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HEATING OF SOLID SURFACES BY AN ELECTRIC ARC

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We have developed a calorimetric probe for measuring unsteady heat fluxes with a resolving time $\Delta t < 10^{-3}$ sec. We have determined the flux to solid surfaces from an electric arc stabilized by a rotating cylinder.

An increase of the efficiency of high-temperature technological processes in many cases requires the use of intense sources for heating materials with a long operative life. Thanks to successes in producing jet arc plasmatrons, the problem of obtaining continuous heat flux densities $q < 5 \cdot 10^3$ W/cm^2 can be considered solved. Higher fluxes are achieved with a relatively low coefficient of utilization of the energy input [1-3]. In addition, the large dynamic head on the surface of a heated body limits the use of jet generators to solve problems of the heat treatment of materials when a surface film of molten material is present.

An arc plasma has a higher temperature and a lower flow velocity than a plasmatron jet. In view of this, it is of interest to investigate the creation of devices for heating the surfaces of bodies directly by an electric arc. The construction of one such plasmatron is described in [3]. In the present article we report the results of a study of the surface heating of bodies by using a similar device whose mode of operation is explained in Fig. 1a. The ends of the plasmatron electrodes were arranged in such a way that the plasma column was oriented parallel to the surface being heated 3. Its position in space is fixed by the rotating cylinder 1, mounted above the surface being treated at a distance d, less than the diameter of the current-conducting column. Because of the viscosity of the surrounding medium, a rotating gas stream is formed around the cylinder which clamps the plasma column simultaneously to the surface of the body and the cylinder.

The temperature of the gas layer between the cylinder and the plasma column is determined largely by the characteristics of the surrounding medium. Since the device operates in the open atmosphere, the temperature of the air layer will be relatively low, and thermal and electrical contacts between the rotating cylinder and plasma are negligible. It was shown experimentally that for currents in the range 30-80 A the arc is shunted onto a current-carrying cylinder 15 mm in diameter only at low rotational velocities $n \leqslant 5$ rps. The discharge is not shunted at high velocities even for quite long ($l > 100$ mm) cylinders. This permits a substantial simplification of the construction and an improvement of the operational characteristics of the device to position the arc by replacing the dielectric cylinder with a metal one. The surfaces of large articles are heated by displacing the plasmatron with a special mechanical device in a direction perpendicular to the axis of the arc.

The intensity of heating of samples was studied by a calorimetric measurement of the heat flux supplied to their surfaces. In most cases such measurements were performed with a probe in the form of a copper rod with a thermocouple pressed into it. The resolving time is determined by the distance from the collecting surface of the probe to the thermocouple. However, the indeterminacy of the position of the heat-sensitive layer in the body of the calorimeter, and the presence in it of appreciable voids, even with tight calking of the thermocouple with two wire outlets, prevented highly accurate measurements of intense unsteady heat fluxes. Additional calibration experiments have their own errors, and therefore do not permit a significant increase in the accuracy of the determination of the heat flux. A major flaw of the probe described is its slow response. As a consequence of the large size

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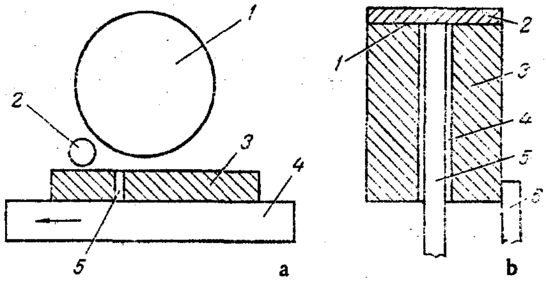

Fig. 1. a) Schematic diagram of plasmatron with clamping of arc: 1) rotating cylinder, 2) plasma column, 3) sample being heated, 4) displacement device, 5) probe; b) film calorimetric probe: 1) heat-sensitive element, 2) Cu film, 3) calorimeter body, 4) layer of electrical insulation, 5) electrode, 6) supply.

of the heat-sensitive layer (not less than 0.5 mm), it is difficult to perform reliable measurements with a frequency higher than 10 Hz.

