Numerical Simulation on Temperature and Microstructure during Quenching Process of Large-sized AISI P20 Steel Die Blocks

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Abstract: In this paper, a model of coupled thermal and phase transformation is described. The temperature and microstructure during the quenching process for large-sized AISI P20 steel die blocks have been simulated using the finite element method (FEM). The optimum quenching technology of large-sized AISI P20 steel die blocks has been proposed based on the simulation results, which not only can effectively avoid quenching cracks and obtain deeper hardened depth, but also can improve the microstructure and properties of the large-sized die blocks.

Key Words: quenching technology, finite element method, AISI P20

QUENCHING has an important influence on the quality of workpieces. However, quenching is a complex process involving thermal, metallurgical and mechanical phenomena. The comprehensive effects during quenching are shown in Fig. 1. It is impossible to describe all these physical phenomena correctly and efficiently with analytical methods. Therefore, numerical simulation has been put on the agenda. With numerical simulation methods, the temperature field and the transformation behavior of austenite during continuous cooling can be calculated and the mechanical properties of workpieces can be predicted.

In recent years, a series of great progresses has been achieved in numerical simulation. The coupling between temperature-phase transformation-stress [1-3], three-dimensional non-linear FEM-based analyses [4-6], the calculation of phase transformation kinetics [7-9], the dealing with abrupt changes in boundary conditions [10-11] have been performed and their achievements have provided a sound basis for the application of numerical simulation methods in guiding manufacturing.

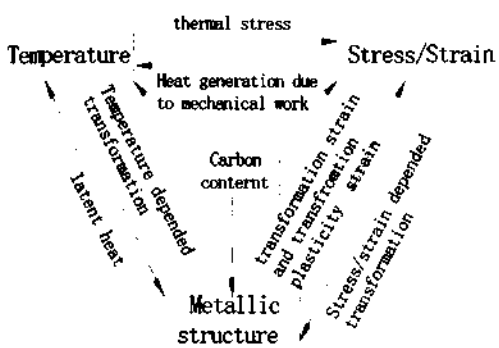


Fig.1 Coupling effects during quenching

In this paper, a model for the prediction of temperature and phase transformation as well as calculation methods of transient temperature and microstructure fields are described in detail. The application of this model and calculation methods is demonstrated for optimizing the quenching technology of forged large-sized AISI P20 steel Die blocks.

1. The Mathematical Model

1.1 Transient Temperature Field

The temperature distribution in a workpiece can be obtained from the solution of the commonly known Fourier equation with appropriate initial and boundary conditions. For a three-dimensional (3D) block, this equation can be written as:

$$\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z})+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

Its boundary condition and the initial condition can be expressed as:

$$-\lambda\frac{\partial T}{\partial n}=h(T_s-T_a) \tag{2}$$

$$T_{t=0}=T_0(x,y,z) \tag{3}$$

Where T is temperature, t is time, λ,ρ,c_p,q are the thermal conductivity, the mass density, the specific heat and the rate of latent heat, respectively. $\partial T/\partial n$ is the temperature gradient perpendicularly to the surface, T_s is the surface temperature, T_a is the ambient temperature and h is the heat transfer coefficient which is input as a function of temperature.

In the Fourier equation, λ, p and c_p depend on temperature and microstructure, as shown in Fig. 2.

$$\psi(T,\xi_k)=\sum\xi_k\psi_k(T) \tag{4}$$

where ψ represents λ, ρ, or c_p, and ξ_k is the volume fraction of constituent k and k represents constituent A (austenite), M (martensite), B (bainite), P (pearlite) or F (pre-eutectoid ferrite)

The increase in temperature due to latent heat is mentioned in the Fourier equation by the rate of latent heat $\dot{q}$. It is given by

$$\dot{q}=\Delta H_k\frac{d\xi_k}{dt} \tag{5}$$

where ΔH_k is the enthalpy of transformation from austenite into constituent k, shown in table 1, $d\xi_k$ is the volume fraction of the constituent k during time dt..

