FEATURES OF NONSTATIONARY PERIODIC CONTACT HEAT TRANSFER

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Results are presented of investigations of nonstationary periodic contact heat transfer performed on special experimental installations and under full-scale tests. The regularity of thermal hysteresis is here disclosed experimentally.

Nonstationary periodic contact heat transfer is observed between such thermally stressed components as the valves and seats of cylinder covers, compression rings, and cylinder or piston, etc., during operation of internal combustion piston engines, compressors, and other-power plants. To a considerable extent this process governs the thermal state of the components assuring operability of the plant as a whole. The process mentioned that also occurs during mechanical treatment, cutting, stamping, extrusion, and transmission of heat being liberated here in the contact interaction domain, governs the stability of the instrument, the accuracy and roughness of the component surface during fabrication.

As we established experimentally earlier [1], the contact heat transfer coefficient α_{ht} is approximately one order lower during nonstationary periodic contact than during stationary contact and this should be taken into account in estimating the thermal state of the components operating under the mentioned conditions. The assumption was expressed that the established decrease in α_{ht} is probably associated with the formation of the actual contact of the surfaces during the nonstationary periodic contact under dynamic loading conditions substantially different from the stationary loading.

During oscillographic analysis of the temperature fluctuations of adjacent surfaces of valve and seat contact (Fig. 1), obtained as a result of testing diesels, the abrupt drop in the temperature of the heated valve surface and the temperature rise of the seat surface that occurred during a time corresponding to the increase or decrease of the density of their pressing because of the change in gas pressure due to fuel combustion were established. The greatest amplitude of the temperature fluctuations here refers approximately to the time of maximal gas pressure.

It was later seen during processing of the temperature fluctuation oscillograms that the temperature values are lower for the seat and higher for the valve in the compression line than in the expansion line at an identical pressure. We called such a regularity thermal hysteresis for nonstationary periodic contact heat transfer.

Research performed earlier on contact heat transfer were analyzed to expose the substance of the obtained regularity. It is noted in [2-6] that the contact thermal resistance curves do not agree under conditions of slow sequential loading and unloading of specimens. Several hours after unloading, the thermal contact resistance is restored to its initial value. The presence of a "lag" in the thermal tests [3] is related to the nature of the microroughness deformation. The area of actual contact is considerably greater at this time upon removal of the load. As the degree of preliminary cold-working increases the aftereffect grows and can reach approximately 60% of the initial elastic deformation in metals [4]. The metal sublayer lying directly under the plastic deformation domain experiences elastic deformations [5] during pressing of the surfaces. These diminish the effective height of the crests carrying the load and tend to approach the contact surfaces, thereby increasing the number of contact points. For a given pressure the contact thermal resistance has two values corresponding to loading and unloading with a 1 h duration of the stabilization of this resistance [6]. The reason for the presence of relaxation is not established physically.

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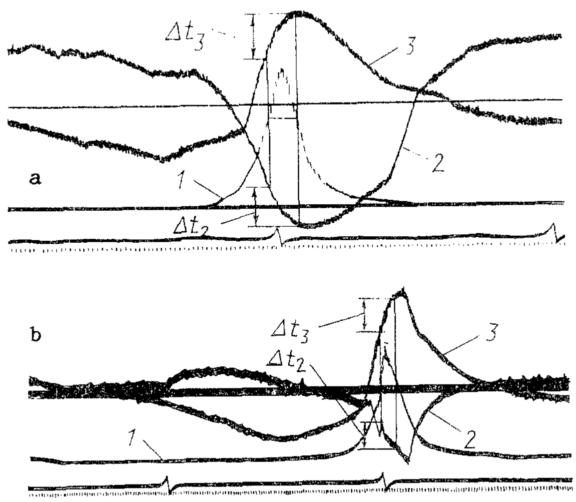

Fig. 1. Oscillograms of temperature fluctuations on adjacent surfaces of valve contact with the heat-insulating film of combustion products (a), with the pure surface (b) and the seat of a diesel: 1) gas pressure in the cylinder; 2) valve temperature; 3) seat temperature; scales: a) pressure 0.36 MPa/mm, valve temperature 0.37 K/mm, seat temperature 0.48 K/mm; b) pressure 0.45 MPa/mm, valve temperature 0.35 K/mm, seat temperature 0.26 K/mm.

