NOTATION

h_{g_1}, enthalpy of the flow in the plane of mixing of the plasma jets; T_{g_1}, temperature; F, focal length; ℓ, expansion limit of the slit; I, intensity of the lines; λ, wavelength; g, statistical weight; f', oscillator strength; E, excitation energy; and k, Boltzmann's constant.

LITERATURE CITED

1. A. L. Mossé and I. S. Burov, Treatment of Dispersed Materials in Plasma Reactors [in Russian], Minsk (1980).
2. N. A. Zyrichev, V. M. Merkushin, and V. I. Ovchinnikov, Abstracts of Reports at the 4th All-Union Symposium on Plasma Chemistry, Part 1, Dnepropetrovsk (1984), pp. 27-28.
3. A. L. Mossé, Proceedings of the International School-Seminar on Heat and Mass Transfer in Plasma Chemical Processes, Minsk (1982), pp. 112-124.
4. P. I. Soroka and V. G. Vereshchak, Studies of Plasma Processes and Devices [in Russian], Minsk (1978), pp. 62-64.
5. I. S. Burov, E. M. Ermolaeva, V. K. Zabrodin, and A. L. Mossé, Izv. Akad. Nauk BSSR, Ser. Fiz.-Energet. Nauk, No. 4, 85-88 (1983).
6. G. V. Galevskii, A. A. Kornikov, Yu. L. Krutskii, and L. K. Lamikhov, Studies of Plasma Processes and Devices [in Russian], Minsk (1978), pp. 117-125.
7. A. N. Knak, A. L. Mossé, and E. M. Ermolaeva, Abstracts of Reports at the 4th All-Union Symposium on Plasma Chemistry, Part 1, Dnepropetrovsk (1984), pp. 89-90.
8. H. Griem, Plasma Spectroscopy [Russian translation], Moscow (1969).
9. L. V. Levshin (ed.), Laboratory Work in Spectroscopy [in Russian], Moscow State Univ. (1976).

THEORETICAL STUDY OF THE KINETICS OF AUSTENITIZATION IN STEELS WITH HEATING BY CONTINUOUS LASER RADIATION

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A determination is made of the degree of austenitization taking place with the diffusional displacement of grain boundaries in different regions affected by laser radiation (LRR). The process of the formation of stable austenite is analyzed.

Laser quenching is characterized by a short time of exposure and high cooling rates. Regions exposed to laser radiation have sections heated to different temperatures, from room temperature to the melting point. In connection with this, different stages of austenitization can be fixed in different sections of an LRR. Here, the stage depends on the temperature–time conditions.

The process of pearlite austenitization consists of the formation of austenite nuclei, a polymorphic $\alpha \rightarrow \gamma$-transformation, dissolution of cementite, and diffusional redistribution of carbon. At a high rate of laser heating the formation of austenite nuclei is activated as a result of a sharp reduction in the critical dimensions of the nuclei. The nucleation mechanism can also change, from a diffusional mechanism to a shear or athermal mechanism. Thus the nucleation process cannot affect the kinetics of austenitization.

When pure iron is heated above the temperature A_{C3} (911°C), the formation of the austenite grain can be examined in two stages: restructuring of the crystalline lattice; concentration-induced redistribution of carbon with the dissolution of cementite [1]. At lower temperatures, these stages can be examined together as a transformation with a concentration-

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driven carbon redistribution. Since the main mechanism is diffusional in nature, the completion of austenitization may be shifted to the high-temperature region if there is an excess supply of heat energy. As a result, the kinetic heating curves have initial ($A_{C_1}^{init}$) and final ($A_{C_1}^{fin}$) transformation temperatures, providing evidence of a shift in the critical points. Examining the available empirical data on the shift of these points during electrical heating [2], for example, it is difficult to follow the kinetics of motion of the boundaries and the degree of transformation of ferrite and cementite. It is therefore natural to examine austenitization processes in pearlitic steel through mathematical models which include heat-conduction and diffusion problems.

