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NUMERICAL SIMULATION OF PEARLITIC TRANSFORMATION IN STEEL 45Kh5MF

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A dilatometric study of steel 45Kh5MF used for making rolling mill rolls is performed. The results of the dilatometric and metallographic analyses are used to determine the kinetics of the perlitic transformation in the steel under continuous cooling. The developed method of numerical simulation of structural transformations under continuous cooling is used to solve the inverse problem and to plot a computational isothermal diagram of decomposition of supercooled austenite in steel 45Kh5MF in the range of perlitic transformation. To check the solution obtained an experimental isothermal diagram of decomposition of austenite in steel 45Kh5MF in the perlitic range is plotted. The data of both diagrams match accurately enough.

Key words: steel 45Kh5MF, numerical simulation, pearlitic transformation, continuous cooling, dilatometric study, isothermal diagram.

INTRODUCTION

Steel 45Kh5MF is a comparatively recent material used in the heavy industry primarily for the production of backup and work rolls for hot rolling. The special features of the phase and structural transformations in continuous cooling of this steel have not been studied in detail. Investigation of these transformations presents practical interest. One of the reasons for such a study is the fact that in most cases provision of the required level of mechanical properties of ready articles requires strict control of the content of the products of decomposition of austenite in the structure. For example, the operating stability of rolling mill rolls requires their appropriate hardenability for creating the demanded thickness of the active layer with required structure (as a rule, the layer should contain no more than 5% of the diffusion products of decomposition of supercooled austenite). Therefore, it is important to estimate theoretically in advance the content of perlite in the structure of the active layer for this or that cooling mode in order to determine the optimum intensity of cooling of the steel in heat treatment.

Since it is often hard to study the formation of structure during heat treatment of articles experimentally, numerical simulation of the processes of decomposition of supercooled austenite has become a frequent instrument of study [1 – 6]. Such computations make it possible to determine with an admissible accuracy the temperature and time ranges of the occurrence of phase transformations in steels cooled at this or that rate without spending much time and material for experiments.

Phase transformations are simulated by three principal methods, namely, a thermodynamic one [1], a cellular automation one [2 – 3], and a kinetic one [4 – 6]. The kinetic method is more popular because it does not require accurate determination of a great number of thermodynamic quantities in contrast to the other two methods. The kinetic method is based on simulation of the kinetics of decomposition of supercooled austenite in continuous cooling with the help of the Kolmogorov – Johnson – Mehl – Avrami equation (we will denote it KJMA in what follows) [7 – 8] and of the Scheil additivity rule [9]. However, the kinetic method of simulation requires the knowledge of the isothermal diagram of decomposition of supercooled austenite, an experimental construction of which may be complicated by a too low or too high stability of supercooled austenite in a specific steel. The problem can be solved by using a thermokinetic diagram of decomposition of austenite in the computation.

The aim of the present work was to develop a method for numerical simulation of perlitic transformation on the basis of dilatometric data obtained in continuous cooling of a roll steel 45Kh5MF.

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METHODS OF STUDY

We studied steel 45Kh5MF with the following chemical composition (in wt.%): 0.45 C, 0.35 Si, 4.8 Cr, 0.42 Mo, 0.2 V, 0.014 P, 0.17 S. The special features of the occurrence of phase transformations in steel 45Kh5MF were determined by the dilatometric method using a Linseis L78 "R.I.T.A" dilatometer.

In order to plot the thermokinetic diagram of decomposition of supercooled austenite we measured the elongation of the specimens under continuous cooling. The specimens were heated to the austenitizing temperature $t_\gamma = 910°C$, held for $\tau_\gamma = 15$ min, and cooled at a rate $v_{\text{cool}} = 0.025 - 5.0$ K/sec. The cooling rate was constant in every test. The temperature ranges of the perlitic, bainitic, and martensitic transformations were detected from inflections on the experimental dilatometric curves. To amend the temperatures of the start and finish of formation of products of decomposition of supercooled austenite the elongation of the dilatometric specimens was differentiated numerically with respect to the current cooling temperature.

