Application of transient nonlinear thermal analysis on quenching of hot die steel

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Abstract. Hot die steels contact with high temperature metals, and possess well thermal conductivity, wear resistance and red hardness. The carbon content should be controlled in the range of 0.3wt.% to 0.6wt.%, and added alloy elements to improve hardenability. The complex composition of the alloy affects its thermal and physical properties. For billets with large volume, it is difficult to measure the temperature of all parts. Through numerical simulation, the temperature field distribution in quenching process of hollow steel pipe with a length of 7 m is obtained by adopting the transient nonlinear thermal analysis algorithm of general finite element software. The results show that the steel temperature decreases to the target temperature of 19°C, it takes about 10 to 12 minutes for the thin wall and 18 to 20 minutes for the thick wall. It is about 4 minutes to descend martensite transition temperature of 265°C at the thick end. Steel temperature decreases to medium temperature, with the wall thickness increases, time slightly longer. The characteristics and phase changing latent heat of hot die steel quenching process are taken into account, and the corresponding treatment is carried out when setting thermophysical parameters. The accurate simulation results are obtained and have certain significance for the research of related materials heat treatment.

1. Introduction

Temperature field simulations about thermal and physical properties of materials mainly include specific heat capacity, phase change latent heat, thermal conductivity and density. The thermophysical parameters of materials are a function of temperature. So in the iterative solution, the parameters varying with temperature can be calculated by interpolation and employed as the approximate value of the relevant parameters at the next moment [1].

Due to the dramatic temperature changes of the quenching process and the temperature measurement complexity of the large workpiece, numerical simulation technologies on quenching process always carry out a large amount of research. The contents covered the phase change of steel quenching [2,3], thermal elastic-plastic [4], phase transformation plasticity and correlation of internal stress with martensite transformation [5], performance and the residual stress after quenching [6], surface heat transfer and boundary conditions [7], the nonlinear thermal analysis of quenching process, temperature and stress field coupling [8], etc.

When metals and alloys are quenched in water, spindle oil and other liquid media, the surface heat transfer coefficient always increases to the maximum value and then decreases as the quenching temperature decreases. In the early stage of quenching, the temperature difference between the workpiece and the medium is significant. When the hot workpiece is suddenly put into the quenching medium, the medium around the workpiece is heated and vaporized. There is a layer of steam film
between the workpiece and the quenching medium. The steam film with poor thermal conductivity leads to a small surface heat transfer coefficient. As the temperature of the workpiece decreases and the quenching time continues, the steam film and bubbles gradually break. The heat transfer between the specimen and the quenching liquid becomes fierce, and the surface comprehensive heat transfer coefficient and cooling speed rapidly increase to the maximum. When the workpiece temperature is low, the surface heat transfer coefficient decreases rapidly with the decrease of temperature difference between quenching specimen and medium.

2. Numerical simulation methods
The analysis involving phase transitions is always transient analysis, and the load in the transient analysis varies with time. In order to accurately describe the quenching process, it is necessary to comprehensively consider the relationship about thermal properties, phase change latent heat, surface heat transfer coefficient, temperature and time for quenching cooling such transient problems. The matrix form of transient nonlinear thermal analysis can be expressed as:

\[ (C(T))[\dot{T}] + (K(T))[T] = (Q(T,t)) \]  

(1)

Where \( (C(T))[\dot{T}] \) is the heat storage phase, \( C(T) \) is the heat capacity matrix, \( K(T) \) is the heat conduction matrix, \( Q(T,t) \) is the heat flux density of heat source contained in the object, \( T \) and \( t \) are the temperature and the quenching cooling time respectively.