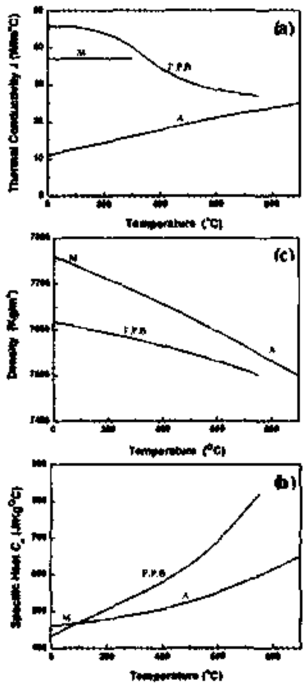


Fig.2 Material properties for AISI P20 steel

Table 1 The Enthalpy of Different Microstructural Constituents[3]

Constituent	F	P	B	M
ΔH ($\times 10^8 J/m^3$)	5.9	6.0	6.2	6.5

During air-cooling, the combined heat transfer coefficient includes radiation transfer coefficient (hr) and convective transfer coefficient (hc), that is

$$h_{air} = h_r + h_c \tag{6}$$

The radiation transfer coefficient, h_r, is represented by

$$h_r = \varepsilon\sigma(T_s^2 + T_a^2)(T_s + T_a) \tag{7}$$

where ε is the radiation emissivity of the surface, set as 0.6 in the paper. σ is the Stefan-Boltzmann constant with the value of $5.768\times10^{-8} W/(m^2K^4)$.

The empirical formula of convective transfer coefficient h_c in air-cooling is approximated as

$$h_c = 2.56\sqrt[4]{T_s - T_a} \tag{8}$$

During water quenching, the heat transfer coefficient as the function of the temperature is shown in Fig. 3.

1.2 Phase Transformation

The phase transformation during continuous cooling is usually predicted by applying an additivity rule to the measured isothermal transformation (IT) curve [12-13]. The IT curve of AISI P20 steel is shown in Fig. 4.

For diffusion-depended transformations (ferrite, pearlite and bainite), incubation and growth periods are treated separately. The incubation period is determined according to Scheil's method. The transformation during continuous cooling begins when the sum $\sum_i \left(\Delta t_i / \tau_i(T)\right)$ becomes equal to unity. $\tau_i(T)$ is the incubation time at temperature T, Δt_i is the time step. The volume fraction of the transformation is calculated according to Avrami equation: $f = 1 - \exp(-bt^n)$, where f is the volume fraction of the new phase, coefficients b and exponent n are determined for each temperature from the IT curve and t is time excluding incubation time.

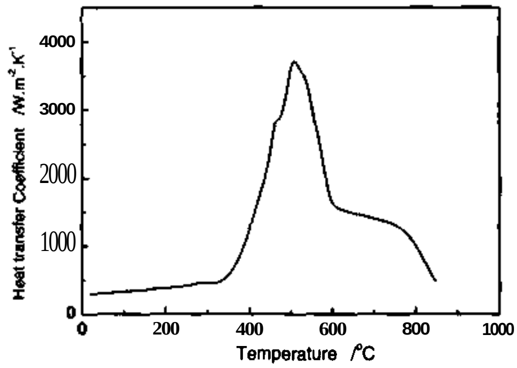


Fig.3 The heat transfer coefficient during water quenching

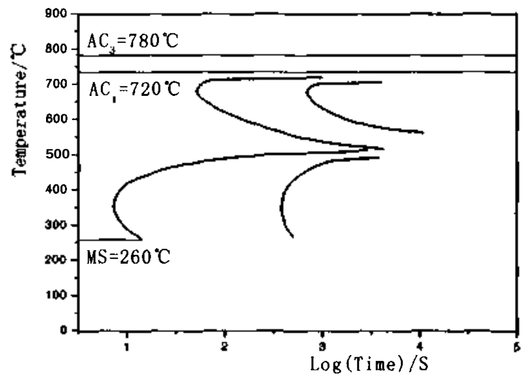


Fig.4 IT curve of AISI P20 steel (Austenitizing temperature: 860℃)

For martensitic transformation, the volume fraction is calculated by the established Koistinen-Marburger law: $f = 1 - \exp(-a(Ms - T))$, where M_s is the martensite transformation start temperature. a is constant and for the AISI P20 steel, α can be calculated from IT curve as 0.023.

