DIMENSIONS AND KINETICS OF LOCAL HEAT SOURCES IN RUBBING SOLID CONTACT

P.N. BOGDANOVICH and V.M. BELOV
Belarus State University of Transport
34 Kirov St., Gomel, 246653 BELARUS

D.V. TKACHUK*
V.A. Belyi Metal-Polymer Research Institute of National Academy of Sciences
32a Kirov St., Gomel, 246050 BELARUS
e-mail: dvtkachuk@inbox.ru

The paper describes the technique for studying the kinetics of thermal processes on real contact spots. Experimental results are presented. The effect of the load on the size distribution of hot spots (sources of heat radiation) is shown. The sliding velocity, surface topography and materials used are shown to influence the number, size, and life of the spots. The ratios of mean dimensions and total area of hot spots to those of the spots making up the real contact area are analyzed.

Key words: friction, frictional heating, high temperature.

1. Introduction

It is common knowledge that in friction materials are subjected to pulse thermal and mechanical loads within real contact zones. A combined effect of these loads and their concentration in small volumes intensify different processes. Among the processes are the motion of dislocations, surface fragmentation, and the formation of microcavities. Active centers, i.e. reactive macroradicals, are generated in polymers and polymer-based materials forming new structures which differ from the initial structures in the crystallinity and cross-linking degrees. With time bonds are gradually breaking under the effect of excessive stresses and weakened by thermal motion. As a result, microdefects appear, propagate, and the surface layer undergoes damage. Particles separated from the basic material are either transferred onto the counterface or removed from the contact zone.

The rates of these processes, their direction and severity, hence the wear rate, depend on the energy state of material microvolumes in the vicinities of real contact spots. Therefore, it is of interest to understand high-speed thermal and mechanical processes affecting the material in the microvolumes and to study their contribution to material failure. The stress-strain state of the friction zone and its effect on the wear of solids were studied in detail earlier (Kostetskii, 1970; Kragelskii *et al.*, 1982). As for thermal processes, they were mainly considered theoretically by Blok who had highlighted the flash temperature concept (Blok, 1937) and paved the way for further research in this field and for other tribologists (Schedrov, 1965; Korovchinskii, 1966; Chichinadze, 1967; Kuhlmann-Wilsdorf, 1987; Archard and Rowntree, 1988). Experimental measurements were primarily performed of the maximum temperature of contact spots and its dependence on P, V -conditions. The temperature was determined based on structural transformations occurring in material surface layers (Starchenko *et al.*, 1989) or by special thermocouples, photocells or infrared transducers capable of providing the integral characterization of radiation from many spots (Dow and Stockwell, 1977; Ghasemi, 1993). The geometry and temperature of local heat sources for sapphire – steel pairs can be studied using a high-speed camera with an exposure time of *4 ms* (Quinn and Winer, 1988). The

* To whom correspondence should be addressed

most probable diameter and life period were found for the spots emitting heat energy, however, a precise estimate of the temperature by the comparison of photographed colours of the heated reference material and contact spots depended, as the authors pointed, on the exposure time during filming and the quality of the photos made.

The current paper describes the experimental results regarding the geometry of emitting spots, regularities of its variations when changing the load and velocity, and the kinetics of thermal processes occurring at the friction interface.

2. Test method

Steel, copper, aluminum, and sapphire were the objects of the study. The specimens were arranged so that the lateral surface of a rotating metal disc contacted the flat surface of a stationary sapphire plate. The dimensions of the specimens were as follows: the metal discs were *180 mm* in diameter and *7 mm* thick; the sapphire plate was *18 mm* in diameter and *1 mm* thick. The initial arithmetic average roughness was $0.02\text{-}0.05\ \mu m$ for the sapphire plate and $0.4-0.6\ \mu m$ for the metal discs.

The developed set-up intended to study thermal processes in the friction zone (Tkachuk and Bogdanovich, 2004a, b) consists of two basic units, namely a high-speed friction machine and a system of temperature field registration (Fig.1). The friction machine allows the sliding velocity to be smoothly varied within the $1-100\,m/s$ range. In the present study, the velocity reached $60\,m/s$, the normal load was up to *2.5N*. The friction coefficient was recorded by the strain gages connected to an amplifier transmitting the signal to an oscilloscope.

