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Calculation of Thermal Stress Field with Non-Linear Surface Heat-Transfer Coefficient during Quenching

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The thermal physical properties were treated as a functions of temperature. On the basis of non-linear surface heat-transfer coefficient by Ref. [2], the temperature field with non-linear surface heat-transfer coefficients was calculated using finite element technique. The experimental results of temperature field coincide with numeral solutions. Finally, the thermal stress was calculated by means of finite element method.

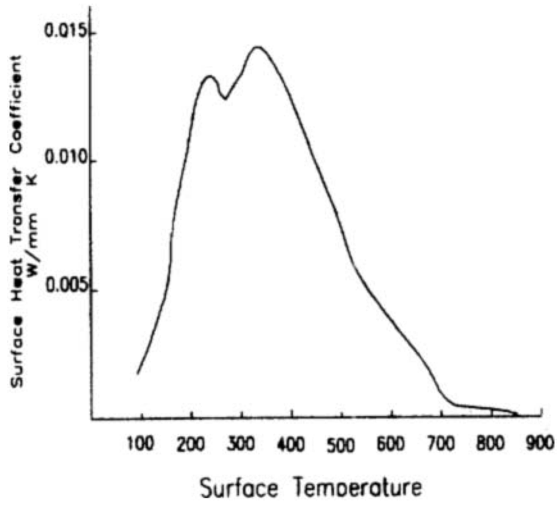
Key words : quenching, thermal stress, finite element method

1. INTRODUCTION

It is well known that the quenching technique can improve the mechanical properties of metallic materials. For this reason, the calculation of the temperature field and thermal stress during quenching has been the subject in many investigations. In past researches, the surface heat-transfer coefficients were usually treated as constants. In the fact, the surface heat-transfer coefficients are non-linear functions of temperature and volume fraction of phase constituents. The accuracy of thermal stress and residual stress during quenching is relatively dependent of the computing accuracy of temperature. The surface heat-transfer coefficients were regarded first as a linear function of temperature by Majorek [1]. This method may improve greatly the computing accuracy of temperature during quenching. CHENG [2] determined the non-linear surface heat-transfer coefficients by the numerical method and the experimental relationships between time and temperature. The specimen selected was a cylinder of 42CrMo steel. In this paper, the temperature field with non-linear surface heat-transfer coefficients was calculated using the finite element technique. The experimental results of the temperature field coincide with numeral solutions. Finally, the thermal stress was calculated by means of the finite element method.

2. SURFACE HEAT-TRANSFER COEFFICIENTS DURING QUENCHING

During quenching, the surface heat transfer coefficients have a great influence upon the microstructure and residual stresses in steel specimen. The variation of this property with temperature has been the subject of investigations. 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 necessary to determine the effect of temperature on the surface heat transfer coefficient while using the actual experimental conditions that were to be used during the subsequent determination of thermal stress and strain. Prince & Fletcher (1980) [4] have an effectively method, which can determine the relationship between temperature and surface heat transfer coefficient during quenching of steel plate. In the Ref. [2], the non-linear estimate method, finite difference method and experimental relationships between temperature and time in quenching were used to determine the surface heat transfer coefficient. The obtained results showed that this technique has good convergence and can determine the effect of surface temperature on the magnitude of surface heat transfer coefficient in various quenching media. The relationship between surface temperature and surface heat transfer coefficient was shown in Fig. 1. The relationship between time and temperature obtained by the thermocouples is shown in Fig. 2. From the Fig. 1, the following conclusions can be obtained: (1) In the initial period during quenching, cooling is slow, at this time, vapor film is formed in the surface of body. Because the thermal resistance of vapor film is larger, the heat conductivity is very poor, the exchange of the heat flux between the workpiece and quenching media is small, and the sur-



Fg. 1. The relation between surface temperature and surface heat-transfer coefficients.

