MATERIAL REMOVAL FROM A SURFACE UNDER THE ACTION OF A REFLECTED SHOCK WAVE

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Using a numerical simulation, [1] studied the effect of moderate energy fluxes (with energy densities $q \sim 10^5$-10^6 W/cm^2) on metals. Upon reflection of strong shock waves in a gas from a rigid wall, more powerful radiant fluxes with a density $q \sim 10^7$ W/cm^2 and above can be obtained. The possibility of thermal processing of metals by the action of the plasma of a reflected shock wave generated by an explosion was shown experimentally in [2]. Such a thermal processing technique can be accompanied by significant removal of mass from the surface of the specimen undergoing processing, as well as formation of a porous zone (Fig. 1) in the freezing melt.

To simulate the process of reflected wave plasma action on a metal surface we will consider normal reflection of a shock wave with a plane front. A diagram of the process is shown in Fig. 2. The shock wave in the gas is reflected from the closed end of the channel (RSW) and, being obstructed by the explosion products (ERP), acts on the wall surface with a radiant flux q for a time period τ. The action time τ corresponds approximately to the plasma ionization time τ_i. In the reflected shock wave pressures of 0.5-1 GPa are achieved. Usually the pressure action time τ_p is greater than the ionization time ($\tau_p \geqq \tau_i$) and is determined by the conditions under which the explosion products expand. Such radiant flux thermal action in the presence of increased pressure differs significantly from laser action on material [3]. The existence of the pressure p mainly affects the boiling temperature of the wall material T^*_p, the value of which can be determined from the Clapeyron–Clausius equation: $T^*_p = T^*_0 \Big/ \left(1 - R\frac{T^*_0}{L}\ln\frac{p}{p_0}\right)$, where L and T^*_0 are the heat and temperature of boiling under normal pressure p_0; R is the universal gas constant. For example, for iron the temperature T^*_p at p = 0.7 GPa is more than twice T^*_0. After removal of the pressure (at time $t = \tau_p$) a superheated region $0 \leqq x \leqq \delta$ with temperature T(x, t) greater than T^*_0 can exist in the surface layer of the wall.

When powerful thermal fluxes act on metals, intense evaporation from the surface occurs. If the state of the reflected wave plasma is stable and immobile, a layer of vapor diffusing into the plasma will be formed at the wall surface. Formation of such a layer can lead to screening of the wall surface from the radiation [4] and, consequently, to a decrease in the intensity of evaporation. If we neglect the evaporation thickness, then to analyze the temperature field at the wall the thickness ℓ can be taken as that or a multifront Stefan-type mathematical model [5] with boundary conditions on the surface:

$$-\lambda\partial T/\partial x|_{x=0} = q,\ t < t_*;$$
$$T|_{x=0} = T^*_p,\ t_* \leqslant t < \tau;\ \partial T/\partial x|_{x=0} = 0,\ t \geqslant \tau,$$

where t_* is the time at which evaporation begins. In numerical studies of this problem by the method proposed in [5], interaction parameters characteristic of wall material processing by a plasma from an explosive source [2] were used. Values of the metal's thermophysical parameters — thermal conductivity λ, specific heat c, and density ρ — were taken as piecewise continuous within the limits of each of the phases existing (in the melt, thermal tempering zone, and the original solid phase).

Figure 3a shows the dynamics of the $\alpha - \gamma - \alpha'$ conversion front $x = \eta(t)$ (line 1), the fusion front $x = \xi(t)$ (line 2), and the boundary of the superheated layer $x = \delta(t)$ (line 3) (the isotherm $T(x, t) = T^*_0$) for characteristic parameters and conditions for action of argon

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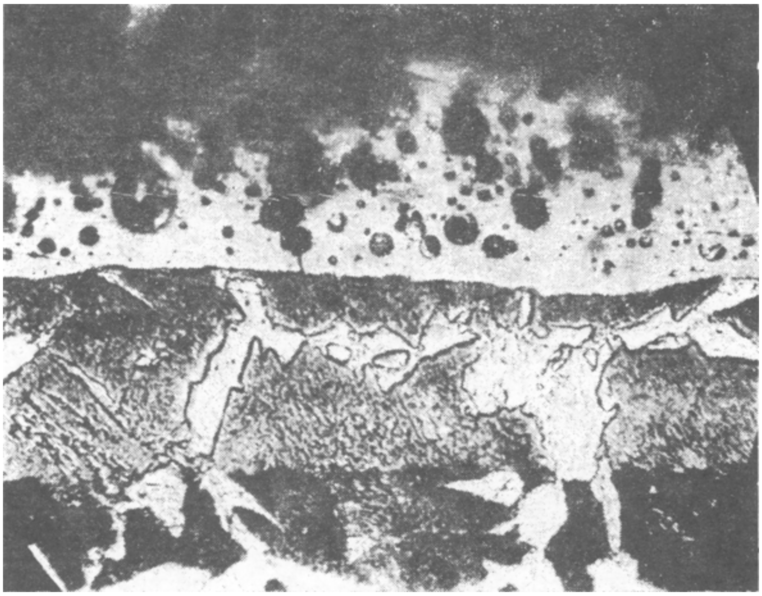

