CALCULATING THE THICKNESS OF AN ANNEALED LAYER IN THE LASER HEAT TREATMENT OF STEEL, WITHOUT SURFACE MELTING

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We examine a method to calculate optimum regimes of laser hardening so as to achieve maximum thickness of the annealed layer.

The thickness of an annealed layer is one of the fundamental parameters in the process of laser hardening of alloys. There are three approaches to the problem of calculating δ. Determining δ on the basis of the position of the isotherm corresponding to the temperature T_r of the $\alpha \to \gamma$-conversion [1, 2] leads to satisfactory results for alloys with a rather fine-grained structure. In the general case, the first of these approaches yields elevated values of δ.

The second approach which takes into consideration the relationship between T_r and the heating rate v makes it possible, to some extent, to reduce the divergence between theory and experiment [3-7]. Calculation of the displacement of the critical points $\Delta T = T_r - T_1$ is based on the theory of isothermal phase conversions with a fluctuating mechanism for the formation of new-phase nuclei. Here we made use of a simplified model of the carbon diffusion process in a semi-bounded body at constant temperature, without consideration of the movement of the phase-separation boundaries [3], while the nonisothermicity was treated in the assumption of a constant ratio between the rate of new-phase center nucleation and the rate at which these nuclei grow, as well as under the assumption of a constant rate of temperature variation over time [4]. Assumptions such as these reduce the accuracy of the calculation. The accuracy of the experimental studies into the displacement of the critical points in the event of rapid heating is determined by the sensitivity and inertia of the measurement method to the degree of steel austenization [3, 4]. Therefore, comparison of theoretical and experimental values of ΔT requires a certain amount of care. In recent years, the point of view according to which the nucleation of the austenite in steel takes place without diffusion, while the temperature of formation for the initial nuclei is virtually independent of the heating rate and the carbon concentration (see, for example, [8, 9] and the references cited there) has gained increasing confirmation. To the extent to which it is not the initial stages of the $\alpha \to \gamma$-conversion that is usually established by experiment, as a consequence of the inadequate physical determinacy in the quantity ΔT, it is expedient to examine the temperature interval $T_m - T_1$ in which the phase conversions take place under conditions of rapid heating and cooling, rather than the displacement of the temperature of the conversion onset. The magnitude of this temperature interval depends on the conditions of laser treatment, the thermophysical and diffusion properties of the alloy, and the state of its original structure.

The temperature values close to T_1 correspond to the onset and conclusion of the conversion. Therefore, the introduction of the additional time (into the calculation scheme), required for the conclusion of the phase transition [4, 7], in the examination of the displacement of the critical point, in a number of cases – although it does raise the accuracy of the calculation – does not fully correspond to the real physical situation of laser alloy heating. From the physical point of view, it is the third approach proposed in [10] that is more solidly based. In accordance with [10] the thickness of the annealed layer is determined from the dimensions of the region in which the $\alpha \to \gamma$-conversion is able to take place, while the cooling rate exceeds the critical value of r_c. In this case, we examined the case of the fluctuating mechanism of the phase transition, whose kinetics are limited by the diffusion of carbon into the growing austenite plate. Given the shearing nature of the $\alpha \to \gamma$-con-

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version, its kinetics are not limited by diffusion, but in order to obtain an annealed structure some carbon saturation of the austenite is necessary, at least to values of $c_r \geq 0.05\%$ [11]. Thus, regardless of the phase-transition mechanism, a significant stage in the laser-annealing process is the diffusion redistribution of the carbon in the austenite.

The corresponding thermal and diffusion problems were solved by means of numerical methods in [10], with these methods making it possible to determine δ on the basis of the given alloy parameters and the conditions of laser treatment. It is the purpose of this paper to achieve analytical relationships between δ and the basic parameters of the process as a change over broad limits for the two mechanisms of steel austenization, with consideration given to the limitations imposed on surface temperature, the determination of the optimum treatment conditions to ensure a maximum δ value, as well as to determine the criteria of applicability for the simplified model, without taking into consideration the role of the diffusion processes.