The quick response of a probe is an important characteristic not only in pulsed experiments, but also in measuring intense steady heat fluxes. The restriction on the residence time of a calorimeter in the high-temperature region without damage requires a rapid entrance and exit of the receiving surface of the probe in making measurements. Thus, by using unsteady diagnostic methods, the range of measurements of intense steady fluxes can be appreciably expanded when using quick-response probes.

The response speed and reliability of measurements with heat flux probes can be increased for a fixed temperature of the receiving surface of the calorimeter by optical or contact methods. Figure 1b shows a probe in which the receiving part is also the heat-sensitive element 1 formed by the copper film 2 and the end of electrode 5 of 0.05 mm diameter constantan wire. A layer of electrically insulating Al_2O_3 4 is deposited on the lateral surface of the electrode by thermal evaporation in a vacuum, or SiO_2 is deposited in a high-frequency discharge in a mixture of gaseous $SiH_4/Ar + O_2$. The dielectric coating prevented the diffusion of molten metal into electrode 5, and in most cases was 1-10 μm thick.

In the next step a centering diaphragm was used to immerse electrode 5 with its protective high-temperature coating in molten copper at T = 1300°K in a cylindrical graphite crucible. After cooling, the body of calorimeter 3 with the built-in electrically insulated electrode of the thermocouple was polished to the 12th class of surface finish, and a copper film 1 was deposited on it by vacuum evaporation from the gaseous phase. Depending on the required response speed, the thickness of the film was 0.1-10 μm, and therefore the error in determining the position of the heat-sensitive layer was more than a factor of 100 smaller than in the probe with the pressed thermocouple. This increases the accuracy of the measurements of the heat flux by the probe described, and makes it possible to study fast processes. The sensitivity of a probe of this type can be increased by using a set of film thermocouples connected in series.

Using the probe described, the heat flux was determined by the semibounded body method [4]. During the heating of a body its temperature T at time t in cross section x is

$$T(x, t) = T_0' + \frac{2q}{\lambda}\sqrt{at}\,\mathrm{ierfc}\left(\frac{x}{2\sqrt{at}}\right). \quad (1)$$

Using this relation, we can estimate the difference between the temperature of the receiving surface of the calorimeter and that recorded by the thermocouple. For example, for a film thickness $\delta = 0.3$ μm and $t = 10^{-3}$ sec, the ratio of the temperature increment of the front surface of the film to that of the calorimeter is $A = (T(\delta, t) - T_0')/(T(0, t) - T_0') = 0.99$.

Thus, with this probe, the temperatures of the receiving surface of the calorimeter and the thermocouple are equal to within 1%. It should also be noted that as a consequence of the volume absorption of radiation by a thin film of the medium under study, determined by electron–phonon processes in the material with an interaction time 10^{-10} sec [5], a heat pulse is transmitted to the heat-sensitive layer more quickly. Therefore, according to [4],

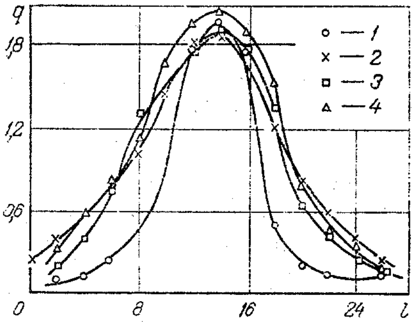

Fig. 2.

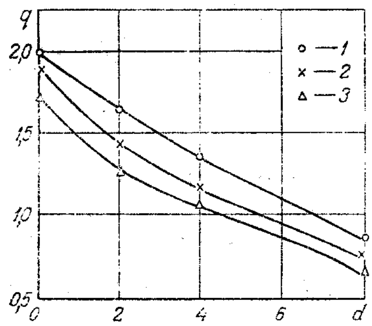

Fig. 3.

Fig. 2. Distribution of heat flux in heating zone with i = 75 A: 1) asbestos cement; 2) steel; 3) silicate brick; 4) quartz. q is in kW/cm^2 and l in mm.