Fig. 1

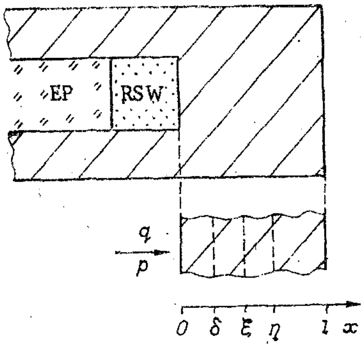

Fig. 2

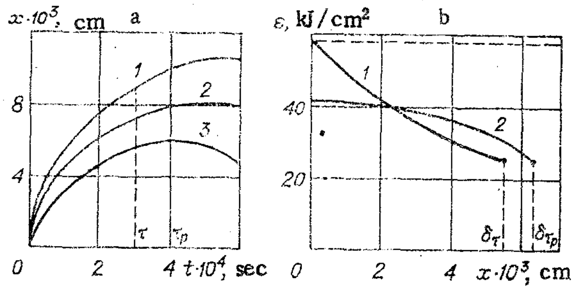

Fig. 3

TABLE 1

Experiment No.	T_c, K	p, GPa	τ_p, msec	τ, msec	Cu		Al		Fe	
					h, mm	δ, mm	h, mm	δ, mm	h, mm	δ, mm
1	45000	1,1	0,6	0,6	0,3	0,19	0,4	0,25	0,1	0,076
2	45000	1,1	1,1	0,6	0,2	0	0,3	0,13	0,05	0,058

plasma on iron: $\tau_i = 3 \cdot 10^{-4}$ sec, $\tau_p = 4 \cdot 10^{-4}$ sec, p = 0.9 GPa, T_c = 41,000°K, $q = 2 \cdot 10^7$ W/cm², T^*_p = 7400°K. After completion of thermal flux action ($t \geq \tau_i$) further motion of the boundaries into the depths of the wall occurs, due to the energy stored in the surface layer. The major portion of the thermal energy is concentrated in the superheated layer $0 \leq x \leq \delta$. The specific thermal energy distribution in the superheated layer at times $\tau_i = t$ and $\tau_p = t$ is shown in Fig. 3b by lines 1 and 2, the dashed line being the energy $\varepsilon^*_0 = \rho(L + cT^*_0)$, necessary for evaporation of iron at atmospheric pressure. It is evident from the graph that the thermal energy in the superheated layer is insufficient to evaporate the entire layer. Partial removal of the material after removal of pressure will be determined by possible boiling in the superheated melt. The presence of pores in plasma-processed specimens (Fig. 1) indicates that volume boiling has occurred, while the smooth distribution of thermal energy in the superheated region up to the moment of boiling (the curve $t = \tau_p$) indicates that practically the entire superheated layer is a zone of developed porosity. At interaction parameters permitting achievement of near-critical values of T^*_p in iron, as well as in other

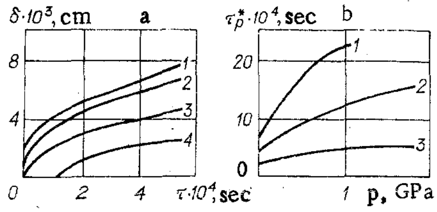

Fig. 4

metals [6], apparently a portion of the thermal energy distribution curve in the superheated layer will lie above the point ε^*_0. In this case gasdynamic removal of vapor with subsequent boiling is possible. In view of the highly energetic process of volume vapor formation in the melted layer one can expect a rapid cooling rate.

In Fig. 4a (p = 2, 1, 0.2, and 0.05; lines 1-4) the thickness of the superheated layer δ is shown as a function of τ, the reflected air plasma action time. At pressures above 1 GPa the value of δ depends weakly on p and is practically independent of the value of the thermal flux acting (sine $t_* \ll \tau_i$). If the pressure action time τ_p is sufficiently large, then the superheated layer may cool to a temperature below T^*_0. Values of the pressure maintenance time τ^*_p necessary for disappearance of the superheated layer are shown as functions of pressure in Fig. 4b ($\tau = 6 \cdot 10^{-4}$, $4 \cdot 10^{-4}$, $2 \cdot 10^{-4}$; lines 1-3). In the case where $\tau_p \gg \tau^*_p$, maximum depth melt zones are achieved without a porous zone.

Experimentally measured depths of mass removal from the surfaces of plasma-processed specimens h lie in the range 0.1-0.5 mm. Table 1 presents experimental values of removal depths h and calculated values of superheated layer thickness δ in various metals for action of argon plasma. The interaction conditions in experiments 1 and 2 differed only in the duration of the action of pressure τ_p. In the second case the superheated layer is completely absent in copper ($\tau_p \geqq \tau^*_p$) so that mass removal is caused by evaporation. The increase in thickness of material removed in experiment 1 can be explained by the presence of a superheated layer, boiling of which produces some contribution to the removal process. In the case of an aluminum or iron wall at a greater thickness δ, the layer removed is larger, while in iron the layer removed is comparable to the thickness of the superheated layer.

Thus, the numerical simulation of reflected wave plasma action on material indicates that a superheated layer develops at the surface, in which volume boiling may occur. The dependence of superheated layer thickness on interaction parameters has been calculated, and it has been shown that the presence of such a layer defines a porous zone and can affect the amount of mass removed from the surface.

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