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SHAPING OF COATINGS OF STABILIZED THICKNESS BY IMMERSION OF A WORKPIECE IN A MELT

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A mathematical model of the process of facing of the workpiece surface by immersion in a melt, which allows optimization of the regime of deposition of a coating of stabilized thickness, has been obtained. It has been known that in facing by immersion in a melt, the initial and boundary conditions set on different technological transitions are interrelated and they affect the final result.

Requirements imposed on the strength, hardness, viscosity, and wear resistance of the surface are very high at the modern stage of scientific and technological progress. However, in a number of cases traditional methods of treatment make it impossible to efficiently obtain the necessary parameters of quality. In this connection, at enterprises, one uses in increasing frequency combined electrophysical methods of surface treatment of workpieces with induction, plasma, electromagnetic, and other sources of energy [1–4].

Traditional methods of treatment enable one, in the context of service and technological continuity (inheritance) [1, 5–7], to propose rational structural schemes of a modified surface. But with combined methods of treatment, the interrelation of the energy fluxes employed in series or parallel schemes of shaping of different surfaces requires that the processes of creation of rational structures of a modified surface be considered.

Since the spatial and temporal scales of the processes and phenomena of the electrophysical methods of treatment in question significantly differ, one employs different equipment and procedures in studying them. We describe results of the interaction of various fluxes of a substance and energy in combined variants in the case of shaping and operation of surfaces, successively supplementing and specifying recommendations on development of the next method in question. Based on the results obtained, we formulate conclusions common to highly efficient shaping of coatings irrespective of their special properties [1, 3].

Employment of Induction Heating. The essence of the process of immersion facing is that the deposited metal solidifies on the oxide-film-free surface of a workpiece immersed in a melt [8]. Heating is carried out by induction. Because of the difference in the temperatures of the melt T_1 and the workpiece T_2 ($T_1 >> T_2$), which specifies the initial conditions of the process, the local melt volume contacting the surface and determined by the boundary conditions is cooled to solidification. After a short period of holding, one removes the workpiece and produces a coating of molten metal on the workpiece surface.

Investigation Methods. We have carried out computer modeling of the temperature fields to investigate heat and mass transfer between the surfaces shaped on the adjacent technological transitions.

To obtain a mathematical model of the technological process we assume that the heat flux, according to the principle of symmetry, is equivalent to the time of its action on the surface. We take the density and thermal diffusivity of the workpiece material and the melt to be equal and the molten bath to be unbounded. To simplify the calculations we admit that the axis of the temperature scale is directed to the absolute zero and take the melt temperature as the origin of this scale. We assume that heat exchange in the system occurs only by conduction.

The change in the temperature of an infinite plate of thickness $2l$ at a certain point A (Fig. 1) from an instantaneous plane source after the time τ [6, 7] is determined as

$$dT_{\text{a}} = \frac{dQ}{Fc\rho\sqrt{4\pi w\tau}} \exp\left(-\frac{x_{\text{a}}^2}{4w\tau}\right), \quad x_{\text{a}} = R - x \,. \tag{1}$$

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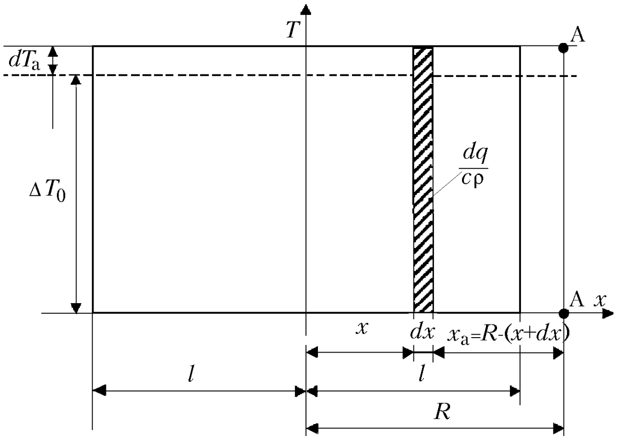

Fig. 1. Diagram of the temperature distribution in the system melt–workpiece.