The temperature field T(x, y, z, t) created in the interaction between a material and a concentrated source of heat energy having a Gaussian distribution [3] and moving over the surface z = 0 of the part being processed via the trajectory

$$x = \varphi(t), \quad y = \psi(t), \quad 0 < t < t_m, \tag{1}$$

can be described within the framework of a quasilinear problem

$$C(T)\frac{\partial T}{\partial t} = \operatorname{div}(\lambda(T)\operatorname{grad} T), \quad t,\ z \geqslant 0, \tag{2}$$

$$T(x,\ y,\ z,\ 0) = T_0(x,\ y,\ z), \tag{3}$$

$$-\lambda(T)\frac{\partial T(x,\ y,\ 0,\ t)}{\partial z} + \alpha T(x,\ y,\ 0,\ t) = A(T)P_{\text{int}}\exp\{-k^2[(x-\varphi(t))^2 + (y-\psi(t))^2]\}. \tag{4}$$

Problem (2)-(4) was solved by an approximate-analytical method. Here, the entire temperature range was broken down into several parts. In connection with this subdivision, the solution itself decomposed into two stages. Besides the first, initial condition, in each stage we also determined the solution obtained at the previous stage at the moment of transition to the next stage. The coefficients C(T), λ(T), A(T) were represented as piecewise-constant in each stage. The linear problems resulting from this approach were solved explicitly with the use of Green's function of the third boundary-value problem [4] for the heat-conduction equation.

Even the first approximation in the model, calculated from the formula

$$T_1(x,\ y,\ z,\ t) = \frac{AP_{\text{int}}}{\lambda}\int_0^t \left\{a\alpha\exp(\alpha z + a^2\alpha^2\tau)\operatorname{erfc}\left(\frac{z}{2a\sqrt{\tau}} + a\alpha\sqrt{\tau}\right) - \right.$$
$$\left. - \frac{1}{\sqrt{\tau}}\exp\left(-\frac{z^2}{4a^2\tau}\right)\right\}\exp\left[-k^2\frac{(x-\varphi(\tau))^2 + (y-\psi(\tau))^2}{1+4a^2\tau}\right]\frac{d\tau}{1+4a^2\tau}, \qquad a^2 = \frac{\lambda}{C}, \tag{5}$$

produces satisfactory qualitative agreement between the results of numerical calculations of temperature fields (5) and data from metallogrpahic studies of the geometry of the structures created during heat treatment.

Since the grain sizes are usually on the order of several micrometers, spatial irregularities in the temperature distribution within a grain can be ignored and we can leave only the dependence on time in (5). This dependence is characteristic for a given depth at the location of the pearlite grain being studied. The relation T(t) will be considered in the diffusional model of the austenite growth mechanism, which was reduced in [5] to the fact that carbon atoms are diffusing continuously within the pearlite grains across cementite–austenite and ferrite–austenite boundaries. These atoms form new monolayers of austenite, high or low in carbon content. This development corresponds to the solution of the problem

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D(T(t))\frac{\partial c}{\partial x}\right), \quad 0 < \xi_1(t) < x < \xi_2(t) \leqslant 0.5\,l_p,$$
$$D(T) = D_0\exp\left(-\frac{E}{R(T-T_a)}\right), \tag{6}$$

where $\xi_1(t)$, $\xi_2(t)$ are a priori unknown displacements of the boundaries of the cementite–austenite and ferrite–austenite phase transitions at the moment of time t:

$$\left.\begin{aligned} &\xi_1(0) = \xi_2(0) = 0.5\,l_r,\ T(0) = A_{C1} = 727\ ^\circ\text{C},\ T(t) > A_{C1},\ 0 < t < t_m,\ T_a = 273\ ^\circ\text{C}, \\ &-D(T(t))\frac{\partial c}{\partial x} = (c_r - c)\frac{d\xi_1}{dt},\ c(x,\ t) = c_{\max}(T(t)),\ x = \xi_1(t)\,(\xi_1(t) > 0), \end{aligned}\right\} \tag{7}$$

