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Calculation of the coupled thermal stress of a cylinder with non-linear surface heat-transfer coefficient and phase transformation during the quenching with various quenching media

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Abstract:-The coupled temperature and stress fields with phase transformation were calculated using finite element technique during the quenching with various quenching medium, which are water and nitrogen gas at atmosphere pressure with various gas velocities. From the TTT diagram of the 45 steel, the CCT diagram was simulated and the volume fraction of phase constituent in continuous cooling was calculated. The thermal physical and mechanical properties were treated as the functions of temperature and the volume fraction of phase constituents. The obtained results show that: (1) The thermal stresses during water quenching are greatly larger than that during the gas quenching; (2). During gas quenching, the higher gas velocities are, the larger magnitudes of thermal stresses, meanwhile, the higher gas velocities are, the better hardness-ability is. Taking gas as quenching medium, such as nitrogen, the thermal stresses and hardness-ability can be controlled; (3). The inelastic-coupled effect should be considered during quenching.

Keywords: phase transformation, finite element method, coupled problem, quenching, non-linear surface heat-transfer coefficient

1 Introduction

By the quenching technique, there are many couple phenomenon, such as the couple effect between thermal stress and phase transformation, that between temperature and phase transformation. These couple phenomenon have great influence on residual stresses and micro-structure of materials after quenching. For this reason, the calculations of the temperature field and thermal stress during quenching have been the subject in many investigations.

In order to obtain the distribution of residual stresses and perfect mechanical properties, it is necessary to control phase transformation, thermal stresses and limit distortions. Up to now, thermal strains and thermal stresses can't be measured. Numerical simulation technology is an effective approach to understand the distribution and variety of thermal strains, thermal stresses and microstructure. In recent years, the numerical simulation of quenching processing in various quenching media is prevailing in the world. Although there are now some special soft-wares, which can simulate quenching processing, namely DEFORM-2, DEFORM-3, the important problem in numerical simulation is the boundary condition of stress and temperature. The calculating accuracy of thermal stresses and strains is closely related to the calculating precision of temperature field. In the numerical simulation, one of the key parameters of the calculation of temperature is the surface heat-transfer coefficient. In past researches, the surface heat-transfer coefficients were usually treated as constants. In the fact, the surface heat-transfer coefficients are the non-linear functions of temperature and volume fraction of phase constituents. 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 and thermal stresses during quenching.

The selected specimen was the cylinder of 45 steel. On the basis of non-linear surface heat-transfer coefficient in Ref.[2] and Ref.[3], the coupled temperature and stress field with phase transformation was calculated using finite element technique during the quenching with various quenching medium, which are water and nitrogen gas at atmosphere pressure with various gas velocities. From the TTT diagram of the 45 steel, the CCT diagram was simulated and the volume fraction of phase constituent in continuous cooling was calculated. The thermal physical and mechanical properties were treated as the functions of temperature and the volume fraction of phase constituents.

2 Surface heat-transfer coefficients

During 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

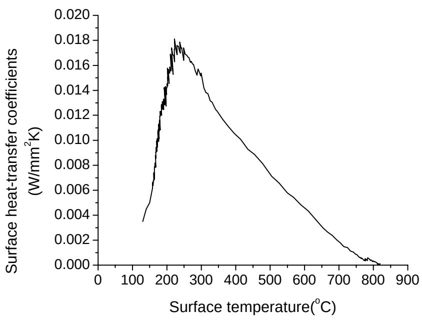


Fig.1 The surface heat-transfer coefficients during water quenching

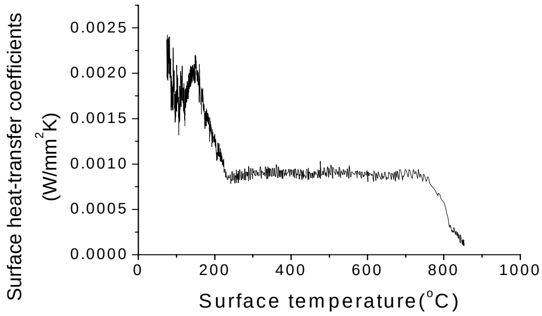


Fig.2 The surface heat-transfer coefficients during nitrogen gas quenching

experimental conditions that were to use 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] and Ref.[3], 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 were shown 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 relationships between surface temperature and surface heat-transfer coefficient are shown in Fig.1 and Fig.2.