The flow rate of heat in cooling by ΔT_0 is

$$dQ = c\rho dx F \Delta T_0\,,\quad \Delta T_0 = (\Delta T_{\text{in}} c_{\text{w}} + n_{\text{w}} + \Delta T_{\text{sup}} c_{\text{w.liq}})/c_{\text{w}}\,. \tag{2}$$

Having transformed (1), after the substitution of (2) into it we obtain

$$dT_{\text{a}} = \frac{\Delta T_0 dx}{\sqrt{4\pi w\tau}} \exp\left(-\frac{x_{\text{a}}^2}{4w\tau}\right). \tag{3}$$

Having integrated (3), we determine the temperature change at point A under the action of the entire set of instantaneous plane heat sources:

$$\Delta T_{\text{a}} = \int_{x_1}^{x_2} \frac{\Delta T_0 dx}{\sqrt{4\pi w\tau}} \exp\left(-\frac{x_{\text{a}}^2}{4w\tau}\right).$$

By introducing the replacement $u = x_{\text{a}}/\sqrt{4w\tau}$, we obtain

$$\Delta T_{\text{a}} = \int_{u_1}^{u_2} \frac{\Delta T_0 \sqrt{4w\tau}\, du}{\sqrt{4\pi w\tau}} \exp\left(-\frac{u^2}{2}\right),$$

whence

$$\Delta T_{\text{a}} = \Delta T_0 \left[\frac{1}{\sqrt{2\pi}} \int_0^{u_1} \exp\left(-\frac{u^2}{2}\right) du - \frac{1}{\sqrt{2\pi}} \int_0^{u_2} \exp\left(-\frac{u^2}{2}\right) du\right] = \Delta T_0\, [\Phi\,(u_2) - \Phi\,(u_1)]\,, \tag{4}$$

where

$$\Phi\,(u_1) = \frac{1}{\sqrt{2\pi}} \int_0^{u_1} \exp\left(-\frac{u^2}{2}\right) du\,;\quad \Phi\,(u_2) = \frac{1}{\sqrt{2\pi}} \int_0^{u_2} \exp\left(-\frac{u^2}{2}\right) du\,.$$

After substitution of the functions $\Phi(u_1)$ and $\Phi(u_2)$ into dependence (4) and transformations we have

$$\Delta T_{\text{a}} = \Delta T_0 \left[\Phi\left(\frac{R+l}{\sqrt{4w\tau}}\right) - \Phi\left(\frac{R-l}{\sqrt{4w\tau}}\right)\right]. \tag{5}$$

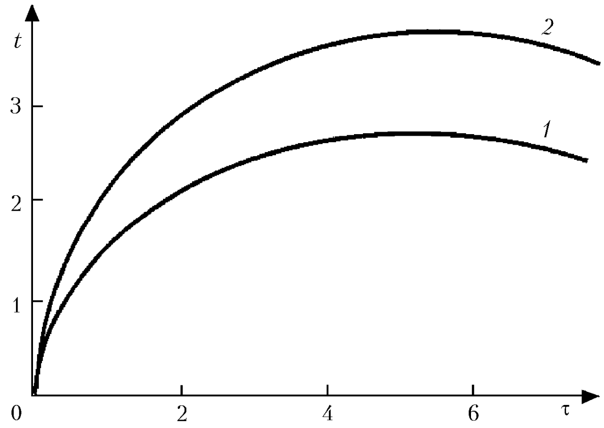

Fig. 2. Deposited-layer thickness t vs. treatment time τ for the main characteristic of the system T_{0ch} = 350°C: 1) ΔT_0 = 500 and ΔT_{sup} = 50; 2) 650°C and 50°C. t, mm; τ, sec.