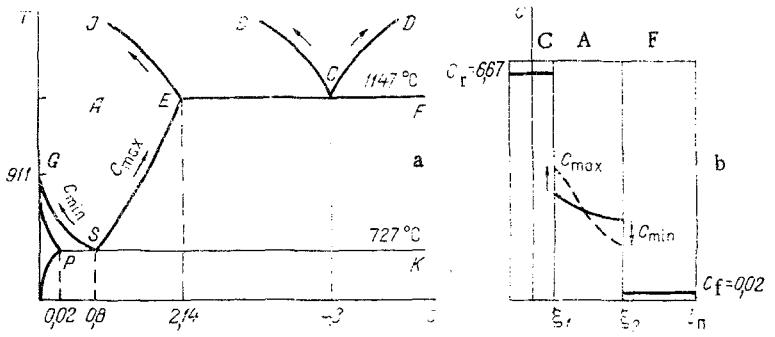

Fig. 1. Section of the iron–cementite diagram [5] (a) and diagram of the change in carbon concentration with the formation of austenite (b). c, %.

$$D(T(t))\frac{\partial c}{\partial x}=(c-c_f)\frac{d\xi_2}{dt},\quad c(x,\ t)=c_{\min}(T(t)),\quad x=\xi_2(t)\ \ (\xi_2(t)<0.5\,l_p),$$
$$\frac{\partial c}{\partial x}=0,\quad x=\xi_1(t)\equiv 0,\ \text{and}\ x=\xi_2(t)\equiv 0.5\,l_p, \tag{8}$$

c_{max} and c_{min} are the limiting concentrations of carbon in the austenite at the boundary with cementite and ferrite, determined by lines SEJ and GS (Fig. 1) of the $Fe–Fe_3C$ diagram at the temperature T(t). The dependence of c_{max} and c_{min} on temperature T was represented in (7) and (8) in the form of functions by the method in [6, 7]:

$$c_{\max}(T)=\begin{cases}0.42\cdot 10^{-5}T^2-0.7\cdot 10^{-2}T+3.57, & T<1147\ ^\circ\text{C};\\ -0.58\cdot 10^{-2}T+10.34, & T>1147\ ^\circ\text{C};\end{cases}$$
$$c_{\min}(T)=1.7-\sqrt{1.13\cdot 10^{-2}T-7.39}. \tag{9}$$

The solution of problem (6-8), besides involving directly finding the distribution of carbon concentration c(x, t) and the unknown boundaries ξ_1 and ξ_2, also entails determination of the time of completion of the ferrite–austenite and cementite–austenite transitions and the total time necessary for homogenization of the austenite phase. After introduction of the new variable through the formula

$$\tau=D_0\int_0^t\exp\left(-\frac{E}{R(T(s)-T_a)}\right)ds \tag{10}$$

we write problem (6)-(8) in the form

$$\frac{\partial c}{\partial\tau}=\frac{\partial^2 c}{\partial x^2},\quad 0<\xi_1(\tau)<x<\xi_2(\tau)\leqslant 0.5\,l_p, \tag{11}$$

and we write the boundary conditions

$$\frac{\partial c}{\partial x}=(c_r-c)\frac{d\xi_1}{d\tau},\quad c(x,\ \tau)=c_{\max}(T(\tau)),\quad x=\xi_1(\tau)\ \ (\xi_1>0), \tag{12}$$
$$-\frac{\partial c}{\partial x}=(c-c_f)\frac{d\xi_2}{d\tau},\quad c(x,\ \tau)=c_{\min}(T(\tau)),\quad x=\xi_2(\tau)\ \ (\xi_2<0.5\,l_p), \tag{13}$$
$$\frac{\partial c}{\partial x}=0,\quad x=\xi_1(\tau)\equiv 0, \tag{14}$$
$$\frac{\partial c}{\partial x}=0,\quad x=\xi_2(\tau)\equiv 0.5\,l_p. \tag{15}$$

The solution of problem (11-15) can be represented [4] in the form

$$c(x,\ \tau)=\int_0^\tau G(x,\ \tau;\ \xi_1(s),\ s)\,\mu(s)\,ds+\int_0^\tau G(x,\ \tau;\ \xi_2(s),\ s)\,\nu(s)\,ds, \tag{16}$$

