CALCULATION OF THE KINETICS OF STEEL AUSTENIZATION IN LASER HEATING

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We examine both the kinetic features and the present the formulation of the problem dealing with the distribution of carbon concentrations in an austenite, as well as the motion of the phase separation boundaries in the case of laser heating of pre-, post-, and eutectoid steels. We also obtain results from calculations carried out on a number of laser treatment regimes on eutectoid steel.

The basic problem with theoretical methods of determining the depth of annealing in laser treatment is the selection of the minimum temperature at which the position of the lower effective laser zone is set. A proposal is made in [1] to raise the annealing temperature by 40-100°C relative to the A_{c1}, but the authors offer no precise method of choosing T_{ann}. Moreover, in an example presented in [1], they choose $T_{ann} = 900°C$, which is 170°C higher than A_{c1}. It is suggested in [2], in high-hyphen speed heating of steel, to make provision for the shift in onset of the transition temperature on the basis of the following formula:

$$T_i = \left(\frac{3K^2a_0^2}{4D}\right)^{1/3} V_i^{1/3}.$$

It is obvious that to the extent that the structural factor a_0 determines the instant at which the austenite fronts link up with each other (the eutectic halt), while the transition in the case of high-speed heating may proceed under conditions of rising temperature, i.e., nonisothermally, so that the quantity determined in this manner will result not in displacement of the onset of the transition, but rather of the end. In this case, after this temperature has been reached, it turns out that there is no point in measuring the time required for the conclusion of the austenization, as was proposed in [3]. Moreover, no consideration is given to the possibility of a $\alpha \to \gamma$ conversion in the cooling stage, and this might reduce the shift in the annealing temperature into the high-temperature region. A refined method was proposed in [4, 5] to determine the annealing depth of perlite steel, based on a calculation of the temperature at which crystal austenite crystal growth ceases in the solution of the problem of carbon diffusion between cementite plates.

Despite the fact that excellent agreement was achieved in the above-cited references between theory and experiment, in comparing the results we find shortcomings that lead to inaccuracies.

It is obvious that the metallographic layer with an altered structure or, in other words, an effective laser zone (ELZ), will be established in perlite steel prior to the austenite fronts coming into contact. Most probably there exists some "instrumental" quantity of austenite which will define the lower metallographic boundary of ELZ. It depends on the chemical composition, the original structure of the steel, and the makeup of the solution used for the etching of the polished microsections, etc., and for the time being it can not be determined by calculation. Consequently, the difficulty lies in the fact that the metallographically determined lower boundary of the ELZ cannot be used to verify any of the conversion-transition stages.

Neither will the change in microhardness coincide with the instant of time at which the austenite fronts come into contact. The increase in the microhardness of the steel can also be observed with an austenite content lower than 100%. At the same time, at the instant of

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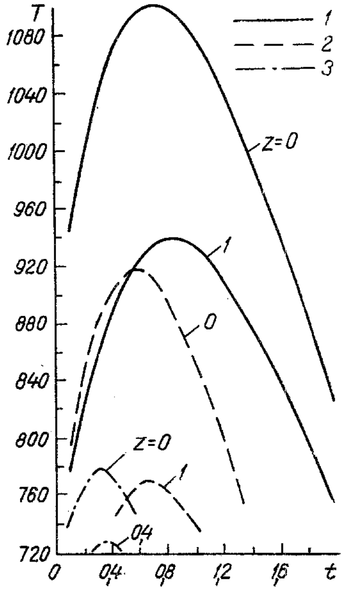

Fig. 1

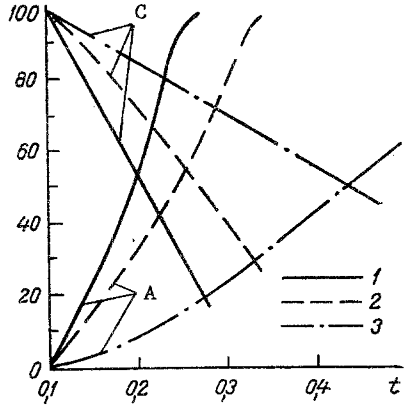

Fig. 2

Fig. 1. Change in temperature over time in supercritical temperature interval for points on the 0_z axis with laser treatment at velocity v, mm/sec: 1) 7.5; 2) 10.0; 3) 12.5. t, sec. T, °C.

