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Research Article

Optimization Design of Insert Hot Stamping Die's Cooling System and Research on the Microstructural Uniformity Control of Martensitic Phase Transitions in Synchronous Quenching Process

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Ultrahigh-strength steel BR1500HS was chosen as the research object. The parameters of insert hot stamping die's cooling system in the synchronous quenching process were calculated, and the cooling system was designed based on the temperature distribution of formed part. Then, by combining FEM simulation and thermal-mechanical coupling theory of synchronous quenching process of hot stamping, the cooling system was optimized. After that, the punch and die were optimally designed based on the simulation of temperature field of formed part as well as dies, and their temperature decreased by 15°C and 12°C, respectively. Next, the microstructural evolution in austenization and synchronous quenching processes was analyzed. By adopting a synchronous cooling system in hot stamping, by optimizing the parameters and control strategies, and by controlling the water velocity in various inserts, the homogeneity of martensitic phase transitions was improved. The results of the application test show that martensitic phase transitions of major parts are uniform under given working conditions, and hardness difference of each part was small.

1. Introduction

The forming process of ultrastrength steel is a typical thermal-mechanical coupling process, which is affected by both plastic mechanics and thermodynamics [1–3]. Therefore, it is of great importance to control the temperature field of formed parts and die accurately. Designing stamping die sensibly can improve the efficiency of cooling system, which has an influence on the quenching process of formed parts and further affects their mechanical properties. During the high-temperature forming process, the microstructure of plate is made up with austenite, while in the synchronous quenching (the cooling and quenching processes occur simultaneously) process, because of the different heat transfer conditions between various positions of formed parts and die, diversified organizations such as ferrite + pearlite, bainite, or martensite will generate and influence the hardness and tensile strength of formed parts. Thus, to control the homogeneity of martensitic phase transitions of BR1500HS hot stamping parts during the cooling process, the optimization design of insert die's cooling system is essential.

There are already some research results of hot stamping technology for ultrastrength steel. Frank et al. from Germany designed the cooling channels of hot stamping die by adopting dynamic optimization analysis, which was a combination of FEM and genetic algorithm. Every working part was optimized during their optimization design, and the method was justified by thermal-mechanical coupling simulation [4]; based on Nakazima theory, Turetta et al. from Italy put forward a new test method to overcome the inferior forming performance of ultrastrength steel to some extent. In their method, the uniaxial tensile test and quenching were conducted simultaneously under different flow stresses, temperatures, and strain rates and the data of phase transformation were got by dilatometer [5]. The number of water gates and cooling channels was chosen by Hoffmann and Steinbeiss as parameters to optimize the uniformity and capacity of cooling system, and a better cooling system of hot stamping die was obtained [6]. The microstructure and mechanical properties of hot formed parts were analyzed by Alexander et al. under different cooling mediums and cooling rates [7]. The processing method of cooling channels in hot stamping die was researched by Karbasian and Tekkaya [8].

In China, Zhu studied the thermal balance and optimization design of cooling system of hot stamping die [9]; Li optimized the cooling system of die for producing automotive bumper [10]; and Wang analyzed the influence of cooling rate and pressure maintaining time on microstructure and mechanical properties by using the mixed cooling system [11]. The effect of cooling channel's diameter and their interval was simulated by Meng [12].

Most research studies available now about the cooling system of die for ultrastrength steel are based on simulation and optimization of parameters of integrated die's cooling system. However, few research studies about optimization design of insert hot stamping die's cooling system and the microstructural uniformity control of martensitic phase transitions in the synchronous quenching process are conducted. The formed parts are quenched by die surface fast in the synchronous quenching process, and the phase transitions of austenite into martensite can strengthen them. In addition, by controlling the water velocity in each insert, the homogeneity of martensitic phase transitions can be improved.

In this paper, the insert hot stamping die's cooling system was optimized based on the features of A pillar of automobile and CAE software. The temperature's change rules of formed parts as well as dies were analyzed, based on which the homogeneity of martensitic phase transitions in the synchronous quenching process was studied.

2. Cooling System of Insert Hot Stamping Die

2.1. Purpose and Experimental Material. The optimization design of die's cooling system is a key point of hot stamping technology, which can determine the quality of formed parts. Meanwhile, the A pillar is one of the most critical components of an automobile. In this paper, we optimized the die for A pillar's production to improve the uniformity of martensitic phase transitions. BR1500HS is a kind of hot rolled plate (1.8 mm) produced by Baoshan Iron & Steel Co., Ltd, which has no clad layer. The composition of BR1500HS is shown in Table 1.

