Journal of Engineering Physics and Thermophysics, Vol. 72, No. 3, 1999

EROSION OF STEELS AND ALLOYS IN THEIR COLLISION WITH A FLUX OF ABRASIVE PARTICLES

L. I. Urbanovich and E. M. Kramchenkov

UDC 620.193.1

We describe a procedure and present results of an investigation of gas-abrasive erosion of metals and alloys at temperatures of 293-80 K.

As noted in [1, 2], by means of experiments one can determine to which of two forms ("ductile" or "brittle") the erosion of any structural material belongs, if identical test specimens made of this material are subjected to bombardment by a flux of abrasive particles with the same impact velocity, but at different angles of attack (in the range from 0 to 90°). The intensity of erosive destruction is determined here from the mass (or volume) carried away from the specimen per unit of the erodent spent. In conformity with the data of the references mentioned, a characteristic feature of the "ductile" regime of destruction is the presence of a maximum in the rate of erosion that lies in the range of the angle of attack of $20-30^{\circ}$, which is typical of plastic metals and alloys. In the "brittle" regime of destruction (glasses, ceramics, hardened steels) the rate of erosion increases with the angle of attack and attains a maximum at $70-90^{\circ}$. Despite the large amount of experimental data on erosion of plastic materials (at room and high temperatures), no universal model has been devised that would be capable of predicting the intensity of erosive destruction with account for regime factors (impact velocity, size and shape of the particles of the erodent, temperature, etc.) and the physicomechanical properties of materials [3]. Therefore it becomes apparent that experimental modeling of the process of gas-abrasive erosion still remains (despite the labor-intensiveness) the most reliable means of investigation. This approach is especially justifiable when experiments are carried out in the region of low temperatures, because of the virtual absence of such data in the literature. An exception is work [4], which contains some results of experiments on erosive destruction of copper, steel, and white cast iron specimens on a centrifugal accelerator at both room temperature and several values of low temperature.

With the support of the Russian Fund for Fundamental Research, we carried out a number of experiments on gas-abrasive erosion of metals and alloys at room and low temperatures. With this aim we resorted to a gas-dynamic means of acceleration of solid particles that was implemented in an experimental setup designed at Lipetsk State Technical University (see Fig. 1).

A gas-carrier (argon or helium) of solid particles is contained under an initial pressure of 15 MPa in cylinder 1 equipped with stop valve 2 and, through reducing valve 30 and flow discharge meter 4, moves in a gas main in the direction of the working chamber of the setup. The gas pressure before and after valve 2 is controlled by displaying manometers 3. Next, the gas-carrier, through valve 5, can enter the working chamber of cryostat 41 (of type KG-15/150) or three-pass control valve 6. The function of valve 6 is to mix the warm flow of gas that bypasses the heat exchanger intended for preliminary cooling of the gas-carrier and a cold flow that passed through the heat exchanger indicated. This allows one to regulate the temperature of the gas-carrier.

The cooled gas-carrier enters the system that supplies abrasive particles, which consists of two three-pass valves 18, two stop valves 29 and 32, a bin filled with abrasive 31 and fitted with filter 35, and calibrated headpiece 33. The system that supplies the erodent performs the following functions.

1. Cooling of abrasive particles 34. The process proceeds when valve 29 is closed and combination of valves 18 supplies the gas-carrier through calibrated headpiece 33 from below upward. The particles are cooled in a fluidized bed. The high heat-transfer coefficients here make it possible to lower the temperature of the abrasive particles to that of the gas-carrier in a rather short time.

Lipetsk State Technical University, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 3, pp. 519-525, May-June, 1999. Original article submitted February 24, 1998.

