INVESTIGATION OF METAL SOLIDIFICATION ON HARDENING BY LASER RADIATION

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A mathematical model for the process of crystallization and formation of a metal structure is proposed for laser processing with melting that takes account of processes in a transient two-phase zone. The criteria for the thermal state of a metal are introduced. It is shown that the thermal stresses, and chemical and physical inhomogeneities in a metal depend nonmonotonically on the parameters of the laser processing. Results of calculations are in good agreement with the experimental data. They can be used to predict the structure of the solidified metal under laser hardening with melting and to determine the optical conditions for this process.

The thermal hardening of metals and alloys by exposure to laser radiation is an effective technology for obtaining quality materials [1-4]. The thermal processes for laser processing with internal heat evolution during phase transitions are studied in [2]. Analysis of these processes taking account of the fact that the metal is in a two-phase state is a timely problem. The present paper is devoted to these problems.

Thermal hardening with melting is based on the local heating of part of the surface under the action of laser radiation until a liquid metal is obtained and the subsequent cooling of this metal with the formation of a qualitatively new level of its structure and properties. Unlike other processes of thermal hardening, which are three-dimensional, heating during laser processing is a surface process [1-3]. Therefore, it can be taken into account by specifying the corresponding boundary condition on the metal surface. This differs significantly, for example, from the situation of laser welding with deep penetration, when an investigation of thermal processes with account of phase transitions calls for consideration of three-dimensional sources in the heat equation [2].

We consider thermal hardening of a plate from an aluminum alloy, the thickness of which is much less than its longitudinal dimensions (Fig. 1). We assume that the plate moves in the direction of the z-axis with the velocity w, and the source of the laser radiation is fixed. The x-axis is directed across the plate and the origin of the Cartesian coordinate system (x, z) is located on its surface.

For the existing velocities w, the length of the zone of liquid metal z_m and the two-phase zone determined by the location of the isothermal surface of completion of solidification, and for the coefficient of temperature conductivity a, the Péclet number $Pe = z_m w a^{-1} \gg 1$ and conductive heat transfer along the z-axis can be ignored as compared with convective heat transfer in the longitudinal direction. We consider also a steady-state regime of hardening, when the thermal field T depends on the three-dimensional coordinates x and z and does not depend on time. We conduct an analysis with the use of the theory of a quasi-equilibrium two-phase zone, which is used effectively in the study of different technological processes [5-8].

The boundary condition of the second kind and the density of heat flow q due to this radiation are specified on the surface of a plate in the zone of action ℓ_c of the laser radiation. On the remaining part of the surface, heat exchange is determined by Newton's law and here the boundary condition of the third kind is specified. A similar condition is specified on the lower surface of the plate. The metal temperature for z = 0 is equal to T_0.

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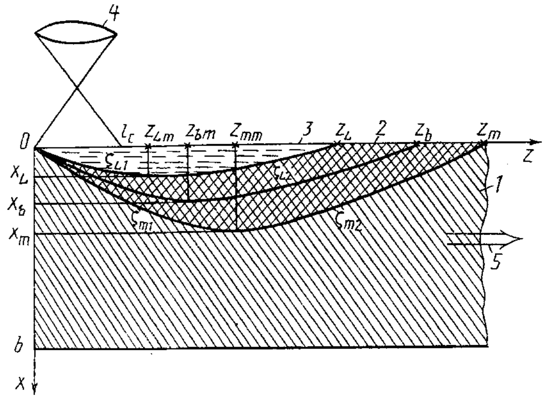

Fig. 1. Diagram of laser hardening with melting: 1) solid phase; 2) two-phase zone; 3) liquid phase; 4) laser; 5) direction of motion of the plate.