The microstructure of BR1500HS before hot stamping is mainly made up with ferrite and pearlite, and when it is heated to 900°C, its microstructure is dominated by austenite. After the forming process in dies, the formed part is cooled at a rational speed to get martensite, which can increase the formed part's strength to 1500 MPa.

2.2. Die Structure and Hot Stamping Part. Figure 1(a) shows the die structure for the hot stamping process, and Figure 1(b) shows the blank as well as a formed part. The hot forming mold system is composed of die, blank holder, punch, and cooling system. Especially, in order to cool the piece quickly, the die and punch are made by some insert blocks. All of this can be explained in Figure 2.

2.3. Cooling System of Insert Hot Stamping Die

2.3.1. Temperature Field Distribution of the Formed Part. Because of energy loss, the part's initial temperature was set as 950°C in simulation (900°C, actually, in practical production). After the hot stamping process (without the cooling process), the temperature distribution of part surface is shown in Figure 3. The heat of blank lost through heat conduction and heat radiation during the hot stamping process and the temperature of the formed part decreased as whole. The heat loss of central section was more difficult than that of edge section, and the temperature of these two positions was 600~700°C and 800~900°C, respectively. In addition, the temperature distribution had a strong relationship with the order and amount of deformation, while they are relatively uniform and within the best temperature range for deformation. From Figure 3, we can see that the cooling channels should be mainly arranged on the top of punch and the water velocity in each insert block should be controlled to increase the cooling efficiency of high-temperature positions.

2.3.2. Structural Design of Insert Hot Stamping Die's Cooling System. The cooling system of hot stamping die usually consisted of two parts: the external water circulation system and power system; the internal cooling channels. Meanwhile, the water circulation system is made up with pipes, and the cooling channels are usually got by boring within the die.

To realize the quenching process of formed parts after forming, the efficiency of cooling system should be enhanced and the temperature distribution of die surface should be as uniform as possible. The layout of cooling channels, the size of insert blocks, and the metal flow of blank should be taken into consideration when designing the insert die structure. Therefore, based on the features of part, the punch is designed to be made up with 8 insert blocks, while the die is consisted of seven insert blocks, as shown in Figure 2.

The insert block 7 of die, which is fixed on die holder by several location pins, is chosen to illustrate the insert cooling system in detail. From Figure 2, we can see that several through-holes are bored in the horizontal direction as cooling channels within insert block 7 and several bores are bored from bottom of block 7 vertically, which intersects the horizontal channels, and a circulating water cooling system is developed.

A new design method of the joint of internal water channels and external pipes is put forward in this paper, where two catch basins are adopted at the contact position of vertical channels and die holder. Then, a through-hole is bored at the bottom of each catch basin, which links it with external pipes, as shown in Figure 2. Therefore, the two catch basins in die holder can link the internal several water

Table 1: Composition of BR1500HS.

Material	C	Si	Mn	P	S	Cr	B	Al	Ti
BR1500HS	0.21	0.27	1.33	0.0098	0.0011	0.12	0.0023	0.039	0.047

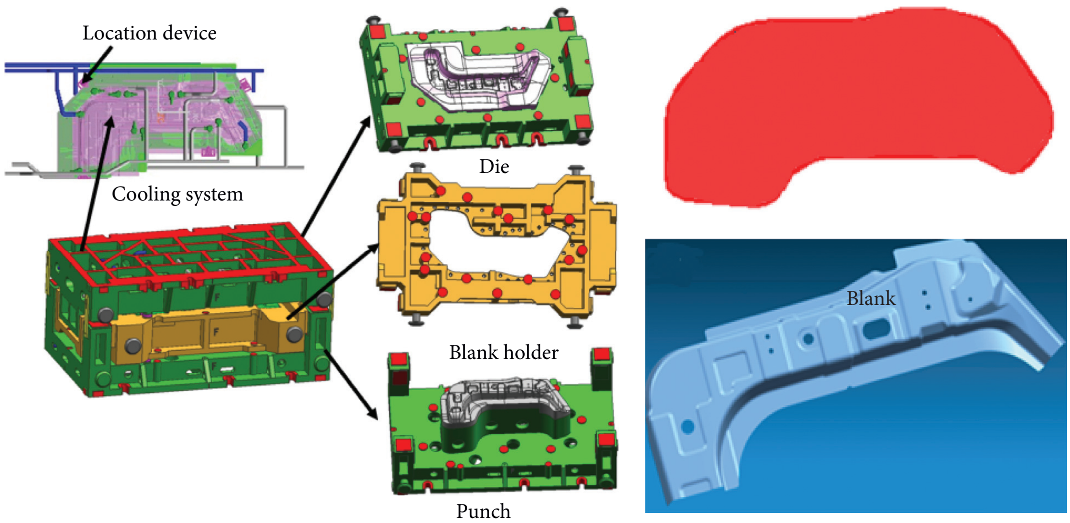


Figure 1: (a) Mold structure; (b) blank and formed part.