1062-0125/99/7203-0496$22.00

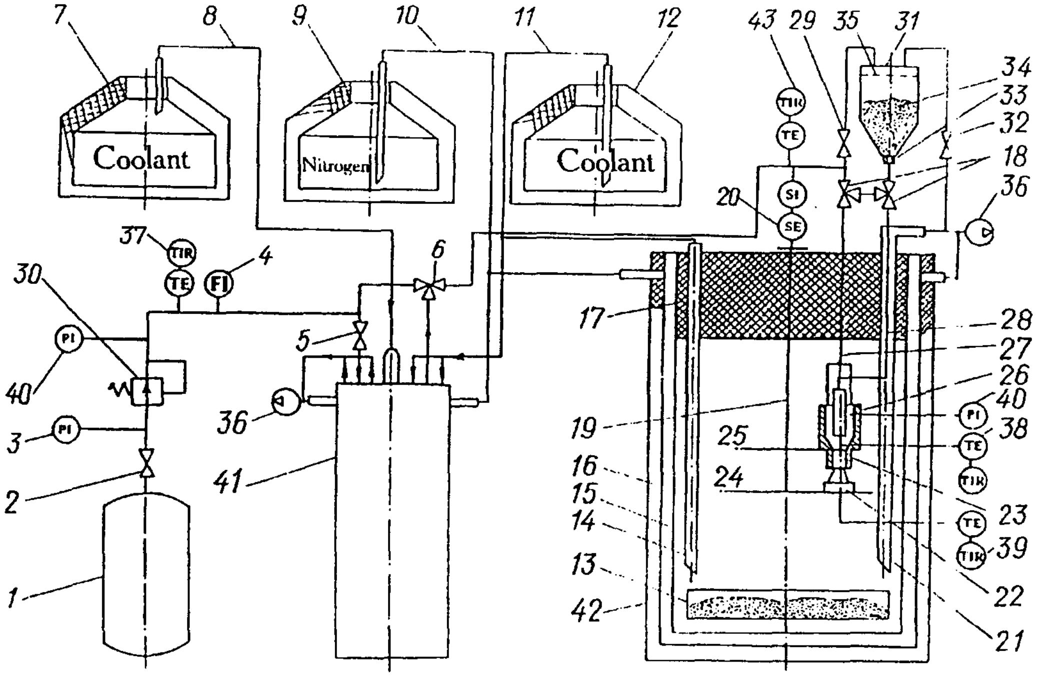

Fig. 1. Schematic of the experimental setup.

2. Supply of abrasive particles to the ejector. With valve 29 partially open and valve 32 closed, the gas-carrier creates a certain excess pressure above the layer of abrasive particles 34. Valves 18 function in such a way that they permit passage of the main body of the gas to ejector 26, equipped with acceleration nozzle 23, and cut off gas main 27 from pipeline 28 in which abrasive particles move.

The gas-carrier and the abrasive particles, on entering ejector 26, form a two-phase flow, which is accelerated in nozzle 23 and attacks the specimen of test material 22.

The ejector is positioned on horizontal fitting platform 25, and test specimens are attached to platform 24. Both platforms are mounted on vertical shaft 19. The shaft is set on rolling-contact bearings placed in cap 17 of cryostat 42 (of type KG-60/300). The cap is provided with polyurethane foam heat insulation. The cryostat has vacuum heat insulation 16 and nitrogen jacket 15. The working chamber has pipe 14 for preliminary cooling of the working space and pipe 21 for evacuation of the waste gas-carrier. In the lower part there is pan 13 for collecting waste abrasive material. To evacuate gaseous cryogenic products (waste gas-carrier, vapors of the coolant and nitrogen from the jacket), exhaust blowers 36 are incorporated that provide supply of gases to gas holders for repeated use or their output from the laboratory room to the atmosphere.

The creation of stable low-temperature zones is ensured by cryogenic vessels 7, 9, 12. Cryogenic vessel 7 is meant for supplying the gaseous coolant through pipeline 8 to the system of preliminary cooling of the gas-carrier (cryostat KG-15/150). Cryogenic vessel 9 is used to fill the nitrogen jackets of cryostats 41 and 42 through pipeline 10 or to fill the nitrogen jackets of other cryogenic vessels (helium ones, etc.). Cryogenic vessel 12 ensures supply of the liquid coolant through gas main 11 to cryostats 41 and 42 and serves for rapid cooling of the cryostats immediately before an experiment and for maintaining the required temperature during the latter.

During experiments it is necessary to measure the following quantities: temperature, flow rate of the gas-carrier, velocity of the particles in the two-phase flow, and pressure. To determine the pressure of the gases during operation of the setup, MT-type elastic spring-element pressure gauges with a scale of values 0–25 MPa and accuracy class 2.5 (3 in Fig. 1) and standard test pressure gauges with a scale of values 0–1 MPa and accuracy class 0.4 (40 in Fig. 1) are used.