Fig. 2. Change in the quantity of austenite and cementite, %, over time with various treatment-process speeds v, mm/sec: 1) 7.5; 2) 10.0; 3) 12.5.

contact the austenite may contain an extremely small quantity of carbon, in connection with which the maximum microhardness of martensite will not be attained. Thus, the microharness measurement can not serve as a basis for comparing theoretical and experimental results.

In such a situation, it is best to deal with the kinetic quantitative relationships of the austenization process with the methods covered in [4, 5], rather than to calculate the annealing depth, thus making it possible to describe the unique features involved in the formation of various classes of ELZ steel structures. It will be possible, on this basis, to render judgement as to the depth of the layer, given one or another structure.

The purpose of the present study is to develop a method to calculate the kinetics of transition for various phases in the process of laser heating preeutectoid, posteutectoid, and eutectoid steels.

The formation of the austenite structure occurs in laser annealing at the heating stage, while in the cooling stage it is converted to martensite. Most valid is a study of the diffusion model of the growth in the austenite grain, analogous to methods described in [4, 5, 6]. Perlite steel with a carbon concentration of 0.8% is represented by ferrite plates with a carbon concentration $c_f = 0.006\%$ and by cementite plates with a carbon concentration $c_c = 6.67\%$. Under high-speed heating conditions, the ferrite fails to reach carbon saturation to the concentration of P and at the temperature of A_{c1} it exhibits a carbon concentration such as that found under normal room conditions, i.e., 0.006% [7]. Consequently, with heating from A_{c1} to 910°C the carbon concentration c_f in the ferrite may change from 0.006 to 0. It is obvious that we can make the assumption that $c_f \simeq 0$ in the calculations over the entire temperature range. In the heating process the carbon concentration in the cementite can change. However, in the calculations particularly of high-speed heating, the assumption of concentration constancy is valid, namely: $c_c \simeq 6.67$.

The austenite grain is formed at the boundary separating the cementite from the ferrite. Its rate of growth is controlled by the rate of carbon diffusion ξ_1 from the "cementite-austenite" boundary to ξ_2 at the "austenite-ferrite" boundary. In this case, for each temperature T the carbon concentration in the austenite at the A-F boundary (c_{min}) is determined from the GS line of the $Fe—Fe_3C$ diagram, while at the C-A boundary (c_{max}) it is determined along the SE line. Then, with provision made for the boundary conditions, we can write the system of equations as follows:

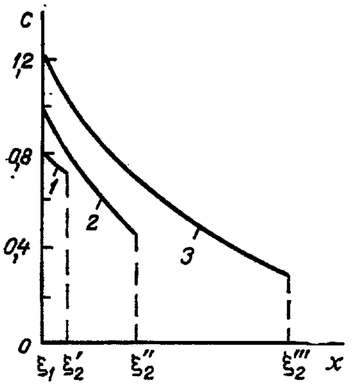

Fig. 3

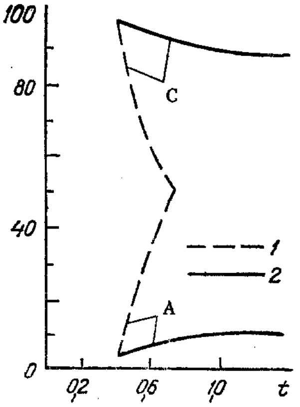

Fig. 4

Fig. 3. Change in the carbon concentration in the austenite as a function of the distance to the cementite-austenite boundary ξ_1 with v = 7.5 mm/sec, z = 0 mm at various instants of the stay time at the temperature A_{c_1}: 1) t = 0.117 sec; 2) 0.168; 3) 0.248 sec, %.

Fig. 4. Change in the quantity of austenite and cementite, %, over time with v = 10.0 mm/sec and z = 1 mm, calculated by a numerical (1) and an analytical-approximate (2) method.