1. Thermal Model. Let the heat source have power W, let it be in the shape of a rectangle with sides ℓ and d, and let it move at a velocity u over the surface of a plate of thickness H. Dropping the nonoptimum conditions of heat treatment from our examination, because a noticeable fraction of the radiant energy is propagated across the direction of motion, we will write the condition of insignificance for the lateral heat removal in the form

$$d \gg \sqrt{a\tau}. \tag{1}$$

When $u \gg a/\ell$, the heat source is fast moving [5] and the effective time of heat effect is determined from the relationship

$$\tau = l/u. \tag{2}$$

The condition that the heat source is fast moving, i.e., $\ell \gg \sqrt{a\tau}$ when $\ell \geq d$, follows from inequality (1), or in other words, it is a necessary condition for the effective utilization of the thermal energy. The requirement of effective cooling by means of the removal of heat into the bulk of the material leads to the condition $H \gg \sqrt{a\tau}$, whose satisfaction together with (1) and (2) makes it possible to use the one-dimensional model for the heating of a semibounded body by means of a nonmoving surface source of heat with a flux density of $q = W/\ell d$. Neglecting the latent heat of the phase transition in the case of $\alpha \to \gamma$-conversion in steel and in the transition of iron into the paramagnetic state (consideration of these expenditures of energy is significant only for rather low values of the laser-pulse energy [12]), we write the equation for the temperature field in the form

$$\theta(z,\ t) = s(t)\,\mathrm{ierfc}\,[R(z,\ t)],\ 0 < t \leqslant \tau, \tag{3}$$

$$\theta(z,\ t) = s(t)\,\mathrm{ierfc}\,[R(z,\ t)] - s(t-\tau)\,\mathrm{ierfc}\,[R(z,\ t-\tau)],\ t \geqslant \tau. \tag{4}$$

The maximum surface temperature of the body (when $t = \tau$) amounts to

$$T_m(0) = 2q\sqrt{a\tau}/\varkappa\sqrt{\pi} = 2q\sqrt{al}/\varkappa\sqrt{\pi u}. \tag{5}$$

At a distance z from the surface, the maximum value for the temperature is attained at the instant of time $t_m > \tau$, which is determined from the relationship

$$z^2\tau = -2a\left(1-\frac{\tau}{t_m}\right)t_m^2\ln\left(1-\frac{\tau}{t_m}\right). \tag{6}$$

The value of t_m increases monotonically as z increases. When $\tau \ll t_m$, $t_m \simeq z^2/2a$. In the general case, the quantities t_m and T_m are dependent not only on z, but on τ.

Expressions (3)-(6), with consideration of (2), describe the heating and cooling of a body by a moving source of heat.

2. The Diffusion Model. We will initially examine austenite formation in laser heating of laminar pearlite for the fluctuating $\alpha \to \gamma$-conversion mechanism in analogy with [10], assuming that the kinetics of the process are determined by the rate of growth for the centers of the new phase and are limited by the diffusion of the carbon. The diffusion problem for the austenite region whose boundaries y_1, y_2 are displaced over time has the form

$$\partial c/\partial t = D\partial^2 c/\partial x^2, \tag{7}$$

$$c[y_1, t] = c_1, \quad c[y_2, t] = c_2, \tag{8}$$

$$(c_{1,0} - c_1)\frac{dy_1}{dt} = D\frac{\partial c}{\partial x}\bigg|_{x=y_1}, \tag{9}$$

$$(c_2 - c_{2,0})\frac{dy_2}{dt} = -D\frac{\partial c}{\partial x}\bigg|_{x=y_2}. \tag{10}$$

For constant values of D the laws governing the movement of the phase-separation boundaries are described by the relationships [10]:

$$y_1 = 2\beta_1\sqrt{Dt}, \quad y_2 = -2\beta_2\sqrt{Dt}, \tag{11}$$

where β_1 and β_2 are the roots of the system of transcendental equations [10, 13]. The solution of problem (7)-(10), with consideration of the concentration relationship of the diffusion coefficient [13] leads to some correction of the quantities β_1 and β_2 while the form of expressions (11) is retained.

In order to make provision for the changes in the coefficient of diffusion under the conditions of laser heating, we will use the approach [14] in accordance with which the position of the phase boundary can be found from the solution of the isothermal problem which describes the process that takes place at the maximum temperature $T_m(z)$ within the equivalent time $t_e < \Delta t$. If the function T(t) near t_m changes rather smoothly, then according to [14]:

$$t_e = \left(2\pi T_m^2/RQ\left|\frac{\partial^2 T}{\partial t^2}\right|_{t=t_m}\right)^{1/2}.$$

Thus, the law governing the growth in the thickness of the austenite plate over time can be presented in the form $Y = y_1 - y_2 = \sqrt{BD_m t}$, where $D_m = D(T_m)$. Equating Y to half the interplate systems h, we obtain an estimate of the time required for the complete austenization of the pearlite:

$$t = h^2/BD_m. \tag{12}$$

The parameter B makes provision for the temperature and concentration relationship of the diffusion coefficient.

