Simulation Study on Vacuum Gas Quenching of Cold Working Dies

Zhenyu Fan1*1, Huizhen Wang[1], Yan Deng[2], Qiang Wang[2], Yuewen Zhai1, Chao Jiang1, Leyu Zhou1, Zhiqiang Li1, and Yuheng Zhan[3*3]

1Department of Materials Science, China Academy of Machinery Beijing Research Institute of Mechanical & Electrical Technology Co.,Ltd., Beijing 100083, China
2Faw Tooling Die Manufacturing Co.,Ltd., Changchun 130013, China
3Department of Aerospace Engineering, Faculty of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

During heat quenching process, temperature transition, microstructure evolution and stress/strain interaction occur simultaneously at different scales. Establishment of a multi-field coupling model need deal with microstructure evolution, thermophysical parameters, and boundary conditions. The specific heat capacity and thermal conductivity of Cr12MoV were obtained using the synchronous thermal analyzer and laser thermal conductivity analyzer. The heat transfer coefficient model of nitrogen was obtained through inverse algorithm. Vacuum Gas Quenching and isothermal quenching were simulated by establishing suitable FEM models. The evolution process of temperature, microstructure, and stress/strain during the quenching process were analyzed. Microstructure evolution during quenching process is predicted successfully. Bainite/martensite multi-phase was formed during isothermal quenching process. The temperature gradient between the surface and center of the cold working die was reduced. Experimental results are compared with FEM simulation results. The comparisons show that the simulation results are consistent with experimental results.

Keywords: *Cr12MoV steel, Cold working dies, Simulation, Vacuum gas quenching, Isothermal quenching, Microstructure evolution*

1. Introduction

Cold working dies are key components in the room temperature forming process, commonly used in forming processes such as extrusion, punching, bending, drawing, cold heading, wire rolling, and twisting. Cr12MoV is one of the commonly used cold working die materials. With the increasing requirements on service life and deformation control, it is necessary to strengthen the dies. Heat treatment is a commonly method for dies strengthening. Traditional heat treatment methods generate a large amount of emissions and pollution. Vacuum heat treatment has the advantages of clean and efficient, and the products have better surface quality. Otherwise, vacuum heat treatment can improve material toughness while ensuring the hardness, by modifying the microstructure of the material[1].

The usual analysis methods are difficult to explore the macroscopic and microscopic evolution during the heat treatment process. Besides, traditional trial-and-error method is costly and consuming. Numerical simulation is an efficient technology to reveal complex multi-field coupling relationships during heat treatment processes. The research on numerical simulation of heat treatment processes began in the 1970s, and the theory is constantly improving, numerical simulation of heat treatment processes has become one of the key research directions in the field. Inoue and Reniecki[2,3] proposed a multi-field coupling theoretical model for the temperature-phase transition-stress interaction during heat treatment, laid the theoretical foundation for the subsequent multi-field numerical simulation of heat treatment.

Due to the rapid cooling rate during the vacuum gas quenching process, there is a large temperature gradient between the surface and center of the cold working die. Thermal stress generated by large temperature gradient is unfavorable for deformation and quality control of the dies. During the quenching process, inhomogeneous cooling leads to excessive residual stress in the dies, making it prone to cracking during service[4]. Temperature gradient could be reduced through isothermal quenching. Lower bainite is a type of microstructure with a good combination of high strength and high toughness[5]. The multi-phase composed of martensite and lower bainite has a better balance between strength and toughness than the single-phase[6]. The traditional isothermal quenching process uses molten salt as the quenching medium. The advantage of salt bath quenching is stable temperature control, but the disadvantage is that treating molten salt causes pollution. The quenching ability of salt bath quenching is higher than that of oil quenching[7]. Based on the goal of low-carbon and environmental protection, it is very important to develop vacuum gas isothermal quenching technology. Development direction including vacuum gas isothermal quenching equipment, numerical simulation technology, temperature control programs, and heat treatment processes. The progress of vacuum heat treatment technology contributes to the further improvement of dies quality and service life.