2. Calculation Methods

2.1 Calculation of Transient Temperature Field

Based on the above transient temperature model, the finite element method (FEM) is used to calculate the transient temperature field of quenching. Due to the symmetry of the block, only the temperature field in one eighth of the block needs to be calculated. The grid spacing is smaller near the surface where the temperature gradient is high. The geometry and FE mesh of the block is shown in Fig. 5.

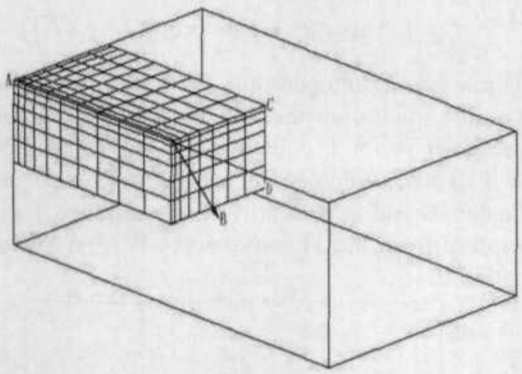


Fig.5 Geometry and FE mesh of the block

If the eight nodes isoparameter element is adopted in the block, the finite element equation can be obtained [14]:

$$[K]\{T\}+[C]\left\{\frac{\partial T}{\partial t}\right\}=\{F\} \quad (9)$$

The backward method was used to discretize the time domain, so the following equation can be obtained.

$$\left([K]+\frac{1}{\Delta t}[C]\right)\{T\}_t=\frac{1}{\Delta t}[C]\{T\}_{t-\Delta t}+\{F\} \quad (11)$$

Where [C] is the heat-capacity matrix, [K] is the conductivity matrix. {F} is the vector of internal heat generation.

Solving this equation step by step, the transient temperature field can be calculated.

2.2 **Calculation of Phase Transformation Field**

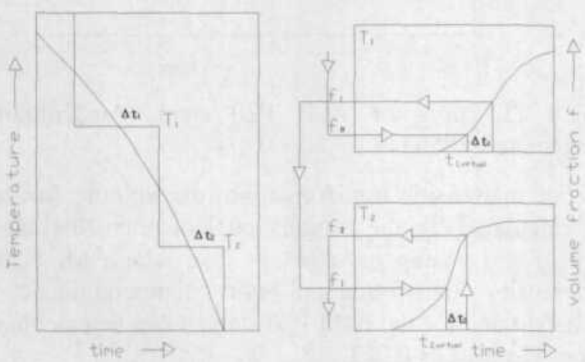


Fig.6 Calculation of transformed new phase during continuous cooling

In order to predict the transformation behavior of austenite during continuous cooling, a continuous time-temperature curve is divided into isothermal steps. Every isothermal step corresponds to an isothermal transformation at a constant temperature. The sequence of the iteration is explained in Fig. 6. If at temperature T_1 the volume fraction of the transformed new phase is f_1, then first according Johnson-Mehl-Avrami equation, the virtual time $t_{2,virtual}$ can be calculated.

$$t_{2,virtual}=[-\frac{\ln(1-f_1)}{b_1}]^{1/n_1} \quad (11)$$

Within $t_{2,virtual}$, the same volume fraction (f_1) would be transformed at temperature T_2. Then adding Δt_2 to $t_{2,virtual}$, the total transformed volume fraction of the new phase (f_2) at temperature T_2 can be obtained with Avrami equation.