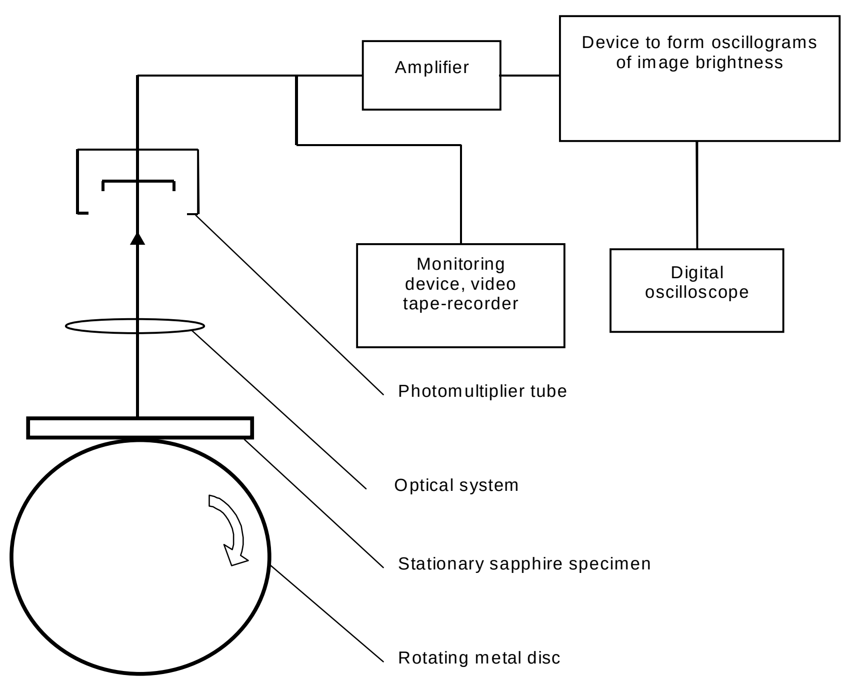

Fig.1. Schematic diagram of set-up used to study local heat sources in high-speed friction contact.

The temperature field registration system incorporates a photomultiplier tube, a monitoring device, a video tape-recorder, an amplifier, a device to form oscillograms of image brightness, and a digital oscilloscope.

The photomultiplier tube comprises a turret head, an accessory lens (magnification *4–25´*) fastened to the head so that to adjust it in the vertical direction, and a TV camera whose optical axis coincides with the lens axis. The tube is locked to a special rack which makes it possible to move the tube in the vertical and horizontal directions and to rotate it through *90 deg*.

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

Heat radiation induced in the friction zone passes the lens, then the TV camera generates an electric signal. It is converted into a high frequency signal and inputs the monitoring device forming a TV image of the contact zone. The image is recorded by the video tape-recorder. The device to form oscillograms of image brightness connected to the video tape-recorder output produces the image brightness distribution along two sections (for example, along and across the sliding direction). The distribution is displayed by the digital oscilloscope as the signal in millivolts.

The set-up was calibrated with an optical pyrometer which served as a standard radiation source and was mounted in the visual field of the photomultiplier tube instead of the friction pair. The brightness temperature of the source was converted into the real temperature taking into account the reflection capacities of the materials under study.

3. Dimensions and shape of local heat sources

When testing the sapphire-metal pairs, hot spots (HS) appear to be the sources of radiation in the visible spectrum. The spots are elongated in the sliding direction taking elliptical shape. The ratio of the minor semi-axis to the major one varies within the *0.25-0.40* range. In the following, the minor axis of HS will be assumed to be the size of a spot. The total area of the spots *S* with respect to the apparent contact area is less than *0.1%* under the given test conditions. This agrees well with the ratio of the real contact area to the apparent one.

