HIGH-SPEED COOLING OF A BIMETALLIC SURFACE UPON THE ACTION OF A CONCENTRATED ENERGY FLUX

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Formation of metastable structures during the solidification of a thin melted layer produced by action of a concentrated energy flux on some material is related to the high rate of cooling. Kraposhin [1] considered thermal conditions for processing of a surface with a laser which would provide cooling rates necessary for formation of metallic glasses from the liquid state. Amorphous layers (15-20 μm) have been obtained in several iron-based alloys [2]. However, in many systems fixation of an amorphous phase requires higher cooling rates.

It is thus of interest to consider the possibility of increasing cooling rates further when a thermal flux has been applied to a bimetallic surface. In this case the cooling rate can be increased by heat absorption accompanying melting of the substrate with its high thermal conductivity. If the melting point of the substrate is not higher than the vitrification temperature of the fused surface layer, amorphization of the latter will be aided due to the absence of crystalline phase nuclei on the surface layer—substrate boundary.

The present study used numerical calculations to analyze the temperature regime developed in bimetals upon action of a concentrated energy flux.

We will consider the case in which the surface of a bimetallic plate consisting of pure metals (Fig. 1) is acted upon by a constant thermal flux q for a period of time τ. Neglecting the kinetics of fusion and subsequent crystallization, we will use the classical Stefan formation to model the temperature regime. Then the temperature distribution T(x, t) in the bimetallic plate satisfies the following problem:

$$c(x, T)\,\rho(x, T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(x, T)\frac{\partial T}{\partial x}\right), \quad 0 < x < l; \quad x \neq \xi, \eta, \delta; \tag{1}$$

$$\left[\lambda\frac{\partial T}{\partial x}\right|_{x=\xi,\eta} = L_{1,2}\rho\frac{d(\xi, \eta)}{dt}; \tag{2}$$

$$\lambda\frac{\partial T}{\partial x}\bigg|_{x=0} = -q; \tag{3}$$

$$\left[\lambda\frac{\partial T}{\partial x}\right]_{x=\delta} = 0; \tag{4}$$

$$T(l, t) = T_0, \quad T(x, 0) = T_0, \quad T(\xi, t) = T_1^*, \quad T(\eta, t) = T_2^*, \quad \xi(0) = 0, \quad \eta(0) = \delta. \tag{5}$$

Here the subscript 1 refers to the surface layer, and 2 to the substrate, ξ(t) and η(t) are the coordinates of the phase fronts; T* and L are the temperature and heat of fusion. The

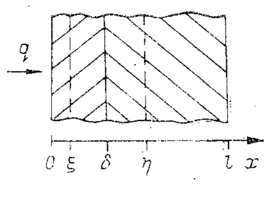

Fig. 1

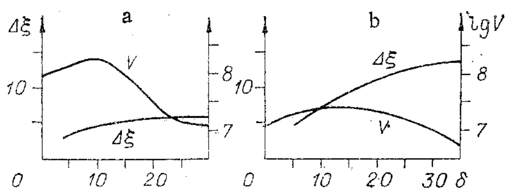

Fig. 2

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TABLE 1

Bimetal	$\Delta\xi$, μm	$\Delta\eta$, μm	V, deg/sec	λ, W/m·deg
Fe	4,0	0	$1{,}3\cdot10^7$	29,7
Fe + Pb	3,9	21,7	$4{,}5\cdot10^7$	19,8
Fe + Zn	3,7	9,5	$8{,}5\cdot10^7$	95,0
Fe + Al	3,6	0	$5{,}1\cdot10^7$	184,0
Fe + Cu	3,4	0	$9{,}8\cdot10^7$	318,0

density $\rho(x, T)$, specific heat $c(x, T)$, and thermal conductivity $\lambda(x, T)$ are discontinuous on the phase boundaries and boundaries between the metals.

The problem of Eqs. (1)-(5) was solved numerically using implicit finite-difference approximations with mobile grids of conservative form [3]. The thermophysical parameters of the bimetal were assumed temperature dependent in explicit form, or as extrapolated from reference data [4, 5]. The value of the thermal flux q and the duration of its action τ were chosen to correspond to the absence of evaporation from the plate surface. In this case the cooling process upon removal of the thermal load ($q = 0$ at $t > \tau$) is completely determined by heat removal into the substrate.

To study the effect of substrate material thermophysical properties on the thermal regime in the surface layer calculations were performed for bimetals of thickness $\delta = 10^{-3}$ cm at fixed thermal effect parameters $q = 10^6$ W/cm^2, $\tau = 10^{-5}$ sec. Table 1 presents results of numerical calculations of melting depth $\Delta\xi$, $\Delta\eta$ and mean cooling rate V (over the interval 2800-700°K) of a thin iron coating on various substrates. The values of thermal conductivity λ presented in the table correspond to the substrate metal. For a given thermal flux and application time, high thermal conductivity of the substrate limits the coating melting depth, but makes it possible to achieve high cooling rates. Use of a copper substrate increases the coating cooling rate by an order of magnitude. The bimetal combination with zinc shows a cooling rate practically comparable to that of the copper or aluminum substrate, despite the significantly lower thermal conductivity. This can be explained by heat absorption due to melting of the zinc (the copper and aluminum do not melt in this regime).

Figure 2 shows calculated melt depths $\Delta\xi$ and average cooling rates V in the bimetal surface layer as functions of thickness δ. The graphs show calculations for the following bimetals: a) iron–copper with thermal flux $q = 2\cdot10^6$ W/cm^2 for time $\tau = 10^{-5}$ sec; b) iron–aluminum for $q = 6\cdot10^5$ for time $\tau = 5\cdot10^{-5}$ sec. It is evident that with decrease in δ the depth of the melted layer $\Delta\xi$ decreases, while the cooling rate V increases, as compared to the rate in a pure iron plate ($\delta = l$). At some $\delta = \delta_*$ the cooling rate reaches a maximum value. This may be related to the fact that decrease in δ leads to significant heating of the substrate, attenuating heat transfer, while with increase in δ the effect of the substrate on the cooling process decreases.

In conclusion it should be noted that melting of the substrate causes an additional increase in surface cooling rate, and that there exists an optimum coating thickness at which the maximum cooling rate is achieved.

LITERATURE CITED

1. V. S. Kraposhin, "Processing of metal surfaces by laser radiation," Poverkhn., No. 3 (1982).
2. G. G. Borodina, Ch. V. Kopetskii, et al., "Formation of an amorphous structure in iron-based alloys upon surface processing by laser radiation," Dokl. Akad. Nauk SSSR, 259, No. 4 (1981).
3. N. I. Pak, "Numerical method for solution of the multifront Stefan problem using mobile grids," Inzh. Fiz. Zh., 45, No. 3 (1983).
4. A. V. Temkin, "Temperature dependence of thermophysical properties of lightly alloyed steels," Izv. Vyssh. Uchebn. Zaved., Energ., No. 8 (1978).
5. I. K. Kikoin (ed.), Tables of Physical Constants [in Russian], Atomizdat, Moscow (1976).