$$f_2=1-\exp(-b_2(t_{2,virtual}+\Delta t_2)^{n_2}) \quad (12)$$

3. Results and Discussion

Shown in Fig. 4, AISI P20 steel has middle hardenability with the composition of 0.25~0.30% C, 0.15~0.25% Si, 0.50~0.70% Mn, ≤0.03% S, ≤0.03% P, 0.20~0.30% Cu, 1.20~1.50% Cr, 0.20~0.30% Ni and ~0.3%Mo. For large-sized AISI P20 die blocks, in order to obtain uniform hardness about 28-35 HRC in the same section within a maximum hardness difference of 3 HRC and the least amount of pre-eutectoid ferrite, a quenchant with high cooling ability should be adopted. And special attention should be paid to avoid quench cracks. Based on the quenching ability of different quenchants, such as oil, polymer quenchant (12% Feroquench), agitated water, and salt water, agitated water is chosen as the quenchant for large-sized AISI P20 die blocks in this paper. Though a large number of blocks in different sizes have been investigated, we only take one of them as an example, whose size is 1700mmX 1000mm×460 mm in this paper.

3.1 Direct Water Quenching

Firstly, direct water quenching technology, that is, completely austenitizing at 860 °C and cooling in agitated water to room temperature, is simulated. Fig. 7 is the calculated distribution of constituents along the height direction of the large-sized die block after direct water quenching.

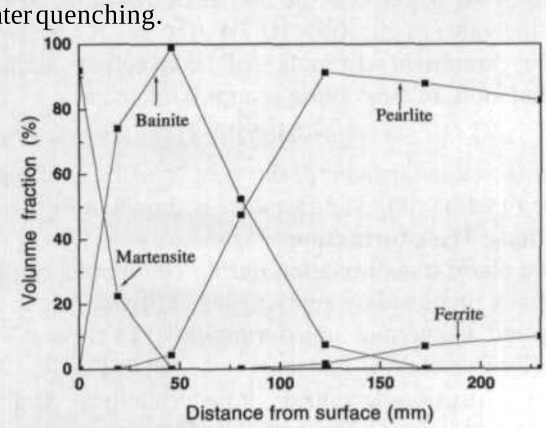


Fig.7 Calculated distribution of constituents along the height direction of the large-sized die block after direct water quenching

Shown in Fig. 7, pearlite appears at about 25mm and ferrite appears at about 100mm from the surface. The volume fraction of ferrite in the core is no more than 10%. Therefore, direct water quenching can make the large-sized block to obtain good microstructures to meet its hardness requirement.

However, the problems of direct water quenching is that quenching cracks always occur in actual production. Cracks usually initiate near the edges and surfaces of the die blocks, as shown in Fig. 8. The reason for cracking is that austenite has been transformed into martensite microstructure at these parts during quenching, as shown in Fig. 9. Therefore, a suitable quenching method should be investigated, further.

