EFFECT OF PRESSURE ON QUENCHING OF STEEL

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The development of new methods of controlling the thermal conditions in the process of quenching steel machine parts is of practical interest, since it is possible to control phase transformations and thus create conditions for obtaining high-strength parts with minimal distortion after heat treatment. It was experimentally shown in [1] that by changing the pressure one can control the surface temperature of the part being quenched, reducing the distortion and the probability of fracture during quenching.

In this work a computer was used for detailed analysis of the effect of pressure on the distribution of temperature fields in plates, cylinders, and spheres. For this purpose, the transient problem of thermal conductivity was solved by numerical calculation.

We used the nonlinear equation of thermal conductivity*

$$\text{div} \left[ \lambda(T) \text{grad} T \right] - c_p \frac{\partial T}{\partial t} = 0$$

with nonlinear boundary conditions in the region of nucleate boiling

$$\left[ \frac{\partial T}{\partial x} + \frac{\rho^*}{\lambda} (T - T_s)^3 \right]_{x=L} = 0$$

and standard boundary conditions of third order in the region of convective heat exchange:

$$\left[ \frac{\partial T}{\partial x} + \frac{a}{\lambda} (T - T_c) \right]_{x=L} = 0,$$

where $T_c < T_s$.

The initial temperature distribution in the body is given in the form of the equation

$$T(x, 0) = \varphi(x).$$

The surface temperature $T_{\text{surf}}$ at which the change from nucleate to convective heat exchange occurs is determined from the equality of the heat flows according to boundary conditions (1) and (2):

$$T_{\text{surf}} = \frac{1}{\beta} \sqrt{2 (T_{\text{surf}} - T_c)} + T_{\nu}$$

where

$$\beta = \frac{75 \lambda \rho \beta_5 \rho_5^{0.5}}{\sigma \left( r \rho^* \beta_5 \right)^{0.7} P_k^{0.2}}; \quad Pr = v \alpha.$$

*The following notations are used: $L$, half the thickness of the plate or radius of the cylinder or sphere; $\lambda_{\text{liq}}$, thermal conductivity of the liquid; $\rho^*$ and $\rho^*$, density of the liquid and the vapor; $a$, thermal diffusivity coefficient; $g$, acceleration of free-fall; $\sigma$, surface tension; $\tau$, specific heat of vaporization; $\nu$, coefficient of kinematic viscosity; $\beta_5$, rate of growth of vapor bubbles; $T_s$, temperature of saturation; $T_c$, temperature of the cooling medium; $a$, coefficient of heat transfer with convective heat exchange; $T_c$, nucleate boiling time; $T_{\text{surf}}$, temperature in the center of the body at the end of nucleate boiling; $T_{\text{nucl}}$, nucleate boiling time; $T_{300}$, cooling time to cool the center of the body from 850 to 300°C; $B_i$, generalized Biot criterion; $K$, G. M. Kondrat'ev's shape factor; $q_{\text{cr}}$, critical density of the heat flow.
TABLE 1

<table>
<thead>
<tr>
<th>Pressure, bars</th>
<th>$T_o$ $^\circ$C</th>
<th>$T_s$ $^\circ$C</th>
<th>$w^*$ m/sec</th>
<th>$Pr$</th>
<th>$r$, W/kg</th>
<th>$\sigma$, N/m</th>
<th>$\rho^*$ kg/m$^3$</th>
<th>$\rho'^*$ kg/m$^3$</th>
<th>$\lambda_{lq}$ W/m-deg</th>
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<td>0.007</td>
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<tr>
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<td>212</td>
<td>-</td>
<td>0.92</td>
<td>1889</td>
<td>0.0050</td>
<td>9.99</td>
<td>0.050</td>
<td>0.55</td>
</tr>
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</table>

Fig. 1. Effect of the shape of the body on nucleate boiling time and the distribution of temperature fields in the process of quenching (2L = 20 mm). a) Plate; b) cylinder; c) sphere. I) Region of nucleate boiling; II) region of convective heat exchange. 1) x = L; 2) x = 0.5L; 3) x = 0.

Fig. 2. Effect of the diameter of a cylinder on nucleate boiling time and distribution of temperature fields in the process of quenching. a) Diameter 60 mm; b) 300 mm; c) 1000 mm. 1, 2, 3 and I, II the same as in Fig. 1.

The values of the physical properties of the liquid at saturation temperature $T_s$ (Table 1) are used in formula (3).

The coefficient of heat transfer $a$ and the growth rate of vapor bubbles were determined from known relationships [2, 3]. The thermal conductivity $\lambda$ and the thermal diffusivity $a$ of steel 12Kh18N9T were calculated from their linear variations with temperature.

The calculations were made by means of the M-220 computer by the distinct finite-difference method. The temperature fields were calculated for plates, cylinders, and spheres of different thicknesses and diameters (10-2000 mm) at pressures up to 20 bars. Figure 1 shows the effect of the shape of the body on the character of the change in temperature within the body and on the surface. The change from nucleate boiling to single-phase convective heat exchange is shown by the dashed lines in Fig. 1. The cooling time during quenching depends to a considerable extent on the shape of the body (Fig. 1). The change from nucleate boiling to convective heat exchange occurs at lower temperature gradients in the plate and at higher temperature gradients in the sphere. With increasing size of the sample the change in the conditions of heat exchange occurs at higher temperature gradients (Fig. 2). The results of calculating the nucleate boiling time $\tau_{nu}$ and the cooling time from 850 to 300$^\circ$C ($\tau_{300}$) in the center of the body are given in Table 2. With increasing size of the