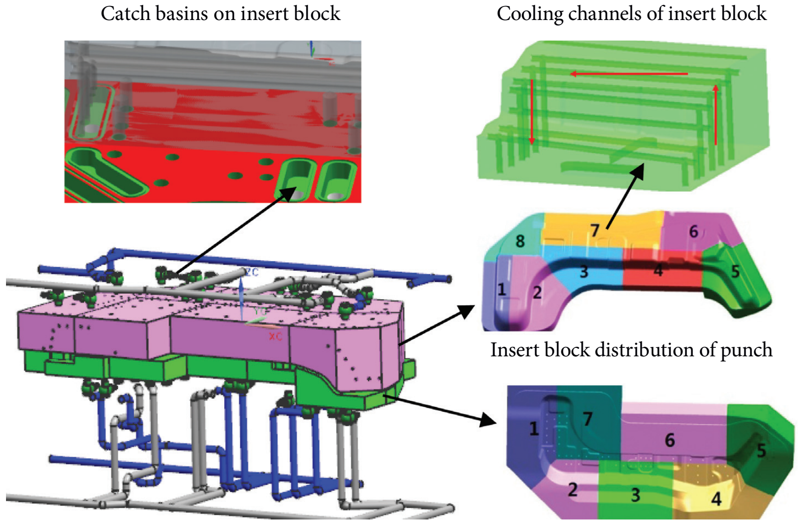


Figure 2: Cooling system in insert hot stamping die.

channels with one external pipe, which is much more compact.

3. Optimization Design of Hot Stamping Die's Cooling System

3.1. Parameters Design of Cooling Channels. The design of cooling channels includes the number, diameter, and position of the channels, which has a crucial influence on the cooling effect and cooling homogeneity of dies surface. To design the parameters of cooling channels rationally, the quenching process characteristics of BR1500HS should be clear: thickness = 1.8 mm; the yield strength σ_b = 462 MPa; the tensile strength σ_s = 627 MPa; and the elongation δ = 20%.

Generally, 10% of blank's heat will be absorbed by air, while the rest heat will be taken away by the cooling system. The heat of each blank is calculated 13 as follows:

$$Q = m \cdot C_p \cdot (T_1 - T_2), \tag{1}$$

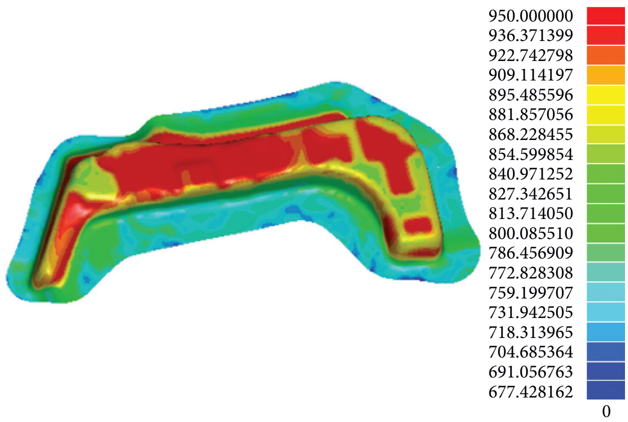


Figure 3: Temperature field distribution of piece.

where m is the mass of A pillar, $m = 5.4\,\text{kg}$; C_p is the heat specific volume of BR1500HS, $C_p = 0.46\,\text{kJ/(kg}^\circ\text{C)}$; T_1 is the temperature when quenching process begins, $T_1 = 850^\circ\text{C}$; and T_2 is the temperature after the quenching process, $T_2 = 420^\circ\text{C}$. The temperature difference can realize the martensite phase transformation and guarantee the high strength of formed parts. Therefore, the heat taken away by the cooling system is as follows [13]:

$$Q_w = 0.9Q = C_w \cdot m_w \cdot \Delta T, \tag{2}$$

where C_w is the heat specific volume of water, $C_w = 4.187(\text{J/(kg}^*\text{K))}$; m_w is the mass of water, which flows through the cooling channels; and ΔT is the temperature difference of water between inlet and outlet, $\Delta T = 15^\circ\text{C}$. The value of m_w is as follows [13]:

$$m_w = \frac{\pi D^2}{4} v t \rho, \tag{3}$$

where v is the water velocity in cooling channels; t is the flow time of water, which means the time for quenching, $t = 15\,\text{s}$; ρ is the density of water, $\rho = 1000\,\text{kg/m}^3$; and D is the equivalent diameter of cooling channels on the cross section of die. So,

$$D = \sqrt{\frac{3.6 \cdot C_p \cdot (T_1 - T_2)}{\pi \cdot C_w \cdot \Delta T \cdot v \cdot t \cdot p}} = \sqrt{\frac{3.6 \times 5.4 \times 0.46 \times (850 - 420)}{3.14 \times 4.1874 \times 15 \times 1000}} \approx \frac{0.03688}{\sqrt{v}}. \tag{4}$$