The statement of the thermal problem of crystallization is of the form

$$\rho c w \psi(T) \frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right), \quad 0 \leqslant x \leqslant b, \ z > 0, \tag{1}$$

$$\psi(T) = 1 + \varkappa c^{-1}(1-k)^{-1}(T_k - T_L)\left(\frac{T_k - T_L}{T_k - T}\right)^{\frac{2-k}{1-k}}, \tag{2}$$

$$T_L \leqslant T \leqslant T_m, \ \psi(T) = 1, \ T > T_L, \ T < T_m, \ T(x, 0) = T_0,$$

$$-\lambda \frac{\partial T}{\partial z}(0, z) = q, \ 0 \leqslant z \leqslant l_c, \tag{3}$$

$$-\lambda \frac{\partial T}{\partial z}(0, z) = \alpha [T(0, z) - T_{b1}], \ z > l_c, \tag{4}$$

$$\lambda \frac{\partial T}{\partial z}(b, z) = \beta [T(b, z) - T_{b2}]. \tag{5}$$

Here ρ, c, and λ are the density, heat capacity, and the coefficient of thermal conductivity; ψ is the effective heat capacity; κ is the latent heat of crystallization; k is the coefficient of impurity distribution; T_k is the melting point of the pure metal; T_L and T_m are the temperature of the liquidus and completion of hardening; α and β are the coefficients of the heat transfer from the upper and lower surfaces of the plate to cooling media with the temperatures T_{b1} and T_{b2}, respectively.

On the basis of the technique described in [6, 8], we introduce the criteria J_1-J_5 of the thermal state of the metal during hardening:

$$J_1 = \varphi_1, \ J_2 = \varphi_2, \ J_3 = \varphi_3, \ J_4 = x_m^{-1} \int_0^{x_m} \theta(x)\, dx, \ J_5 = \tau^{-1} J_4, \ \tau = z_m w^{-1},$$

$$\varphi_i = z_{mm}^{-1} \int_0^{z_{mm}} (b - \zeta_{m1})^{-1} dz \int_{\zeta_{m1}}^{b} f_i dx + (z_m - z_{mm})^{-1} \times$$

$$\times \int_{z_{mm}}^{z_m} (b - \zeta_{m2})^{-1} dz \int_{\zeta_{m2}}^{b} f_i dx, \ i = 1, 2, 3,$$

$$f_1 = \left|\frac{\partial T}{\partial x}\right|, \ f_2 = \left|\frac{\partial T}{\partial z}\right|, \ f_3 = \sqrt{f_1^2 + f_2^2},$$

$$\theta(x) = \begin{cases} w^{-1}(\zeta_{L1} - \zeta_{m1} + \zeta_{m2} - \zeta_{L2}), & 0 < x < x_L, \\ w^{-1}(\zeta_{m2} - \zeta_{m1}), & x_L \leqslant x \leqslant x_m. \end{cases}$$

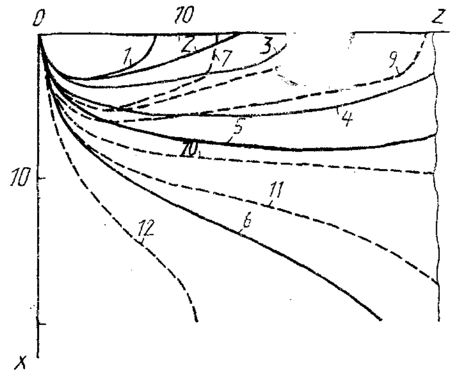

Fig. 2. Distribution of isotherms in a solidified metal for the basic version of calculations (1-6) and w = 15 mm/sec (7-12): 2 and 8) T_b; 1 and 7) T_L; 3 and 9) T_m; 4 and 10) 400°C; 5 and 11) 300°C; 6 and 12) 100°C. x, z, mm.

TABLE 1. Dependences of the Transverse and Longitudinal Dimensions of the Zone of Phase Transition on the Parameters of the Laser Processing and a Plate

l_c, mm	w, mm/sec	q, 10^8 W×m^{-2}	b, mm	T_0, °C	x_L	x_b	x_m	z_{Lm}	z_{bm}	z_{mm}	z_L	z_b	z_m
					mm								
0,5	25	6	20	20	3,06	3,14	3,68	2,56	2,70	3,84	8,30	14,80	18,14
1,0	25	6	20	20	5,80	5,94	6,90	8,94	9,28	12,66	26,38	47,58	58,34
0,5	35	6	20	20	2,16	2,22	2,62	1,80	1,94	3,08	6,04	10,68	13,18
0,5	25	10	20	20	4,98	5,10	5,96	6,38	6,62	10,12	19,96	35,90	43,56
0,5	25	6	10	20	3,06	3,14	3,68	2,56	2,70	3,82	8,32	15,76	22,56
0,5	25	6	20	200	3,68	3,82	4,82	3,84	4,40	6,96	11,58	24,44	32,12

