Explicit Finite Difference Method used in Determination of the Surface Heat-transfer Coefficients of 60Si2Mn Steel during Gas Quenching

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Abstrac:-The surface heat-transfer coefficients of 60Si2Mn quenched by Nitrogen gas are calculated by nonlinear estimate method, explicit finite difference method and the experimental date. The relations between surface heat-transfer coefficient in 88m/s and surface temperature of steel cylinders are given. Based on the solved surface heat-transfer coefficients, the temperature field is obtained by solving heat conduction. In calculation, the thermal physical properties of material are treated as the functions of temperature. The results of calculation coincide with the results of experiment.

Keywords—gas quenching; surface heat-transfer coefficient; inverse problem of heat conduction；finite difference method;

I. INTRODUCTION

Heat treatment is a process of heating and cooling a solid metal to obtain the desired properties. After undergoing the quenching process, the properties of metal and alloy such as surface hardness, strength, microstructure, service life, and mechanical properties etc., can be greatly improved. Treating metal and alloy with high velocity gas quenching is a kind of heat treatment technique that can improve the material properties by cooling the specimen down quickly. In order to find out the best quenching way to quench steel researches should be made on the technique of the high velocity gas quenching.

The surface heat-transfer coefficient is a key parameter in numerical simulation of quenching process. The explicit finite difference method, nonlinear estimate method and the experimental relation between temperature and time during quenching have been used to solve the inverse problem of heat conduction. The relationships between surface temperature and surface heat transfer coefficient of cylinder have been given. In calculation, physical properties were treated as the function of temperature and volume fraction of constituent. The results obtained have been shown that this technique can determine effectual the surface heat transfer coefficients during gas quenching.

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II. CALCULATION METHOD OF NON-LINEAR HEAT TRANSFER COEFFICIENTS

During gas quenching, the surface heat transfer coefficients have a great influence upon the microstructure and residual stresses in steel specimen. The results obtained are very sensitive to small variation in the experimental conditions, which may lead to considerable discrepancies in the value obtained. Therefore, it must be found necessary to determine the effect of temperature on the surface heat transfer coefficient while using the actual experimental conditions that were to use during the subsequent determination of thermal stress and strain. Prince & Fletcher [1] have an effectively method, which can determine the relationship between temperature and surface heat transfer coefficients during quenching of steel plate.

2．1 The Non-linear Heat Conduct Equation and Its Finite Difference Scheme

The specimen is a ϕ25mm×60mm cylinder of 60Si2Mn steel. For the axial symmetry specimen, the heat conduction equation in middle of specimen is

$$C_V \rho \frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{1}$$

where λ , C_V and ρ denote thermal conductivity, specific heat capacity and density of material respectively. C_V and λ are the functions of temperature. T , r and t denote temperature, radius and time. According to the finite difference discrete method of nonlinear heat conduct equation, the finite difference scheme of the nonlinear heat conduct equation can be given by

$$T_j^{i+1} = F \times T_j^i + G \times T_{j+1}^i + D \times T_{j-1}^i \tag{2}$$

in Eq. (2)

$$F = 1 - \frac{\Delta t}{[(C_v\rho)_j^i + \Delta H]\Delta r}\left(\frac{\lambda_{j+1}^i + \lambda_j^i}{2\Delta r} + \frac{\lambda_j^i + \lambda_{j-1}^i}{2r_j}\right) \tag{3}$$

$$G = \frac{\Delta t(\lambda_{j+1}^i + \lambda_j^i)}{2[(C_v\rho)_j^i + \Delta H]\Delta r}\left(\frac{1}{\Delta r} - \frac{1}{r_j}\right) \tag{4}$$

$$D = \frac{\Delta t(\lambda_j^i + \lambda_{j-1}^i)}{2[(C_v \rho)_j^i + \Delta H]\Delta r}(\frac{1}{\Delta r} + \frac{1}{r_j}) \quad (5)$$

$$\lambda_j^i = \sum_{k=1}^{4} \phi_k \lambda_k \quad (C_v \rho)_j^i = \sum_{k=1}^{4} \phi_k (C_v \rho)_k \quad (6)$$

where k=1 austenite, k=2 ferrite/pearlite, k=3 bainite, k=4 martensite, ϕ_k is the volume fraction of constituent, λ_j^i and $C_v \rho_j^i$ denote the thermal conductivity and specific heat capacity at j nodal in i time step respectively, Δr is the distance between the two inner nodal of the finite difference girding, Δt is the time step, rj is the radius of the j nodal, and ΔH is the latent heat of phase transformation.