In facing by immersion in a melt, we have a phase transition, i.e., crystallization of the liquid metal. Based on this, we determined the real change in the temperature at point A from the following considerations: if $\Delta T_a \le \Delta T_{sup} c_{liq}/c_{sol}$, we take $\Delta T_a' = \Delta T_a c_{liq}/c_{sol}$; if $\Delta T_a > \Delta T_{sup} c_{liq}/c_{sol}$, a certain quantity of heat will go to compensate for the heat flux released in crystallization and into subsequent cooling. Then the heat-balance equation will be

$$\Delta T_a c_{sol}\,\rho dV = \Delta T_{sup} c_{liq}\,\rho dV + n\rho dV + (\Delta T_a' - \Delta T_{sup})\, c_{sol}\,\rho dV\,. \tag{6}$$

The first term on the right-hand side of Eq. (6) determines the quantity of heat necessary for cooling the superheated melt to the crystallization temperature, the second term determines the release of heat in crystallization, and the third term determines heat release after the crystallization.

Having transformed (6), we obtain the dependence

$$\Delta T_a' = \Delta T_a + \Delta T_{sup} - \frac{n}{c_{sol}} - T_{sup}\frac{c_{liq}}{c_{sol}}\,, \tag{7}$$

for which there can be two cases:

$$\Delta T_a \le \frac{n}{c_{sol}} + \Delta T_{sup}\frac{c_{liq}}{c_{sol}}\,, \tag{8}$$

where the source ensures compensation for the heat released in crystallization (here $\Delta T_a' = \Delta T_{sup}$) and

$$\Delta T_a > \frac{n}{c_{sol}} + \Delta T_{sup}\frac{c_{liq}}{c_{sol}}\,, \tag{9}$$

where subsequent cooling of point A occurs; $\Delta T_a'$ is computed from formula (7).

As a result, the main characteristic of the facing system is the dependence

$$T_{0ch} = \frac{n}{c_{sol}} + \Delta T_{sup}\frac{c_{liq}}{c_{sol}}\,, \tag{10}$$

whose physical meaning is that this dependence enables us to determine the minimum difference of the temperatures of the melt and the workpiece at which facing will occur.

The calculations from (5) with the use of (7)–(9) allow a nomogram from which we can determine the parameters (coating thickness and time) and can optimize the technological process of facing. However the real thickness of the surface faced will be somewhat smaller than the calculated thickness. The reason is that in the mathematical model, no account is taken of heat transfer by convection and radiation. Therefore, we have introduced into (5) two correction factors, K_1 and K_2, whose values are determined by the properties of the materials of the workpiece and the melt and by the conditions of heat and mass exchange. They enable one to establish both the temperatures of the materials at a given point and the time of the process.

With account for the correction factors, dependence (5) takes the form

$$\Delta T_{\mathrm{a}} = K_1 \Delta T_0 \left[\Phi\left(\frac{R + l}{\sqrt{4 w \tau K_2}} \right) - \Phi\left(\frac{R - l}{\sqrt{4 w \tau K_2}} \right) \right]. \tag{11}$$

From the calculated data of (11), we have constructed a nomogram (Fig. 2) according to which one can optimize facing parameters for the required thickness of the coating layer deposited. We took the heat capacity of the material of the workpiece of structural steel c_{sol} = 0.7 J/(g·$^{\mathrm{o}}$C) (in the solid state) and c_{liq} = 0.9 J/(g·$^{\mathrm{o}}$C) (in the liquid state) and the specific melting heat n = 200 J/g [9, 10]. The coefficients $0.82 < K_1 \le 0.92$ and $0.85 < K_2 \le 0.95$ established experimentally are close to unity. Thus, for a plate of thickness 12 mm a deposition layer equal to 2 mm must be shaped in 2 sec at ΔT_0 = 500$^{\mathrm{o}}$C and ΔT_{sup} = 50$^{\mathrm{o}}$C and in 1 sec at ΔT = 650$^{\mathrm{o}}$C and ΔT_{sup} = 50$^{\mathrm{o}}$C.

Consequently, from the required coating thickness t obtained according to the mathematical model (11), which takes account of all the main characteristics of the facing system, we can determine the facing time τ. It must be borne in mind that the required thickness can be obtained by successive technological transitions.