In accordance with [13], assuming that

$$D(T, c) = (0.07 + 0.06c)\exp[-Q/RT], \tag{13}$$

we obtain for Q = 32,000 J/mole the characteristic values of B in the interval 0.6-0.9, which corresponds to the physical situation in which the greater part of the pearlite volume being considered becomes austenitic near the maximum temperature. Consideration of another geometric shape for the austenite nuclei, as well as the consideration of the diffusion interaction of the growing centers and the presence of excess phases can all be examined within the framework of the given approach, based on an analysis of the more complex diffusion problem [13].

In the case of a shear mechanism for the $\alpha \to \gamma$-conversion, the austenization of steel proceeds rapidly, and the subsequent carbon saturation of the austenite comes about relatively slowly because of the gradual dissolution of the cementite.

If the thickness of the cementite plate is considerably smaller than h, then we can examine the diffusion problem for a plate of constant thickness. In this event, the solution of Eq. (7), with the boundary conditions $c(0, t) = c_2$, $c_1 = c(h/2, t) = c(-h/2, t)$, for a constant value of D has the following form [15]:

$$\frac{c(x, t) - c_1}{c_2 - c_1} = \sum_{n=1}^{\infty}\frac{2}{\mu_n}(-1)^{n+1}\cos\left(\mu_n\frac{2x}{h}\right)\exp(-\mu_n^2\mathrm{Fo}),$$

$$\mu_n = (2n - 1)\pi/2, \quad \mathrm{Fo} = 4Dt/h^2.$$

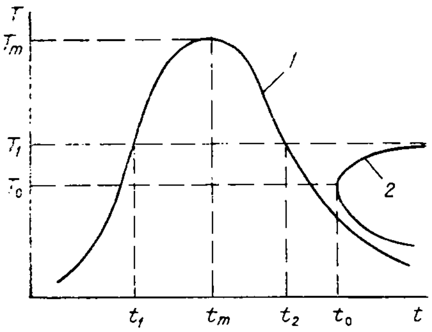

Fig. 1

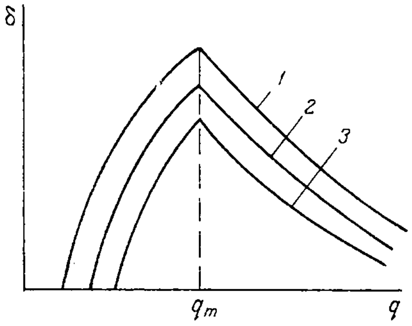

Fig. 2

Fig. 1. Temperature regime for the annealing of a layer of thickness δ: 1) nature of the change in temperature over time; 2) thermokinetic diagram of austenite decomposition.

Fig. 2. Nature of the relationship between the thickness of the annealed layer and the energy flux density: 1) partial annealing zone; 2, 3) complete annealing zone; 2) h_2; 3) $h_3 > h_2$.

Assuming that $c(0, t) = c_r$ and limiting ourselves to the first two terms of the series (which in the case of $Fo > 0.1$ yields an accuracy of 2%), we obtain the expression, determining the value of Fo_1, at which the minimum concentration c_r is attained at the center of the plate:

$$\frac{c_r - c_1}{c_2 - c_1} = \frac{4}{\pi}\left\{\exp\left(-\frac{\pi^2 Dt}{h^2}\right) - \frac{1}{3}\exp\left(-\frac{9\pi^2 Dt}{h^2}\right)\right\}.$$

The time required for the diffusion process is found from the condition $h^2 Fo_1 = 4D\Delta t$.

Transition to the isothermal conditions in analogy with the way in which this was done in [11], yields $h^2 Fo_1 \simeq 12D(T_m)\Delta t\sqrt{T_m R/Q}$, i.e., the condition of complete annealing can be described by expression (12), where in the given case $B = 12(Fo_1)^{-1}\sqrt{T_m R/Q}$. With $c_r = 0.05\%$ the estimates show that the characteristic values of B are 15-60, i.e., the time required for the complete annealing in the case of a shear austenization mechanism is smaller by factors of ten than in the case of a fluctuation phase-conversion mechanism.