2. Materials and methods

The material used in this study is Cr12MoV cold working die steel, and the chemical composition is listed in Table 1. According to Archimedes' principle, the density of Cr12MoV is measured as 7.67 g/cm^3. The specific heat capacity of Cr12MoV were obtained using the STA-449C synchronous thermal analyzer. The thermal conductivity of Cr12MoV were obtained using the LFA457 laser thermal conductivity analyzer. The specific heat capacity and thermal conductivity are listed in Table 2.

[1*] Graduate Student, China Academy of Machinery Beijing Research Institute of Mechanical & Electrical Technology Co.,Ltd.

*3 Graduate Student, Beijing Institute of Technology

Table 1 Chemical composition of Cr12MoV cold working die steel

C	Si	Mn	Cr	Mo	V
1.45-1.7	≤0.40	≤0.40	11.0-12.5	0.40-0.60	0.15-0.30

Table 2 Chemical composition of Cr12MoV cold working die steel

Temperature/K	Specific heat capacity /J(g·K)$^{-1}$	Thermal conductivity/W(m K)$^{-1}$
473	0.390	23.8
673	0.403	21.1
873	0.468	19.5
1073	0.510	17.1
1273	0.364	15.7

The heat transfer coefficient of nitrogen in the vacuum environment was calculated and iterated using the inverse algorithm program in FEM simulation software. The heat transfer coefficient of nitrogen is listed in Table 3. The material composition and various parameters were imported into FEM software for establishing material models. The workpiece model of Cr12MoV cold working die is showed in Figure 1.

Table 3 Heat transfer coefficient of nitrogen

Temperature/K	Heat transfer coefficient /W(m^2·K)$^{-1}$
323	0.034
473	0.307
673	0.552
773	0.723
873	0.959
1073	0.754
1293	0.603

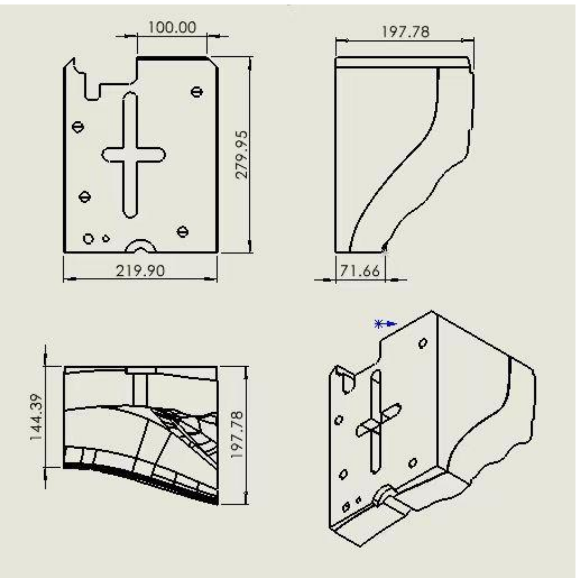

Figure 1 Basic dimensions of Cr12MoV cold working die

The continuous cooling transformation (CCT) and time temperature transformation (TTT) curves of Cr12MoV have been obtained in previous study[8]. Based on previous study, the heat treatment process was developed. Figure 2 shows the specific heat treatment process. The preheating process includes two stages: 875K/120min and 1125K/60min. Then the workpiece was heated to 1293K and held for 90 minutes. And the following two quenching processes have been developed (gas quenching pressure was 0.6 MPa):

(1) Q1: gas quenched the workpiece to room temperature directly.

(2) Q2: gas quenched the workpiece to 833K for 10 minutes, gas quenched it to 553K for 5 hours and then gas quenched it to room temperature.

The composition and thermophysical parameters, phase transition model, workpiece model, and other parameters were imported into FEM software to establish the vacuum gas quenching simulation model for Cr12MoV cold working die.