To plot an experimental isothermal diagram of decomposition of supercooled austenite in the perlitic range we resorted to isothermal holds of the dilatometric specimens in the range of 640 – 750°C for 10 h. After the hold the specimens were cooled at a rate of about 50 K/sec for the austenite not decomposed during the hold to undergo martensitic transformation.

The microstructure of the specimens was studied with the help of light microscopy on transverse laps. The volume fractions of the structural components were computed using metallographic analysis and the SIAMS 700 software.

The kinetics of the perlitic transformation under continuous cooling was evaluated by the formula [10]

$$P = \frac{\Delta l_{\gamma(t)} - \Delta l_{\text{cur}}}{\Delta l_{\gamma(t)} - \Delta l_{\alpha(t)}}, \tag{1}$$

where P is the fraction of the transformation, $\Delta l_{\gamma(t)} = a_\gamma t + b_\gamma$ is the temperature dependence of the absolute elongation of the austenite, Δl_{cur} is the absolute elongation of the specimen at the current cooling temperature, and $\Delta l_{\alpha(t)} = a_\alpha t + b_\alpha$ is the temperature dependence of the absolute elongation of the perlite. Figure 1 presents the variation of the fraction of perlite under continuous cooling.

The results of the metallographic study performed in [11, 12] were used to evaluate the fractions of the structural components for each cooling rate of the range studied, and the kinetics of the perlitic transformation was normalized depending on the fraction of the formed perlite. In this way we obtained experimental kinetic curves of perlitic transformation in steel 45Kh5MF in the range of cooling rates of 0.025 – 0.100 K/sec.

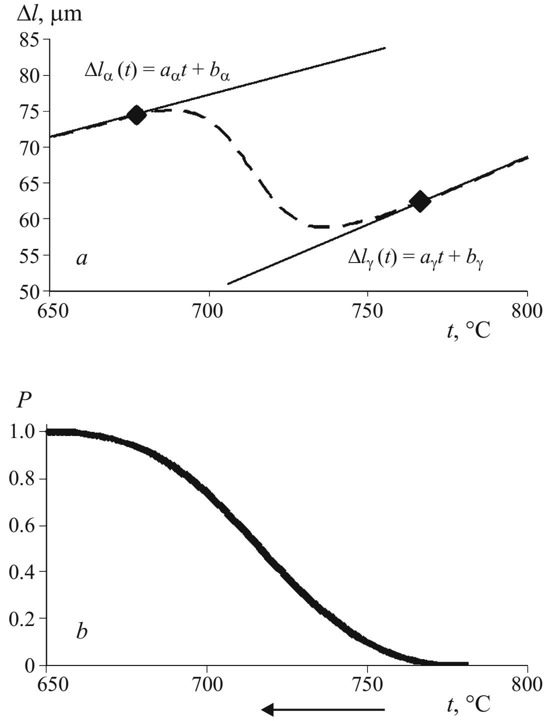

Fig. 1. Variation of the length Δl of a specimen in perlitic transformation (*a*) and experimental curves of decomposition of austenite (P is the fraction of the transformation) in continuous cooling of a dilatometric specimen from 910°C at a rate of 0.035 K/sec (*b*).

Numerical simulation of the kinetics of the perlitic transformation was performed with the help of the KJMA equation [7, 8]

$$P = 1 - \exp(-k\,\tau^n), \tag{2}$$

where P is the volume fraction of the forming phase, τ is the time of the isothermal hold (sec), and k and n are temperature-dependent parameters of the equation.

Equation (2) is valid for isothermal conditions. Therefore, the kinetics of the transformations under continuous cooling is modeled with the use of the additivity rule [9, 13]. In this case the cooling curve is broken with respect to the temperature into successive isothermal steps with duration $\delta\tau$. Each step corresponds to the isothermal transformation at the given constant temperature. Thus, the fraction of the phase formed in each cooling stage depends on the fraction of the phase formed in the preceding stage and on the temperature attained.