3. Thickness of the Annealed Layer. To carry out the alloy annealing process, the alloy must first be heated above temperature T_1. Assuming in (3) and (4) that $T(\varphi, t) = T_1$, we obtain the equations which determine the boundaries t_1 and t_2 of the time interval in which the austenization of the steel for a layer of thickness φ is possible:

$$1 = s(t_1)\,\mathrm{ierfc}\,[R(\varphi, t_1)], \tag{14}$$

$$1 = s(t_2)\,\mathrm{ierfc}\,[R(\varphi, t_2)] - s(t_2 - \tau)\,\mathrm{ierfc}\,[R(\varphi, t_2 - \tau)]. \tag{15}$$

If conditions (12) are satisfied, the time interval $\Delta t = t_2 - t_1$ is adequate for the diffusion redistribution of the carbon. At given values of τ, q, and h, system of equations (12), (14), (15) determines the quantities t_1 and t_2, as well as the thickness φ of the layer, for which annealing of the alloy becomes possible with sufficiently rapid cooling. The condition for prevention of austenite decomposition in a layer of thickness ψ has the form $T(\psi, t_0) \leq T_0$ (Fig. 1). The maximum possible value of ψ is determined from relationship (4) when $T(\psi, t_0) = T_0$:

$$T_0 = T_1 s(t_0)\,\mathrm{ierfc}\,[R(\psi, t_0)] - s(t_0 - \tau)\,\mathrm{ierfc}\,[R(\psi, t_0 - \tau)]. \tag{16}$$

The thickness δ of the annealed layer is determined by the minimum value of φ and ψ. The maximum value of δ is reached when $\varphi = \psi$ and increases with increasing q until the surface is heated to the maximum permissible temperature T_2 which, in view of some instability in the parameters of laser emission, must be lower than the melting point of the alloy. The condition that the maximum surface temperature T_n be equal to T_2 has the form

$$T_2/T_1 = s(\tau) = 2q\sqrt{a\tau}/\varkappa T_1\sqrt{\pi}. \tag{17}$$

System of equations (12), (14)-(17), when $\varphi = \psi = \delta$, uniquely defines the unknown quantities q, τ, t_1, t_2, δ, i.e., the given values of t_0, T_0, T_2, a, and h correspond to the optimum values of τ_m, q_m at which the maximum magnitude of the thickness for the hardened layer is attained.

Let us examine certain special cases in which the solution is presented in analytical form. When $R(\delta, t_2) \le R(\delta, t_1) \ll 1$, $R(\delta, \tau_2 - \tau) \gg 1$, Eqs. (14) and (15) yield $t_1 \simeq t_2 \simeq \tau$ and

$$\delta = \delta_1 \simeq \frac{2}{\sqrt{\pi}}\sqrt{a\tau} - \varkappa T_1/q = \frac{2}{\sqrt{\pi}}\sqrt{a\tau}\,(1 - T_1/T_n) = \\ = \frac{2}{\sqrt{\pi}}\sqrt{al/u} - \varkappa T_1 ld/W. \tag{18}$$

When $d = \ell$, formula (18) changes into the corresponding expression for the thickness of the annealed layer, as obtained in [2]. It follows from (18) that δ_1 increases with an increase in T_n, τ, q and with a reduction in u, γ, d. The quantity δ_1 is a nonmonotonic function of ℓ. With condition (17) satisfied, $T_n = T_2$, and with consideration of (16) we obtain

$$\tau_m = 4t_0/\omega^2, \tag{19}$$

$$q_m = \frac{1}{4}\sqrt{\pi/at_0}\,\varkappa T_2\omega, \tag{20}$$

$$\delta_{1,m} = \frac{4}{\sqrt{\pi}}\left(1 - \frac{T_1}{T_2}\right)\frac{\sqrt{at_0}}{\omega}. \tag{21}$$

The optimum values of q_m and τ_m can be attained with various combinations of the parameters u, ℓ W, and γ, related to each other by relationships (2) and $q = W/\gamma\ell^2$. However, the conditions of insignificance for the lateral removal of heat and the finiteness of the component thicknesses, which we examined above, impose additional limitations on the range of change in the parameters u, ℓ, γ, and W. Thus, inequality (1) defines the minimum values for the power and dimensions of the heat source, beneath which no optimum treatment regimes can be achieved:

$$W \gg W_0 = q_m a\tau_m/\gamma = \varkappa T_0\sqrt{\pi a t_0}\left[1 + \left(\frac{T_2}{T_0}\right)^2\right]/\gamma\omega^2, \tag{22}$$

$$l \gg l_0 = \sqrt{a\tau_m}/\gamma = \sqrt{2at_0}/\gamma\omega. \tag{23}$$

We have to increase γ in order to reduce the quantities W_0 and ℓ_0, i.e., to elongate the spot in a direction perpendicular to the motion of the laser beam. The minimum value of u is determined from relationships (1) and (2):