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D(T)\,\frac{\partial c}{\partial x}\right), \tag{1}$$

$$D(T)\,\frac{\partial c}{\partial x}\bigg|_{x=\xi_1(t)} = (c_{\mathrm{C}} - c(x,\ t))|_{x=\xi_1(t)}\,\frac{d\xi_1}{dt},\quad c(x,\ t)|_{x=\xi_1(t)} = c_{\max}(T(t)), \tag{2}$$

$$-D(T)\,\frac{\partial c}{\partial x}\bigg|_{x=\xi_2(t)} = (c(x,\ t) - c_{\mathrm{f}})|_{x=\xi_2(t)}\,\frac{d\xi_2}{dt}, \tag{3}$$

$$c(x,\ t)|_{x=\xi_2(t)} = c_{\min}(T(t)),$$

$$D(T) = D_0 \exp[-E/RT]. \tag{4}$$

The solution of the formulated problem presupposes determination of the carbon concentration c(x, t), the velocities of boundary motion $d\xi_1/dt$ and $d\xi_2/dt$ and the determination of the C → A and F → A transition times. At the instants of C → A and F → A transition halts, the motion of the boundaries ξ_1 and ξ_2 ceases, Eq. (2)-(3) lose their significance, and the problem of equalizing the carbon concentrations in the austenite is solved on the basis of Eq. (1), for which the initial conditions are the concentration values $c_{\max}$ and $c_{\min}$ derived at the instant at which the motion of the boundaries ξ_1 and ξ_2 ceases.

For preeutectoid steel (a carbon concentration from 0.02% to 0.8%) the diffusion problem must be solved in two steps. In the first step, where we have the P → A transition and the transition of the excess ferrite at the perlite boundary, the relationships (1)-(4) are entirely valid. In the second step, after solution of the perlite cementite we have the process of redistributing the carbon between the earlier perlite grain and the excess ferrite. In a perlite grain with a dimension of Δ_c the average carbon concentration should be assumed to be equal to 0.8%. In an excess-ferrite plate with a dimension of Δ_f the carbon concentration remains equal to 0. Thus, problem (1) must be solved with the following initial conditions:

$$c(x,\ 0) = 0.8,\quad 0 < x < \Delta_{p/2},\quad c(x,\ 0) = 0,\quad \Delta_{p/2} < x < \Delta_{p/2} + \Delta_{f/2}. \tag{5}$$

Here we will place the coordinate origin at the center of the former perlite grain.

For posteutectoid steel (carbon concentration from 0.8 to 2.14%), Eqs. (1)-(4) are entirely valid, in analogy with the case of the description of the P → A transition. After the perlite-cementite has been dissolved and the carbon redistributed, we have the process of the solution of the excess cementite in the former grain. In this case, the initial conditions for problem (1) have the form:

TABLE 1. Quantity of Austenite and Cementite (%), Determined by Numerical and Approximate-Analytical Methods, for Various Treatment Speeds and at Various Instants of Time

Determined phase component	Treatment speed v, mm/sec, and time t, sec					
	$v=7{,}5$, $t=0{,}25$		$v=10{,}0$, $t=0{,}3$		$v=12{,}5$, $t=0{,}4$	
	numerically	analytically	numerically	analytically	numerically	analytically
austenite with						
$z=0$	100	88	82	20	51	8
$z=1$*	55	13	31	0	—	—
cementite with						
$z=0$	28	98	42	99	59	99
$z=1$	48	94	62	94	—	—

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*z, mm.

$$\begin{cases} c(x,\ 0)=6.67, & 0<x<\Delta_{c/2}, \\ c(x,\ 0)=0.8, & \Delta_{c/2}<x<\Delta_{c/2}+\Delta_{c/2}, \end{cases} \tag{6}$$

where Δ_c represents the dimension of the plate. The coordinate origin here is found in the center of the excess cementite plate.

At the instant that the excess cementite is dissolved, the motion of the boundary is brought to a stop and it then becomes necessary to solve the problem of equalizing the carbon concentrations in the austenite on the basis of Eq. (1), for which the initial conditions are the concentration values c_{max} and c_{min}, derived for the instant at which the motion of the boundary ξ_1 is brought to a halt.