The results of the investigations will be discussed based on the assumption that the real contact spots are the sources of radiation which are recorded as hot spots. We should therefore expect that their most probable dimensions may coincide. The topography of the steel discs and the average diameter of a contact spot calculated following the procedure from (Sviridenok *et al.*, 1990) indicate that the average diameter of the spot d_{cs} should be within the $20-28\mu m$ range under the chosen P, V -conditions. It should be noted that the contact was assumed to be elastic in the calculations. However, actually some contact spots are deformed elastoplastically. As a result, the average diameter may shift towards greater values.

The experimental results show the average HS diameter d_{hs} to range from *34* to $41\mu m$. Therefore, the HS area cannot be a precise parameter for characterizing the area of a real contact spot. Two factors are involved in this difference. The inequality $d_{hs} > d_{cs}$ results, in the first place, from the poor linear resolution of the measuring system. Spots less than $6\,\mu m$ in diameter visible in the display would not be seen on the photo used to obtain the dimensions. In the second place, the halation around the brightest contact spots is an error source when measuring d_{hs}. The deviation between the experimental d_{hs} and calculated d_{cs} values becomes greater with increasing temperature. The halations of two or more adjacent spots could merge to give one hot spot in the experiment. The diameter d_{hs} may also be somewhat overestimated if one assumes the local sources and the flash temperature point to be located in the subsurface layer of one of the rubbing members rather than at the interface.

The images (Fig.2) were obtained from a fixed portion of the contact area (the time interval between the shots is $120\,ms$). They illustrate the kinetics of HS generation and development. During the first loading cycles small HS are generated (Fig.2a; arrow 1). With time asperities in contact undergo wear, their contact area, hence the HS dimensions, increase (Figs 2b-d; arrow 1). Two or more neighboring spots could coalesce to form one spot (Figs 2a, b) usually with a higher brightness. Owing to the wear and plastic flow of the material the load is redistributed onto adjacent sites and the HS dimensions and brightness decrease. The damaged HS is split up into several smaller spots (Fig.2, arrow 2) and eventually disappears. New spots appear or those which had appeared continue developing.