In the quenching process accompanied by phase change, enthalpy can be defined. The heat storage property, namely phase change latent heat, can be calculated and superimposed into the specific heat capacity matrix. Since the simulation process includes air cooling before quenching, boundary conditions and material properties that change with temperature. Such as surface convection coefficient, thermal conductivity coefficient, enthalpy, etc., which have typical characteristics of nonlinear thermal analysis. These parameters are applied according to the temperature function. The ingredients of hot die steel are shown in Table 1.

| Element | C  | Si  | Mn  | Cr  | Ni  | Mo  | V   |
|---------|----|-----|-----|-----|-----|-----|-----|
| Mass fraction (%) | 0.35–0.45 | 0.80–1.10 | 0.80–1.10 | 1.30–1.50 | 2.50–3.50 | 0.40–0.60 | 0.20–0.60 |

The density is calculated according to the influence coefficient of elements in the steel [9].

\[ \rho = \rho_0 + x \cdot V \rho \]  

(2)

Where \( \rho_0 \) is the density of pure iron, \( x \) is the mass fraction of elements contained in steel, \( V \rho \) is the effect to the steel density of increasing the element content by 1 wt.%. The values of \( V \rho \) are listed in Table 2.

| Element | C    | Si   | Mn   | Cr   | Ni   | Mo   | V    |
|---------|------|------|------|------|------|------|------|
| \( V \rho \)(g/cm³) | -0.06 | -0.035 | -0.0034 | -0.006 | 0.011 | 0.024 | -0.018 |

Hot die steel quenching process:
910°C solid solution → air cooling 2 minutes → quenching in 19°C flowing water for 40 minutes.

Thermal conductivity and specific heat capacity are inherent properties of materials, which are related to the composition, density, temperature factors of materials. In this paper, the thermal conductivity and specific heat capacity vary between 30–35 W/m•K and 480–570 J/kg•K, respectively.
The overall fluctuation range is small. Firstly, the emissivity is set as 1 on the basis of black body in the simulation process, and then it is determined according to the oxidation condition of material surface when the temperature is measured. According to the ratio between the measured temperature of the infrared thermometer and the material surface, 0.93°C is higher than 600°C and 0.85°C is lower than 600°C

Surface heat transfer coefficient for air cooling after solid solution treatment, according to the empirical value [9] combined with the calculation. The air at 20°C is naturally convection on the surface of the steel tube, and the heat transfer coefficient can be obtained about 70W/m² • K. All material parameters used for calculation are shown in Table 3. With the change of temperature, the values of thermal conductivity coefficient and specific heat capacity change rarely, so the average values are taken. However, in the quenching process, due to the strong heat exchange between the material surface and the medium, the heat transfer coefficient is not stable. Currently, there is no reliable measurement method, and the calculated value is only given according to the three stages of the quenching process [10].

### Table 3. Parameters of materials.

| Density/(kg/m³) | Thermal conductivity coefficient/(W/m · K) | Specific heat capacity/(J/kg · K) | Surface heat transfer coefficient/(W/m² · K) | Stefan-Boltzmann constant/(w/(m² · k⁴)) |
|-----------------|------------------------------------------|----------------------------------|------------------------------------------|----------------------------------------|
| 7830            | 32                                       | 520                              | Flowing water: 2000                      | 5.67e-8                                 |
|                 |                                          |                                  | Gas: 70                                  |                                        |

3. Analysis of air cooling temperature field

The eight-node three-dimensional hexahedron element was selected as the unit entity type, and the three-dimensional thermal element was selected as the surface effect element. There were 37,624 elements in the calculation material, and the time step was 10s. The mesh is divided by tetrahedron or hexahedron mapping pattern. Figure 1 shows the temperature distribution cloud diagram during air cooling of hot die steel tube normalizing. Different colours represent the corresponding temperature.

![Figure 1. Temperature distribution cloud diagram during air cooling of hot die steel tube normalizing.](image)

Figure 2 to 4 show the temperature changes of nodes at different positions in tube. Results show that after 2 min of air cooling, the 125 mm thin-walled temperature of node 6 and node 15 decreases from 1183 K to 1093.23 K and 1121.65 K, respectively. With 155 mm wall thickness, node 98 and node 99 temperatures are 1116.87 K and 1126.00 K, respectively. The node 62 and node 45 temperatures of 200 mm thick-walled are 1127.30 K and 1106.12 K, respectively. The closer it is to the end of the pipe, the faster temperature will drop. This is mainly due to additional heat dissipation from the end surface of the pipe. In the early stage, the temperature drop of billet is fast, and then gradually slows down. The absolute value of the slope of temperature change curve decreases with the time elapse.
4. Temperature field analysis of quenching process

Quenching can be divided into three stages: membrane boiling, transition boiling and nucleation boiling [7].