$$u \gg u_0 = \gamma\sqrt{a/\tau_m} = \gamma\omega\sqrt{a/2t_0}. \tag{24}$$

The minimum thickness of the component for which it is possible to obtain a hardened layer of thickness δ_m is determined by the inequality

$$H \gg H_0 = \sqrt{a\tau_m} = 2\sqrt{at_0}/\omega. \tag{25}$$

For example, when $a = 0.2$ cm²/sec, $\varkappa = 1$ W/(cm·deg), $t_0 = 4$ sec, $T_0 = 500$°C, $T_2 = 1000$°C, $\gamma = 4$, formulas (19)-(25) yield: $\tau_m = 2.5$ sec, $q_m = 1250$ W/cm², $\delta_m = 0.22$ cm, $W_0 = 156$ W, $\ell_0 = 0.17$ cm, $u_0 = 1.2$ cm/sec, $H_0 = 0.7$ cm.

Let us consider yet another case in which the inequalities $R(\delta, t_2) \le R(\delta, t_1) \ll 1$, $R(\delta, t_2 - \tau) \ll 1$ are satisfied and the diffusion processes play a significant role. In this case $t_1 < \tau < t_2$, $h^2 > BD_m\tau$, and the solution of systems (12), (14), (15) yield

$$\delta = \delta_2 \simeq -\frac{\varkappa T_1}{q} + \sqrt{\frac{1}{4}\left(\frac{\varkappa T_1}{q} + \frac{4a\tau}{\pi}\,\frac{q}{\varkappa T_1}\right)^2 - \frac{4ah^2}{\pi BD_m}}. \tag{26}$$

As h increases, we have an increase in the time required for the diffusion process, and the thickness of the complete annealing layer is reduced. With an increase in q and τ the quantity δ increases monotonically until the surface temperature attains the limit value of T_2.

With a further increase in q, maintaining $T_n = T_2$ at the surface requires the corresponding reduction in τ, which leads to a reduction in δ (Fig. 2). The maximum value of $\delta_{2,m}$ is achieved with the τ_m, q_m given by relationships (19) and (20):

$$\delta_{2,m}=\left(\frac{4}{\sqrt{\pi}}\sqrt{at_0}/\omega_0\right)\left(\frac{1}{2}\sqrt{[1+(T_2/T_1)^2]^2-h^2\omega_0^2/BD_mt_0}-1\right). \tag{27}$$

Let us note that although $\delta_{2,m}$ diminishes with increasing h, the optimum treatment regime does not depend on h, since the quantities τ_m and q_m are determined from the condition of rather rapid cooling of the layer, at whose surface the temperature reached values of T_2, i.e., exclusively by means of thermal processes. Nor do the limit values of the treatment conditions W_0, ℓ_0, u_0, H_0 depend on h, and these, in this case, are described by formulas (22)-(25). For a steel with an initial pearlite-plate structure with $h = 10^{-4}$ cm, formula (27) yields $\delta_{2,m} = 0.13$ cm for a fluctuation mechanism and $\delta_{2,m} = 0.19$ cm for a shearing mechanism of steel austenization. The limiting role of carbon diffusion makes itself felt in the reduction of δ_2 relative to δ_1. The quantity $\xi = \delta_1 - \delta_2$ determines the thickness of the incomplete alloy-annealing layer. In accordance with (18) and (26), the parameter ξ increases with increasing h and depends nonmonotonically on q, τ, ℓ, and u. A detailed analysis of the case of incomplete annealing and of the influence exerted by the magnitude of ξ on the operation properties of the component parts is beyond the scope of this paper.

4. Range of Permissible Laser-Annealing Regimes. A minimum value of q_1 exists for the given values of h and τ, below which annealing is impossible even in the layer at the surface. At the surface R(0, t) = 0 the solution of system (12), (14), (15) has the form

$$t_1=\frac{1}{3}\tau(1-\varepsilon)+\frac{1}{3}\tau\sqrt{3+(1-\varepsilon)^2},$$
$$q_1=\varkappa T_1\sqrt{\pi}/2\sqrt{at_1},\ \varepsilon=2h^2/BD_m\tau,\ t_2=t_1+\frac{1}{2}\varepsilon\tau. \tag{28}$$