The boundary condition is

$$\lambda \frac{\partial T}{\partial r}\bigg|_{\Gamma} = h(T_S - T_\infty) + C_V \rho \frac{\partial T}{\partial t} \quad (7)$$

h , T_S and T_∞ denote surface heat-transfer coefficient, specimen temperature of surface boundary and temperature of quenching media.

In order to solve the heat conduct equation with nonlinear surface heat transfer coefficient, the nonlinear estimate method is adopted, i.e. let a parameter

$$\varphi = \sum (T^{\exp} - T_{l+1}^{cal})^2 \quad (8)$$

to be minimized, we have

$$\frac{\partial \varphi}{\partial h} = (T^{\exp} - T_{l+1}^{cal}) \frac{\partial T_{l+1}^{cal}}{\partial h} = 0 \quad (9)$$

where T_{l+1}^{cal} is $l+1$the iterative value of temperature,$T^{\exp}$ is the measured temperature. T_{l+1}^{cal} can be written as Taylor polynomial

$$T_{l+1}^{cal} = T_l^{cal} + \frac{\partial T}{\partial h}\Delta h \quad (10)$$

With the help of Equation 16, Equation 17 and the convection condition on boundary, an incremental surface heat transfer coefficient Δh can be expressed in the following form:

$$\Delta h = \xi \frac{\lambda}{T_s - T_\infty} \frac{T^{cal} - T^{\exp}}{\Delta r} \quad (11)$$

If the nodal of finite difference don't pace on the position of thermocouple, it is necessary to obtain a predicted value of temperature at the thermocouple position by interpolation between the appropriate nodal temperatures.

2.2 Calculating Procedure

The thermal properties (λ , $C_V \rho$) at various node were calculated by using the linear interpolation method according to Table 1. After an estimate value h_0 of surface heat-transfer coefficient was given, the heat conduction equation (4) can be solved and the computation temperature values at node are obtained. If $\left|T_l^{cal} - T^{\exp}\right| > \delta$, a new value of h ($h = h_0 + \Delta h$) will be chosen. T_{l+1}^{cal} is repeated until $\left|T_l^{cal} - T^{\exp}\right| \le \delta$, in which δ is an inherent error. In this way, the changes of surface heat-transfer coefficient in temperature and the temperature field are obtained. In the calculation, time interval is automatically obtained. According to the stability of explicit finite difference scheme, the maximum Δt is chosen as the time interval during calculation.

$$\Delta t \le \frac{2\Delta r C_V \rho}{\frac{\lambda_{j+1} + 2\lambda_j + \lambda_{j-1}}{\Delta r} - \frac{\lambda_{j+1} - \lambda_{j-1}}{r_j}} \quad (12)$$

Table 1: The thermal properties of 60Si2Mn steel in different temperatures.

Temperature/℃	20	200	300	400	500	600	700	800
λ /W·(m·K)-1	28.717	29.308	30.145	30.982	30.145	28.899	27.633	24.402
C/J·(kg·K)-1	453	528	544	599	641	749	871	637

III. EXPERIMENT

The experimental investigations were carried out using cylinder specimen made out of the Steel 60Si2Mn containing 0.60 wt.-% of carbon, 2.0 wt.-% of silicon, 0.35 wt.-% of chromium and 0.6 wt.-% of manganese. The specimen is a cylinder of 60Si2Mn steel which dimension is φ25mm×60mm. After austenized for 25 minutes, the specimens were quenched by high speed Nitrogen gas which velocity is 88m/s. The change of temperature during quenching was measured by thermocouples. A computer recorded experimental data. The thermocouple 1 is placed 1mm distance from the cylinder surface of specimen, thermocouple 2 is on the axis of the cylinder. The temperature values measured by thermocouple 1 are key parameters for solving the nonlinear heat conduction equation. The temperature values measured by thermocouple 2 were used to examine the calculated results. The measured values of temperature are shown in Fig. 1.