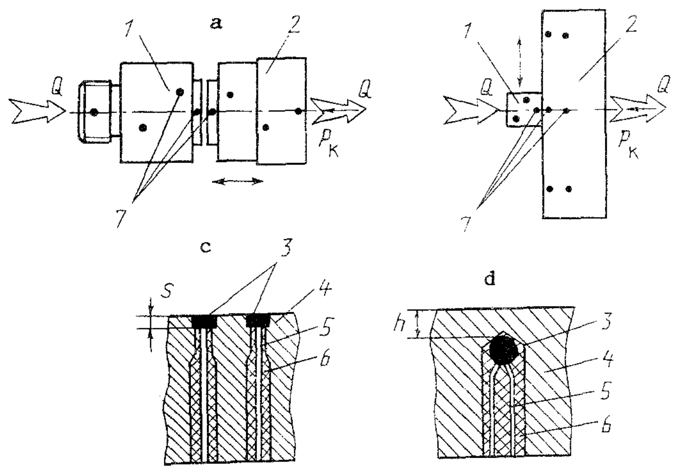

Fig. 2. Diagram of thermocouple arrangement in specimens 1 and 2, heat supply and removal Q under axial periodic squeezing (a), squeezing and friction (b), construction of the surface thermocouples (c) and stationary thermocouple (d): 3) hot thermocouple junction; 4) specimen wall; 5) thermal electrode in the glass thread; 6) thermal insulation; 7) site of thermocouple installation.

The thermal resistance of a contact spot in the stationary state and a short time interval was investigated theoretically in [7]. The process of heat transmission through the contact zone was simplified on the basis of an assumption about extension of the results of a single contact to the whole contact surface. Under the simplifications presented and the theoretical investigations the thermal hysteresis phenomenon was not clarified.

Periodic contiguity was simulated in [8]by closing and opening a special breaker by using an analog computer. The coefficient was assumed equal to infinity or the value of the stationary α_{ht} during closure of both contact elements and equal to zero during opening. Therefore the investigation of α_{ht} and taking account of those characteristics governing the real nonstationary contact heat transfer process as the area of the actual contact, the mechanical properties, the surface roughness, etc., were not performed.

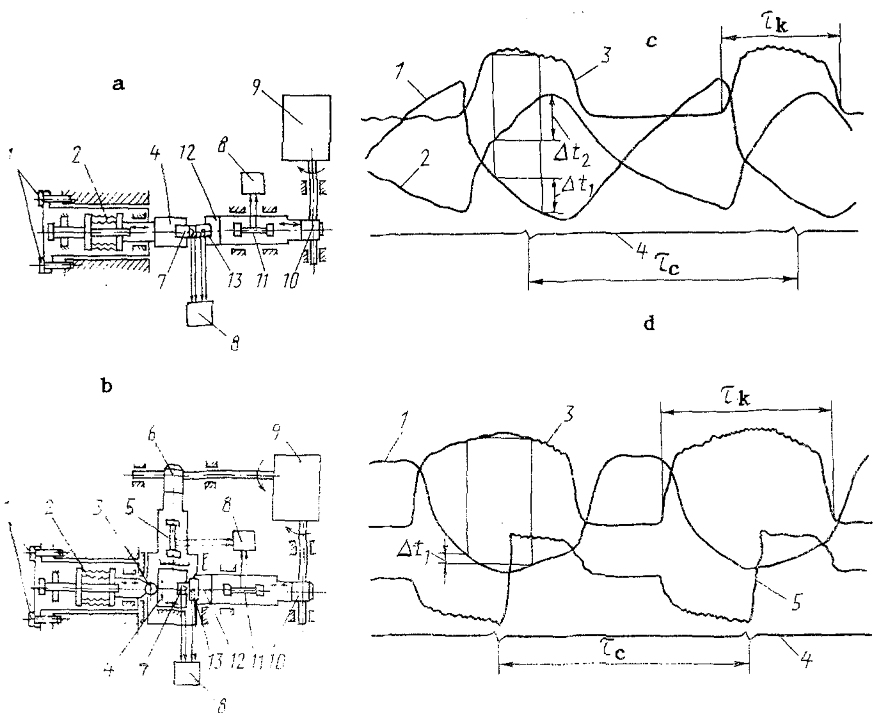

Fig. 3. Diagram of testing installations with axial periodic squeezing (a), with squeezing and friction (g), and appropriate oscillograms obtained during their operation (c), (d); 1) temperature of heated and 2) cooled specimen; 3) contact pressure; 4) cycle duration marker; 5) friction force; pressure scale 40 N/mm; temperature 0.4 K/mm, and friction force 10 N/mm.