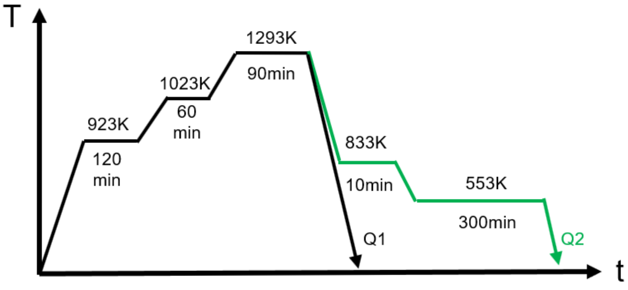

Figure 2 Heat treatment process

The calculation model for temperature variation is the Fourier three position heat conduction equation:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+Q \\ =\rho\cdot C_p\frac{\partial T}{\partial t} \quad (1)$$

In equation (1), ρ - material density; Q - phase transition latent heat; λ - The thermal conductivity of the material; C_p - Specific heat at constant pressure.

The heat exchange between the workpiece and the heat exchange medium is described using the third type of boundary condition:

$$-\lambda\frac{\partial T}{\partial n}\bigg|_s=h_T\left(T-T_f\right) \quad (2)$$

Subscript S - the boundary area of the object, h_T in equation (2) is the surface heat transfer coefficient of the quenching medium; T_f is the temperature of the quenching medium.

Using the Koistinen Marburger equation to describe martensitic transformation[9]:

$$f=1-\exp(-\alpha(\mathrm{Ms}-T)) \quad (3)$$

In equation (3), f is the amount of martensite transformation, M_S is the starting temperature of martensite transformation, T is the temperature at a certain time during the cooling process, α is the kinetic parameter that reflects the rate of martensite transformation, and the value is related to the composition and temperature of the material.

The bainite transformation belongs to a diffusion type phase transition and is described using the Avrami[10] equation of isothermal transformation kinetics:

$$f = 1 - \exp\left(-bt^n\right) \tag{4}$$

In equation (4), t is the transformation time, b and n are the bainite transformation kinetics parameters are related to material composition and transformation temperature.

Using thermal elastoplastic constitutive equations to describe the strain state during heat treatment:

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} + \dot{\varepsilon}_{ij}^{T} + \dot{\varepsilon}_{ij}^{tr} + \dot{\varepsilon}_{ij}^{tp} \tag{5}$$

The components in equation (5) are elastic strain, plastic strain, thermal strain, phase transformation strain, and phase transformation plastic strain, respectively.

3. Results and discussion

3.1 Temperature variation

Due to the irregular shape of the die and the different cooling rates at different positions, there are certain temperature gradients in the center and surface of the die. As shown in Figure 3, the selected points P1 and P2 are located on the surface and center of the die, respectively. Figure 4 shows the cooling curves of Q1 and Q2 processes at the selected points. It was found that, the temperature difference between P1 and P2 points in the Q2 process is smaller than the temperature difference in the Q1 process. Figure 5 shows the temperature distribution of the die when point P1 temperature is 724K. The temperature difference between P1 and P2 points has decreased from 411K to 124K. After isothermal treatment at 833K, the temperature gradient between the surface and center of the die significantly decreased. The small temperature gradient helps to reduce the accumulation of stress in the die during the quenching process.

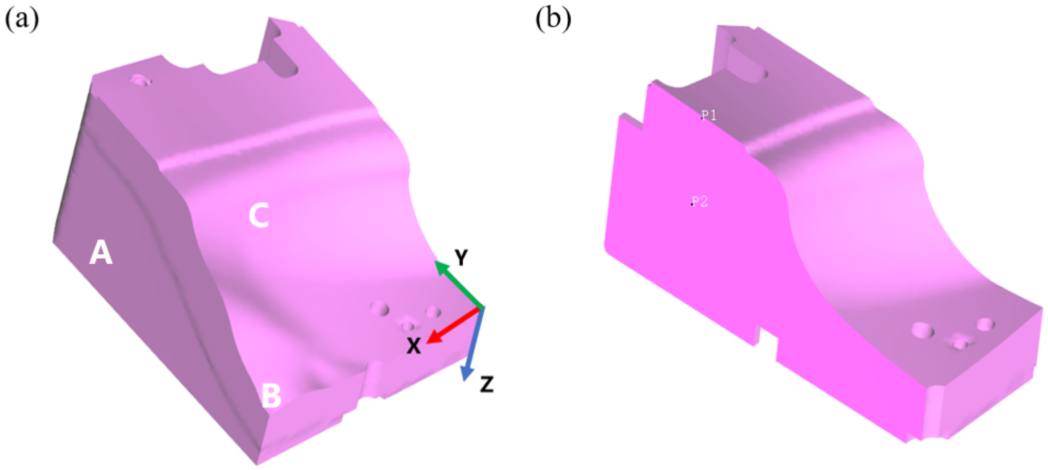

Figure 3 (a) Datum coordinates and (b) select point location of Cr12MoV cold working die