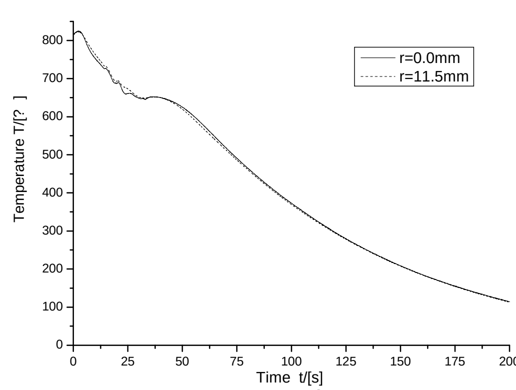

Figure 1: Experimental values of temperature.(88m/s)

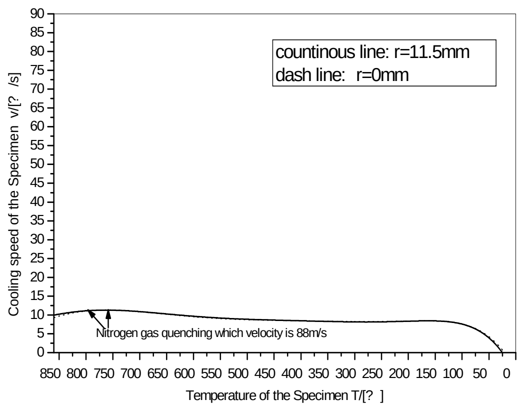

Figure 2: Average cooling speed of the specimen

IV. The Calculated results and Conclusions

The relations between surface heat-transfer coefficient and surface temperature are non-linear during high pressure gas quenching, as shown in figure 3. In the initial period during quenching, the increase of the surface heat-transfer coefficient is rapid. This shows that the exchange of the heat flux between the workpiece and quenching media is large. It is noted that at temperature of 650℃, there is a sudden change in the surface heat-transfer coefficient, because of martensite phase transformation in this temperature. After the end of martensite phase transformation, the change in the surface heat-transfer coefficient is small.

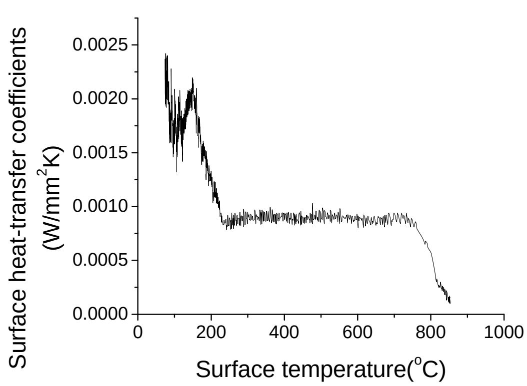

Figure3: The relationship between surface heat transfer coefficients and surface temperature

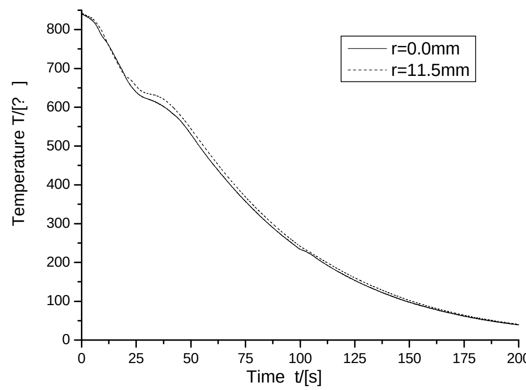

Figure4: The calculated temperature field.

The calculated result of temperature field is shown in figure 4. These five curves denote the change of temperature with time at the position of r = 0,11.5mm of the cylinder, respectively. In the calculation of temperature field, the non-linear relations between surface heat-transfer coefficient and surface temperature were taken into account.

From figure 1 and 4, the calculated values coincide with experimental values. It show that the surface heat-transfer coefficient obtained during the gas quenching can be used in simulation of temperature field during gas quenching.

Testing of cooling curves of work-pieces during nitrogen gas quenching process shows that the temperature difference of interior work-piece is small. It can be predicted that cooling of the interior work-piece is almost homogeneous and corresponding thermal strains and thermal stresses are rather small.

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