Here z_{mm} and x_m are longitudinal and traverse coordinates of the maximal deviation of an isothermal surface of completion of hardening from the plane x = 0; ζ_m are the transverse coordinates of the given surface consisting of two parts: ζ_{m1} $(0 \leqslant z \leqslant z_{mm})$ and ζ_{m2} × $(z_{mm} < z \leqslant z_m)$; θ(x) is the time during which the metal is in a two-phase state; ζ_{L1} and ζ_{L2} are parts of an isothermal surface of liquidus ζ_L for $0 \leqslant z \leqslant z_{Lm}$ and $z_{Lm} < z \leqslant z_L$ respectively (Fig. 1); τ is the time during which the metal is in a melted state; f is the total temperature gradient; x_L is a tranverse coordinate of the maximal deviation of the isothermal surface of liquidus from the plane x = 0. The value of x_m determines the depth of melting of the metal during hardening.

The criteria J_1, J_2, and J_3 determine the average temperature gradients in a solidified part of the plate, which are responsible for thermal stresses arising during crystallization. The value of J_4 is the average time during which the metal is in a two-phase state, which determines to a great extent the degree od development of chemical and physical inhomogeneities in the process of crystallization. The criterion J_5 is the ratio between the value mentioned above and the time τ.

The heat problem (1)-(5) was solved numerically with the help of a computer. Equation (1) was approximated by an implicit two-layer finite-difference method of Laasonen [9]. A computational algorithm is similar to the algorithm described in [6, 7].

We considered thermal hardening of a plate from the AMG6 aluminum alloy. In the basic version of calculations b = 20 mm, w = 25 mm/sec, ℓ_c = 0.5 mm, q = $6 \cdot 10^8$ W/m², T_0 = 20°C, $T_{b1} = T_{b2}$ = 20°C, α = 100 W/(m²·K), β = 100 W/(m²·K). As a temperature of completion of hardening we assumed the temperature T_m = 546°C, for which the section (fraction) of a liquid phase S = 0.05.

We proceed by considering results of calculations. Isothermal surfaces, in a crystallized metal, shift noticeably when the velocity w of the plate processing increases (Fig. 2). The depth of penetration (Table 1) increases with an increase in ℓ_c, q, and T_0 and a decrease in w. The longitudinal dimensions of the zone of phase transition change in a similar way.