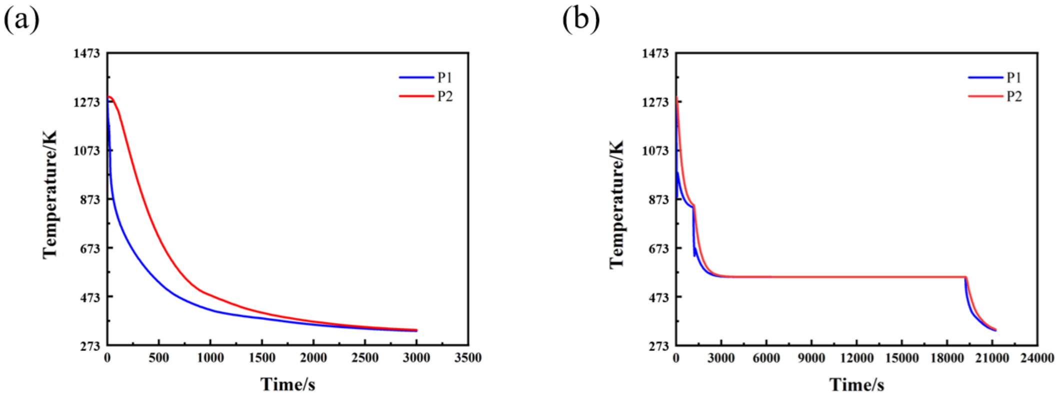

Figure 4 The cooling curves of (a) Q1 and (b) Q2 processes at the selected points

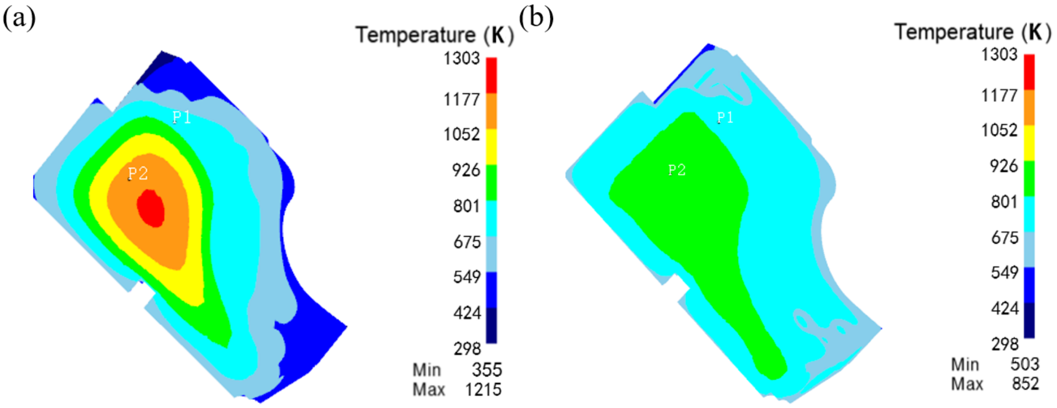

Figure 5 The temperature distribution of the die of (a) Q1 and (b) Q2 processes when point P1 temperature is 724K

3.2 Microstructure evolution

Figure 6 shows the phase content curves at the selected points, it was found that, martensite was mainly formed in Q1 process, martensite and bainite was mainly formed in Q2 process. Continuous cooling transformation occurs within the material in the Q1 process, martensitic transformation occurs instantly when the point reaching Ms temperature. Therefore, it is found from Figure 7 that the distribution of martensite volume fraction at a certain moment exhibits a gradient distribution which is similar to the temperature distribution. On the other hand, diffusion type phase transition occurs in Q2 process. Due to the small temperature gradient and long transformation time during the isothermal transformation process, the distribution of bainite volume fraction is relatively uniform during the transformation process.