As is seen from this analysis, there is no accounting for the specific features of periodic contact interaction at high frequency, short duration, and nonstationarity of the fluxes through the contact zone governing the operation of a number of responsible components and the instrument, which makes utilization of the results of the mentioned research difficult. In this connection, nonstationary periodic contact heat transfer was investigated.

The method used for the investigation is based on recording the temperature fluctuations on the contact surfaces with subsequent mathematical processing of the test data. In this case

$$\alpha_{ht} = \frac{q}{t_1 - t_2}. \tag{1}$$

Determination of the specific thermal flux q was by two methods: by using the integral of the heat conduction differential equations and by the method of electrothermal analogy. The temperature field in the specimen contact zone is considered with sufficient accuracy as one-dimensional, i.e., dependent only on one coordinate x in a direction perpendicular to the contact surface. Then according to the first method — by using the integral of the thermal conductivity differential equation for a solid body — the specific heat flux on a surface can be determined as

$$q_{x=0} = \lambda \frac{\partial t}{\partial x} = q_{st} + \lambda \sum_{k=1}^{\infty} \sqrt{\frac{k\omega}{2a}} \left[(A_k + B_k) \cos k\omega\tau + (B_k - A_k) \sin k\omega\tau\right]. \tag{2}$$

The temperature fluctuations on the surface are

$$t_{x=0} = t_{st} + \sum_{k=1}^{\infty} (A_k \cos k\omega\tau + B_k \sin k\omega\tau). \tag{3}$$

Computations using (2) and (3) were carried out on an electronic computer.

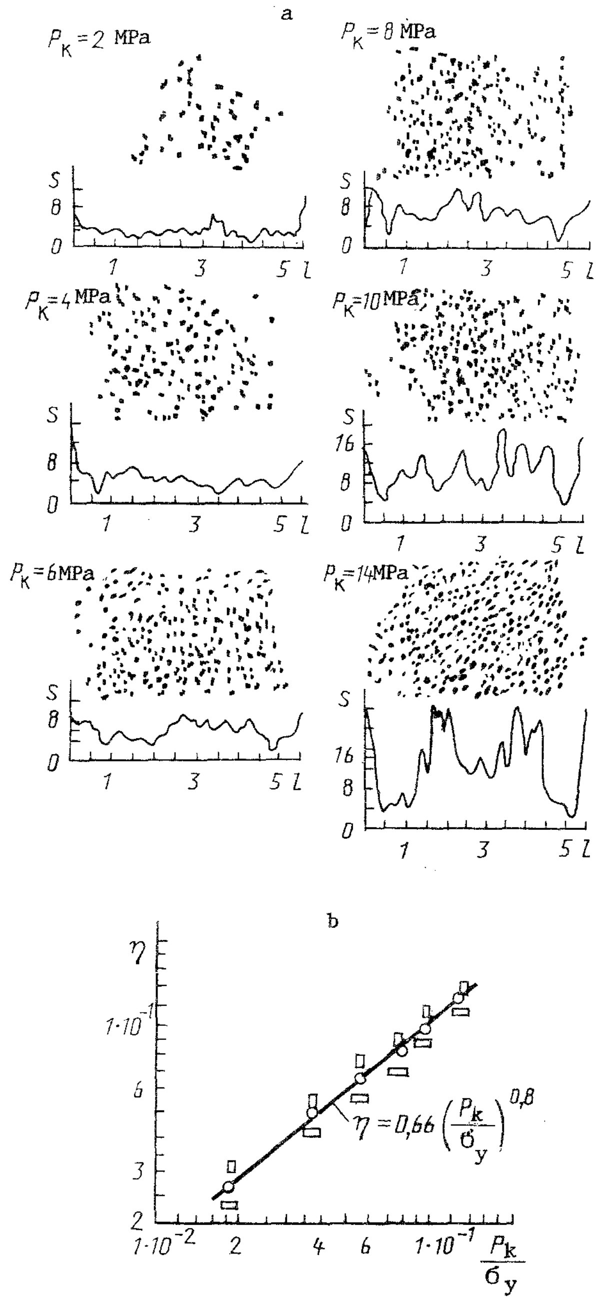

Fig. 4. Spots of actual contact on autoradiograms and their corresponding photometric curves characterizing the blackening density S (in relative units) during intersection of the contact surface l (mm), as the contact pressure P_k changes (a), and dependence of the relative actual contact area η on the ratio P_k/σ_B (b).