When $v = 1\,\text{m/s}$, $D = 36.88\,\text{m}$. Based on the law of conservation of mass [13],

$$\frac{\pi D^2}{4} v \cdot t \cdot p = n \cdot \frac{\pi d^2}{4} v \cdot t \cdot p, \tag{5}$$

where n is the total number of cooling channels in one cross section and d is the diameter of each separate cooling channel [13]. Thus,

$$d = \frac{D}{\sqrt{n}}\,\text{mm}. \tag{6}$$

In actual production, the thickness of blank is ignored, and thus, the contact area between die and formed part equals to the surface area of blank [13]:

$$n \geq \left(\frac{S}{\pi Dl}\right)^2, \tag{7}$$

where S is the surface area of blank, $S = 529896\,\text{mm}^2$, and l is the length of one cooling channel, $l = 1200\,\text{mm}$.

$$n \geq \left(\frac{529896}{3.14 \times 36.68 \times 1200}\right)^2 = 15.26. \tag{8}$$

Therefore, the minimum number of cooling channels in one cross section is 16, and the diameter of each separate cooling channel is calculated as follows [13]:

$$d = \frac{D}{\sqrt{n}} = \frac{36.88}{\sqrt{16}} = 9.22\,\text{mm}. \tag{9}$$

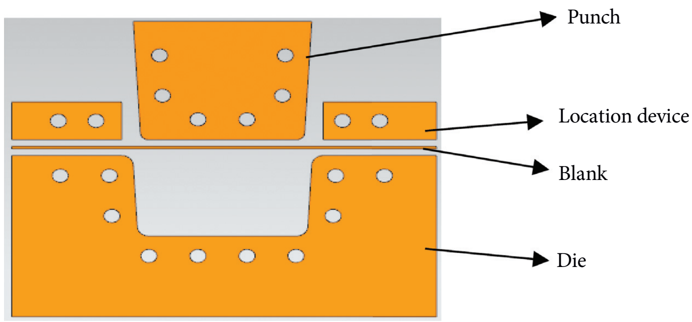
The round number of d is 10 mm.

3.2. Structural Optimization of Cooling System Based on FEM

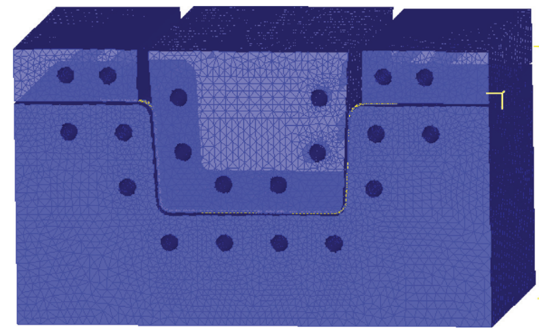
3.2.1. FEM Modeling. The research object is A pillar of automobile, as shown in Figure 1(b). This part is big and complex-shaped, and the hot stamping die for it is consisted of 15 insert blocks, which makes the simulation time-consuming if we simulate its forming process integrally. Therefore, a model of U-shaped part, which was very similar to the middle structure of A pillar, was established based on its geometric dimension, as shown in Figure 4(a). The process of establishing of a finite model was constructed in Figure 4(b). Then, the influence law of cooling system's parameters was simulated on CAE software, and the simulation parameters are as follows: the initial temperature of BR1500HS blank is 950°C; the die material is 5CrMnMo; the initial temperature of dies was 20°C; the temperature of water at inlet is 20°C; the heat conduction coefficient of water is 4174 W/m·K; and the time for both pressure maintaining and quenching processes is 15 s.

3.2.2. Parameter Setting. The hot stamping is a complex process along with temperature variation and phase transformation, and in this process, stress and strain affect each other. Therefore, in order to improve the accuracy of the numerical simulation of the hot stamping process, accuracy of data on the thermal properties of water and materials, thermal conductivity, and other essential data are required, such as thermal physical property parameters of hot die work steel 5CrMnMo and BR1500HS, which is shown in Table 2. The thermal properties of water are shown in Table 3, and basic thermal physical parameters of air (485°C) are shown in Table 4.