Comparing the SEM map of the samples subjected to vacuum gas quenching experiments in the vacuum gas quenching furnace, it was found that the microstructure of the material in Q1 process is mainly martensite and residual austenite, while the microstructure of the material in Q2 process is mainly bainite/martensite multi-phase and residual austenite.

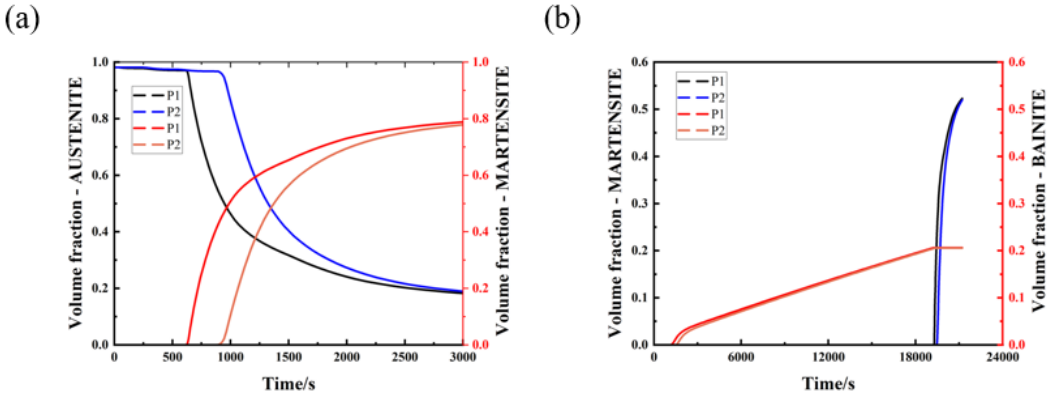

Figure 6 The phase content curves of (a) Q1 and (b) Q2 processes at the selected points

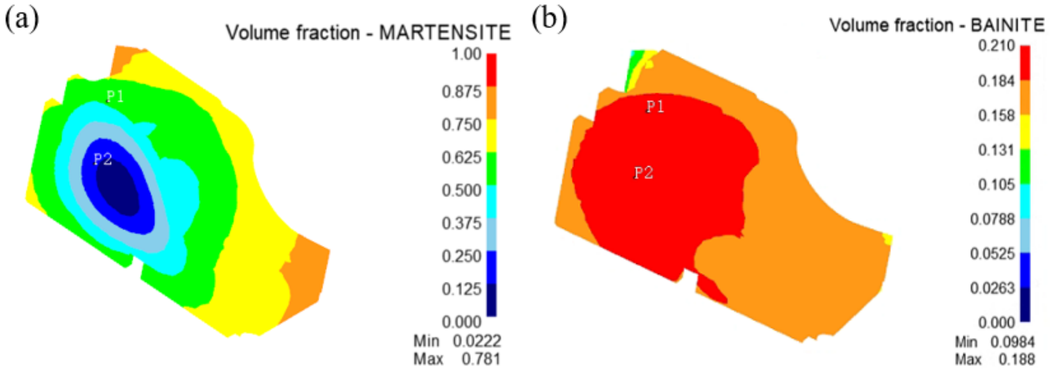

Figure 7 The phase volume fraction distribution of (a) Q1 and (b) Q2 processes in the quenching process