The volumetric flow rate of the gas-accelerator was measured by a PM-2.5G rotameter. At the factory the rotameter was calibrated with air. The accuracy of measurements was 2.5%. To raise the accuracy, we carried out individual calibration of the rotameter with argon at an atmospheric pressure of 98 kPa and a temperature of 20°C. In order to accurately determine the flow rate when the gas parameters differ from those indicated above and when

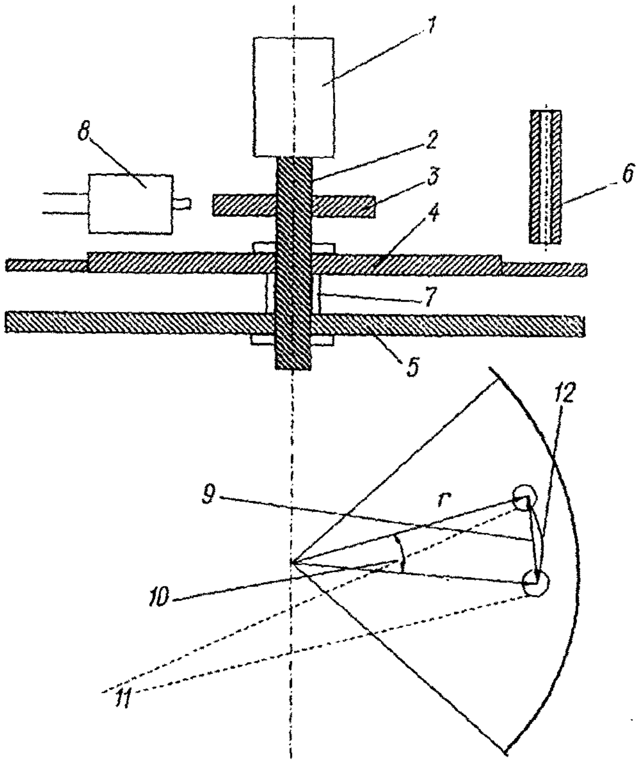

Fig. 2. Schematic of the two-disk device for measuring the average velocity of the particles: 1) synchronous motor; 2) shaft; 3) gear; 4) upper disk; 5) lower disc; 6) nozzle; 7) separating bushing; 8) transducer of the speed of rotation; 9) distance between marks; 10) angle of rotation; 11) erosion marks; 12) arc.

different gases (helium, air, nitrogen, etc.) are used, a special computer program was developed that makes it possible to compute mass and volumetric flow rates of gas in an appreciable range of gas parameters. The program takes account of the deviation of the properties of real gases from perfect ones, and this raises the accuracy of determination of flow rate.

During experiments it is necessary to determine the temperatures of the gas ahead of the rotameter (with a view to accurate determination of the volumetric and mass flow rates), ahead of the entrance to the system that supplies abrasive particles, ad in the ejector and of the test specimen.

The carry out measurements in the temperature range of 4.2–300 K, cryogenic thermometers based on TVO-type resistors with a nominal value of 1000 Ω (38 in Fig. 1) [5] were selected as most suitable. Here a four-wire circuit with power supply from a specially designed block with a constant current of 10 μA and a stability no poorer than 10^{-5} is used. The resistance is determined from the difference of potentials across the resistor by an Shch1516 digital voltmeter of class 0.05 (37, 39, 43 in Fig. 1). Each of the sites indicated had one temperature-sensitive element that had been calibrated individually.

Note that the parameters of the TVO-type resistors as cryogenic thermometers comply well with the requirements of a technical experiment on cryogenic setups in the wide temperature range of 2–400 K. Used correctly, they give an accuracy no poorer than 1% [6].

The most complex problem in carrying out experimental investigations on the study of gas-abrasive erosion is determination of the velocity of the solid particles in the two-phase flow. Measurements on the setup designed were based on the double-disk technique [7]. The following structure was suggested for use in a KG-60/300 cryostat (Fig. 2).

Two disks, upper 4 (which has two radial slots) and lower 5 ones, separated by bushing 7, are attached to shaft 2 of synchronous motor 1 (SD-09M). Fixed on this shaft is gear 3, which, while rotating, generates pulses in rotational-speed transducer 8 (20 in Fig. 1). These pulses are transferred via the panel that controls the setup to a 7TÉ tachometer, which measures the speed of rotation of the shaft. The synchronous motor has a speed of rotation of 3000 rev/min (50 Hz) and can be reversed. Therefore, during measurement of the velocity of the particles two marks are made, namely, when the motor rotates in the two directions.