3 Mathematical mode of continuous cooling

In the past, a number of studies have dealt with prediction of microstructure evolution of steel during cooling. Usually, the temperature-time curve is discretized in series of isothermal steps. On each step the volume fraction of new phase formed is calculated by using isothermal kinetics. The isothermal transformation kinetics of ferrite/pearlite and bainite is modeled according to the law developed by Johnson-Mehl[1]

$$\phi_k = 1 - \exp(-bt^n) \tag{1}$$

in which b and n can be determined by the experimental data of isothermal phase transformation.

k =1 ferrite/pearlite, k =2 bainite. From the Eq.(1), $\phi_i(i=1,2)$ is the function of temperature and time. According to Reference [1,2,3] b and n was approximated by polynomials, i.e.

$$\lg b = C_{0k} + C_{1k}T + C_{2k}T^2 + C_{3k}T^3 \qquad (2)$$
$$n = D_{0i} + D_{1i}T + D_{2i}T^2 + D_{3i}T^3$$

The constants C_{jk} and D_{jk} were determined by the TTT diagram of 45 steel and minimum quadrate method, and were listed in table 1.

Table 1 The constants in Eqn.(2)

	C_{0k}	C_{1k}	C_{2k}	C_{3k}
$k=1$	-0.3283×10^{2}	0.1520	-0.02348	1.200×10^{-6}
$k=2$	-6.358	0.01854	0.222×10^{-4}	0.0
	D_{0k}	D_{1k}	D_{2k}	D_{3k}
$k=1$	0.1472×10^{2}	-6.256	0.9245×10^{-3}	-0.4691×10^{-6}
$k=2$	-21.93	0.1102	-0.1216×10^{-3}	0.0

In order to calculate volume fraction of constituent during continuous cooling by means of Eq.(1), we adopted the technique developed by Ivan Tzitzelkov[5], i.e., the temperature-time curve is discretized in series of isothermal steps. On each step the volume fraction of new phase formed is calculated by using isothermal kinetics. The time transformation τ^* of each step should be

$$\tau^* = \left[\frac{\lg(1-\phi_m)}{-bT_{m+1}}\right]^{\frac{1}{nT_{m+1}}} \qquad (3)$$

Therefore, Eq.(1) becomes

$$\phi_k = 1 - \mathbf{exp}[-b(\Delta t + \tau^*)^n] \qquad (4)$$

For the volume fraction of the constituent in martensite, we calculate it by means of following formula[1]:

$$\phi_M = (1-\phi_1-\phi_2)[1-(\frac{T-M_f}{M_s-T})^{2.5}] \qquad (5)$$

where M_s and M_f denote initial temperature and final temperature of martensite phase transformation.

4 The Finite Element Formula of coupled Problem

The specimen selected $\phi 20\times 60$ mm cylinder of 45 steel and was quenched into still water 20℃ or by nitrogen gas with various velocities from a temperature of 850 ℃. The non-linear heat conduct equation is

$$\lambda\frac{\partial^2 T}{\partial z^2} + \lambda\frac{\partial^2 T}{\partial r^2} + \lambda\frac{1}{r}\frac{\partial T}{\partial r} + Q^{-1}\sigma_{ij}\dot{\varepsilon}_{ij} = \rho C_\rho\frac{\partial T}{\partial t} \qquad (6)$$

where $Q^{-1}\sigma_{ij}\dot{\varepsilon}_{ij}$ is the damp of the inelastic deformation to thermal wave, in which Q^{-1} is the inner dissipation of metal[11] , C_v and λ denote specific heat capacity and thermal conductivity, which are the function of temperature and the volume fraction of phase constituents, that is

$$\lambda = \sum_{k=1}^{4}\lambda_k\phi_k \quad C_v\rho = \sum_{k=1}^{4}(C_v\rho)_k\phi_k \qquad (7)$$

The boundary condition of heat transfer is

$$\left.\frac{\partial T}{\partial n}\right|_{\Gamma} = h(T)(T_a - T_\infty) \qquad (8)$$

here $h(T)$ is the surface heat-transfer coefficients, which are the functions of temperature, and was determined from Fig.1.[2,3], T_a and T_∞ denote the surface temperature of a cylinder and the temperature of quenching media. Because the plastic strain rate is higher during the quenching, in the numerical calculation mechanical constitutive relation with dependent of strain rate was adopted, the thermal elasto-viscoplastic model [7,8] is

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

$$B_{ij} = -b_2 \dot{\varepsilon}^p_{ij} B_{ij} - b_1 \dot{\varepsilon}^p_{ij} \left(\frac{\tau}{D}\right) \qquad (9)$$