The periodically varying thermal flux at the wall was recorded directly by the second method by using the connection of a simulating RC loop consisting of a resistor and capacitor in the measuring circuit.

The analogy between the heat conductivity

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial x^2}, \quad q = -\lambda\frac{\partial t}{\partial x}$$

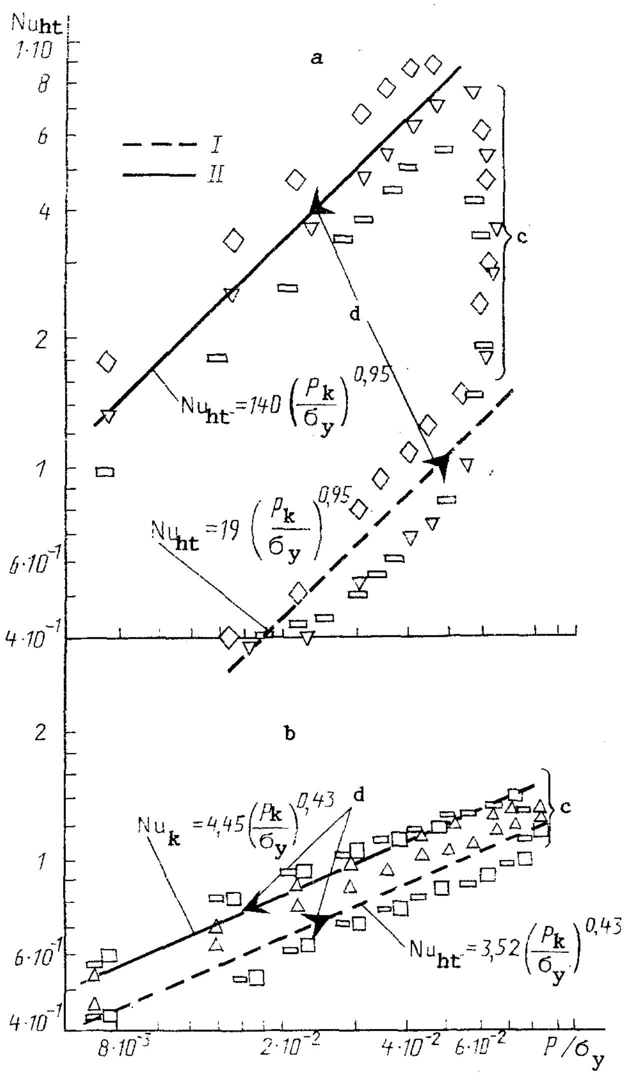

Fig. 5. Dependence of Nu_{ht} on P_k/σ_B under loading (I) and unloading (II) of contact surfaces without heat-insulating film (scale, organic clay, etc.) (a) and with the film (b), the transition zone (c), the direction of process progress (d).

and electrical conductivity

$$\frac{\partial U}{\partial \tau} = \frac{1}{RC}\frac{\partial^2 U}{\partial x^2}, \quad I = -\frac{1}{R}\frac{\partial U}{\partial x}$$

equations is characteristic for a one-dimensional thermal flux.

Equality of the temperature, specific heat, thermal resistance, heat flux, and time scales is set up to conserve the proportionality at corresponding points of the model and the full scale. In this case a definite section of the analog RC loop corresponds to a definite depth of the full-scale wall from the surface and the current measured therein with the thermal flux scale taken into account yields a direct value of the thermal flux. Then q is expressed in terms of the characteristics of the measuring system by the dependence

$$q = \frac{\lambda R}{\mu k_a}\frac{y_q}{c_\ell}. \tag{4}$$

Upon simultaneous recording of the current at two insignificant distances from the model surface (x_1 and x_2) by using the equations $q_{x=0} = q_{x_1}\exp(x_1\gamma)$; $q_{x=0} = q_{x_2}\exp(x_2\gamma)$ we determined γ and the specific thermal flux on the contact surface.