If we take the distance between the upper surfaces of disks 4 and 5 to be equal to S, then a particle that has the average velocity w_p will cover this distance through the radial slot in the time $\tau = S/w_\mathrm{p}$ and will leave a mark (erosional damage) on disk 5. In this time the disks will turn through an angle $\gamma/2$. On reversal of the motor the angle between the marks will become equal to γ.

The reversibility of the motor makes it possible to increase the distance between the marks, and there is no need to make a mark when the motor is inoperative.

The time of rotation of the disks by the angle γ (corresponding to the doubled velocity of the abrasive particles) is

$$\tau = \frac{\delta}{2\pi\omega R}\,. \tag{1}$$

Solving (1) together with $\tau = S/w_\mathrm{p}$, expressing the arc δ in terms of the segment l, and not forgetting about the doubling of the velocity, we obtain

$$w_\mathrm{p} = \frac{\pi\omega S}{\arccos\left(1 - \frac{l^2}{2R^2}\right)}\,. \tag{2}$$

For example, if a mark has the radius $R = 88$ mm, the distance between the marks $l = 6$ mm, the speed of rotation of the disks is 50 Hz, and $S = 16$ mm, we have

$$w_\mathrm{p} = \frac{\pi\, 50\cdot 0.016}{\arccos\left(1 - \frac{36}{2\cdot 88\cdot 88}\right)} = 36.8\ \text{m/sec}\,. \tag{3}$$

The specimens of test materials are made in the form of cylinders with the dimensions ∅18.5 × 8 mm. The diameter of a specimen is selected in such a way that in all of the test regimes the two-phase jet could impinge entirely on its surface, i.e., all the particles could participate in the wear of the surface of the test material. Before conducting experiments the specimens are ground, polished, washed with alcohol, dried in a medium of inert gas, and weighed with an analytical balance to $\pm 10\ \mu$g. Prior to the experiment, the abrasive particles are fractionated within the range 0–2000 μm with a standard set of sieves. Before the setup is started, a portion of particles is weighed and used for filling bin 31 (Fig. 1), which then is sealed. The bed of abrasive particles is blown by an inert gas (the gas-carrier) to remove humid air from the bed. Then, liquid nitrogen is delivered into the nitrogen jackets of the cryostats, and a period of the cooling of the setup begins. Blowing of the bed of abrasive particles with the cooled gas-carrier is continued. At the first stage, cooling of the working chambers of the cryostats is done by passing nitrogen vapor from a nitrogen jacket. On attainment of the saturation temperature in the chambers, supply of other coolants begins (depending on the temperature needed). As soon as this temperature is attained, the two-disk device (Fig. 2) fixed on shaft 19 is actuated (Fig. 1), and the rated speed of rotation and the working expenditure of abrasive particles, which is determined by the gas pressure in bin 31 and the diameter of calibrated nozzle 33, are specified (Fig. 1).

When the two-disk device rotates in the two directions, two erosive marks appear on the upper surface of disk 5 (Fig. 2) that allow one to calculate the average velocity of the particles (see formula (2)). While the velocity of the particles is being measured, the temperature, pressure, and flow rate of the gas-carrier, the pressure in the bin with the abrasive, and the temperature of the test specimens are fixed. Then, the two-disk arrangement is replaced by platform 24 (Fig. 1) on which up to 12 test specimens can be attached. The angle of inclination of each of the specimens with respect to the axis of the gas-abrasive flux can be the same and can equal 15–90°. Each of the specimens can be set at different angles of attack (within the same range of angles).

It is also known that for the majority of metals and alloys in the initial (relatively brief) stage of the process the rate of erosion is variable, which is succeeded by a stationary regime for which $\Delta m/m_e$ = const [8]. To determine the time of onset of the stationary stage of the process, what is important is successive use of twelve identical (of the same material) specimens, located in the working chamber, that are identically oriented in space and have the same temperature. Each of the specimens was exposed in turn to the two-phase jet, whose time of attack on the next specimen is increased. After completion of erosion of the surface of all twelve specimens, their withdrawal from the chamber, and determination of the removal of mass (by weighing each specimen before and after the experiment) we can construct a "total" curve of the rate of erosion versus the mass of spent erodent (or versus the time) for an unchanged angle of attack and a constant impact velocity of the particles. On this curve one can easily separate the two characteristic stages of the erosive process. Our experiments show that usually the first three specimens experience erosive destruction in the nonstationary stage, whereas the remainder do this in the stationary regime. Proceeding from this, it is possible, in the same temperature regime in one series of experiments, to obtain, for example, two curves of "rate of erosion – mass of spent erodent ": the first one using six specimens at one angle of attack and the other using the other half of the specimens with a changed angle of attack. This approach substantially accelerates the execution of extremely laborious experiments and, on the other hand, improves their reproducibility.