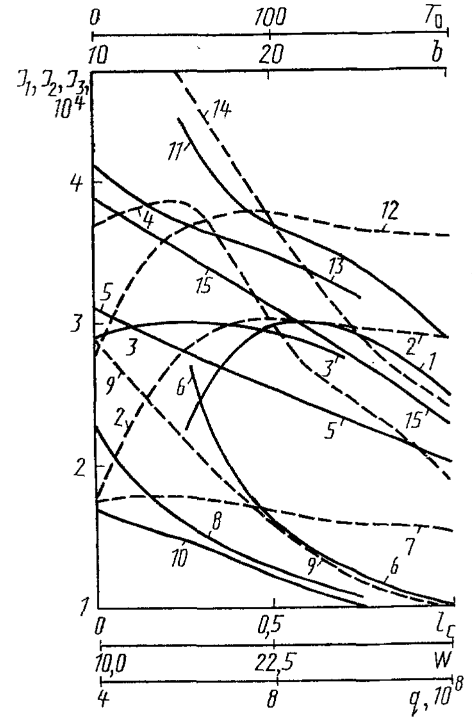

Fig. 3

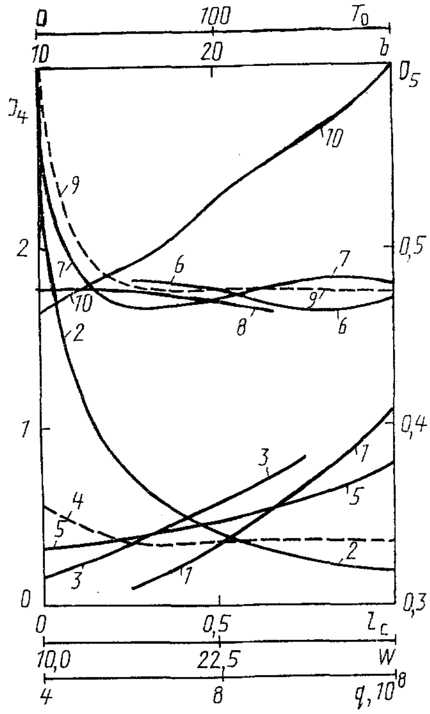

Fig. 4

Fig. 3. Dependences of the criteria of thermal states of a metal: J_1 (1-5), J_2 (6-10), J_3 (11-15) on ℓ_c (1, 6, 11), w (2, 7, 12), q (3, 8, 13), b (4, 9, 14) and T_0 (5, 10, 15). J_1, J_2, J_3, K/m; T_0, °C; b, ℓ_c, mm; w, mm/sec; q, W/m^2.

Fig. 4. Dependences of criteria of the metal thermal state J_4 (1-5) and J_5 (6-10) on ℓ_c (1, 6), w (2, 7), q (3, 8), b (4, 9), and T_0 (5, 10); J_4, °C.

As is seen from Fig. 3, the criterion J_1 decreases with an increase in T_0 and changes nonmonotonically with an increase in ℓ_c, w, q, and b, reaching its maximal values for $\ell_c \approx 0.6$ mm, $w \approx 22.5$ mm/sec, $q \approx 6 \cdot 10^8$ W/(m^2·K), $b \approx 14$ mm. The values of J_2 and J_3 decrease when the ℓ_c, q, b, and T_0 increase and depend nonmonotonically on the w. The criterion J_2 has its maximum for $w \approx 15$ mm/sec, J_3, for $w \approx 21$ mm/sec. The criterion J_4 increases with increase in the ℓ_c, q, T_0 and decrease in the w and b. After $b \approx 16$ mm the value of J_4 does not practically change. The criterion J_5 decreases with an increase in q and b and a decrease in T_0 and depends nonmonotonically on ℓ_c and w, reaching its minimal values for $\ell_c \approx 0.75$ mm and $w \approx 15$ mm/sec and the maximum when $w \approx 30$ mm/sec. After $b \approx 16$ mm the value of J_5 does not practically change.

Based on the meaning of the criteria of the metal thermal state J_1-J_5 [6, 8], we can assume that thermal stresses in the zone of hardening decrease with an increase in ℓ_c, q, b, and T_0 and have the maximum for $w \approx 21$ mm/sec (Fig. 4). The chemial physical inhomogeneities in a solidified metal decrease with an increase in q and b (up to $b \approx 16$ mm), a decrease in T_0 and reach their minimal values when $\ell_c \approx 0.75$ mm and $w \approx 15$ mm/sec. Therefore, the optimal regime of hardening among the regimes considered above is the following: $\ell_c \approx 0.75$ mm, $w \approx 15$ mm/sec $b \approx 16$ mm, $q = 10^3$ W/m^2, and $T_0 = 50$°C.

Solidification of a metal during hardening by the laser radiation was analyzed for the 08Kh18N10T steel plate. The regularities of the process are similar to those described above.

Results of calculations are in good agreement with the available experimental data. It is noted in [2] that for laser processing of the 08Kh18N10T steel, when w = 30 mm/sec the depth of metal melting is 3 mm. This value lies between the calculated values of x_b and x_m, equal to 2.92 mm and 3.46 mm, respectively.

Conclusions. 1. A mathematical model of metal solidification during laser hardening with melting is proposed, which takes account of processes in a transient zone of the two-phase state.

2. The results obtained that are in good agreement with the experimental data can be used to predict the kinetics and to determine optimal conditions for metal solidification under laser hardening.

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