METAL RUPTURE UNDER THE EFFECT OF CONCENTRATED HEAT FLUXES

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The temperature distribution during metal heating by a concentrated surface heat source is found numerically. The shapes of the melted puddles are analyzed, and dependences are constructed connecting the quantitative characteristic of metal rupture to the heat source parameters.

The effect of concentrated heat fluxes on various metals is frequently encountered in engineering. Material rupture is a result of such an effect. The regularities of such capture have been studied by many investigators for different purposes [1-4].

In certain cases it is sufficient to solve a one-dimensional problem to describe the heat process [5-7]. However, if the degree of propagation of the heat process is equal to or exceeds the transverse dimensions

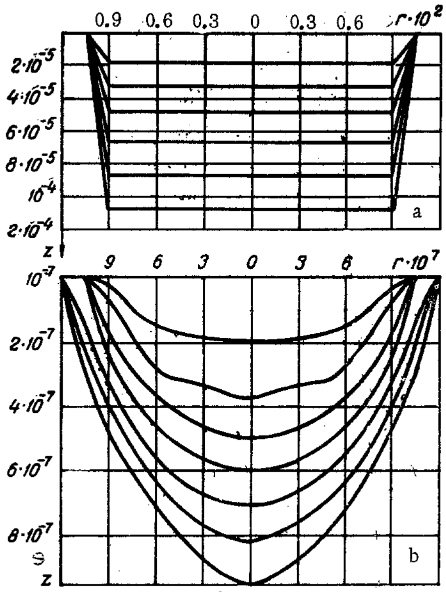

Fig. 1

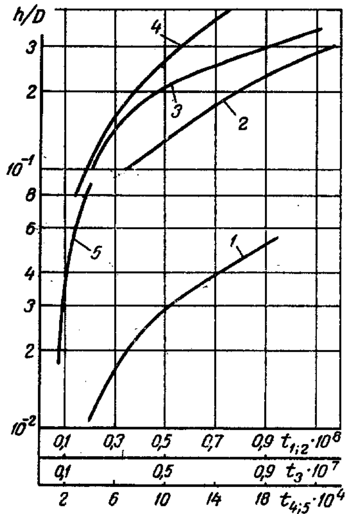

Fig. 2

Fig. 1. Development of the melted puddle in a metal with time: a) for $q_B = 4.17 \cdot 10^9$ W/m^2; $R_0 = 10^{-2}$ m; $t_1 = 9.6 \cdot 10^{-5}$ sec; time interval between curves $3 \cdot 10^{-5}$ sec; b) for $q_B = 12.5 \cdot 10^{11}$ W/m^2; $R_0 = 10^{-6}$ m; $t_1 = 2 \cdot 10^{-9}$ sec, time interval $2 \cdot 10^{-9}$ sec.

Fig. 2. Time dependence of the ratio between the depth of the melted puddle and its diameter for different q_B and R_0: 1) $q_B = 12.5 \cdot 10^{11}$ W/m^2; $R_0 = 10^{-5}$ m; 2) $4.17 \cdot 10^{11}$ and 10^{-6} respectively; 3) $12.5 \cdot 10$ nd 10^{-6}; 4) $4.17 \cdot 10^9$ and 10^{-4}; 5) $4.17 \cdot 10^9$ and 10^{-3}.

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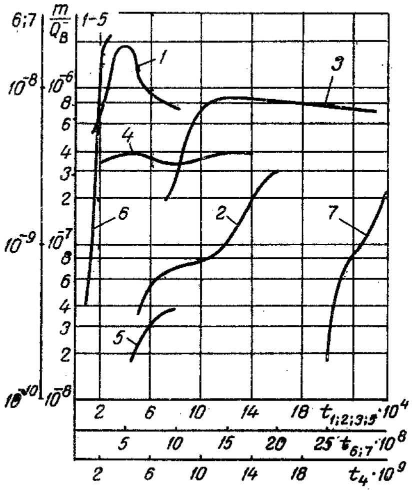