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

where the material parameters can be found in the Ref.[7,8]. The elastic properties E and μ are the function of temperature and the volume fraction of phase constituents[6], that is

$$E = \sum_{k=1}^{4} E_k \phi_k \quad \mu = \sum_{k=1}^{4} \mu_k \phi_k \qquad (10)$$

The equilibrium equation is

$$\sigma_{ij,j} = \left\{ D_{ijlm} \left[\varepsilon_{lm} - \varepsilon^p_{lm} - \alpha \delta_{lm}(T-T_0) \right] \right\}_{,j} \qquad (11)$$

Application of the Galerkin finite element method to the rate form of Eq.(6) ~Eq.(11), if the 8 nodes iso-parameter element was adopted, the finite element formula can be obtained

$$[K]\{\dot{u}\} = \{\dot{F}^b\} + \{\dot{F}^p\} + \{\dot{F}^{th}\} = \{\dot{F}\} \qquad (12)$$

$$[C]\{\dot{T}\} + [S]\{T\} = \{\dot{Q}^p\} + \{\dot{Q}^s\} = \{\dot{Q}\} \qquad (13)$$

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, $\{\dot{F}^{th}\}$ is a nodal force vector that accounts for thermal strain. $[C]$ and $[S]$ is the consistency matrix and the conductivity matrix, respectively. $\{\dot{Q}^p\}$, $\{\dot{Q}^s\}$ is the rate of heat supply vector due to the heat convection across the boundaries and the inelastic effect.

5 Calculated Results

Table 2 the thermal physical properties in various phase are listed in Table 2 . [6]

T in	20	200	250	300	350	450	500	700	900	phase
$C_v\rho$	4.1	4.3					4.58	4.75	4.9	A
	3.78	4.23					4.87	5.31	5.74	F/P
$(10^{-3} Ws/mm^3K)$	3.78	4.23		4.46		4.87		5.31		B
	3.76	4.22	4.34	4.45	4.55					M
λ	1.5	1.7					2.1	2.3	2.5	A
	4.9	4.4					3.7	3.2	2.7	F/P
$(10^{-2} W/mmK)$	4.9	4.4		4.2		3.8		3.4		B
	4.3	3.9	3.8	3.7	3.6					M
E	2.00	1.88		1.81			1.63	1.44	1.2	A
	2.10	1.98		1.91			1.74	1.44	1.05	F/P
$(10^9 N/mm^2)$	2.10	1.98		1.91			1.74	1.44		B
	2.10	1.98	1.96	1.91	4.55	1.83	1.74			M
ν	0.29	0.303		0.309			0.323	0.337	0.350	A
	0.28	0.293		0.300			0.306	0.317	0.330	F/P
	0.28	0.293		0.300			0.306	0.317		B
	0.28	0.293	0.297	0.300	0.303	0.305	0.306	0.317		M

Notes: A denotes austenite, F/P denotes ferrite/pearlite, B denotes bainite, M denotes martensite

For the 45 steel during gas quenching, the initial temperature and final temperature of ferrite/pearlite transformation is 735 and 470 , respectively; the initial temperature of bainite transformation is 570 ;

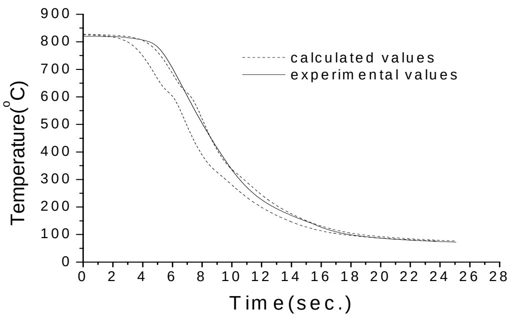


Fig.3 The comparison between experimental and calculated values of temperature during gas quenching

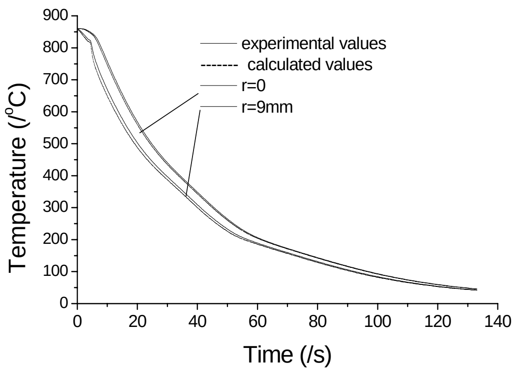


Fig4 Comparison between experimental and calculated values of temperature during water quenching