Investigation of heat transfer during transmission of the heat Q although the specimen contact zone (Figs. 2a and b) was performed by using chromel—copel thermal electrode leads of 0.2-mm diameter insulated by glass thread and heat resistant lacquer. The hot junction of the thermocouple in the form of a 0.9-1.1 mm ball was here fabricated by using an electrode arc and was welded to the wall by condenser welding (Fig. 2c and d). In addition it was riveted to the under-endface part of the hole with subsequent grinding of the contact surface, which assured a depth of the under-endface S of the order of (0.15-0.25) ± 0.001 mm and 2-2.5 mm spacing between the leads. The temperature fluctuations and thermal fluxes were recorded with an electronic amplifier and loop oscilloscope connected to appropriate thermocouples. The specimens were fabricated from special steels and cast iron with λ = 20-45 W(m·K) used for motor component fabrication whose thermal state and capability are determined by periodic contact heat transfer.

The heat transfer was investigated by using research installations we developed (Figs. 3a and b). These latter assure periodic interaction, nonstationary squeezing pressure and thermal flux through the specimen contact zone (Fig. 3a) and, in addition, mutual friction (Fig. 3b) with physical simulation of the work of pairs of components of the valve, seat, piston ring, cylinder type [9, 10]. The specimens can be fabricated specially or cut out of real components with inherent execution of the contact surfaces, materials and treatment.

The specimen being heated 7 was installed in an electrical heater 4 while the specimen being cooled 13 was in the aqueous refrigerator 12. The refrigerator 12 with the specimen 13 interacting with the specimen 7 was set into reciprocating motion by the driver 9 by means of a loading mechanism in the form of a profiled cam 10. It was installed here in the heater 4, which was supported on a set of springs 2 with adjustable precompression through the carrying roller 3, thereupon the force squeezing the specimens during the working cycle varied as a function of the profiled cam 10 and the characteristics of the springs 2. The specimen 7 in combination with the heater 4 simultaneously (Fig. 3b) performed reciprocating motion due to a displacement mechanism in the form of a profiled cam 6 connected to the driver 9 perpendicular to the motion of the refrigerator 12, whereupon friction between the specimens 7 and 13 was produced. The duration of the contact period τ_k between the specimens 7 and 13 during the operating cycle τ_c was regulated by screws 1 because of heater 4 displacement relative to the refrigerator 12. Correspondence between the cycle period and the magnitude of the contact pressure P_k was achieved by matching the operation of the loading and displacement mechanisms for, say the piston rings for which the greatest P_k corresponds to stoppage of the specimen 7 and change in the direction of its motion to the reverse. The installations were equipped with sensors to measure the squeezing force 11, the friction 5, and the temperature of the specimens 7 and 13 that were connected to the appropriate magnifying devices 8. To check the heat flux through the contact zone in the specimens 7 and 13, surface and stationary thermocouples were installed.

As is seen from the oscillograms (Figs. 3c and d), during an axial periodic contact and during contact with friction the temperature of the specimen 1 being heated drops after the beginning of contact during this period τ_k, while that of the specimen 2 being cooled grows correspondingly to the contact pressure 3. Simultaneously (Fig. 3d), the friction force 5 grows while reversing its direction analogously to the change in the direction of specimen displacement.

It is seen in the analysis of the temperature curves 1 and 2 that the momentum of the heat flux being transmitted through the contact zone at the frequency of the contacting process f_c during τ_k, results in thermal hysteresis. It consists of lower values of the temperatures for the specimen being heated and higher for the specimen being cooled by Δt_1 and Δt_2, respectively, during unloading as compared with loading by the pressure P_k of the contact surfaces.

Since one of the main parameters governing the thermal hysteresis (and in the process of nonstationary contact heat transfer as a whole) is the relative area of the actual contact η, then it was investigated. It should be kept in mind that until now there have been no methods to determine this parameter for nonstationary periodic contact. The determination for even stationary contact for real components is fraught with significant difficulties since the utilization of computational dependences [11, 12] seldom yields a correct result, apparently due to the absence of taking the specific contact conditions into account here. Consequently, experimental methods that can be separated into five groups: determination of the proximity of the contact surfaces by using the curve of the reference surface, measurement of the electrical conductivity of the contact, study of the change in the physical properties of the surface, utilization of optical phenomena, and application of thin surface films, have been used extensively in determining η. The first three methods are suitable for determining η between rough and smooth surfaces and are not suitable for the investigation of real materials and their components. Optical methods are applicable only for transparent materials.