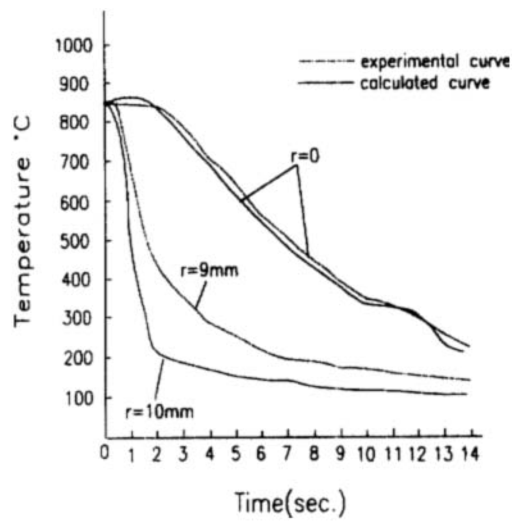


Fig. 2. The comparison between experimental temperature and calculated curve.

face heat-transfer coefficient is very small. (2) With increasing quenching time, the vapor film is cracked progressively. From the relationship between surface temperature and surface heat transfer coefficient, the cooling rate increased rapidly. The exchange of heat flux between the workpiece and quenching media also rapidly increase. Therefore, the surface heat-transfer coefficients increase progressively, when the vapor film is cracked completely, and the maximum value is obtained during the nucleate boiling stage within the range 200°C~520°C. The maximum value of surface heat-transfer coefficient is 0.0156 W/mm^3K, which coincides with experimental value 0.015 W/mm^3K. (3) It is noted that at temperatures of 200°C~350°C, there is a sudden change in the surface heat-transfer, because of martensite phase transformation in this range of temperature.

3. FUNCTIONAL AND FINITE ELEMENT FORMULA

The specimen selected was $\phi 20\times 60$ mm cylinder of 42CrMo steel and was quenched into 20°C still water from a temperature of 850°C. The change of temperature during quenching was measured by thermocouples, and experimental data were recorded by computer. The non-linear heat conduct equation is

$$\lambda\frac{\partial^2 T}{\partial z^2}+\lambda\frac{\partial^2 T}{\partial r^2}+\lambda\frac{1}{r}\frac{\partial T}{\partial r}=\rho C_\rho\frac{\partial T}{\partial t} \tag{1}$$

where C_v and λ denote specific heat capacity and thermal conductivity, which are a function of temperature. Eq. 1 is a non-linear equation. The boundary condition of heat transfer is

$$\left|\frac{\partial T}{\partial n}\right|_A = h(T)(T_a - T_\infty) \tag{2}$$

where h(T) is the surface heat-transfer coefficient, which is a the function of temperature, and was determined by finite difference method, non-linear estimate method and the experimental relationship between time and temperature [2]. T_a and T_∞ denotes the surface temperature of cylinder of 42CrMo steel and the temperature of quenching media. The functional of the above problem is

$$K_n = -\int_{t_{n-1}}^{t_n}\int_\Omega\left\{\frac{\lambda}{2}\left[\left(\frac{\partial T}{\partial r}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right]+C_\rho TT\right\}d\Omega dt$$
$$+\int_{t_{n-1}}^{t_n}\int_\gamma h(T_{n-1})\left(\frac{T^2}{2}-T_\infty - T\right)dsdt \tag{3}$$

where $h(T_{n-1})$ is the surface heat-transfer coefficients at t_{n-1}, {T} is fix in variational operation [3]. If the 8 nodes iso-parameter element was adopted, the finite element formula can be obtained

$$[C]\{\dot{T}\}+[S]\{T\}=\{\dot{Q}\} \tag{4}$$

in which [C] and [S] are the consistency matrix and the conductivity matrix, respectively. {Q} is the rate of heat supply vector due to heat convection across the boundaries. The comparison between the calculated values and experimental values is shown in Fig. 2. The calculated values coincide with the experimental values.

4. FINITE ELEMENT FORMULATION FOR THERMAL STRESS

Because the plastic strain rate is higher during quenching, classical mechanical constitutive relation which is independent of strain rate isn't advisable. In the numerical calculation, mechanical constitutive relation which is dependent of strain rate was adopted, and the thermal elasto-viscoplastic model [5] is

$$\dot{\varepsilon}_{ij}^{p} = \frac{3}{2}\dot{\varepsilon}_0\left(\frac{\tau}{D}\right)^n\left(\frac{S_{ij}-B_{ij}}{\tau}\right)$$

$$\text{with } B_{ij} = -b_2\dot{\varepsilon}_{ij}^{p}B_{ij} - b_1\dot{\varepsilon}_{ij}^{p}\left(\frac{\tau}{D}\right) \quad (5)$$

$$\text{and } D = -d_2\dot{\varepsilon}_0 D + d_1\dot{\varepsilon}_0$$

where the material parameters can be found in the Ref. [5]. The equilibrium equation is

$$\sigma_{ij\cdot j} = \{D_{ijlm}[\varepsilon_{lm} - \varepsilon_{lm}^{p} - \alpha\delta_{lm}(T - T_D)]\}_{ij} \quad (6)$$