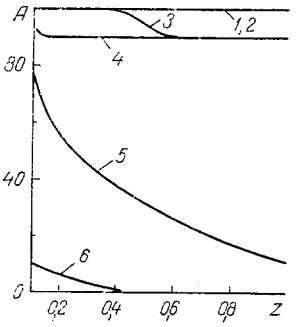

Fig. 2. Curves of change in the maximum amount of stable austenite through the depth of the LRR for different rates of laser treatment, 10^{-3} m/sec: 1) 2.5; 2) 5.0; 3) 6.0; 4) 7.5; 5) 10.0; 6) 12.5. A, %; z, mm.

where

$$G(x,\ \tau;\ \xi,\ s) = \frac{1}{2\sqrt{\pi(\tau - s)}} \exp\left[-\frac{(x-\xi)^2}{4(\tau - s)}\right].$$

Conditions (12)-(15) and the properties of the thermal potentials (16) lead us to a system of nonlinear integrodifferential equations in the unknowns $\mu(\tau)$, $\nu(\tau)$ and $\xi_1(\tau)$, $\xi_2(\tau)$:

$$-\frac{\mu(\tau)}{2} - \int_0^\tau \frac{\partial}{\partial x} G(\xi_1(\tau),\ \tau;\ \xi_1(s),\ s)\,\mu(s)\,ds - \int_0^\tau \frac{\partial}{\partial x} G(\xi_1(\tau),\ \tau;\ \xi_2(s),\ s)\,\nu(s)\,ds = (c_r - c_{\max}(T(\tau)))\frac{d\xi_1}{d\tau}, \quad (17)$$

$$-\frac{\nu(\tau)}{2} + \int_0^\tau \frac{\partial}{\partial x} G(\xi_2(\tau),\ \tau;\ \xi_1(s),\ s)\,\mu(s)\,ds + \int_0^\tau \frac{\partial}{\partial x} G(\xi_2(\tau),\ \tau;\ \xi_2(s),\ s)\,\nu(s)\,ds = (c_{\min}(T(\tau)) - c_f)\frac{d\xi_2}{d\tau}, \quad (18)$$

$$c_{\max}(T(\tau)) = \int_0^\tau G(\xi_1(\tau),\ \tau;\ \xi_1(s),\ s)\,\mu(s)\,ds + \int_0^\tau G(\xi_1(\tau),\ \tau;\ \xi_2(s),\ s)\,\nu(s)\,ds, \quad (19)$$

$$c_{\min}(T(\tau)) = \int_0^\tau G(\xi_2(\tau),\ \tau;\ \xi_1(s),\ s)\,\mu(s)\,ds + \int_0^\tau G(\xi_2(\tau),\ \tau;\ \xi_2(s),\ s)\,\nu(s)\,ds. \quad (20)$$

Regularization is performed in system (17)-(20) with small τ [7]. At $\tau > \varepsilon$, (17)-(20) is solved [8] by numerical methods on a computer with the use of piecewise-linear approximation of the unknown boundaries $\xi_1(\tau)$, $\xi_2(\tau)$ and the densities $\mu(\tau)$, $\nu(\tau)$.

In the calculations, the absorption coefficient A = 0.65, the parameters D_0 and E in (6) were given values of $1.3 \cdot 10^{-4}$ m^2/sec and 131 kJ/mole, R = 8.31 J/mole/K, and the interlamellar distance ℓ_p in the pearlite was equal to 525 nm with a cementite layer thickness ℓ_r = 61 nm. The thermophysical coefficients were taken from [9] for steel 45.

Information on the velocity of the boundaries, recalculated with Eq. (10) for the time scale t, allowed us to determine the degree of transformation of each phase – austenite, ferrite, and cementite – at different points and different moments of time.

The completed calculation of the kinetics of austenitization of pearlitic steel with a radiation intensity W = 1 kW and a spot diameter d = 3 mm ($P_{int} = 4W/\pi d^2$) showed that the range of treatment rates which corresponds to $\varphi(t) = vt$, $\psi(t) = 0$ in (1) can be broken down into several intervals (Fig. 2). At a treatment rate v = 2.5 mm/sec, the temperature at a depth down to 1 mm exceeds the melting point, which leads to complete austenitization after about 0.1 sec.