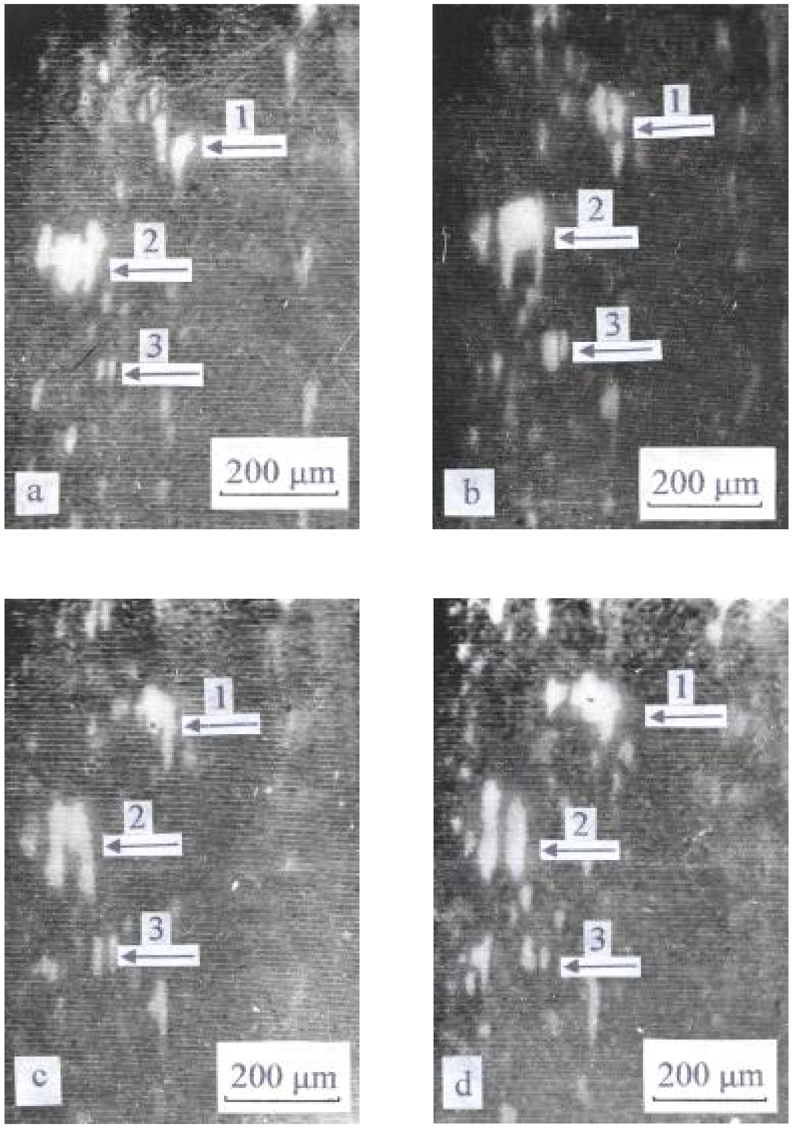

Fig.2. Kinetics of size and shape variation of hot spots in sapphire-aluminum contact at $P = 1.8\,N$ and $V = 47.5\,m/s\ (f = 0.17)$.

The life of HS depends on the wear resistance of the materials, *P*, *V* - conditions, and the topography of the mated surfaces. It may vary by three or four orders of magnitude depending on these factors. Figure 2 shows the effect of the topography on the life. For example, the spot about $150\mu m$ in size is formed and reaches the maximum brightness in $0.5\ s$ (Fig.2, arrow 1). The spot about $200\mu m$ in size is split up into three smaller spots (Fig.2, arrow 2). However, this time is sufficient for the smaller HS (Fig.2, arrow 3) to pass the whole cycle from generation (Fig.2a) to degradation (Fig.2d). The analysis of heat generation kinetics shows that the HS life can vary from milliseconds to several seconds depending on the spot size.

With increasing P and V the wear rate of the mated members increases. The sites of contact points vary faster resulting in a shorter HS life. The shape of HS also varies: at a high sliding velocity the spots are elongated in the sliding direction; at a low velocity the shape factor being determined by the ratio of the width to the length of a spot rises. For example, if V varies from 59.3 to $23.7\ m/s$ the shape factor augments from 0.26 to 0.36.

It can be seen from Fig.3 showing the size distribution of HS that spots below $50\,\mu m$ in size make the main contribution to the total number N_0 of spots counted on a definite area of the friction surface. The number of HS whose sizes are within the $50-80\,\mu m$ range does not exceed 20%. With increasing the normal load the HS distribution curve becomes flatter. A greater number of larger HS found at heavier loads can be explained, we believe, by the plastic deformation of asperities in contact and vaster areas of single contact spots as well as by overlapping halations of neighboring spots due to their high radiant intensities. If the sliding velocity varies within the $20-60\,m/s$ range the HS size distribution does not change markedly.

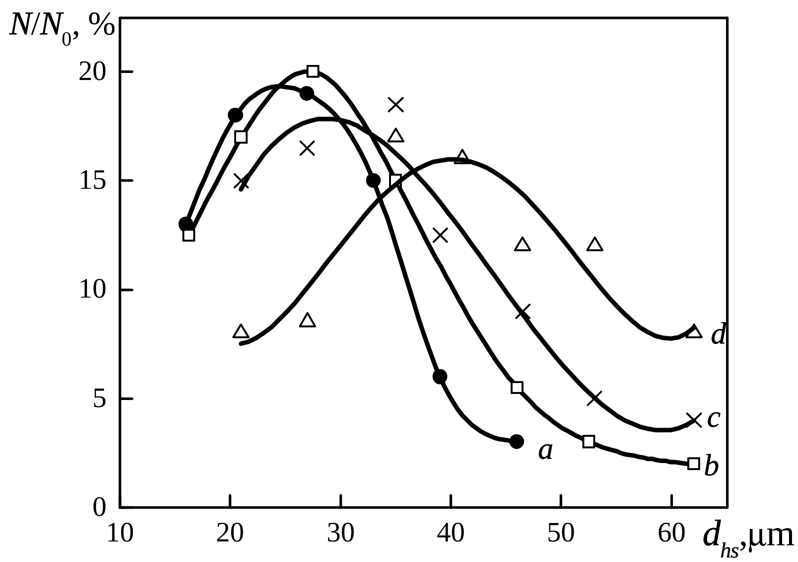

Fig.3. Hot spot size distribution (sapphire-aluminum pair) at $V = 47.5\,m/s\ (f = 0.17-0.21)$; $a - P = 0.6\,N$; $b - 1.2$; $c - 1.8$; $d - 2.4\,N$.