Based on the DSC404C differential scanning calorimeter, the specific heat capacity of the material is tested using the sapphire method. By comparing the measurement results of the known specific heat standard sample and the unknown specific heat test sample, the specific heat value of the unknown sample is calculated.



(a)



(b)

Figure 4: Establishment of the finite element model of the U-shaped part.

Table 2: Thermal physical property parameters of hot die work steel 5CrMnMo and BR1500HS.

Material	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Specific heat (J/kg·K)
5CrMnMo	7850	210	0.3	400
BR1500HS	7800	210	0.3	

Table 3: Basic thermal physical parameters of water.

Density (kg/m^3)	Thermal conductivity (W/m·K)	Specific heat (J/kg·K)	Kinematic viscosity (m^3/s)
998	4174	0.55	1.00$e-6$

Table 4: Basic thermal physical parameters of air (485°C).

Temperature (°C)	Density (kg/m^3)	Specific heat (J/kg·°C)	Thermal conductivity (W/m·K)	Viscosity (m^3/s)	Thermal expansion rate (1/K)
460	0.471	1087	0.055	3.48e^{-6}	1.32e^{-3}

Specific heat capacity curve fitting of BR1500HS is shown in Figure 5(a). Specific heat capacity curve fitting of CrMnMo is shown in Figure 5(b).

3.2.3. Parameter Optimization. From Figure 6(a), we can see that the temperature of punch corners was higher because of the longer distance to cooling channels, which resulted in heat accumulation. Meanwhile, the two cooling channels at the top of punch walls contributed little to the cooling efficiency. Therefore, the four cooling channels at punch walls moved down, and the diameter of the two cooling channels at punch corners increased from 10 mm to 12 mm, as shown in Figure 5(b). The parameter optimization improved the cooling effect at punch corners, and the cooling efficiency of each cooling channel was also enhanced, which led to the highest temperature of the punch decreasing by 15°C.

Although the overall temperature of die is a little higher than that of punch, the temperature distribution of die is similar to that of punch, and die corners witnessed the highest temperature. Therefore, a similar optimization method was adopted, which included moving the two cooling channels inwards and increasing their diameter from 10 mm to 12 mm. Meanwhile, one more cooling channel was added to each side wall to improve the cooling efficiency here, as shown in Figure 7. The highest temperature of die decreased by 12°C.

3.3. Temperature Field Analysis of U-Shaped Part. To analyze the temperature field's change rule of punch and die in the synchronous quenching process, the heat transfer process of both individual production and quantity production was simulated. In individual production, the initial temperature of die was 20°C. In quantity production, the initial temperature of die was 20°C in the first stamping process, while the initial temperature of die in the next stamping process was the temperature of die after the synchronous quenching process in the previous stamping process. The time for synchronous quenching process in both individual production and quantity production was 15 s.

Four reference points were chosen to track the temperature change of formed part. The heat transfer coefficient of cooling water was 4021 (W/(m^2·K)), and the water velocity was 1 m/s. Figure 8 shows that the maximum and minimum temperatures of the formed part were 187°C and 53.6°C, respectively, in individual production.

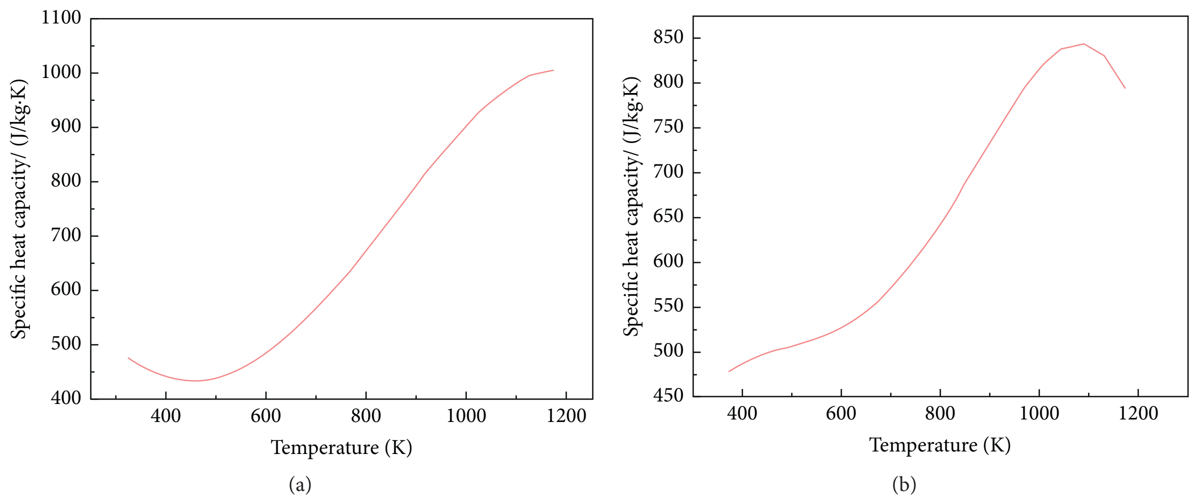


Figure 5: Specific heat capacity curve: (a) BR1500HS; (b) CrMnMo.