In the treatment-rate range 5.0-7.5 mm/sec, the temperature on the LRR surface does not exceed the melting point, and different stages of austenitization can be seen on the kinetic curves (Fig. 3). First of all, it is evident that the austenitization process proceeds most intensively during the heating stage and that it slows during the cooling stage. The transformation of ferrite into austenite takes place more rapidly than the dissolution of cementite, which is consistent with conventional viewpoints regarding transformation kinetics at the point A_{C_1}. The most austenite is found in the surface layers, while it decreases going away from the surface. When the temperature passes through 1147°C, the quantity of austenite

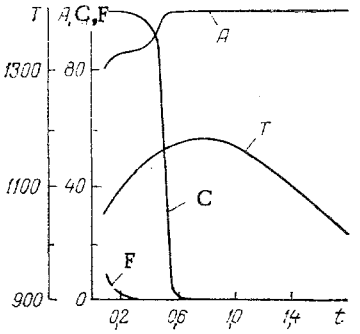

Fig. 3. Theoretical critical curves of the change in temperature (T) and the quantity of austenite (A), ferrite (F), and cementite (C) at a depth of 400 μm in the laser treatment of pearlitic steel at the rate $6 \cdot 10^{-3}$ m/sec. T, °C; A, C, F, %; t, sec.

suddenly increases from 88 to 100%, while the amount of cementite decreases from 97% to 0. This is evidently a consequence of the formation of the liquid phase at the austenite-cementite boundary. The completed calculation, with a constant carbon concentration in the austenite during heating to 1147°C, i.e., without allowance for the possible formation of a liquid phase, leads to long retention of austenite at the level of 88% of its original amount and 94-97% of the original amount of cementite.

At a treatment rate of 10.0 m/sec, different microvolumes of the LRR are heated in the temperature range between A_{C_1} and A_{C_3}. In this case, there is a substantial change in the amount of austenite and ferrite through the depth. The amount of stable austenite is less than 40% even at a depth greater than 300 μm (see Fig. 2). Thus, it can be concluded that this treatment rate is the limiting rate. A further increase in treatment rate to 12.5 mm/sec leads to a situation whereby the formation of stable austenite begins only in the surface layer at a depth of 100 μm ($A \leq 10\%$). Treatment at such a rate is obviously inefficient, since it will produce a structure and properties which are highly nonuniform through the depth and it will diminish hardness in the lower layers of the LRR.

NOTATION

x, y, z, Cartesian coordinates; t, τ, dimensional and dimensionless time; T, temperature; λ, thermal conductivity; C, heat capacity; $a^2 = \lambda/C$, diffusivity; α, heat-transfer coefficient; P_{int}, incident heat flux; A, absorption coefficient; D, diffusion coefficient; v, treatment rate.

LITERATURE CITED

1. J. Christian, Theory of Transformations in Metals [Russian translation], Moscow (1978).
2. V. I. Gridnev, Yu. Ya. Meshkov, S. P. Oshkaderov, and V. I. Trefilov, Physical Principles of the Electrothermal Strengthening of Steel [in Russian], Kiev (1973).
3. N. N. Rykalin, A. A. Uglov, and A. N. Kokora, Laser Treatment of Metals [in Russian], Moscow (1975).
4. A. N. Tikhonov and A. A. Samarskii, Equations of Mathematical Physics [in Russian], Moscow (1972).
5. Yu. M. Lakhtin, Physical Metallurgy and the Heat Treatment of Metals [in Russian], Moscow (1983).
6. V. E. Kashkakha, Equations in Partial Derivatives and Problems with a Free Boundary [in Russian], Kiev (1983), pp. 60-63.
7. E. I. Kim, S. N. Kharin, and G. I. Bizhanova, Izv. Akad. Nauk Kaz. SSR, Ser. Fiz. Mat., No. 5, 40-43 (1984).
8. Chuang Szekely, Heat Mass Transfer, 14, No. 9, 1285-1294 (1971).
9. Physical Properties of Steels and Alloys [in Russian], Moscow (1967).