Heat transfer coefficient is very important for quenching process. Figure 5 shows the application of heat transfer loads on the inner and outer surfaces of steel tubes. As a parameter of the boundary condition, it has noteworthy influence on the simulation accuracy. Therefore, in quenching heat analysis, it is necessary to obtain an accurate relationship curve between surface temperature and heat transfer coefficient of materials. However, it is difficult to measure surface heat transfer coefficient in practice. In this paper, the method combining empirical value and theoretical calculation is used to estimate the surface heat transfer coefficient. The quenching medium is flowing water.
Figure 5. Heat transfer loads on the inner and outer surfaces of steel tubes.

Figure 6. Temperature distribution curve in the quenching process of hot die steel pipe. (a) the thinnest wall, (b) the mid-wall, (c) the thickest wall.

The latent heat release of quenching specimens can be described by using the equivalent heat capacity method at constant pressure. Comparatively accurate physical parameters are obtained by combining theoretical calculation with actual measurement. As can be seen in figure 6, near the martensite phase transformation temperature, the slope of temperature distribution curve are changed. The overall trend is with lower temperature, its absolute value decrease and then increase. Phase change latent heat release can lead to slow cooling speed near the martensitic transformation point of material, and increased cooling speed until phase change latent heat released in full. The faster temperature drops, the earlier this kind of phenomenon appears, the lower corresponding temperature shows.

5. Conclusions
The steel pipe is quenched to the target temperature of 19°C, it takes about 10 to 12 minutes for the thin wall, 18 to 20 minutes for the thick wall, and 14 to 16 minutes for the longitudinal center of the pipe. The radial centers of hot die steel pipe wall quenching to martensite transition temperature, the
thick wall and thin wall take about 233s and 123s, respectively. With the pipe wall thickness increasing, time slightly longer in the process of steel quenching to medium temperature.

References
[1] Zhou C, Liao D M, Chen T et al 2013 Numerical calculation and program development of temperature field in air cooling process based on finite element method Foundry 62 850-4
[2] Fernandes F, Denis S and Simon A 1985 Mathematical model coupling phase transformation and temperature evolution during quenching of steel Mater. Sci. Technol. 1 838-44
[3] Ning Q H, Dong J Y and Li Y G 2018 Finite element simulation of water spray quenching for large size NM450 steel plate Heat Treat. Met. 43 221-6
[4] Rammerstorfer F G, Fischer D F and Mitter W 1981 On thermo-elastic-plastic analysis of heat treatment processes including creep and phase changes Comput. Struct. 1981 771-9
[5] Denis S, Egautier, Simon A et al 1985 Stress-phase-transformation interactions basic principles, modelling, and calculation of internal stresses Mater. Sci. Technol. 1 805-15
[6] Wang L, Li Z L, Yang D F et al 2015 Finite element simulation and experimental study on residual stress of atomized gas quenching Hot Work Technol. 44 175-8
[7] Xie J B 2003 Numerical simulation and application research of metal and alloy quenching in different media (Kunming: Kunming University of Science and Technology)
[8] Zhang L Q, Wang J, Luo X M et al 2017 Study on coupling simulation of flow field, temperature field, structure field and stress field in heat treatment process Heat Treat. Met. 42 181-6
[9] Tan Z and Guo G W 1994 Thermophysical Properties of Engineering Alloys (Beijing: Metallurgical Industry Press)
[10] Kopun R and Skerget L 2012 Experimental and numerical investigation of boiling flow in a vertical pipe with phase change using a multi-fluid modelling approach Adv. Fluid Mech. IX 74 219-30