The kinetics of the transformation of perlite in steel 45Kh5MF was modeled by the method of [14]. The initial data for the modeling were the known rates of cooling of the dilatometric specimens and the corresponding experimentally determined fractions of perlite. The computation was performed in the following succession.

We specified the form of the isothermal C-curve of decomposition of austenite (for example, using the data of [15]

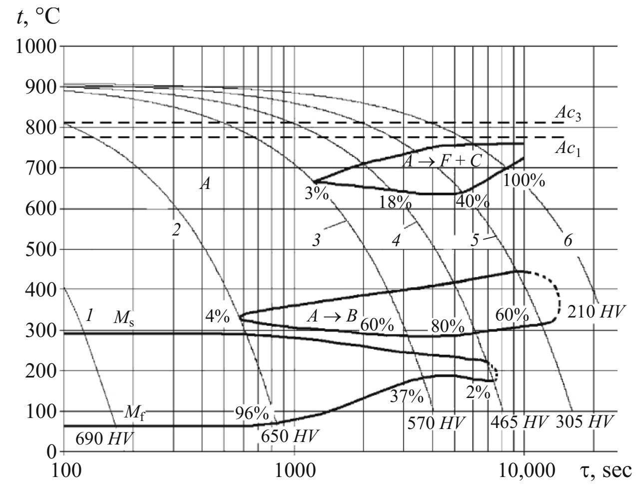

Fig. 2. Thermokinetic diagram of decomposition of supercooled austenite in steel 45Kh5MF ($t_\gamma = 910$°C, $\tau_\gamma = 15$ min) obtained for the following cooling rates: *1*) 5 K/sec; *2*) 1 K/sec; *3*) 0.2 K/sec; *4*) 0.1 K/sec; *5*) 0.05 K/sec; *6*) 0.025 K/sec.

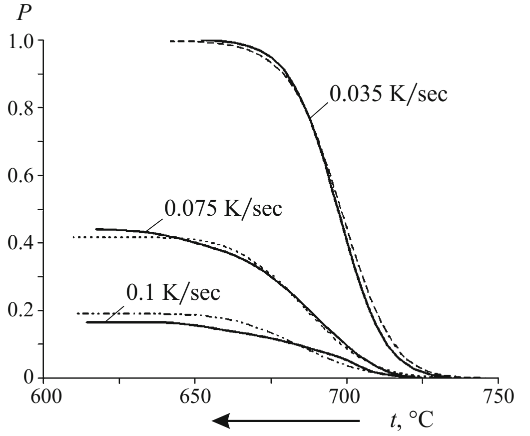

Fig. 3. Experimental (the solid lines) and computed (the dash lines) curves of formation of perlite in continuous cooling of steel 45Kh5MF at constant rates (given at the curves): *P* is the fraction of the formed perlite.

for a steel with close chemical composition), for which we determined the temperature-dependent parameters of the KJMA equation *n* and *k* in the temperature range of decomposition of austenite for the fist stage, i.e.,

$$n = \ln\left(\frac{\ln(1-P_s)}{\ln(1-P_f)}\right) \Big/ \ln\left(\frac{\tau_s}{\tau_f}\right); \tag{3}$$

$$k = \frac{-\ln(1-P_s)}{(\tau_s)^n}, \tag{4}$$

where P_s, P_f are the fractions of the new phase at the start and finish of the transformation on the isothermal curve of decomposition of austenite (we took $P_s = 0.01$ and $P_f = 0.99$), τ_s and τ_f are the times of the start and finish of the isothermal transformation at the specified temperature of the hold, respectively (in seconds).

We broke the known thermal trajectories of cooling of the dilatometric specimen into a number of successive isothermal holds with a constant temperature step.

Now we computed the fraction of perlite formed under continuous cooling with the help of the Scheil additivity rule, i.e.,

$$P_2 = 1 - \exp(-k(\tau' + \Delta\tau)^n); \tag{5}$$

$$\tau' = \sqrt[n]{\frac{-\ln(1-P_1)}{k}}, \tag{6}$$

where P_2 is the fraction of the decomposition of austenite in the given isothermal step at temperature t_2, P_1 is the fraction of the decomposition of austenite in the preceding isothermal step at temperature t_1 ($t_1 > t_2$), τ' is the virtual time required for attaining degree P_1 of decomposition of austenite at temperature t_2 (sec), and $\Delta\tau$ is the actual time step determined by the cooling rate of the specimen (sec).