The method of thin films based on fixating the indicating substance on one surface after its interaction with the second surface, on which this surface had first been superimposed [13], turned out to be the most acceptable for experimental determination of the contact area of specimens from real components. The radioactive isotope ^{63}Ni (β radiation with 0.067 MeV energy) was selected as indicating substance, was superimposed on the contact surface by chemical nickel plating with a 0.3-0.4-μm coating thickness.

The investigations were performed on both nonoperating components after their abrasion and after their combined operation by using a special loading apparatus. The actual contact area was determined by the intensity of the isotope radiation transferred to the adjacent contact surface after 3 h of contact. The isotope distribution at sites of actual contact was determined from an autoradiogram on x-ray film after its interaction with the adjacent contact surface and subsequent photographic treatment.

The determination of η from the autoradiograms obtained was performed by planimetry magnified 30-40 times by using an epidioscope of the contact area and photometry with a MF-4 microphotometer and analysis of the change in blackening density S of the autoradiograms (Fig. 4). Under static loading this parameter is described satisfactorily by the equation

$$\eta = 0{,}66\,(P_k/\sigma_y)^{0{,}8}. \tag{5}$$

The influence of the duration of the fixed contact on η can be taken into account by the Ishlinskii equation, which after manipulation has the form

$$\eta_\tau = b\left[\varepsilon_\infty^{\nu+1} - (\varepsilon_\infty^{\nu+1} - \varepsilon_0^{\nu+1})\exp\left(-\tau\,\frac{r(\nu+1)}{r/a+\nu}\right)\right]^{\nu/(\nu+1)}, \tag{6}$$

where ε_0 is the closure for zero contact time, ε_∞ is the closure corresponding to a completely formed contact, r is the relaxation velocity, and a is the aftereffect velocity.

It is seen from (6) that the contact area grows quite rapidly in the first period, its growth is then slowed down and the magnitude of this area tends to a certain constant value. However, the formula does not take account of the dynamic periodic nature of the load application.

To estimate the change in η during specimen contact on the research installations (Figs. 3a and b), we analyze the nature of the change in P_k during this process. Let us separate it into three periods.

The first period lasts from the beginning of contact until a time corresponding to the equality of the stretching force of the set of springs and the force due to the mechanism of loading of the installation. The spring-loaded heated specimen is fixed while the cooled specimen moves under the action of rigid coupling to the loading mechanism and tends to overcome the force of preliminary stretching of the springs. Since one of the contact surface is fixed while the second acts on the first with a definite force, then the latter is realized in deformation of the microroughness apex.

In the second period, which lasts up to a time corresponding to the achievement of the maximal P_k, a certain compression occurs. The velocities of these contact surfaces are equilibrated. Consequently, a redistribution of the deformations between individual roughness apices occurs, accompanied by an increase in η, because of the absence of an obstacle to rectification of the roughness apices of the surface profiles subjected to elasticity forces.

The third period corresponds to unloading of contact surfaces moving at identical velocity. A time factor τ_k acts on magnification of η because of continuation of the more complete formation of contact spots. At this time the decrease in P_k contributes to reduction of η.

This nature of the contact interaction can also be extended to the whole surface being subjected to periodic contact during replacement of the action of the set of springs of the installation by the roughness elasticity forces.

It is seen from this analysis of the change in P_k during a nonstationary periodic contact that substantial influence on η is exerted by the nature in the change and magnitude of P_k, as well as the duration τ_k.

Experimental investigations on installations and during component tests permitted establishment of the influence of the magnitude and nature of the application of P_k (loading or unloading) during contact surface interaction on the intensity of the nonstationary periodic contact heat transfer. Certain results of these investigations to measure the contact heat transfer Nusselt number are represented in Fig. 5.

We see from our results that the heat transfer intensity is governed by the direction of passage of the process *d* and is higher during unloading of the contact surfaces than during loading for both pure surfaces and those having a heat-insulating film. The latter, consisting of scale and other low heat-conductive deposits is formed during operation of a number of components and reduces the heat transfer intensity significantly. The transition zone *c* of the appearance of the detected thermal hysteresis is seen that is characterized by growth of Nu_{ht} for an approximately identical value of P_k/σ_B during unloading of the contact surfaces as compared with their loading.