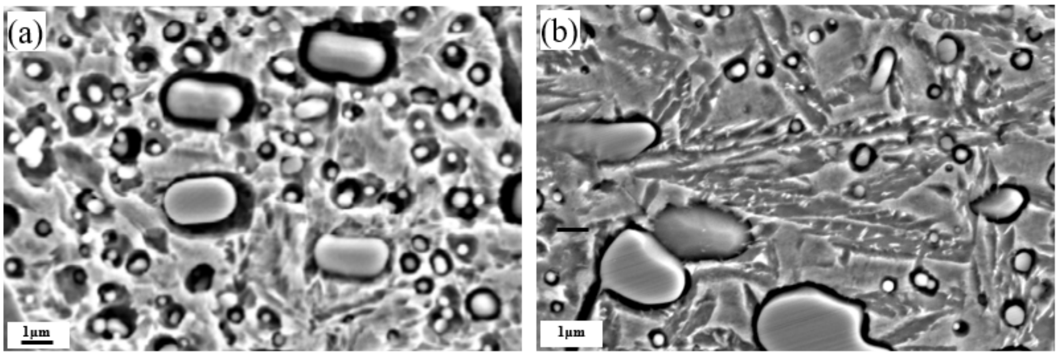

Figure 8 SEM map of microstructure of (a) Q1 and (b) Q2 processes

3.3 Stress/Strain distribution

The stress on the cavity surface of the die is mainly compressive dress at the end of quenching process from Figure 9. In Q1 process, the Z-direction stress of P1 was 16.0 MPa and P2 was 79.5 MPa. In Q2 process, the Z-direction stress of P1 was 11.5 MPa and P2 was 30.0 MPa. Comparing the Z-direction stress values of P1 and P2 when cooled to room temperature, it was found that the stress values of both points in Q2 process were lower than those in Q1 process. It was found that the stress is mainly concentrated at the edge of surface A from Figure 10, as surface A was the bottom surface of the die when it enters the furnace. It was found that the position with larger strain is also at the edge of plane A from Figure 11. During the quenching process, the edges were cooled first, and martensite was formed and generated microstructure stress. This part of the strain is mainly caused by thermal stress and microstructure stress. And isothermal quenching process reduced the stress at the edges, the extreme stress value at the tip decreased from 1210MPa to 857MPa. The risk of cracking at the tip due to stress concentration was reduced. Bainite transformation is a diffusion type phase transition with a smaller volume expansion than martensitic transformation. During isothermal quenching, bainite is formed to replace a portion of martensite, thereby reducing the microstructure stress generated by phase transformation. Therefore, the formation of bainite/martensite multi-phase helped to reduce residual stress in the die and improved stress concentration. Stress reduced and the strain caused by stress was reduced.

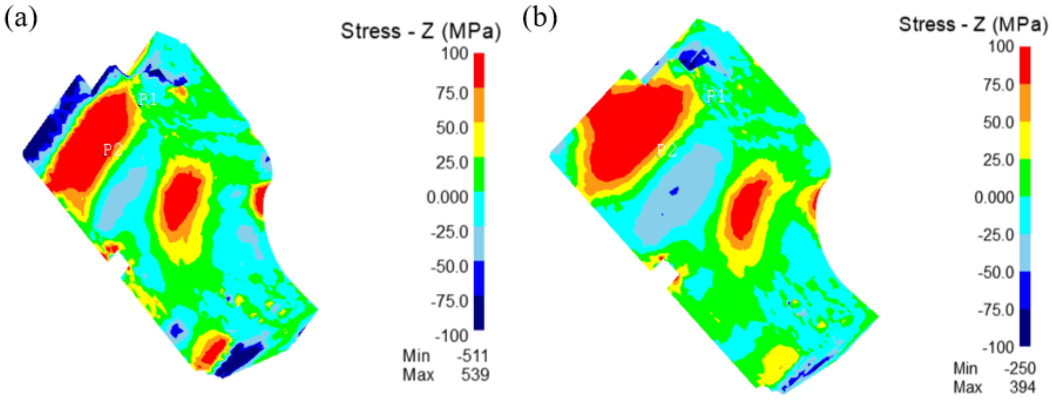

Figure 9 Z-direction stress distribution of the die of (a) Q1 and (b) Q2 processes