Application of Galerkin finite element method to the rate form of Eq. 5 and Eq. 6, if the 8 nodes isoparameter element was adopted, gives the following finite element formula.

$$[K]\{\dot{u}\} = \{\dot{F}^b\} + \{\dot{F}^p\} + \{\dot{F}^{th}\} = \{\dot{F}\} \quad (7)$$

in which [K] is the stiffness matrix, $\{\dot{F}^b\}$ is a boundary traction nodal force vector, $\{\dot{F}^p\}$ is a nodal force vector that accounts for inelastic effect, and $\{\dot{F}^{th}\}$ is a nodal force vector that accounts for thermal strains.

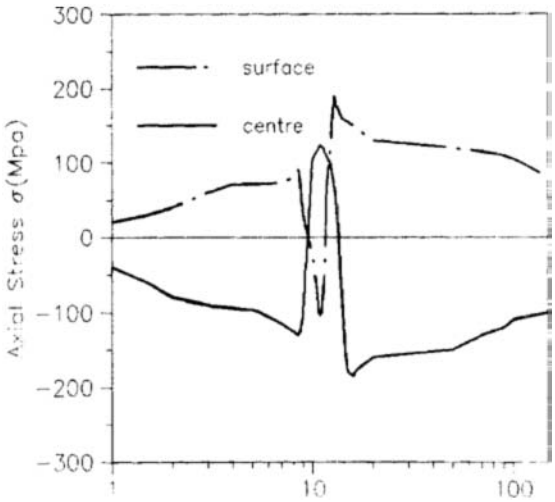


Fig. 3. The surface and center axial stresses in the meddle plane of the cylinder during quenching.

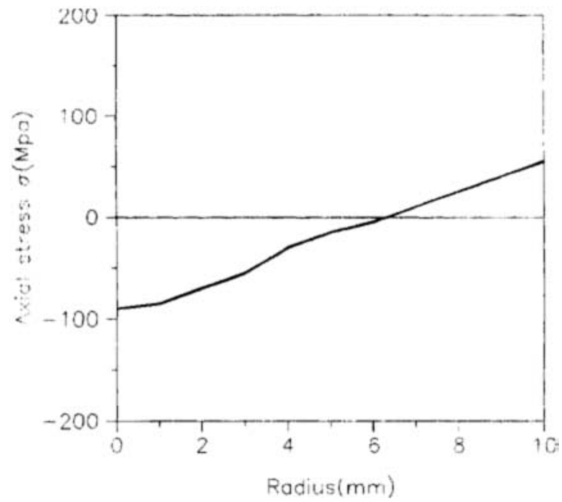


Fig. 4. The axial residual stress in the meddle plane of the cylinder after quenching.

5. THE CALCULATED RESULTS

The specimen selected was $\phi 20\times 60$ mm cylinder of the 42CrMo steel and was quenched into 20°C still water from a temperature of 850°C. The surface and center axial stresses in the middle plane of the cylinder during quenching were shown as in the Fig. 3. The axial residual stresses in the middle plane of the cylinder after quenching. The following conclusions can be obtained from Figs. 2~4.

1. At the axis (at the r=0), the temperature calculated with the non-linear surface heat-transfer coefficients is in good agreement with the experimental values. During quenching it is necessary to consider the non-linear effect for the surface heat-transfer coefficients when the temperature field is calculated.

2. In the rapid cooling, the mechanism of the heat exchange for boiling has not yet been clear and the measuring technique of the surface heat-transfer coefficients is not perfect. The technique in Ref.[2], in which numerical calculation and the measuring method of temperature field are simple and stable, can determined effectively the variation of the surface heat-transfer coefficients with temperature, and is easy to be realized in the engineering application.

3. In calculation of the thermal stress during quenching, the classical mechanical constitutive relation which is independent of strain rate isn't advisable. The mechanical constitutive relation which is dependent of strain rate should be adopted, especially in the nucleate boiling stage.

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