Fig. 3. Dependence of heat flux on distance between clamping block and surface being treated at i = 75 A for various rates of rotation: 1) 3150; 2) 2500; 3) 1700 rpm. d is in mm.

in many cases q can be determined without knowing the thickness δ of the layer sputtered on the calorimeter, although this thickness can be determined to within 5% by contemporary technical means [6]. Analysis showed that without taking account of the value of δ, measurements of q accurate to within 3% can be made with the probe at a frequency of 1 kHz. The accuracy of the measurements of q can be appreciably increased both by decreasing δ and by performing calculations of q taking account of δ.

The massive copper calorimeter in the probe under consideration was used to model a semi-bounded body. The response speed of the calorimetric probe is determined by the rate of the thermoelectric effect: the time of electron transitions between the two metals (10^{-8} sec) [7], and the mass of the junction. In our case the mass of the junction is equal to the mass of the film over the end of the constantan electrode, and is ∿500 times smaller than for the wire thermocouple. For this reason, the probe under consideration has an appreciably faster response time than the calorimeter with a pressed wire thermocouple.

We investigated the heating of the surfaces of samples of ceramics, silicate and asbestos cement materials, and steel. The probe was mounted flush with the surface of the sample which was translated with a velocity v = 5 mm/sec relative to the column in a direction perpendicular to its axis by a mechanical device driven by an electric motor. The electrical signal of the calorimeter was recorded with a light-beam oscillograph. The accuracy of the measurements was increased by placing ahead of the oscillograph a device based on an operating 153UD2 amplifier [7] to suppress the in-phase interference, which is very important in experiments using plasmatrons.

Figures 2 and 3 show the heat flux distribution in the heating zone as a function of the distance of the rotating cylinder from the heated surface of the sample and its material. The maximum $q = 2 \cdot 10^3$ W/cm^2 occurs at the minimum separation d = 0.2 mm with a current i = 75 A. The shape and size of the distribution $q(l)$ are practically identical for all the samples investigated. The profile $q(l)$ was broader for silicate materials than for quartz, asbestos cement, or steel. The profile $q(l)$ is noticeably asymmetric as a result of the one-sided stabilization of the plasma column by the rotating cylinder.

Ablation heating of the sample surfaces occurred in the experiment. Since vapors of the materials studied have different thermophysical characteristics, the fact that $q(l)$ is independent of the type of material can be accounted for by the small content of vaporized material in the boundary layer. This is largely a result of the high tangential velocity $v \approx 5$ m/sec of the stabilizing air stream and the low rate of evaporation. For example, for $q_m = 2$ kW/cm^2, mass was removed at the rate of 36 $g/m^2 \cdot sec$ from one of the most severely damaged samples (silicate brick), and the maximum vapor velocity is ∿1 m/sec. It is believed that the vapor of a sample material is carried away from the heating zone practically instantaneously, and heat exchange between arc and sample is determined mainly by the transfer properties of the air plasma.

The dependence of the heat flux on the discharge current is more important. When the discharge current i is increased from 20 to 75 A the maximum heat flux to asbestos cement increases by a factor of 10. The uniform character of this dependence indicates substantial possibilities of increasing the surface heating of samples by using higher discharge currents.

Analysis of the results obtained shows that a rotating cylinder ensures reliable space-time fixation of the plasma column on the surface being heated. The energy density input to the surface is increased ∿50% by further clamping of the plasma column.

The principle of the plasma device described can be used as a basis for producing efficient technological devices for heating materials. The heat flux probe proposed can be employed in both research and technology to monitor high-temperature processes.

NOTATION

n, rotation velocity, rps; T, temperature, °K; x, coordinate; t, time, sec; T_0', initial temperature of calorimeter; q, heat flux density, kW/cm^2; λ, thermal conductivity, W/m·°K; v, velocity, m/sec; d, distance from the surface of the clamping block; δ, thickness of layer; a, thermal diffusivity, m^2/sec.

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