Numerical Analysis of quenching and cooling process of Cr12MoV Die Steel under Thermo-mechanical Coupling condition

Xianjin Fan*, Wei He*  
School of Materials Science and Engineering, Liaoning Technical University, Fuxin, Liaoning, 123000, China.  
*Corresponding author e-mail: xcb@lntu.edu.cn, *lintucltw@163.com

Abstract. Cr12MoV die steel has the characteristics of good wear resistance, small quenching deformation, high hardenability and hardness, so it requires high heat treatment process. With the emergence of computer simulation technology, it is convenient for the evolution and calculation of quenching process. In this paper, by using the technical route of combining nonlinear surface heat transfer coefficient with finite element simulation, the thermo-mechanical coupling theory is applied to the quenching process of Cr12MoV steel, and the temperature field and stress field within 300s before quenching are studied with the help of ABAQUS finite element software. The results show that the node temperature decreases with the increase of quenching time, the lowest temperature at edges and corners is about 21 ℃, the heat flux vector increases with the increase of quenching time, the yield stress increases with the increase of quenching time, and the maximum corner stress is about 751MPa. The experimental results of this paper are beneficial to the evolution calculation of material quenching process and the optimization of heat treatment method.

Keywords: Cr12MoV steel; thermal-mechanical coupling; surface heat transfer coefficient; quenching cooling; numerical simulation.

1. Introduction  
For many years, Cr12MoV steel is one of the most widely used cold work die steels at home and abroad. With the development of industry, higher requirements are put forward for the quality, performance and variety of die steel. Although the strength and hardness of Cr12MoV steel are high, its toughness is poor, especially during quenching, it is difficult to control the change of properties [1]. ABAQUS software is a large-scale nonlinear finite element software which integrates the human-computer interaction platform of modeling, analysis and simulation, which can simulate many problems in other engineering fields, such as heat conduction, mass diffusion and thermoelectric coupling analysis [2]. After the "first Conference on Internal stress calculation of Metal Materials Heat treatment" held in Swedish University in 1984, the research work of numerical simulation of heat treatment was pushed to the most exciting part. Since then, with the increasing number of similar international conferences, it has also brought the
research work in this field into a practical track [3]. Inoue and Reniecki proposed a theoretical model considering the interaction between mechanical behavior and thermal phase transition [4].

In China, the commonly used numerical analytical methods such as "finite difference method" and "finite element method" have been successfully applied to the simulation of temperature field and stress field of practical workpieces such as plastic mould, GCr15 steel hollow cylinder, P20 steel large mould and so on [5]. In this paper, based on the thermal-mechanical coupling theory, the simulation results after heat treatment are analyzed, and the thermodynamic parameters required by the model are determined, which is intended to optimize the heat treatment process.

2. Pre-processing stage
In order to analyze the temperature and stress changes of Cr12MoV die steel during quenching, the quenching process can be simulated and analyzed by ABAQUS finite element analysis software. By changing different process parameters, the magnitude of stress change and mold temperature distribution under different process parameters are analyzed, and then the change law and the optimum quenching temperature, quenching time and quenching speed are summarized.

2.1. Modeling and Meshing
The simulation sample size adopts the national standard model, and the model is established by Solidworks software, and the part model in sat format is imported into ABAQUS, and the model is shown in Fig. 1(a). The HeatTransfer type is used in the Mesh, and the 10-node DC3D10 type is selected. A total of 25021 units are divided. Five of these points will be taken as the research object, and the meshing will be shown in Fig. 1(b).

![Fig. 1](image)

Fig. 1 Finite element modeling and meshing: (a) Establishment of die steel model and (b) meshing

2.2. Parameter setting and Load increase
The test material is Cr12MoV die steel, whose chemical composition is shown in Table 1 [6]. The change of temperature has little effect on its performance parameters, and it can be treated as a constant without affecting the experimental results, and the data are shown in Table 2.

| Chemical element | C  | Cr  | Mo  | V   | Mn  | Si  | P   |
|------------------|----|----|-----|-----|-----|-----|-----|
| Content (Wt%)    | 1.5| 12 | 0.81| 0.21| 0.42| 0.31| 0.001|

Table 1. Chemical composition of Cr12MoV die steel [6]
Table 2. Cr12MoV performance parameters

| Performance Parameters | Mass density (Kg/m³) | Young’s modulus (×10⁵MPa) | Poisson's ratio | Specific heat capacity J/(Kg·℃)⁻¹ |
|------------------------|----------------------|---------------------------|-----------------|-------------------------------|
| Parameters             | 7850                 | 2.11                      | 0.28            | 460                           |

In the experiment, 300s before quenching is taken as the research time. In the process of setting the load, the temperature of the quenched part is 1030 °C, the boundary condition is convective heat transfer, and the quenchant is oil.

Considering the nonlinear properties of the thermophysical parameters of the material, there is a certain error between the temperature and stress distribution of the quenching process and the actual measured values, and the thermal parameters are the parameters of temperature, stress and time, and the microstructure of the quenching process changes greatly. The temperature span is also large, so the thermal parameters cannot be regarded as constant values, but must be regarded as a function of temperature [7]. The function types are shown in Fig. 2 (a), 2(b).