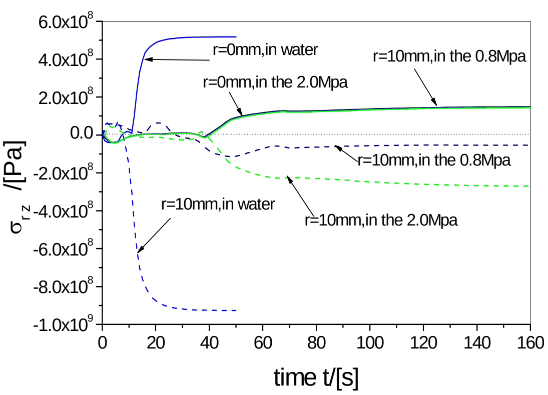
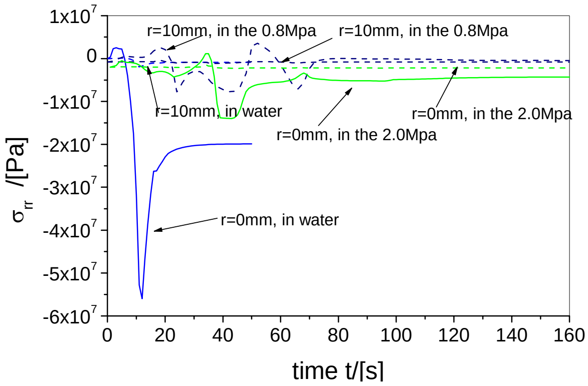


Fig.5The distribution of thermal stresses σ_{rz}

M_s=275 , and M_f=40 , $\Delta H_{\gamma-\alpha,100\%} = 0.628 Ws/mm^3$.



For the 45 steel during water quenching, the initial

Fig.6 The distribution of thermal stresses σ_{zz}

temperature and final temperature of ferrite/pearlite transformation is 735 and 470 , respectively; the initial temperature of bainite transformation is 570 ; M_s=340 , And M_f=200 .The thermal physical properties in various phases and the thermal mechanical properties are listed in Table 2.

Fig.3 and Fig.4 shows the comparison of temperature values between experimental and calculated values during gas quenching under 2.0Mpa nitrogen and water quenching, respectively. From the Fig.3 and Fig.4, the calculated values of temperature field are coincided with the experimental value.

The distributions of thermal stresses σ_{rz} on the surface and that in the center during 2.0Mpa , 0.8Mpa nitrogen and water quenching were shown in Fig.5. The various nitrogen velocities have not influence on the thermal stresses σ_{rz} in the center, and have greatly influence on that on the surface. The thermal stresses during water quenching are greatly larger than that during the gas quenching.

The variations of thermal stresses σ_{zz} during water quenching and gas quenching were shown in Fig.6. In the period of phase transformation, thermal stresses σ_{zz} in the center varied greatly, under the different gas velocities, its variation is different. The various nitrogen velocities have not influence on the thermal stresses σ_{zz} in the center, and have greatly influence on that on the surface. The thermal stresses during water quenching are also greatly larger than that during the gas quenching.

6 Conclusions

(1). The calculated results of the temperature and the comparison between the calculated values and experimental values were shown as Fig.3 and Fig.4. From the Fig.3 and Fig.4, the calculated values coincide with the experimental values coincided with experimental values. It is shown that during quenching it is necessary to consider the non-linear effect for the surface heat-transfer coefficients when temperature field was calculated.

(2). In the rapid cooling with gas water medium, the mechanism the heat exchange for boiling has not yet been clear and the measured technique of the surface heat-transfer coefficients is not perfect. The technique in Ref.[2] and Ref.[3], in which numerical calculation and the measured method of temperature field is simple and stable, can determined effectively the variation of the surface heat-transfer coefficients with temperature, and is easy to be realize in the application of engineering.

(3). In the period of phase transformation, the thermal stresses varied greatly.

(4). During gas quenching with various gas velocities, the higher gas velocities are, the larger magnitudes of thermal stresses, meanwhile, the higher gas velocities are, the better hardness-ability is. Taking gas as quenching medium, such as nitrogen, the thermal stresses and hardness-ability can be controlled.

(5). The thermal stresses during water quenching are greatly larger than that during the gas quenching.

(6). Obtained results have been shown that the inelastic-coupled effect should be considered during quenching.

Acknowledgment

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