Since the values of the concentrations c_{max} and c_{min}, as well as the coefficient of carbond diffusion in the austenite, are dependent on temperature, the solution of the above-cited problems can be based on the determination of the thermal cycles for each microvolume in the steel being processed. Below, we make use of the approximation-analytical solution of quasilinear problem of heating steel with laser emissions with spot Gaussian energy distribution such as that described in [6] in the following formulation:

$$C(T)\,\frac{\partial T}{\partial t}=\operatorname{div}(\lambda(T)\operatorname{grad}T)\quad\text{with}\ t,\ z>0, \tag{7}$$

$$T|_{t=0}=T_0(x,\ y,\ z), \tag{8}$$

$$\left(-\lambda\frac{\partial T}{\partial z}+\alpha T\right)\Big|_{z=0}=AP_{\text{int}}\exp\{-k^2[(x-\varphi(t))^2+(y-\psi(t))^2]\}, \tag{9}$$

where A is the absorption factor set equal to 0.65. Figure 1, for steel, shows the change in temperature over time in supercritical temperature interval for those points on the surface and at the Oz axis, at a depth of 1 mm, when subjected to treatment under the following regimes: radation power P = 1 kW, spot diameter d_p = 3 mm, treatment speeds v = 7.5, 10.0 and 12.5 mm/sec. We see that in these regimes the surface of the steel is heated without melting, i.e., the transitions take place in the solid state.

The problem of the displacement of the separation boundaries ξ_1 and ξ_2 and the determination of the carbon concentration in the austenite during laser treatment of the eutectoid steel is solved by the method of finite differences in explicit form. After having brought Eq. (1)-(4) to the difference form, we obtain the following (the index of the previous time layer has been dropped):

$$c(i,\ k+1)=c(i)+\frac{D\Delta\tau}{h^2}\,[c(i+1)-2c(i)+c(i-1)], \tag{10}$$

$$\Delta x_1=-\frac{D\Delta\tau}{h}\left[\frac{c(ix_1+1)-c_{max}}{c_{max}-c_c}\right], \tag{11}$$

$$\Delta x_2=\frac{D\Delta\tau}{h}\left[\frac{c(ix_2-1)-c_{min}}{c_{min}-c_f}\right], \tag{12}$$

where k is the number of the time layer; c(i) is the carbon concentration in the i-th point of the austenite calculation region ($i_{x_1} < i < i_{x_2}$); $\Delta\tau$ is the time interval; h is the interval along the coordinate x; $\Delta x_{1,2}$ is the displacement of the boundaries ξ_1 and ξ_2 beyond the solution interval; $i_{x_{1,2}}$ are the instantaneous coordinates of the boundaries ξ_1 and ξ_2. The thickness of the cementite plate and the interplate distance, dependent on the initial heat treatment of the steel, have been set equal to $\Delta_c = 61$ nm, $\Delta_p = 525$ nm.

The lines of the Fe—Fe_3C GS and SE are approximated by the quadratic parabola method, and the temperature relationships of concentration are derived as a reason, namely,

$$c_{\min} = 1.18 - \sqrt{\frac{T}{147.5} - 4.78}, \tag{13}$$

$$c_{\max} = 3.46 - \sqrt{16.3 - \frac{T}{78.8}}. \tag{14}$$

According to [7], we have selected $D_0 = 16$ mm/sec, E = 136 kJ/(g·atom), R. = 8.31441 ± 0.00026 $J \cdot mol^{-1} \cdot K^{-1}$ [8]. The calculations were performed on an "Electronica-60" minicomputer with a program compiled in BASIC. Figure 2 shows the relationships derived in the solution of the austenite carbon diffusion problem at the surface for the thermal cycles illustrated in Fig. 1. First of all, we see that under the conditions in which the layer is heated to a temperature above the temperature of point A_{c3}, the change of the perlite into austenite occurs much more intensively than the solution of the cementite. With heating below 940°C, when v = 10 mm/sec, this difference is reduced, while with v = 12.5 mm/sec, when we have heating to a temperature no higher than 780°C, both processes proceed at approximately the same speed. Particular influence is exerted on the austenization process by the speed of treatment. With v = 7.5 mm/sec, the austenite at the surface is 100% at the instant of time t = 0.55 sec or during the stay time at a temperature above that of point A_{c1} equal 0.15 sec. With v = 12.5 mm/sec, at the surface when t = 0.4 sec we have only 50% austenite and it does not exceed 70% at the end of the treatment process, i.e., the ferrite has not been completely changed into austenite. Obviously, processing at this speed is inefficient, despite the fact that up to a temperature in excess of 727°C a layer of thickness 0.4 mm can be heated.