In the main experiments it is worthwhile to set the same temperature regime, pressure, and flow rate of the gas-carrier, flow rate of the abrasive particles, and, ultimately, specified velocity of impact of the particles with the surface of the test materials as in the preliminary experiments in which the velocity of the particles was determined. During the tests we fix the readings of the flowmeter, gauges, and secondary devices to find the temperatures at the points of measurements. The expenditure of abrasive particles (of known mass) is determined from the time spent to empty the bin. The flow density of abrasive particles in the gas flow is calculated from the measured flow rates of the gas-carrier and abrasive. If a change in the expenditure of abrasive particles is required (in a new series of experiments), the replacement of calibrated nozzle 33 is envisioned (Fig. 1).

The series of experiments ends with the withdrawal of the specimens from the working chamber of the setup. Then, they are again washed with alcohol, dried in a gas jet, and weighed with an analytical balance. The difference between the masses of the specimens before and after the experiment gives the value of the removal of mass for the time of the test.

The state and structure of the worn surface can be investigated by profilometering and optical and scanning electron microscopy.

We investigated the erosion of ShKh15, 40Kh2N2MA, and 12Kh18N10T steel specimens and VT-1 and D16T alloy specimens. As the erodent, we used dry quartz sand of Staroverovka deposit with a grain size of 0.2–0.315 mm (ShKh15, 40Kh2N2MA, D16T) and 0.100–0.160 mm (12Kh18N10T, VT-1). The expenditure of erodent was 0.1 g/sec. Each value of the intensity of erosive destruction (rate of erosion) $\Delta m/m_e$ (in a stationary regime) was found on the basis of at least three measurements.

Figure 3a presents dependences (for a temperature of 293 K) of the intensity of erosive destruction of 40Kh2N2MA steel specimens of different strength on the angle of attack at an average velocity of the particles of 50 m/sec. Before performing the main experiments, three batches of specimens were obtained with different hardnesses, which was attained by changing the regime of thermal treatment: heating to 870 ^{o}C for hardening, holding in the furnace for 30 min, hardening in oil, and then tempering at temperatures of 200, 400, and 600 ^{o}C. The hardness HRC was determined at three points at each tempering temperature and then was converted into megapascals. From Fig. 3a it follows that: 1) the maximum of the rate of erosion for specimens with a hardness H = 3090 MPa falls on an angle of attack of 50^{o}, and at H = 5240 MPa on 60^{o}. With a right angle of attack the destruction of harder specimens was more intense: the rate of erosion at H = 4410 and 5240 MPa was 1.26 and 1.39 times higher than at H = 3090 MPa. At angles of attack smaller than 48^{o} a clearly defined reverse picture begins to emerge: the intensity of destruction is higher, the lower the value of the hardness. This phenomenon can be explained by a difference in the mechanism of destruction: at angles of attack smaller than 48^{o} microcutting is predominant, whereas at larger angles it is multiple elastoplastic deformation [9].

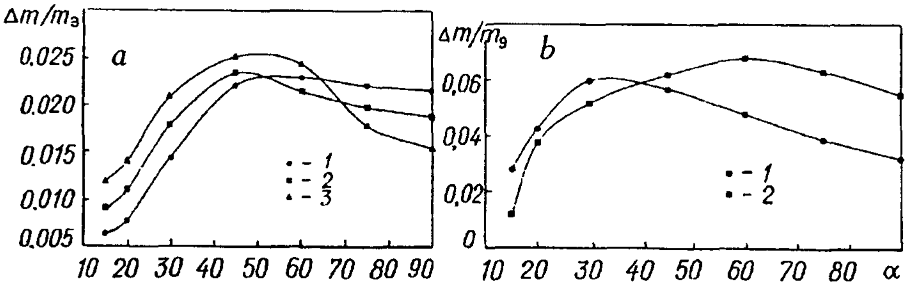

Fig. 3. Intensity of destruction of 40Kh2N2MA steel (a) and ShKh15 steel (b) versus angle of attack for different values of the hardness of the target material and the temperature: a: 1) $H = 5240$ MPa, 2) 4410, 3) 3090; b: 1) $T = 293$ K, 2) 145. $\Delta m/m_e$ mg/g; α, deg.