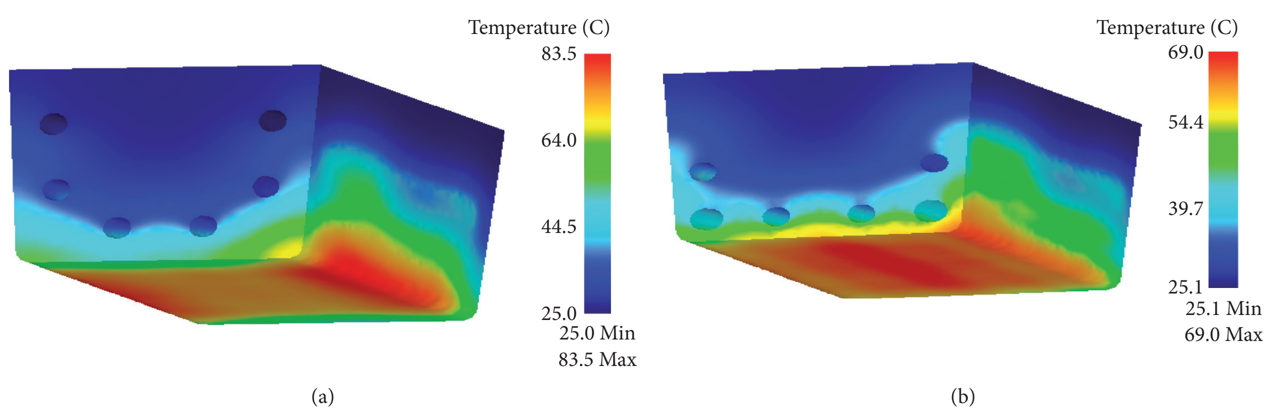


Figure 6: Parameter optimization of the cooling channels in punch.

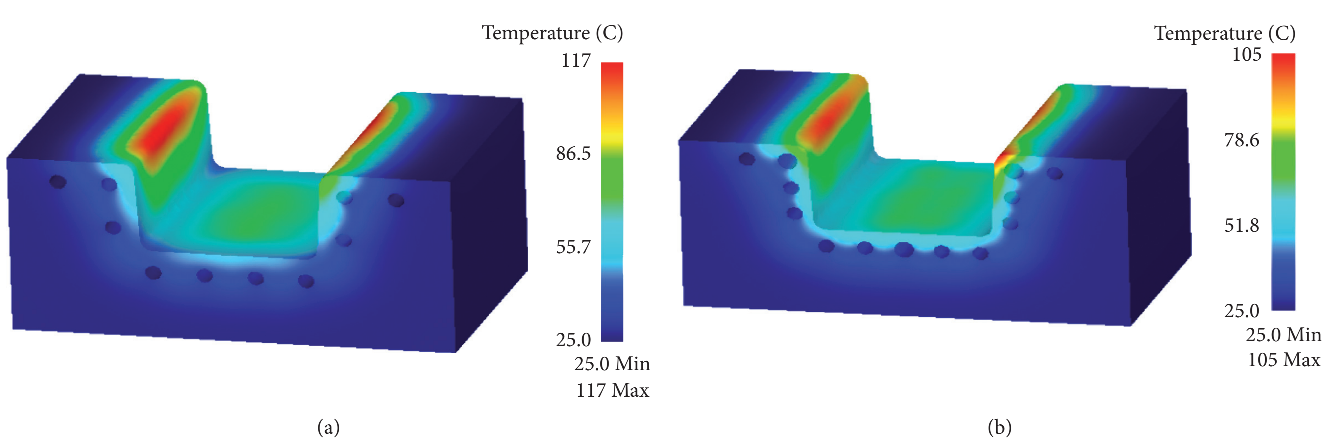
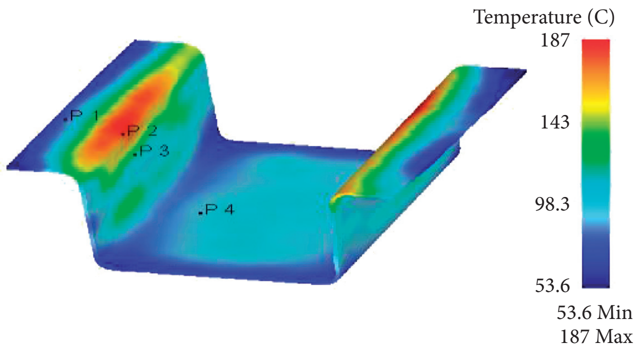


Figure 7: Parameter optimization of the cooling channels in die.

