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# TEMPERATURE DISTRIBUTION IN SURFACE LAYERS OF RUBBING SOLIDS

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***Abstract***

*The aim of the study is to propose a modified method of determining temperature distribution in thin surface layers of friction members and obtain data on the temperature, its gradient and distribution in depth of the layers. The optical-electron scanning technique was used to study temperature distribution in depth of rubbing bodies. The material of surface layers is shown to undergo severe thermal loading (the temperature gradient along the normal to the interface reaches $10^4$ K/mm). Three kinds of temperature distribution in depth of the material have been registered and the existence of a subsurface heat source has been proved.*

***Key words:*** *temperature, temperature distribution, temperature gradient, heat source*

## 1. INTRODUCTION

The repeated simultaneous thermal and mechanical loading of mated materials at friction and machining causes friction-induced thermal fatigue. It appears as cracks on the material surfaces due to the accumulation of irreversible transformations occurring in the materials. When machining such inorganic materials as diamond, silicon, and ceramics thermal phenomena play a leading role in their failure which results mainly from thermal cracking. For example, the lack of data on temperature fields in the zone of cutting of natural diamonds increases rejects by 5 – 7%. Therefore, the knowledge of temperature fields in the zone of contact between the tool and 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 abrasive machining of hard inorganic materials deserve comprehensive study. Experimental investigations carried out using thermocouples [1] and thermography methods [2, 3] give data for estimating the average surface temperature. 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 tribological heat problems based on the assumption of heat source location. To predict the operation of a friction unit it is necessary to know the heat partition factor. This implies the study of the distribution of heat between the friction members.So, the study of the 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 materials susceptible to thermal cracking and to improve their wear resistance as well as to propose methods of controlling 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 sliding velocities to reduce their friction-induced thermal fatigue.

## 2. EXPERIMENTAL TECHNIQUE

The geometry like “plane-on-plane” is used when measuring temperature distribution in depth of rubbing bodies. A sapphire plate 1 mm thick or a glass one 3 mm thick contacts the flat surface of a rotating metallic or glass disc 7 mm thick and 180 mm in diameter.

The set-up developed to study temperature fields in the friction zone consists of two main units which are a high-speed friction machine and a system of temperature field registration. The friction machine allows the sliding velocity to be smoothly varied within 1-100 m/s range. The friction coefficient is measured by strain gages connected to an amplifier transmitting the signal to an oscillograph.

The registration system incorporates an optical-electron transducer (OET), a monitoring device (MD), a video tape-recorder (VTR), an amplifier (A), a device to form oscillograms of image brightness (DFO), and a digital oscillograph (DO).

The optical-electron transducer comprises a turret head, an accessory lens fastened to the head, and a TV camera whose optical axis coincides with the lens axis. The transducer is locked to a rack which makes it possible to move the transducer in the vertical and horizontal directions.

The monitoring device is a TV monitor with the low-frequency signal connected to OET through an amplifying and commutating unit.

Heat radiation induced in the friction zone passes the lens then the camera generates the electric signal. The latter is converted into the high-frequency signal and input in MD forming a TV image of the contact zone. The image is recorded by VTR. DFO connected to VTR output forms the image brightness distribution along two sections (for example, along and perpendicular the sliding direction) which is displayed by DO as the signal in millivolts.

With the test geometry used it is possible to determine the temperature under the surfaces of both stationary and moving specimens. The temperature is measured along the marker line perpendicular to the sliding direction. The marker line can be moved along the sliding velocity over the image of the contact area site being examined [4]. In reality the profiles of the mated surfaces are not seen since the linear resolution of the measuring system is 5 μm that is by an order or two larger the profile arithmetic average roughness. Thus, we fail to determine the marker line location whether it is within the contact spot or between the spots. The section of the friction track corresponding to the marker position may contain several spots hence the temperature averaged over these spots is registered.

The measuring system is calibrated with a pyrometer which is used as a standard radiation source and mounted in the visual field of OET instead of the friction pair. The brightness temperature of the source is converted into the real temperature with account for the reflection capacity of the materials under study. The mean error of subsurface temperature measurement is about 2%.