Fig. 3. Time dependence of the masses of melted (1-4) and evaporated (5-7) metal for different q_B and R_0: 1) $q_B = 4.17 \cdot 10^9$ W/m^2; $R_0 = 10^{-3}$ m; 2) $4.17 \cdot 10^9$ and 10^{-4} respectively; 3) $12.5 \cdot 10^8$ and 10^{-3}; 4) $12.5 \cdot 10^{11}$ and 10^{-6}; 5) $4.17 \cdot 10^9$ and 10^{-3}; 6) $12.5 \cdot 10^{11}$ and 10^{-6}; 7) $4.17 \cdot 10^{11}$ and 10^{-6}.

of the heat source, the one-dimensional approximation is inapplicable.

The three-dimensional problem of heat propagation is solved herein and the regularities of metal rupture are analyzed. Metal evaporation and motion of the evaporation front deep in the metal are hence taken into account. The flux distribution over an area of radius R_0 was assumed uniform. The computation was carried out on a digital computer.

For the axisymmetric case the heat conduction equation in cylindrical coordinates is (for $z > 0$)

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right). \tag{1}$$

The solution was carried out under the following boundary conditions: for $0 \le r \le r_0$ the flux balance on the metal surface is

$$q_B = -\lambda \left.\frac{\partial T}{\partial z}\right|_{z=\eta} + q_{\text{eva}}(T|_{z=\eta}), \tag{2}$$

and for $r > r_0$

$$0 = -\lambda \left.\frac{\partial T}{\partial z}\right|_{z=\eta} + q_{\text{eva}}(T|_{z=\eta}), \tag{3}$$

and the equation of evaporation front motion is

$$\gamma \frac{d\eta}{dt} = \sqrt{\frac{M}{2\pi R}} \cdot \frac{10^{6+k-\frac{l}{T|_{z=\eta}}}}{760 T|_{z=\eta}}, \tag{4}$$

$$T(t,\ \infty,\ z) = T_0;\quad T(t,\ r,\ \infty) = T_0. \tag{5}$$

The coefficients k and l were taken from [8]. The initial condition was taken as

$$T(0,\ r,\ z) = T_0. \tag{6}$$

The temperature dependence of the thermophysical parameters was taken into account in computations with (1)-(4).

The Riesman–Rockford method [10] was used for the numerical solution of (1). By knowing the temperature distribution at the time t, the temperature at the time $t + \tau$ can be found from the relationship

$$\frac{T(t+\tau) - T(t)}{\tau} = a\left[\Delta_r T(t+\tau) + \Delta_z T(t)\right], \tag{7}$$

where

$$\Delta_r f(r) = \frac{\left(1 - \frac{1}{2r}\right) f(r-\rho) - 2f(r) + \left(1 + \frac{1}{2r}\right) f(r+\rho)}{\rho^2}$$

and

$$\Delta_z f(z) = \frac{f(z-h) - 2f(z) + f(z+h)}{h^2}.$$

A relationship of the form

$$\frac{T(t+2\tau) - T(t+\tau)}{\tau} = a\left[\Delta_r T(t+\tau) + \Delta_z T(t+2\tau)\right] \tag{8}$$

was used to find the temperature at the time $t + 2\tau$. It is easy to see that (7) and (8) reduce to the solution of systems of linear equations with tridiagonal matrices, where $T(t + \tau)$ is the unknown in (7), say. Each such system can be solved by the factorization method [11]. The advantage of this method is that it is stable for any relationships between τ, ρ and h. The error is $0(\tau + h^2 + \rho^2)$.

The temperature distribution, and therefore, the location of the melting and evaporation boundaries for copper at different times were obtained in the computation. The development of the melted puddles in the metal is shown in Fig. 1, and the time dependence of the ratio between the puddle depth and its diameter in Fig. 2.