Experimental Results and Their Discussion. It has been established that facing by immersion in a melt is suitable for shaping of a coating of thickness to 4 mm. We can recommend the following regime: temperature of the workpiece before facing 850–900$^{\mathrm{o}}$C, temperature of the melt 1500$^{\mathrm{o}}$C, and time of holding of the workpiece in a melt 1.5–2.5 sec.

The results of the investigations of the metal coatings of steel workpieces faced with PhBKh alloy show that there are inclusions of flux and cavities in the fusion zone and directly in the base of the metal coatings themselves for samples whose activation was carried out at a temperature to 800$^{\mathrm{o}}$C. At an activation temperature of 850$^{\mathrm{o}}$C or higher, irrespective of the superheating of the melt, a chemical bond is established in facing and a monolithic joint of the deposited alloy with the base is ensured. High-quality metal coatings, without cavities and pores, are shaped at the activation temperatures indicated. However, as the results of the experiments have shown, when the superheating of the melt was no higher than 15–20$^{\mathrm{o}}$C, the layer of a solidified alloy was deposited nonuniformly. The coatings were thicker than 3 mm, and their exterior surface was uneven. As the superheating of the melt increased to 25–50$^{\mathrm{o}}$C, the deposited layer of the additional wear-resistant alloy followed the surface of the sample. The surface of the deposited layer was smooth, and its thickness was fairly uniform. The latter was 1.8–2.3 mm per side for cylindrical samples.

The thickness of the solidified alloy depends not only on the initial values of the activation temperature and the superheating of the melt but also on the duration of stay of the sample in the melt. If this time is longer than 2.0–2.5 sec, its thin parts (especially the edge) are superheated and their surfaces are fused. The total covering of all the workpiece surfaces with alloy is attained on condition that the stay of the sample in the melt is 0.8–1.4 sec. The thickness of the solidified layer is 1.5–2.0 mm per side. Investigations of the fusion zone show that the deposited layer has a monolithic joint with the metal (Fig. 3a).

The microstructure of the base metal — 45 steel — after the facing is coarse-grained ferrite-perlite (Fig. 3b). This is a consequence of the superheating of the base metal and holding it at this temperature. Thus, from 850–900$^{\mathrm{o}}$C in activation, the base metal is then heated to a temperature of 1400$^{\mathrm{o}}$C in 1.0–1.5 sec.

In subsequent slow cooling of the workpieces in air, we observe a significant growth of the grains. Such a structure of the base metal is undesirable, since it has low hardness (30 HRC) and wear resistance.

In air cooling, the microstructure of the alloy is made up of coarse primary chromium carbides and the matrix, which in turn consists of ledeburite with inclusion of residual austenite (Fig. 3c and d).

The microstructure of the alloy is characterized by the coarse-grained nature of the primary carbides and their elongated shape and orientation perpendicularly to the surface to be faced. The latter can be explained by the presence of directional removal during the solidification of the additional alloy (Fig. 3d). The carbides in the plane that is in parallel to the heat-transfer surface have the shape of polyhedrons; they are comparatively uniformly distributed over