## 3. RESULTS AND DISCUSSION

The distribution of the temperature in depth of friction member surface layers and the position of the distribution curve maximum are governed by the properties of the mated materials and the load and velocity conditions. When the silica glass stationary specimen rubs against the titanium rotating disc the dependencies of the temperature under the glass 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 silica glass – aluminum pair also demonstrates the dependencies without subsurface

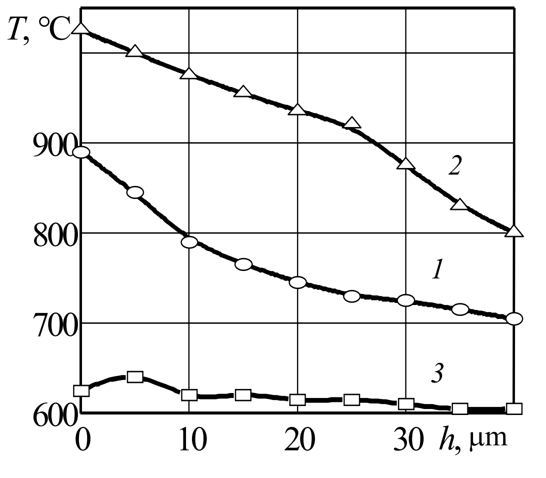


**Fig. 1:** *Temperature distribution in depth of silica glass stationary specimen rubbing against titanium (1, V = 18 m/s), aluminum (2, V = 22 m/s), and steel (3, V = 20 m/s) discs;*

temperature maxima within the whole load and velocity range being used. At the velocity ≤ 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 severely 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. It diminishes with decreasing nominal pressure and increasing sliding velocity. This can be attributed to a less deep penetration of counterface asperities into the glass surface layer and a shorter lifetime of friction junctions.

At the velocity > 45 m/s the flat portion of the distribution curve is not registered because plastic deformation occurs within very thin surface layers of glass.

In this friction pair silica glass contacts mainly with the 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 is located within the softer material and produces the surface temperature maximum.

The temperature distribution having a subsurface maximum is typical for the silica glass – steel pair. The maximum is located approximately 5 μm beneath the glass friction surface (Fig. 1, curve *3*). At the velocity ≤ 20 m/s the friction coefficient for this pair is below 0.25. Saverin's studies [5] 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 used load and velocity ranges. Therefore, we can suppose that maximum heat generation occurs 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 descending.

When the pressure is increased the difference between the surface and 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 friction coefficient to grow and the temperature to decrease monotonically.

The 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. The distribution curves for both disc and plate are similar despite the fact that conditions of cooling of their materials differ. Since similar materials are in contact they are deformed plastically before single adhesion bonds rupture. Therefore, in both members heat is generated in a volume beneath the material friction surface and the temperature distribution in depth is divided into two portions with different temperature gradients along the normal to the interface (Fig. 2, *b*). As the sliding velocity increases, the material volumes being deformed adjacent to adhesion bonds apparently become smaller and the flat portion of the distribution curve is not registered (Fig. 2, *a*).

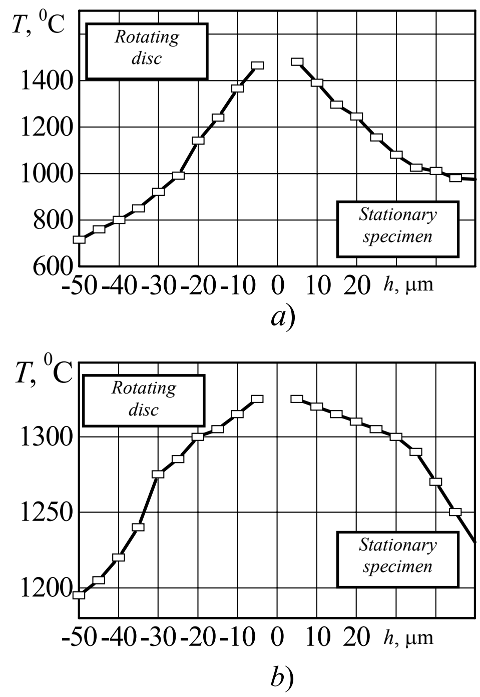


**Fig. 2:** *Temperature distribution in depth of members of silica glass – silica glass pair at $p_a$ = 0.1 MPa, V = 50 m/s (a) and $p_a$ = 0.3*

The temperature gradient along the normal to the interface for the rotating disc may exceed by 50% that for the stationary specimen despite the fact that both materials have the same heat conductivities. The reason is that the disc material near the friction surface is "cool" when entering the contact zone while the plate material is being continuously heated.

## 4. CONCLUSIONS

1. The temperature distribution in thin surface layers of rubbing bodies has been experimentally studied at high sliding velocities. It has been shown that heat generation occurs in surface layers tens micrometers thick (the silica glass – aluminum pair) when the hardnesses of the mated materials are much different. This is explained by the penetration of plastic deformation deeper into the softer material of the pair. A similar pattern of heat generation is typical for the contact of like materials (the glass – glass pair) and can be attributed to the 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 it decreases with increasing velocity.

2. A subsurface heat source may exist in the silica glass – steel pair. It has the temperature maximum below the glass friction surface and with increasing velocity > 20 m/s transforms to the surface source.

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