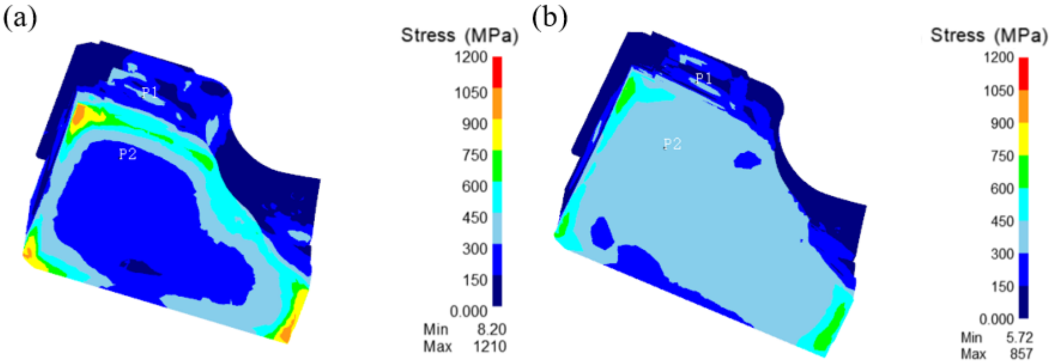

Figure 10 Effective stress distribution of the die of (a) Q1 and (b) Q2 processes

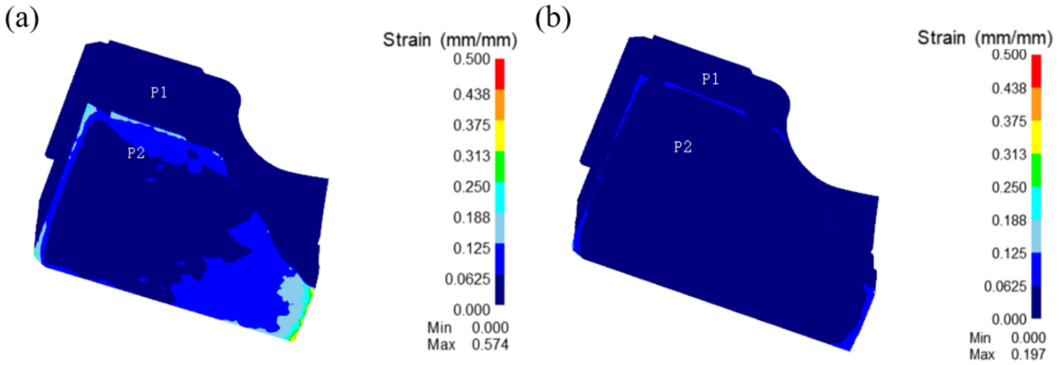

Figure 11 Effective strain distribution of the die of (a) Q1 and (b) Q2 processes

4. Discussion

The Cr12MoV cold working die has irregular shapes in this study, and the dimension of the die varies greatly at different positions. The cooling rate on the surface of the die is relatively high in the cooling process, while the cooling rate at the center is relatively slow. Therefore, a large temperature gradient is generated between the surface and center of the die. Temperature gradient generates thermal stress. On the other hand, the thinner position undergoes phase transformation by cooling first. Phase transformation generates volume expansion, leading to the formation of microstructure stress. Excessive accumulation of thermal stress and microstructure stress leads to excessive residual stress or stress concentration, and then causes premature cracking and failure of the die. In summary, the first issue to be addressed for die heat treatment is the temperature gradient problem. Using high thermal conductivity materials, increasing gas quenching pressure and isothermal quenching are both feasible methods. According to this study, vacuum gas isothermal quenching has a significant effect on reducing temperature gradient. From the perspective of organizational transformation and stress distribution, vacuum gas isothermal quenching has significantly reduced residual stress and improved stress concentration. To address the problem of stress concentration in thin-walled areas, insulation cotton filling can be used to improve it. In accordance with existing research results, isothermal quenching can be extended to the study of heat treatment technology for other dies. The intermediate state of the die during heat treatment is well presented with the help of numerical simulation technology. The combination of numerical simulation and experimental research methods can significantly improve efficiency, and subsequent secondary development can further improve the model and improve simulation accuracy.

5. Conclusions

(1) The Vacuum gas isothermal quenching process significantly reduced the temperature gradient between the surface and center of the dies.

(2) After vacuum gas isothermal quenching process, the microstructure of Cr12MoV cold working die was bainite/martensite multi-phase and residual austenite.

(3) The vacuum gas isothermal quenching process reduced residual stress and is beneficial for improving the service stability of cold working dies.

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