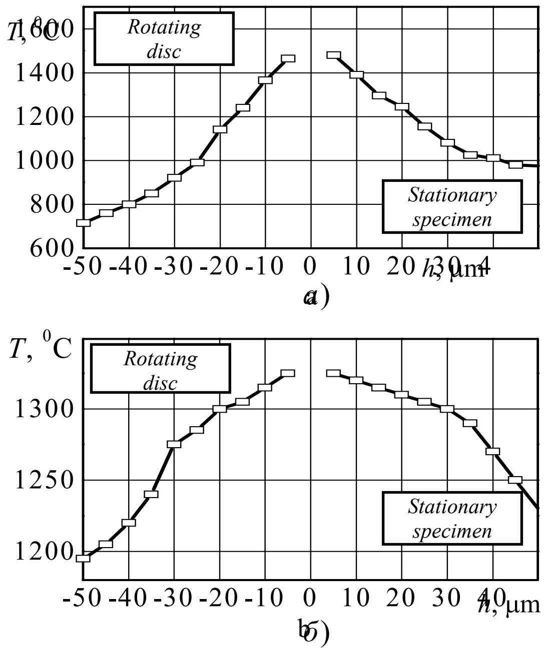

Fig. 2. Temperature distribution in depth of the members of the silica glass – silica glass friction pair at $p_a = 0.1$ MPa, $V = 50$ m/s (*a*) and $p_a = 0.3$ MPa, $V = 20$ m/s (*b*)

For friction parts different glasses – silica glass the experimental dependence of the flash temperature on the disc material heat conductivity is monotonously decreasing like the calculated dependence. Everything else being equal (heat generation rate is equal, no effects caused by oxidation and films occur, contact spot shapes are similar), we can study the influence of the material heat conductivity on the contact spot temperature.

4. CONCLUSIONS

1. Temperature distribution of thin surface layers of rubbing bodies has been experimentally studied at high sliding velocities. It has been shown that the process of heat generation spans surface layers tens micrometers thick (the silica glass – aluminum pair) when the mated materials have significantly different hardness. This is explained by the penetration of plastic deformation to a high depth into the softer material of the pair. Similar pattern of heat generation is typical for the contact of like materials (glass – glass pairs) and can be attributed to plastic deformation induced by strong adhesion and being spread over thick material layers. As the normal load increases the depth of the volume heat source rises while with increasing velocity it decreases.
2. A subsurface heat source may exist in the silica glass – steel pair. The source has a temperature maximum below the glass friction surface. With increasing velocity $V > 20$ m/s it transforms to the surface source.
3. The descending dependence of the contact spot temperature on the heat conductivity of the mated materials agreed well with a theoretical viewpoint has

been experimentally proved for non-oxidative materials (glass – glass pairs). In case of glass – metal pairs the dependence may be of different pattern that is owing to the contribution of heat effect of metal oxidation reactions into heat generation and to the influence of oxide film properties on heat transfer into the bodies in contact.

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