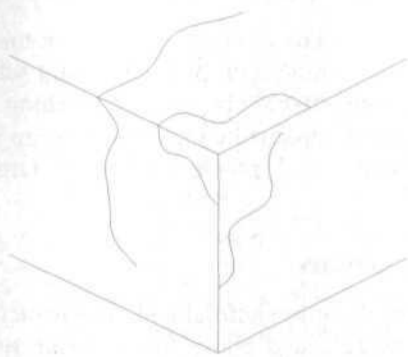


Fig.8 Illustration of quenching cracks of the large-sized die block

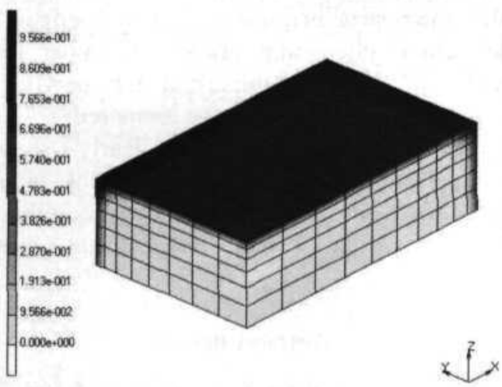
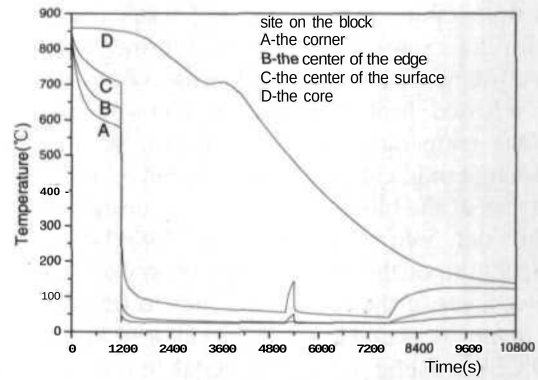


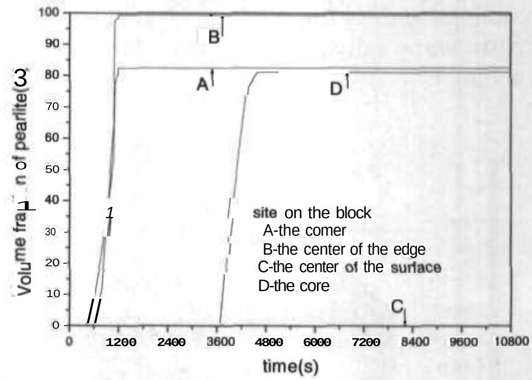
Fig.9 Martensite distribution after direct water quenching

3.2 Water Quenching with Precooling And Self-Tempering

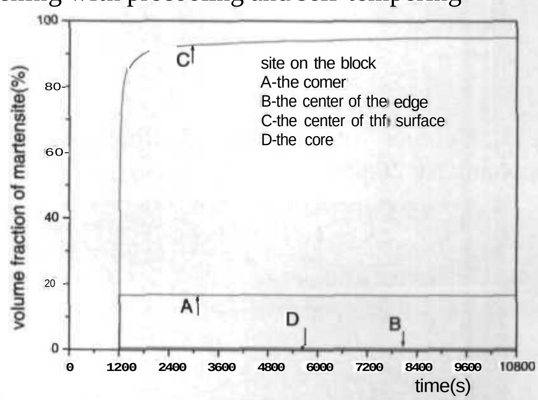
For the above large-sized block, the technology of water quenching with precooling and self-tempering is precooling in air for 1200s→quenching in water for 4000s→taking the block in air for 200s→cooling in water for 2400s→lifting the block out of water cooling in air to room temperature. Calculated cooling curves and history of pearlitic and martensitic transformations at locations in the block (refer to Fig. 4) during quenching are shown in Fig. 10. The contour of pearlite distribution after precooling for 1200s is shown in Fig. 11. Fig. 12 shows the iso-surface contours of pearlite arround the corner of the block after precooling for 1200s. And the distribution of constituents along height direction of the large-sized die block after water quenching with precooling and self-tempering is shown in Fig. 13.



a) Cooling curves during water quenching with precooling and self-tempering



b) History of pearlitic transformation during water quenching with precooling and self-tempering



c) History of martensitic transformation during water quenching with precooling and self-tempering

Fig. 10 Simulated results during quenching

As can be seen from the above simulated results, during precooling in air, a pearlitic microstructure is formed near the edges of the block (A and B in Fig. 5), which will not cause quenching cracks in the subsequent water quenching. During subsequently cooling in water, the temperature at the surface decreases below 100℃, which is already below the M_s point. Therefore, austenite at the surface of the block transforms into martensite. If continuing to cool in water, cracks may appear at the surface because of the brittleness of newly formed martensite. However, at this time, taking the block out of water and staying in air for 200s can enable the newly formed martensite to be self-tempered and its brittleness to decrease because the released heat from the center will increase the surface temperature to 200℃ or so. In other words, self-tempering can effectively avoid cracking at the surfaces of the block. After self-tempering, the block is again put into water to cool for 2400s, so the temperature of the block continues to decrease and the center layer of the block continues to transform. After the center temperature also deceases to approximately 300°C, the overall block can be taken out of water and cool in air to room temperature. In addition, by comparison of Fig. 13 with Fig. 7, it is shown that precooling and self-tempering can not affect the microstructure distribution of the block after quenching.