We compared the theoretical curves of perlitic transformation with the experimental curves for the dilatometric specimens cooled at different rates. When the deviation was considerable, the form of the isothermal *C*-curve was corrected and computation was repeated.

The procedure was repeated until the computed and experimental curves describing the variation of the fraction of perlite in continuous cooling matched each other satisfactorily and the difference in the computed and the experimentally determined fractions of perlite was no greater than 5%.

RESULTS AND DISCUSSION

We used the data of the dilatometric studies to determine the critical points for steel 45Kh5MF in heating and obtained $Ac_1 = 775 \pm 2$°C and $Ac_3 = 811 \pm 2$°C. We also found the temperature and time ranges of the structural transformations in the steel under continuous cooling. This allowed us to plot a thermokinetic diagram of decomposition of supercooled austenite in the studied steel (Fig. 2).

We plotted experimental curves of variation of the fraction of perlite (Fig. 3) using the dilatometric curves obtained for cooling rates ranging within 0.025 – 0.100 K/sec, which corresponded to perlitic transformation in steel 45Kh5MF, and the data of the metallographic analysis. When the cooling rate was increased from 0.035 to 0.100 K/sec, the rate of formation of perlite decreased substantially, and its content in the structure fell from 100 to 20%.

The method of numerical simulation of structural transformations described above was used to plot theoretical curves of perlitic transformation in the studied range of cooling rates (Fig. 3).

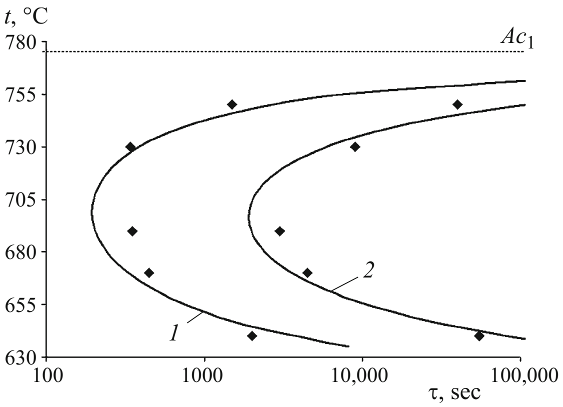

Fig. 4. Experimental (the labels) and theoretical (the lines) isothermal diagrams of decomposition of supercooled austenite in steel 45Kh5MF.

The simulation allowed us to determine the location of the lines of the start and finish of perlitic transformation on the computed (“ideal” in the terms of [16]) isothermal diagram of decomposition of supercooled austenite in steel 45Kh5MF (Fig. 4). According to the computational data, the temperature of the minimum resistance of supercooled austenite in steel 45Kh5MF to decomposition of the first stage is about 700°C, and the incubation period corresponding to this temperature is about 200 sec.

To check the adequacy of this solution experimentally we performed a dilatometric study of steel 45Kh5MF under isothermal conditions in the temperature range of 640 – 750°C corresponding to the range of its perlitic transformation. The study gave us experimental points of the start and finish of perlitic transformation corresponding to 1 and 99% perlite (Fig. 4).

The theoretical isothermal diagram of decomposition of austenite in steel 45Kh5MF coincided with the experimental one satisfactorily. The observed shift of the computed values of the start and finish of perlitic transformation toward shorter isothermal holds is connected with the fact that the position of the experimental points is affected by the final rate of cooling of the specimen to the temperature of the isothermal hold, which has also been observed in [16] and [17].

Thus, an “ideal” curve of decomposition of supercooled austenite can be plotted on the basis of a dilatometric study of the steel under continuous cooling with the help of the method of successive approximations. This permits simulation of structural transformations in a continuously cooled steel with technically admissible accuracy. Such computations have great practical significance for the development of modes of heat treatment for steel articles making it possible to choose an expedient intensity of quenching cooling for obtaining the optimum proportion of structural components and the required level of mechanical properties in the articles.