Figure 4 shows the dependence of the ratio of the HS total area S to the area S_0 visible in the measuring system versus the normal load. In this case the area S_0 was selected with a high radiant intensity and HS concentration. The total area of HS can be seen to increase with the load. Nevertheless, at sliding velocities exceeding $30\,m/s$ the load growth from $P = 1.8\,N$ does not lead to a greater total area of HS. At $V = 47.5\,m/s$ the area S is found to decrease within the mentioned load range. The effect of two factors could explain the phenomenon. On the one hand, at heavy loads and high sliding velocities contact spots can breakdown in one loading cycle (one revolution of the disc) of a short duration, therefore, the life period of HS is smaller (about one microsecond) than the exposure time required. On the other hand, in reality the number of contact spots either somewhat decreases or becomes stable. This assumption can be indirectly supported by the descending dependence of the friction coefficient on the velocity. For example, if the sliding velocity rises from 22.5 to $59.3\,m/s$ the friction coefficient decreases from 0.25 to 0.15.

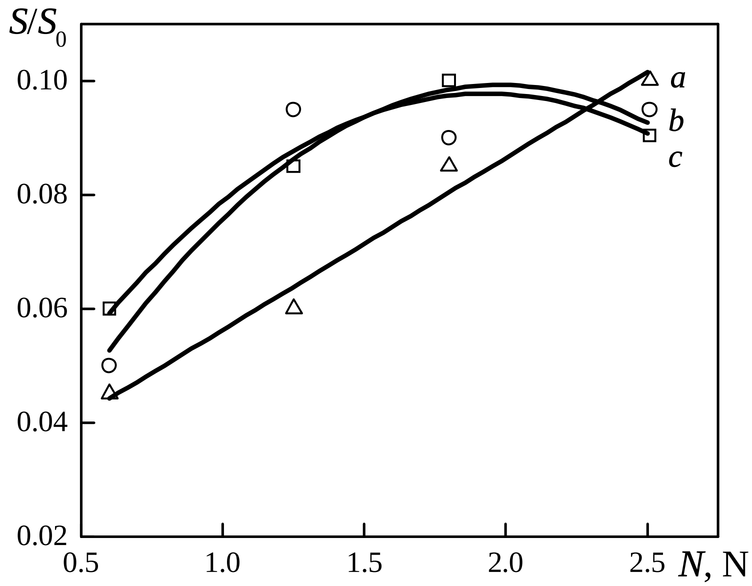

Fig.4. Effect of normal load on relative area of hot spots in sapphire-steel contact: $a - V = 27.3\,m/s$; $b - 35.6$; $c - 47.5\,m/s$.

A similar situation arises when testing the sapphire-aluminum and sapphire-copper pairs under moderate *P*, *V* - conditions. In this case the normal load varies within the $0.03 - 0.5\,N$ range and the velocity does not exceed $40\,m/s$ at the lightest load. The lightest loads at which single contact areas still have power adequate to emit light in the visible spectrum are as follows: $P = 0.03\,N$, $V = 13.5\,m/s$ for copper; $P = 0.02\,N$, $V = 12\,m/s$ for aluminum. The deviations in the minimum *P* and *V* result, probably, from the higher friction coefficient measured for the sapphire-aluminum pair $(f = 0.38)$ compared with that for the sapphire-copper pair $(f = 0.22)$. The curves describing the size distribution of HS and the effect of the load on the distribution do not differ markedly for the metals under study. Unlike the sapphire-steel contact, the sapphire-aluminum one produces spots more elongated in the sliding direction. The average value of the shape factor ranges from *0.1* to *0.28* with varying *P* and *V*. The highest radiant intensity is observed for the sapphire-aluminum pair while the lowest one for the sapphire-copper pair.