![Functional Images of all kinds of Thermal parameters in Cr12MoV: (a) Linear expansion coefficient and (b) Thermal conductivity](image)

Fig. 2 Functional Images of all kinds of Thermal parameters in Cr12MoV: (a) Linear expansion coefficient and (b) Thermal conductivity

2.3. Results and Discussion

Because the quenching and cooling process of die steel belongs to unsteady solid heat transfer, the Fourier law of heat transfer and the law of conservation of energy should be satisfied [8], and its differential equation is shown in Eq. 1.

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q = \rho c_p \frac{\partial T}{\partial t}.
\]

In the formula: \( k \) is thermal conductivity \([J/(Kg·℃)⁻¹]\); \( \rho \) is the density \((Kg/m^3)\); \( c_p \) is specific heat capacity \([J/(Kg·℃)]\); \( \frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z} \) are temperature gradients in \( x, y \) and \( z \) directions, respectively \( (℃/m) \); \( q \) is the internal heat source strength of the material, which is related to the type of phase transition.

2.4. Simulation analysis of temperature field results

In this paper, the temperature field model of Cr12MoV steel under quenching cooling condition is established by using ABAQUS software. When the sample is heated to 1030 °C, Fig. 3(a) and Fig. 3(b) shows the temperature field distribution of die steel cooled to 300s. Because point a is in the corner, the heat dissipation capacity is stronger than other parts, and the e point is in the center of the mold surface, so the heat dissipation capacity is weak. When quenching and cooling for 100s, the maximum heat flux of the die is at point b, and its value is \( 4.08 \times 10^4 \text{W/m}^2 \); when the minimum value at point e is
1.76×10⁴W/m² for 300s, the heat flux at point b is 4.93×10⁴W/m², and the heat flux at point b is 4.93×10⁴W/m² when the minimum value at point e is 1.76×10⁴W/m². At this time, the e-point heat flux becomes 3.37×10⁴W/m². Because the corner a-point temperature drops to room temperature at 300s, but the e-point temperature at the center of the mold surface is still higher, so the heat flux is quite different.

The experiment shows the time changes of the five points in Fig. 1(b) in Fig. 4. At the beginning of quenching cooling, because the die surface is in direct contact with the quenching oil, the surface temperature decreases sharply, but the temperature at point a decreases rapidly because point an is in an angular position, and the temperature difference between point an and the center is larger than the other four points [9].

With the extension of cooling time, the difference increases gradually, and the whole temperature distribution tends to be smooth. Finally, the a point of the sample is gradually close to room temperature, while the rest of the temperature is still slow. On the other hand, the temperature of the e point in the center of the mold surface is higher, so there is a great difference in heat flux between the e point and the a point. At 300s, the maximum difference in heat flux between the two points is 5.1×10³W/m².

Fig. 3 Variation of heat flux in quenching cooling temperature field of die steel: (a)100s and (b)300s

Fig. 4 Variation of temperature field: (a) Node change law and (b) Variation law of heat flux

2.5. Simulation analysis of stress field results

After the calculation of the temperature field, the thermal stress analysis can be carried out on the basis of the heat conduction just now.

In order to make the yield point always fall on the yield surface, under the condition of using vonMises yield criterion and only considering isotropic hardening of the material, it can be seen from the Eq. 2 that the equivalent stress \( \sigma \) should satisfy [10]:

\[
\bar{\sigma} = \sigma_y + r(P) + \sigma_p = \sigma_y + r(P) + K P^m
\]  

(2)
In the formula, \( \sigma_y \), \( p \), \( r(p) \) and \( \sigma_v \) are yield stress, equivalent plastic strain, hardening stress and stress caused by creep viscosity, respectively.

In this section, the temperature field data obtained from the temperature field analysis in the previous section are used to simulate the thermal stress of the casting in the form of temperature load. Because of the symmetry of die steel, select its symmetry point a point for thermal stress analysis in the first 300s of the quenching and cooling process:

It turns out that; with the change of temperature difference in the cooling process, the internal stress and principal stress of Cr12MoV die steel have changed in varying degrees, in which the change of equivalent stress is the most obvious, the maximum value is 751.10MPa, the change of compressive stress is not obvious, the maximum principal stress and minimum principal stress change greatly, the specific changes are shown in Fig. 5.

In the stress change, the equivalent stress increases with the increase of quenching time, and the compressive stress decreases at first and then increases at 300s, which is due to the rapid decrease of surface temperature and slow decrease of core temperature during quenching cooling. With the passage of time, the surface temperature decreases slowly, while the core decreases rapidly, and the temperature difference changes on the contrary, and the maximum compressive stress is 95.22MPa. The maximum principal stress increases with the increase of time, and the minimum principal stress decreases with time. The maximum principal stress is 402.57MPA and the minimum principal stress is -389.38MPA. Because the stress is caused by temperature, the quenching state is in medium temperature quenching. The difference is caused by the combined effect of latent heat release and the application of the elastic-plastic model of the whole die.

![Fig. 5 Quenching thermal stress change process: (a) Internal stress change process; (b) Principal stress variation process](image)

3. Conclusion
In this paper, combined with the quenching experiment of Cr12MoV steel, the variation rules of four representative points in the process of heat treatment in the first 300s were studied by using ABAQUS software:

When the surface of the die steel is in direct contact with the quenching oil, the surface temperature decreases sharply, the edge and corner position a point, the temperature difference between the edge and the center is larger than the other four points, and the heat flux increases with the increase of the cooling process, and the change law of the temperature field is consistent with the reality: The internal stress increases with the increase of temperature, and the principal stress shows the opposite trend.

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