The results obtained are approximated by the dependences: for surfaces with heat-insulating film:

Under loading

$$Nu_{ht} = 3{,}52\left(\frac{P_k}{\sigma_y}\right)^{0{,}43}, \tag{7}$$

Under unloading

$$Nu_{ht} = 4{,}45\left(\frac{P_k}{\sigma_y}\right)^{0{,}43}; \tag{8}$$

For pure surfaces:

Under loading

$$Nu_{ht} = 19\left(\frac{P_k}{\sigma_y}\right)^{0{,}95}, \tag{9}$$

Under unloading

$$Nu_{ht} = 140\left(\frac{P_k}{\sigma_y}\right)^{0{,}95}. \tag{10}$$

Taking account of the expression for the contact heat transfer coefficient

$$\alpha_{ht} = \frac{Nu_{ht}\lambda_{av}}{\delta_{eq}} \tag{11}$$

and the dependence of the thickness of the inter-contact gap

$$\delta_{eq} = (h_1 + h_2)\left(1 - 0{,}34\sqrt[3]{\frac{P_k}{\sigma_y}}\right) \tag{12}$$

the computed equation to determine α_{ht} with thermal hysteresis taken into account will have the following form

$$\alpha_{kt} = \frac{Nu_{ht}\lambda_{av}}{(h_1 + h_2)\left(1 - 0{,}34\sqrt[3]{\frac{P_k}{\sigma_y}}\right)}, \tag{13}$$

where Nu_{ht} for surfaces with and without heat-insulating film under loading and unloading is determined by (7)-(10).

Computations using (13) showed that the divergence from experimental data is less than 20%.

The obtained criterial dependences characterize the influence of the experimentally established thermal hysteresis and the presence of a heat-insulation film on the contact surface on the intensity of nonstationary periodic contact heat transfer.

It is seen from the analysis performed that the nature of the change in contact interaction and in the pressure P_k exerts a governing influence on the area of actual contact in addition to its duration during nonstationary periodic contact heat transfer. Consequently, during loading η does not succeed in being formed to its magnitude obtained during unloading, which indeed results mainly in thermal hysteresis in the process mentioned. It is also established that the presence of a heat-insulation film on the contact surface, as compared with its absence, reduces the heat transfer intensity by approximately an identical degree under both loading and unloading.

The obtained results and criterial dependences can be utilized to determine the boundary conditions and to raise the accuracy of computations of the thermal state of components, the control and redistribution of heat passing through their contact zone. The criterial dependences developed are suitable in a range of variation of the following parameters

$$\frac{P_k}{\sigma_y} \leqslant 1{,}4 \cdot 10^{-2}; \ \frac{\tau_k}{\tau_c} = (1{,}6 \ \ldots \ 8) \cdot 10^{-1}; \ f_c = 2 \ \ldots \ 12 \text{ Hz};$$
$$\lambda_{av} = (3{,}5 \ \ldots \ 7) \cdot 10^{-2} \text{ W/m·K}; \ h_1, \ h_2 = 1 \ \ldots \ 7 \ \mu\text{m}.$$

NOTATION

Here α_{ht} is the contact heat transfer coefficient; P_k, contact pressure; λ, λ_{av}, a, heat conductivity coefficients of the materials of the contact pair, the intercontact medium, and the thermal diffusivity; σ_y, material yield point; η, relative area of actual contact; τ_k, τ_c, durations of the contact and the working cycle; f_c, frequency of the contact cycles; δ_{eq}, equivalent thickness of the inter-contact gap; h_1, h_2, roughness heights of the contact surface profiles; $b\nu$, relative closure of the surfaces; t_1, t_2, instantaneous temperatures of the contact surfaces; q, q_{st}, specific and stationary thermal flux through the contact zone; k, ordinal number denoting the order of the harmonic, ω, cyclic frequency of the oscillations; τ is the time measured from an arbitrary beginning; A_k, B_k, Fourier series coefficients; R, C, specific electrical resistivity and capacitance; U, I, voltage and current intensity in corresponding points of the simulating loop; μ, thermocouple sensitivity; k_a, amplifier gain coefficient; c_ℓ, loop constant.

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