When $\varepsilon \ll 1$ formulas (28) yield $t_1 \simeq t_2 \simeq \tau$, $q_1 \simeq \kappa T_1\sqrt{\pi}/2\sqrt{a\tau}$; when $\varepsilon = 1$, we have $\tau_1 = \frac{\tau}{\sqrt{3}}$, $t_2=\tau\left(\frac{1}{2}+\frac{1}{\sqrt{3}}\right)$, $q_1\simeq\varkappa T_1\sqrt{\pi}\sqrt[4]{3}/2\sqrt{a\tau}$; when $\varepsilon \gg 1$, we find that $t_1 = \tau/2\varepsilon$, $t_2 = \tau\varepsilon/2$, $\Delta t = \tau/2\cdot(\varepsilon - 1/\varepsilon) \simeq t_2$, $q_1 = aT_1\sqrt{\varepsilon}/\sqrt{2a}\tau = aT_1h/\tau\sqrt{aBD_m}$.

The range of values for q in which annealing is possible without melting of the surface falls between q_1 and q_m.

When $\varepsilon \le 1$, the diffusion of the carbon exerts no noticeable influence on the process of laser steel annealing, the quantity $\Delta q = q_m - q_1$ diminishes monotonically with an increase in τ, but it is different from zero for any finite value of τ. Thus, on satisfaction of the condition

$$h\leqslant\sqrt{B\tau D_m/2} \tag{29}$$

the thickness of the hardened layer may be calculated on the basis of the simplified formula (18). For $h = 10^{-4}$ cm, $D_m = 5\cdot10^{-8}$ cm²/sec condition (29) is satisfied when $\tau \ge 0.6$ sec for B = 0.8 and with $\tau \ge 0.04$ sec for B = 40. When $\varepsilon \gg 1$, we cannot ignore the diffusion processes nor the influence exerted by the state of the initial alloy structure. An increase in h leads to an increase in q_1, i.e., as the structure becomes more coarse, the range of permissible regimes is reduced. Since $q_1 \propto 1/\tau$, $q_m \propto 1/\sqrt{\tau}$, we find that Δq diminishes with a reduction in τ. When $\tau < \tau_1 = 4(T_1h)^2/\pi T_2{}^2BD_m$, annealing of the surface is impossible without melting ($\Delta q < 0$). The coarser the initial structure and the higher the instability of the laser-emission parameters, the greater the magnitude of τ_1, while the range of permissible values of τ is smaller. The maximum permissible value of the energy flux density $q_3 = \frac{\pi\varkappa T_2^2}{4T_1h}\sqrt{\frac{BD_m}{a}}$ corresponds to the quantity τ_1. When $q > q_3$, the surface melts faster than the time required for the diffusion processes in the surface layer, and annealing becomes impossible for any value of τ.

The conditions under which laser annealing becomes possible, i.e., $q_1 < q_m < q_3$, $\tau_m > \tau_1$, lead to the inequality

$$(T_1T_0/T_2^2+T_1/T_0)^2<\pi BD_mt_0/h^2. \tag{30}$$

If the characteristics of the alloy fail to satisfy relation (30), only partial annealing of the alloy is possible, or annealing with a melted surface. Since in the case of laser heating the role of the shear mechanism in the $\alpha \to \gamma$-conversion increases (which leads to a considerable increase in the parameter B), the range of permissible annealing regimes increases substantially and it becomes possible to harden such alloys, where traditional annealing had proved to be impossible.

NOTATION

δ, thickness of the complete-annealing layer; T_1, equilibrium temperature of the phase transition; $T_m(z)$ and $t_m(z)$, maximum temperature in the z layer and the time at which it is attained; T_2, limit surface temperature; T_0 and t_0, thermokinetic parameters of the austenite decomposition diaphragm (Fig. 1); q, energy flux density; τ, effective operating time of the heat source; q_m and τ_m, optimum treatment regimes; a, thermal diffusivity; $\varkappa$, thermal conductivity; Q and D, activation energy and the diffusion coefficient for the carbon in the austenite, $D_m = D(T_m)$; h, characteristic dimension of the original structure; H, thickness of the component part; $\gamma = d/\ell$, extent to which the heat source has been elongated; c, concentration of the carbon in the austenite; c_1, c_2, $c_{1.0}$, $c_{2.0}$, values of this concentration near the phase boundaries [13]; $R(z, t) = z(2\sqrt{at})^{-1}$; $s(t) = 2q\sqrt{at}(\varkappa T_1)^{-1}$; $\omega = T_2/T_0 + T_0/T_2$; $\omega_0 = (T_2^2 + T_0^2)/T_1^2$; $\theta = T/T_1$.

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