4. Kinetics of heat sources

The phenomenon of how HS are developing at the friction interface is of interest. A single spot is found to move during its life along the sliding direction. The length and direction of the motion depend on the load, sliding velocity, and materials. When testing the sapphire-copper and sapphire-aluminum pairs, HS and the disc move in the same direction while in case of the sapphire-steel pair HS move mainly in the direction opposite to that of the disc. Such spots are typically from *40* to $90\,\mu m$ in size; however, at least half of the spots do not change their sites on the contact area during their life.

Figure 5a represents the kinetics of how HS change their sites on the sapphire-steel interface. Four shots were taken with intervals of *80 ms*. The $30\,\mu m$ size spot found against mark 4 (arrow 1) is seen to move by $38\,\mu m$ during the first *80 ms* in the direction opposite to *V*. During the next *160 ms* the displacement of the spot decreases to about $50\,\mu m$. The analysis of the remaining three shots shows the spot to shift owing to the disappearance or separation (and subsequent disappearance) of the spot lower part and the development of the upper part. The upper part of the spot is developing since two smaller spots (marked by arrow 2) appear at the top and merge with the main spot. The spot of $15\mu m$ (shot 4, arrow 3) separates from the lower part of the HS.

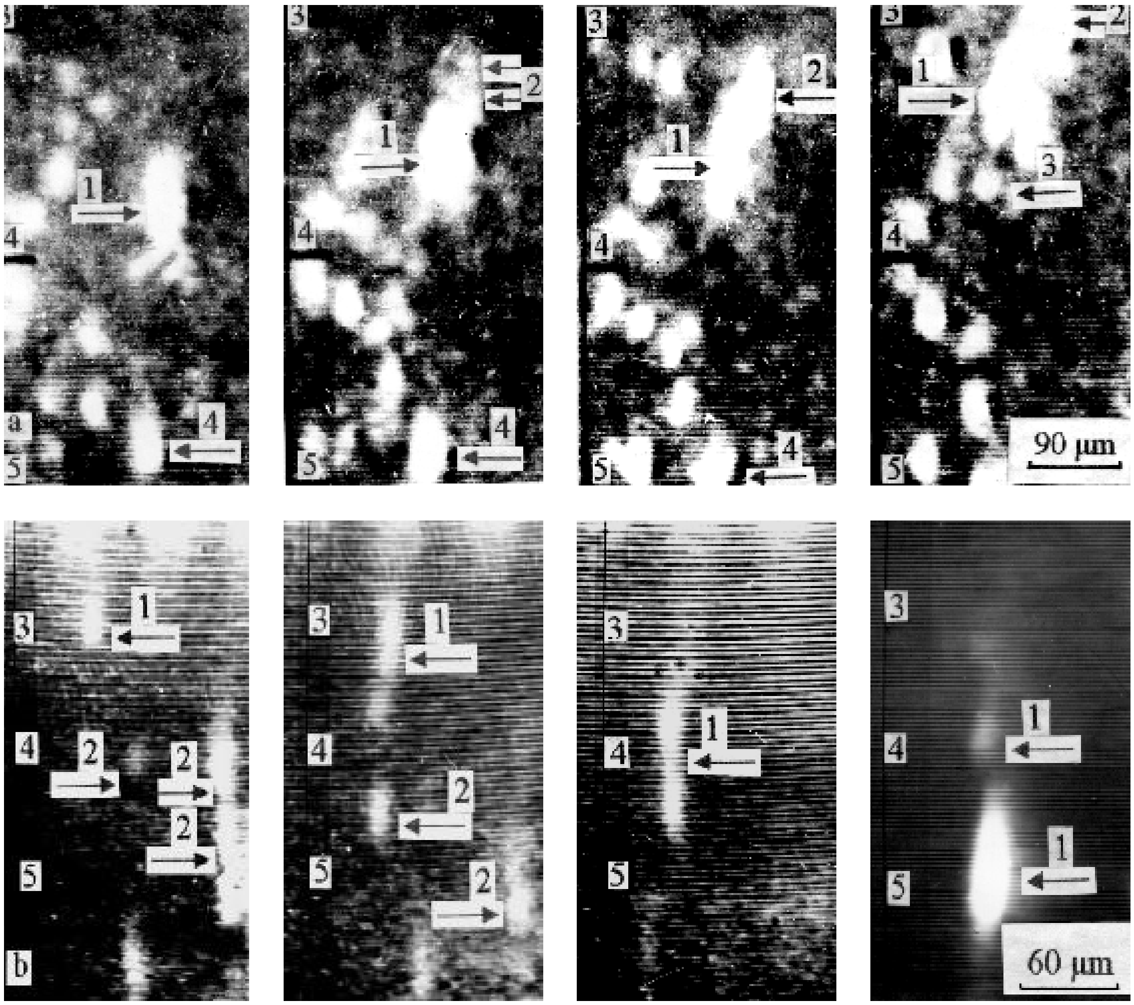

Fig.5. Displacement of hot spots within contact zone as contacting materials wear out: *a* – sapphire-steel, $P = 1.8\,N$, $V = 47.5\,m/s$, interval between shots equals *80 ms*; *b* – sapphire-aluminum, *P=0.43 N*, $V = 12.3\,m/s$, interval between shots equals *40 ms*.

When aluminum rubs against sapphire, HS shift over the contact region in the sliding direction (Fig.5b). The portion of the moving spots in their total number is 2-3 times less than that for the sapphire-steel contact. It can reach *70-80%* increasing with the velocity and load. A similar situation occurs for the sapphire-copper pair. The motion of HS along the contact zone is easily observed, for example, if we consider the spot near mark 3, as shown by arrow 1 in Fig.5b. During the first *40 ms* the spot remains almost stationary. It only changes its dimensions elongating in the sliding direction (shot 2). In subsequent *40 ms* the spot reaches mark 4; then it divides into two spots and moves in the same direction. The life periods of HS are much shorter for the sapphire-aluminum and sapphire-copper pairs than those for the sapphire-steel one being about *40-90 ms*.