In such a case the initial data for the simulation are results of computation of the temperature fields over the cross section of the article due to cooling with different intensities (by the method of [18]) and a computed isothermal diagram of decomposition of austenite determined by the method suggested. The temperature fields due to quenching of rolling mill rolls can be computed using experimentally determined relations between the heat transfer coefficient and the surface temperature, for example, for the case of cooling in an ambient of sprinkled water [19].

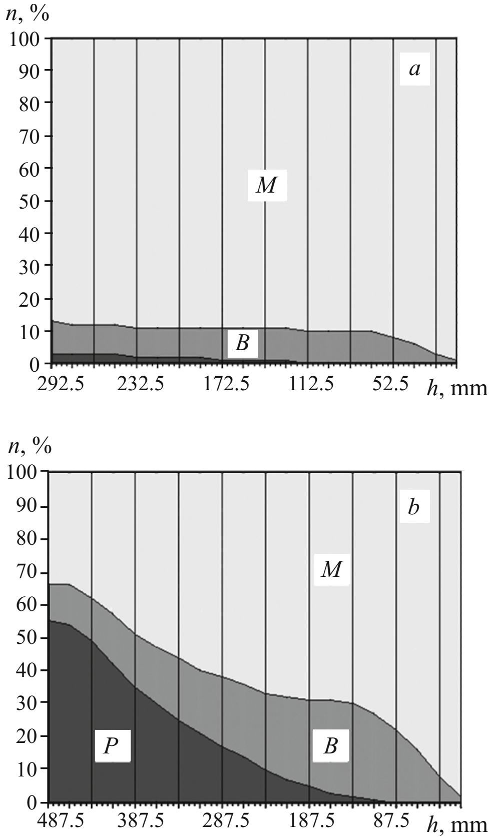

Fig. 5. Distribution of structural components over cross section of the barrel of a roll from steel 45Kh5MF (*h* is the distance from the surface over the radius of the barrel) in cooling in a water sprinkling device: *a*, *b*) roll diameters of 0.6 and 1.0 m, respectively; *M*) martensite; *B*) bainite; *P*) pearlite.

The computations performed in [19] show that a roll 0.2 m in diameter from steel 45Kh5MF cooled in a water sprinkling device has a through hardenability. A roll 0.6 m in diameter contains 85 – 100% martensite in the structure over the whole of the cross section, and the content of perlite does not exceed 5% in the axial zone. In the case of water sprinkling quenching of a roll 1.0 m in diameter the thickness of the hardened layer is 115 – 125 mm (Fig. 5).

CONCLUSIONS

1. We have determined the critical points in heating of steel 45Kh5MFA, namely, $Ac_1 = 775 \pm 2$°C and $Ac_3 = 811 \pm 2$°C, studied the kinetics of perlitic transformation in steel 45Kh5MF under continuous cooling, and plotted a ther-

mokinetic diagram of decomposition of supercooled austenite in the steel at cooling rates ranging within 0.025 – 5.000 K/sec.

2. We have developed and tested a method for computational-experimental simulation of structural changes in steels under continuous cooling. Numerical simulation of perlitic transformation of austenite in steel 45Kh5MF has been performed and the lines of the start and finish of isothermal perlitic transformation have been computed. The results of the computation match the experimental data accurate to 5%.

3. A dilatometric study of isothermal decomposition of austenite in steel 45Kh5MF in the temperature range of 640 – 750°C has been performed. The plotted experimental isothermal diagram of decomposition of supercooled austenite in the perlitic range agrees satisfactorily with the computational one.

4. The computed diagram has been used to model the structural transformations occurring due to water sprinkling quenching of rolling mill rolls of different diameters from steel 45Kh5MF. This proves the possibility of forming a hardened layer with a thickness of 115 – 125 mm on the surface of hot-rolling rolls 1.0 m in diameter from steel 45Kh5MF by water sprinkling quenching.

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