The influence of temperature on the intensity of erosive destruction of ShKh15 steel specimens at different angles of attack (the average velocity of impact is 50 m/sec) can be judged from Fig. 3b. The maximum of the intensity of erosive destruction on reduction of the temperature from 293 to 145 K is displaced to larger angles of attack from 30° (a typically "ductile" regime of destruction [1]) to 60°. The value itself of the erosion-rate maximum increased by 17%. A characteristic feature is also that at angles of attack $\alpha > 40°$ erosion occurs more intensely at $T = 145$ K and at $\alpha < 40°$ the values of its intensity are higher under conditions of room temperature.

For specimens of D16T Duralumin and ShKh15 steel, at a right angle of attack and an average velocity of the particles of 50 m/sec dependences of the intensity of erosive destruction on temperature (100– 293 K) are found that are approximated respectively in the form

$$\frac{\Delta m}{m_e} = -3\cdot 10^{-6}T^2 - 2\cdot 10^{-4}T + 0.41\,, \tag{4}$$

$$\frac{\Delta m}{m_e} = -0.0002T + 0.0757\,. \tag{5}$$

From an analysis of Eqs. (4) and (5) it follows that with a decrease in the temperature from 293 to 120 K the rate of erosion increases: by a factor of 4.3 for D16T Duralumin and 1.7 for ShKh15 steel. According to [4], similar conditions of the experiment (angle of attack, temperature interval) for St. 3 steel lead to an increase in the intensity of erosive destruction by a factor of 2.2 (the erodent is quartz sand of grain size 1.0 and 1.2 mm, the impact velocity is 82 m/sec). It should be emphasized that the procedures of the investigation of St. 3 steel [4] and ShKh15 steel and D16T alloy specimens were different but nevertheless the nature of the effect of low temperatures on the erosion of the materials is found to be the same.

NOTATION

S, distance between the upper surfaces of the rotating disks; w_p, velocity of the particles of erodent; τ, time; γ, angle between erosion marks; δ, length of the arc between erosion marks; l, distance between erosion marks; ω, angular velocity of rotation of the disks; R, radius of the erosion marks; Δm, removal of mass of the specimen; m_e, mass of spent erodent; $\Delta m/m_e$, intensity of erosive destruction; α, angle of attack; T, absolute temperature. Abbreviations: MT, industrial pressure gauge; TVO, heatproof, moistureproof, bulk (resistor); KG, helium cryostat; RM-2.5G, rotameter modernized for measuring the flow rate of gas media (G); SD, synchronous motor; TE, electronic tachometer; PI, device for measuring pressure; FI, device for measuring flow rate; TI, device for measuring temperature; SI, device for measuring rotational speed (all devices are indicating); TE, temperature-sensitive element; TIR, device for measuring temperature, indicating and recording; SE, element indicating the speed of rotation.

REFERENCES

1. S. E. Smeltzer, M. E. Gulden, and V. A. Compton, Transactions of ASME, Ser. D [Russian translation], **102**, No. 3, 225-228 (1970).
2. A. Evans, A. Ruff, and S. Viderhorn, Erosion [Russian translation], Moscow (1986).
3. P. V. Rao and D. H. Buckley, Transactions of ASME, Ser. A [Russian translation], **107**, No. 3, 75-81 (1985).
4. H. H. Lepikson and V. V. Siimpoeg, Trudy Tallinnsk. Politekh. Inst., Ser. A, No. 2712, 31-36 (1969).
5. V. G. Grebenkina, Bulk Resistors [in Russian], Kiev (1976).
6. V. I. Datskov, L. V. Petrova, and G. P. Tsvileva, Cryogenic Thermometers Based on HMB-type Resistors and Their Application [in Russian], Dubna (1987).
7. A. W. Ruff and L. K. Ives, Wear, **39**, 195-198 (1975).
8. P. V. Rao and D. H. Buckley, Proc. Sixth Intern. Conf. on Erosion by Liquid and Solid Impact, Cambridge (1983), pp. 38/1-38/11.
9. V. N. Vinogradov, G. M. Sorokin, and M. G. Kolokol'nikov, Abrasive Wear [in Russian], Moscow (1990).