To explain the above process one could suppose that HS motion is related to the different wear rates of the disc and plate. Since the wear rate of the sapphire plate is somewhat higher than that of the steel disc, the friction track widens with time owing to sapphire wear. As sapphire wears out, the point of its contact with a disc asperity will move further away from the middle of the track with every disc revolution. However, the asperity becomes smaller in the height, thus the contact point moves closer to the middle of the track. Acting simultaneously, these processes result in the shift of HS in the direction opposite to disc motion. The velocity of this motion is small compared with that found for the sapphire-copper pair. Both higher wear rates of aluminum and copper compared with that of sapphire and the plastic flow of these metals in the contact zone reduce the disc asperity height with every revolution. As a consequence, HS move quickly in the direction of the disc motion.

5. Conclusions

Summarizing the above experimental results the following general regularities for local heat sources in dry friction can be derived.

1. Heat sources in the friction zone are spots elongated in the sliding direction whose dimensions, shape, and life are governed by the mechanical characteristics of the mated materials and load and velocity conditions. With increasing the sliding velocity or reducing metal microhardness the ratio of the spot width to the length decreases.
2. The size of spots emitting heat energy is mainly within the $2-250\mu m$ range. Their size distribution curve has the maximum shifting to larger sizes with increasing the sliding velocity and load or when shifting to metals with a lower elastic modulus.
3. Heat sources can move along the sliding velocity vector during their life. The direction of motion depends on the ratio of the wear rates of the mated materials while the speed of motion is governed by load and velocity conditions. When the wear rate of sapphire is less than that of the metal the spots move parallel to the sliding velocity and *vice versa*.

Nomenclature

d_{cs} – contact spot diameter
d_{hs} – hot spot diameter
f – friction coefficient
N_0 – total number of hot spots counted on definite area of friction surface
P – normal load
S – total area of hot spots
S_0 – area of hot spots visible in measuring system visual field
V – sliding velocity

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