To analyze the influence of cooling system on the punch and die in quantity production, a continuous production of 10 parts was simulated. Figure 9 shows the temperature distribution of the second, fourth, eighth, and tenth formed part. From the figure, we can see that, with the increasing times of stamping process, the highest and lowest



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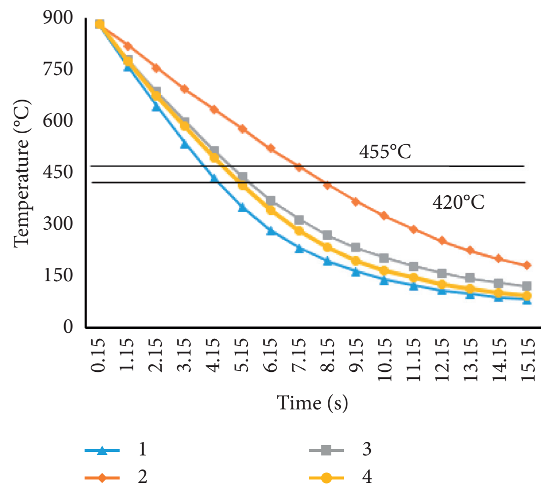
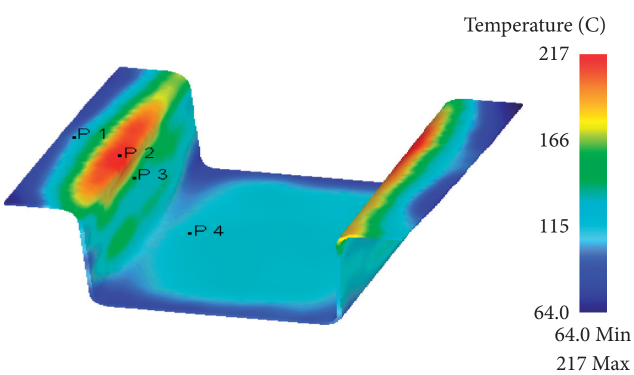


(b)

FIGURE 8: Temperature distribution of the formed part and change rule of reference points' temperature during the synchronous quenching process in individual production.



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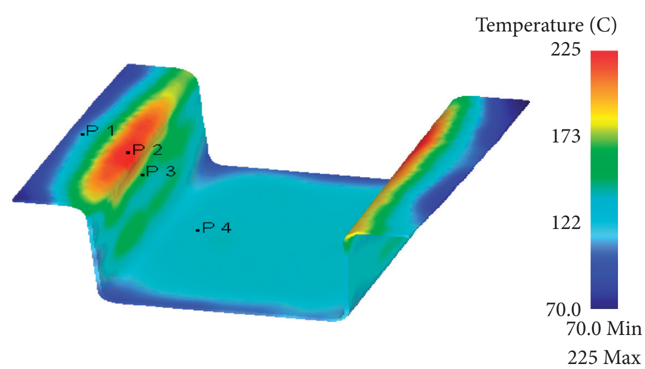

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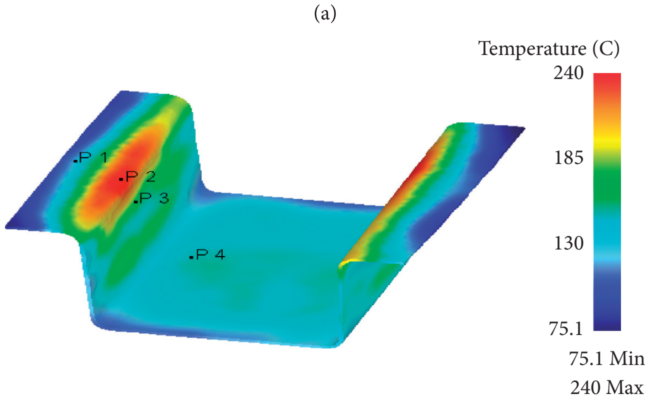

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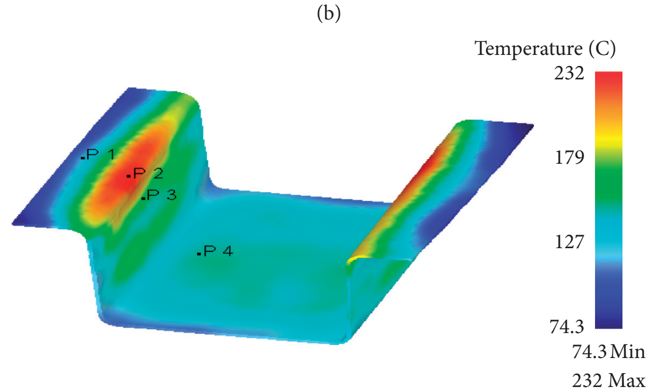

(d)

FIGURE 9: Temperature distribution of the formed part after the synchronous quenching process in quantity production: (a) the second formed part; (b) the fourth formed part; (c) the eighth formed part; (d) the tenth formed part.

temperatures as well as the temperature field distribution of the formed part stabilized.