We can see from Fig. 3 that in the vicinity of the boundary ξ_1 the concentration rises from 0.8 to 1.2% over time. Near the ξ_2 boundary at the point at which the austenite fronts come into contact, when t = 0.248 sec, or with the stay time at the temperature above A_{c1}, equal to 0.148 sec, the carbon concentration in the austenite is slightly greater than 0.3%. Obviously, this is the extreme case for the attainment of martensite with high hardness at the center between the cementite plates after cooling. With an increase in the processing speed, the joining of the austenite fronts into perlite colonies will not occur at the surface or in the transition to layers situated at great depth and the microhardness in the ELZ of the perlite steel in this case will diminish.

We have compared the results by a numerical method and by an approximation-analytical method, such as that described in [7]. From the results shown in Table 1 and in Fig. 4 we see that in carrying out these calculations by the numerical method, the quantity of austenite is greater, while that of the cementite is smaller, relative to the data produced by the appoximation-analytical method. The kinetic curves for the austenite and cementite in the former case are considerably steeper than in the second case.

NOTATION

T, temperature; K, angular coefficient for the relationship between the argument of the Crump function and temperature, for steels K = 230°C; a_0 structural factor, i.e., half the distance between two adjacent centers of austenite crystalization; D, coefficient of carbon diffusion in austenite; v_h, heating rate; c, carbon concentration; D_0, preexponential factor of the diffusion coefficient; E, activation energy; R, universal gas constant; C, heat capacity; λ, coefficient of thermal conductivity; α, heat-exchange factor; P_{int}, incident heat flux; A, absorption coefficient; x, y, z, Cartesian coordinate; φ, ψ, angular coordinates; k, coefficient of Gaussian source concentration; t, time.

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EXCHANGE OF HEAT IN AN ORTHOTROPIC BOUNDED CYLINDER UNDER COMBINED BOUNDARY CONDITIONS OF THE FIRST, SECOND AND THIRD KINDS

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We present the results from a study of a two-dimensional nonsteady temperature field and the heat flows in an orthotropic bounded cylinder. A method is proposed for the determination of the thermophysical properties and their ratios, as well as for the determination of the coefficient of heat exchange at the side surface.

In contemporary manufacturing, science and engineering, new materials are being utilized to an ever-increasing extent, and many of these exhibit significant nonuniformity (anisotropy). Among these materials we can include complex composition laminar structures (quasianisotropic materials).

We must recognize that the theoretical and experimental foundations on which the methods employed to study thermophysical properties (TPP) of anisotropic materials [1-5] are in need of further refinement and development [6].

It was demonstrated in [7, 8] that the solutions of two- and three-dimensional thermal conductivity problems can be employed to describe the processes of transfer in orthotropic media. For the case of heat exchange in a medium of constant temperature these solutions were made part of the method [1] for the determination of the coefficients of thermal diffusivity in solid materials. The method calls for the fabrication of two (or three) specimens of various sizes, these subsequently subjected to testing in accordance with a regular regime method. As an example of an integrated study of TPP we can point to a method based on the one-dimensional solution of the thermal-conductivity problem for a specific flow of heat [3]. The investigation in this case is carried out by specifying a recorded thermal flow, initially in one, and then in another, mutually perpendicular direction. It should be pointed out that in [1-4] no analysis is undertaken with regard to the dynamics of the development of temperature fields and flows of heat ascribed to anisotropy.

It is the purpose of the present study to develop a method for the determination of the TPP of materials, using specimens in the shape of an orthotropic bounded cylinder and to analyze the unique features encountered in the development within that cylinder of temperature fields and heat flows.

Formulation of the Problem. A bounded orthotropic cylinder of height h and diameter 2R with TPP λ_r, a_r, λ_z, a_z is given. The initial temperature of the object is T_0 = const. At some instant of time a constant flow of heat with a specific density of q_0 is applied to one of the ends of the cylinder (the coordinate origin is located in the active plane of the source), while a constant temperature T_c, different from the initial temperature, is maintained at the other end of the cylinder. At the side surface of the cylinder we note that

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