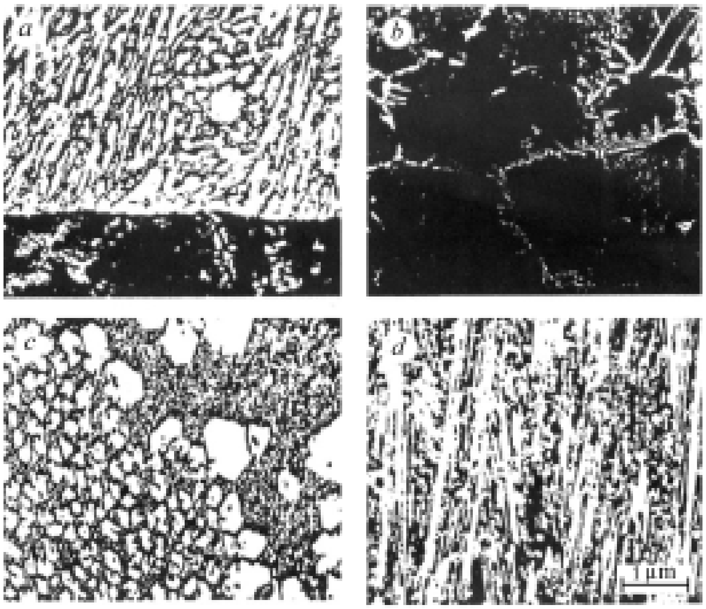

Fig. 3. Photographs of the microstructure of the fusion zone in induction facing by immersion in PhBKh-6-2 melt (a), of the base material of the workpiece (b), and of the deposited alloy on the source side of the exterior coating surface (c) and in the plane perpendicular to the heat-transfer surface (d). × 200.

the surface and are cemented in the plastic matrix (Fig. 3c). Such a structure of the deposited layer of hardness 53–55 HRC is preferable as applied to the surfaces of workpieces operating in an abrasive medium.

However the hardness of the deposited alloy only indirectly characterizes the wear resistance of material in interaction with an abrasive medium. An increase in the hardness improves the wear resistance of chromic cast irons, but only the matrix hardness can increase for them since the primary chromium carbides do not experience structural changes in the process of heat treatment. One can significantly increase the hardness by transformation of the matrix austenite to martensite or bainite, which is possible with significant subcoolings and high cooling rates in quenching.

To determine the possibility of controlling the formation of the structure of the base metal by subsequent heat treatment we investigated the influence of different kinds of heat treatment: normalization, oil quenching, and water quenching.

In normalization, the samples were heated to a temperature of 850^{o}C, held for 15 min, and cooled in air. After the normalization, we obtained a ferrite-perlite structure with a medium-size grain (Fig. 4a). The hardness of the material, 28 HRC, is unsatisfactory for the surfaces of workpieces operating under abrasive wear.

In quenching, the samples were heated to a temperature of 850^{o}C and were cooled in spindle oil to a temperature of 20^{o}C. The structure of the base material after oil quenching — troomartensite — possesses a sufficient hardness (52 HRC) and is fine-grained (Fig. 4b). However oil quenching involves high cost of production; therefore, this kind of heat treatment is rarely employed.

Water quenching directly after facing and cooling-down in air to the quenching temperature is the most expedient technologically. The samples were quenched after cooling-down from the facing temperature (1500^{o}C) to the quenching temperature ($850–900^{o}$C) by cooling in water with a temperature of 20^{o}C. The structure of the base metal represents martensite with troostite portions (Fig. 4c). The appearance of the portions of troostite in water quenching is attributed to the decrease in the cooling rate due to the low thermal conductivity of the deposited layer (high-alloy cast iron) and it ensures a sufficient viscosity of the material. Such a structure of hardness, 54 HRC, is the most favorable as far as wear-resistance conditions are concerned. The structural state of the deposited metal remains constant; the structure remains ledeburite but finer-grained with an excess of small carbides (Fig. 4d). The coating hardness in this case is 58 HRC.

Measurement of the microhardness of the phase components of the deposited metal has shown the following: the microhardness of the carbide phase is independent of the cooling medium and is 14,500 N/mm^{2}, while the micro-

