CALCULATIONS ON REDUCTIVE CASE-HARDENING OF STEEL

L. G. Gal'perin and A. P. Baskakov

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An analytical solution is given for the diffusion problem as regards carburization annealing of steel. Nomograms are constructed for the concentration distribution and the time required.

There is some loss of carbon from the surface layer when steel billets are heated for rolling; the depth of the decarburized layer is dependent on the material, the heating time, the carbon potential, and the temperature. Accumulation of carbon by reduction is also provided by appropriate annealing; calculations have been reported [1] on this carburization. The time required is found by considering the carbon distribution in the surface layers subject to an arbitrary given initial distribution of the form

$$c(x,\ 0) = c_1 + (c_0 - c_1)\exp(-\alpha x), \tag{1}$$

where α is a coefficient characterizing the rate of approach of the concentration to c_1 during motion within the specimen, and this is determined by experiment. A disadvantage of the method of [1] is the need to construct a set of $c = c(x,\ t)$ curves for each particular case in order to calculate the time.

We have constructed a general solution in dimensionless variables by using as our initial distribution the exact solution for the diffusion problem for a semiinfinite body [2]:

$$c(x,\ 0) - c_0 = (c_1 - c_0)\,\Phi\left(\frac{x}{\sqrt{4D_1 t_1}}\right)$$

where Φ is the error integral.

Figure 1 compares the initial distribution for ShKh-15 steel (points) with calculated results from (1) (curve 1) and (2) (curve 2). We used the data given in [1] for this purpose. It is clear from Fig. 1 that

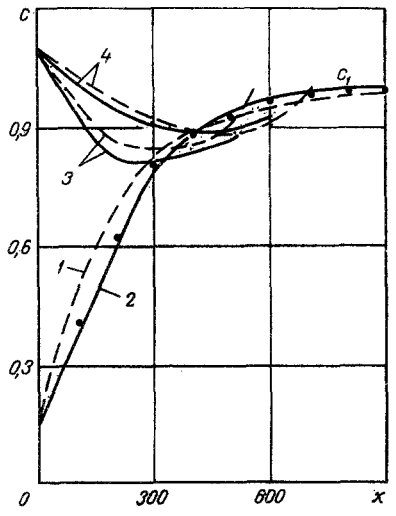

Fig. 1. Reductive carburization of ShKh-15 steel [1]. The solid lines represent the present method, the broken lines the method of [1]; the points correspond to the experimental initial distribution; 1, 2) calculated initial distribution; 3, 4) concentrations after 3 h and 6 h respectively, c, wt.%; x, μ.

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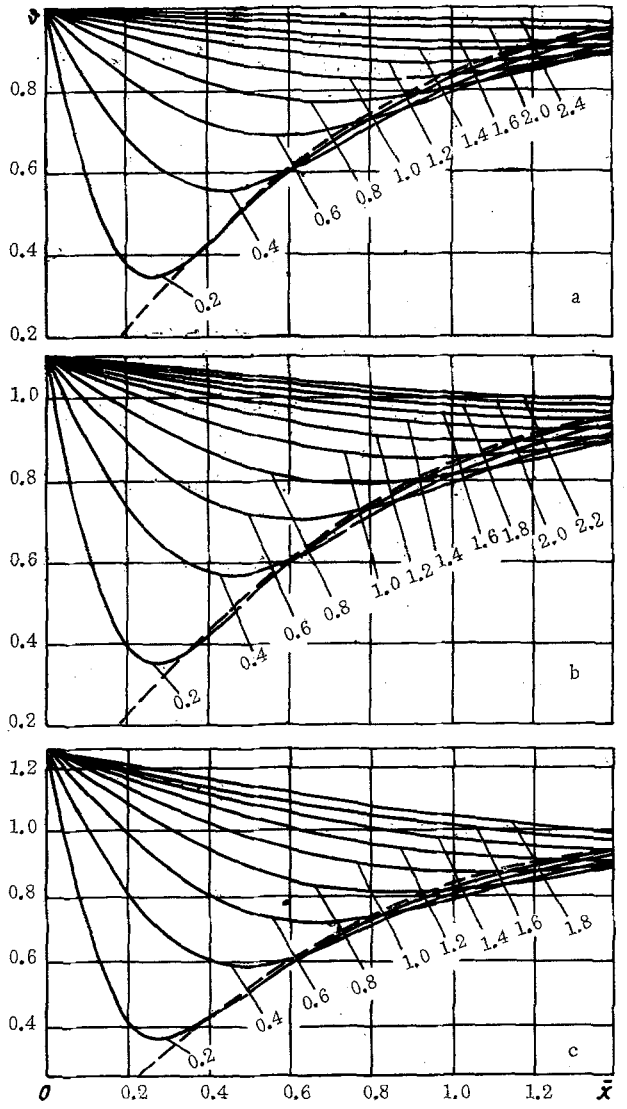