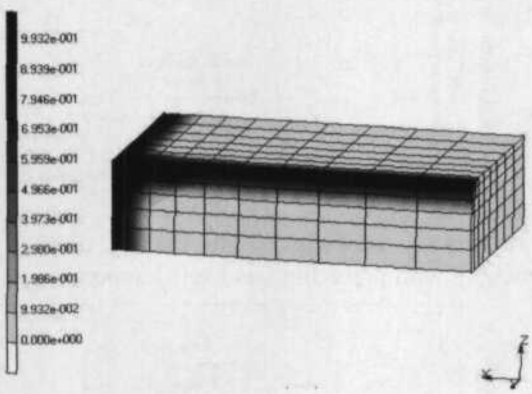


Fig. 11 Contour of pearlite distribution after air precooling for 20min

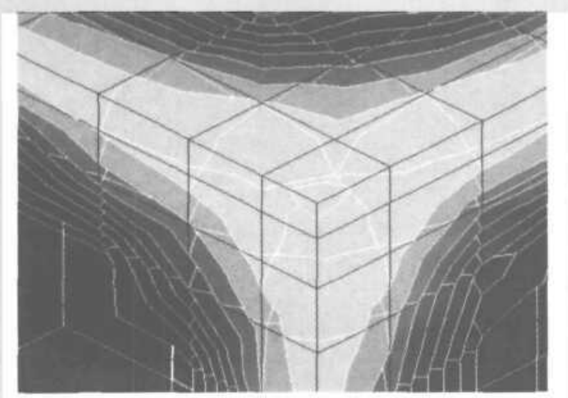


Fig. 12 Iso-surface contours of pearlite arround the corner of the block after precooling for 20min

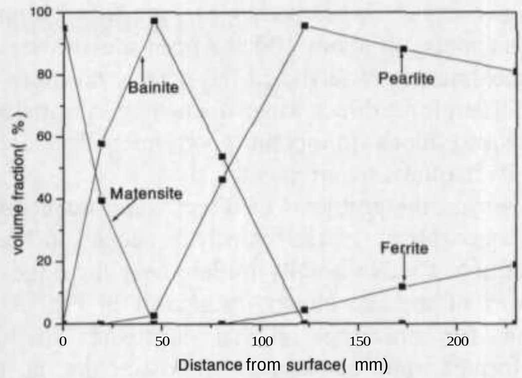


Fig. 13 Calculated distribution of constituents along the height direction of the large-sized die block after water quenching with per-cooling and self-tempering

The above analysis clearly shows that the technology of water quenching with precooling and self-tempering not only can effectively avoid quenching cracks and obtain deeper hardened depth, but also can improve the microstructure and properties of the large-sized die blocks.

4. Conculsions

(1) Based on the thermal and microstructural models, the temperature and phase fields during quenching of the large-sized AISI P20 steel die block are simulated.

(2) A technology of water quenching with precooling and self-tempering is proposed. By precooling in air, a pearlite microstructure formed at the edges of the blocks where quenching cracks are most likely to generate and by self-tempering, the newly formed martensite microstructure can be tempered.

(3) The simulated results clearly show that precooling and self-tempering does not reduce the hardened depth. Moreover, precooling and self-tempering can effectively prevent quenching cracks.

Acknowledgment

The authors wish to thank the Shanghai No.5 Steel Plant for supporting this work.

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