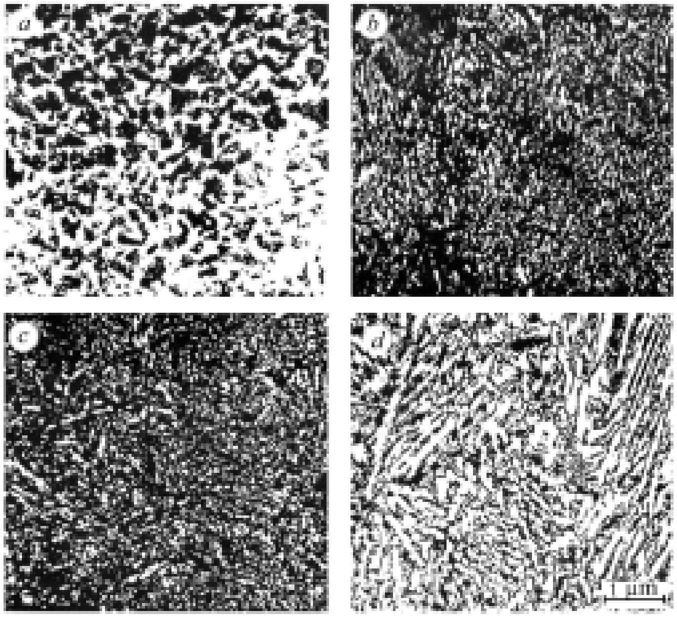

Fig. 4. Photographs of the microstructure of the base metal after normalization (a), oil quenching (b), and water quenching (c) and of the deposited alloy after cooling-down in air and water quenching (d). × 500.

hardness of the matrix is 3000–4000 N/mm^2 in air cooling of the sample and 5700–6500 N/mm^2 in water cooling. This allows the assumption that part of the austenite has changed to a more solid phase, i.e., ledeburite, in quenching.

Thus, heat treatment of the faced samples with cooling-down to a temperature of 850–900^{o}C with water quenching enables one to obtain the most favorable structure of the base and deposited metal. According to the results of experimental investigations, the rate of cooling of a workpiece in air in the temperature interval 850–900^{o}C is equal to 13^{o}C/sec, while the rate of its cooling in water with a temperature of 20^{o}C is equal to 110^{o}C/sec. We have determined the time of cooling-down to a quenching temperature of 850–900^{o}C equal to 40–45 for the workpiece hardened by facing by immersion in a melt.

The results obtained in investigating facing by immersion in a melt show the following:

(1) in treatment, the initial and boundary conditions set on different technological transitions are interrelated and they affect the final result; thus, the size of grains and their orientation relative to the heat-transfer surface, which are formed in high-speed cooling after the facing, can be changed as a result of thermal treatment;

(2) in the technological process, the transition can act as a barrier; therefore, preheating of a workpiece to the activation temperature is necessary for the total adhesion of the materials of the additional alloy and the base;

(3) a change in the structure of the coating-material matrix is observed in high-speed heat treatment, and part of the austenite changes to ledeburite as a result of quenching; we have the inheritance of the solid inclusions of the carbide phase irrespective of the quenching temperature and the cooling medium.

NOTATION

dQ, rate of flow of the heat through a plane instantaneous surface; J; dq, elementary flow rate of heat, J; F, area of the plate, cm^2; l, half the plate thickness, cm; c, heat capacity of the material, J/(g·K); ρ, density of the material, g/cm^3; w, thermal diffusivity, W/(cm·K); τ, time from the beginning of the process, sec; x_a, distance from point A to a plane instantaneous heat source, cm; R, distance from the axial line of the plate to point A, cm; x, distance from the axial line of the plate to the surface of the plane heat source, cm; dx, surface thickness of the instantaneous heat source, cm; ΔT_{in}, difference between the melting temperature of the molten material and the initial temperature of the workpiece, K; c_w, heat capacity of the workpiece material, J/(g·^{o}C); n_w, specific melting heat of the workpiece material, J/g; ΔT_{sup}, superheating temperature of the melt, i.e., difference between the temperature of the melt and the melting temperature of the molten material, K; $c_{w.liq}$, heat capacity of the molten material of the workpiece, J/(g·^{o}C);

$x_1 = R - l$, distance from point A to the nearest point of the plate's plane, cm; $x_2 = R + l$, distance to the far point of the plate's plane, cm; $\Delta T'_a$, real temperature at point A, K; c_{sol}, heat capacity of the coating material in the solid state, J/(g·°C); c_{liq}, heat capacity of the molten material, J/(g·°C); dV, volume of the elementary layer, cm^3; n, specific melting heat of the coating material, J/g; t, coating-layer thickness, mm. Subscripts: a corresponds to point A; in, initial temperature; w, workpiece; sup, superheating temperature; w.liq, liquid state of the workpiece material; sol, solid state of the workpiece material; liq, liquid state of the melt; ch, main temperature characteristic of the alloy; 1, initial value of the function; 2, final value of the function; 0, initial value of the melt temperature.

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