Fig. 2. Calculated nomograms for concentration and time. The broken lines are initial distributions for η of: a) 1.0; b) 1.1; c) 1.25. The numbers on the curves are values of τ.

representation of the initial distribution via (2) corresponds more closely to the experimental observations; therefore, the concentration distribution during carburization is determined by the diffusion behavior for a semiinfinite body with the initial distribution of (2) and the boundary condition

$$c|_{x=0} = c_2. \tag{3}$$

The following is the solution [2]

$$\frac{c(x,\ t)-c_0}{c_2-c_0} = 1-\frac{1}{\sqrt{4\pi D_2 t}}\int_0^\infty\left\{\left[1-\frac{c_1-c_0}{c_2-c_0}\Phi\left(\frac{\xi}{\sqrt{4D_1t_1}}\right)\right]\times\left\{\exp\left[-\frac{(x-\xi)^2}{4D_2t}\right]-\exp\left[-\frac{(x+\xi)^2}{4D_2t}\right]\right\}\right\}d\xi. \tag{4}$$

We introduce the dimensionless variables

$$\bar{x} = \frac{x}{\sqrt{4D_1t_1}}, \qquad \bar{\tau} = \frac{\sqrt{4D_2t}}{\sqrt{4D_1t_1}}$$

and the dimensionless parameter $\eta = (c_2-c_0)/(c_1-c_0)$, which enables us to present the results in the dimensionless form

$$\vartheta = \frac{c(x,\ t)-c_0}{c_1-c_0} = f(\bar{x},\ \bar{\tau},\ \eta).$$

Calculations performed with a Minsk-22 computer enabled us to construct nomograms for the carbon concentration as a function of η (Fig. 2). The base quantity ($\sqrt{4D_1t_1}$) can be found by processing the $c = c(x, 0)$ experimental data via (2) or from the depth δ of the decarburized layer, which is determined as in [1] via the distance from the surface corresponding to a carbon concentration of $0.9c_1$:

$$\Phi\left(\frac{\delta}{\sqrt{4D_1t_1}}\right) = \frac{0.9c_1-c_0}{c_1-c_0}. \tag{6}$$

The argument $\delta/\sqrt{4D_1t_1}$ is found from tables of the error integral [3].

Calculations of the carburization via these nomograms amounts to determining $\bar{\tau}$ as corresponding to the required distribution pattern; the processing time t is found from $\bar{\tau}$ in accordance with

$$t = \frac{\bar{\tau}^2(4D_1t_1)}{4D_2}, \tag{7}$$

while the dimensional coordinates of the points are found from the formula

$$x = \bar{x}\sqrt{4D_1t_1}. \tag{8}$$

On the whole, the concentration distribution $c = c(x, t)$ is found from the nomograms as above by converting the dimensionless variables, ϑ, $\bar{\tau}$, and $\bar{x}$ as well as the parameter η to dimensional quantities in accordance with (5), (7), and (8).

Curves 3 and 4 of Fig. 1 compare the calculations by the above method with the results of [1] for ShKh-15 steel treated for 3 and 6 h respectively; Fig. 1 shows that calculations by the method of [1] give somewhat higher values. It was assumed in solving the problem [1] that the steel during carburization was in the γ state.

NOTATION

c_0, c_1, and c_2	are the % carbon at surface of decarburized metal, in bulk, and during carburization, respectively;
D_1 and D_2	are the diffusion coefficients (m^2/sec) for carbon during decarburization and carburization;
α	is the experimental factor (m^{-1});
t_1 and t	are the carburization and carburization times;
δ	is the depth (m) of decarburized layer;
x	is the coordinate reckoned from the surface into the metal.

LITERATURE CITED

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