The shape of the melted trace in the metal is determined by the size of the source, and heat flux, and the effective time. Processing the results of the computation showed that the melting isotherm can have both a compressed shape characteristic for one-dimensional heat propagation (Fig. 1a) and a more complex curvilinear shape (Fig. 1b) for different heat source parameters. To describe the metal rupture process for the parameters corresponding to Fig. 1a, it is sufficient to solve the heat conduction problem in a one-dimensional approximation. If the melting isotherms have a complex shape (Fig. 1b), it is then necessary to solve the three-dimensional heat propagation problem.

It follows from the results of computing the three-dimensional problem taking account of evaporation that the one-dimensional approximation is applicable under the condition $R_0 \geq 4\sqrt{at}$. The conditions of the source size hence exceed the degree of melting by an order of magnitude and more.

The dependences connecting the quantitative characteristics of metal rupture (the mass of the melted and evaporated metal) to the heat source parameters are quite important from the viewpoint of the technological application of concentrated heat fluxes.

Time dependences of the mass of melted and the mass of evaporated metal are shown in Fig. 3 for different heat sources. The influence of the radius of the heat source on the mass of melted metal can be represented by comparing curves 1 and 2 in Fig. 3 for the same flux $4.17 \cdot 10^9$ W/m^2. For a greater radius, the specific wear exceeds the wear at the lesser radius somewhat. This can be explained by the fact that the shape of the hole at the lesser radius is approximately hemispherical and high heat losses occur because of fluxes in the radial direction.

The computations carried out showed that the temperature distribution is nonuniform within the source for certain sizes of the heat source and fluxes, although the heating is accomplished for a uniform flux distribution. The cathode spot of an electric arc is a heat source with a flux on the order of $12.5 \cdot 10^{10}$ W/m^2 and a $\sim 10^{-5}$ m radius [9]. Under such heat source parameters the temperature distribution is nonuniform and, consequently, the electron current, the ion current determined by the quantity of evaporated atoms, and other quantities will be nonuniformly distributed. This means that both the current and the heat flux probably vary within the cathode spot.

NOTATION

T	is the temperature, °C;
a	is the coefficient of temperature conductivity;
r, z	are the coordinates;
λ	is the coefficient of heat conductivity;
q_B	is the heat flux, W/m^2;
q_{eva}	is the heat flux due to evaporation;
γ	is the density of electrode material;
M	is the molecular weight;
R	is the universal gas constant;
k, l	are the evaporation constants;
T_0	is the initial temperature, °C;
t, τ	is the time;
h	is the depth;
R_0	is the radius of the domain on which the heat flux acts;
η	is the coordinate of the evaporation front;
e	is the electron charge;
$Q_B = q_B \pi R_0^2 t$	is the heat going into heating.

LITERATURE CITED

1. N. N. Rykalin, Computations of Heat Processes in Welding [in Russian], Mashgiz, Moscow (1951).
2. B. R. Lazarenko (editor), "Problems of electrical processing of materials," Transactions of Central Scientific Research Institute of the Leningrad Electrical Industry of the Academy of Sciences of the USSR [in Russian] (1960).
3. B. N. Zolotykh, Author's Abstract of Doctoral Dissertation [in Russian], Moscow (1968).
4. G. V. Butkevich and E. M. Tseirov, Byulleten' VÉI, No. 6 (1941).
5. A. S. Zingerman, Izv. VUZ. Élektromekhanika, No. 5, 87 (1960).
6. G. S. Belkin and V. Ya. Kiselev, Zh. Tekh. Fiz., 36, 384 (1966).
7. A. G. Goloveiko, Inzh.-Fiz. Zh., 13, No. 2 (1967).

8. M. Knoll, F. Ollendorf, and R. Rompe, Tabellen, Formeln und Kurven zur Physik und Technik der Elektronen und Ionen, Berlin (1935).
9. I. G. Kesaev, Cathode Processes of an Electric Arc [in Russian], Nauka, Moscow (1968).
10. W. Wasow and G. Forsythe, Difference Methods of Solving Partial Differential Equations [Russian translation], IL (1963).
11. V. K. Saul'ev, Integration of Equations of Parabolic Type by a Mesh Method [in Russian], Fizmatgiz (1960).