Four reference points were chosen at the same positions to track the temperature change of these ten parts, as shown in Figure 10. From Figure 10, we can see that the temperature of formed parts after the synchronous quenching process had a slight increase at beginning, and with the increasing times of stamping process, the temperature of each part tended to be steady. Therefore, the heat accumulation generated during quantity production was

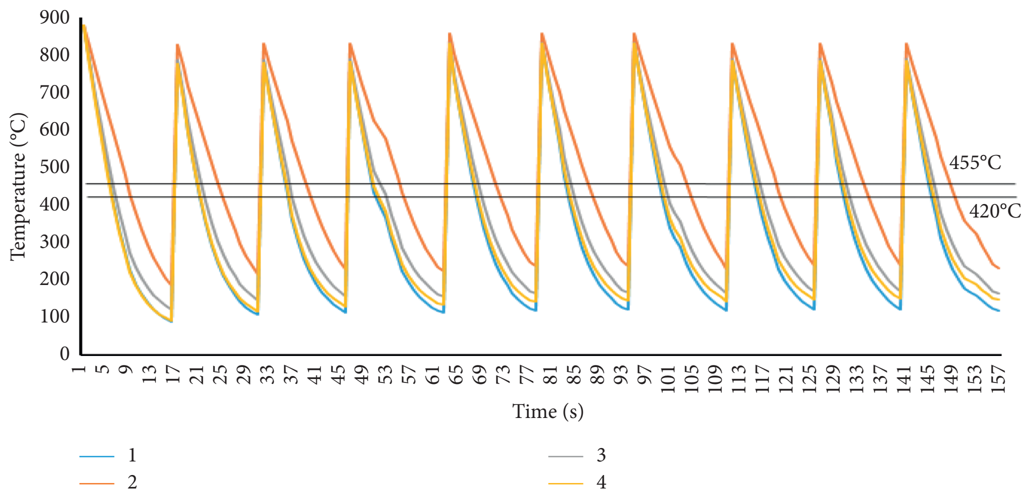

FIGURE 10: Change rule of reference points' temperature during the synchronous quenching process in quantity production.

taken away by the cooling system, which guaranteed a stable temperature field for each part.

4. Microstructural Uniformity Control of Martensitic Phase Transitions in Synchronous Quenching Process and Application Test

At the beginning of the ultrastrength steel's hot stamping process, austenitic transformation occurred when the blank was heated to 900°C and the microstructure changed to austenite from ferrite + pearlite. The grain size and the homogeneity degree of austenite were key factors influencing the microstructure and properties of the formed part. After the forming and cooling processes, the microstructure of the formed part turned out to be martensite and a little bainite. Therefore, by controlling the heat temperature and cooling speed, the microstructural evolution rule of ultrastrength at the heating and quenching processes can be analyzed, which is beneficial to improve the production's quality.

4.1. Microstructure after Synchronous Quenching Process. To realize the synchronous quenching of ultrastrength, insert hot stamping die was adopted. By controlling the water velocity of each insert block and by regulating the parameters as well as control strategies, the uniformity of martensitic phase transitions in the synchronous quenching process was improved.

Heat BR1500HS to 900°C, cool it, and then use the reagent (alcohol + hydrochloric acid) to corrode it. The microstructure at the heating and the quenching process is shown in Figure 11. After heat preserving for 2 mins at 900°C, the austenite crystal nucleus developed at the interface between ferrite and cementite. When the cementite dissolved in austenite completely, an approximately uniform austenitic microstructure was got, as shown in Figure 11(a). In addition, the reasonable heating temperature and heat preserving time were of great importance on the martensitic phase transitions in the synchronous quenching process. Figure 11(b) shows that uniform martensite developed when the high-temperature austenite cooled at a high speed to below 420°C, which could strengthen the formed part.

4.2. Application Test. In the application test, the heat preserving process of blank lasted for 2 mins at 900°C to get complete austenite. The cooling speed was 40°C/s; the unit deformation force of blank was 2.2 MPa; the unite blank holder force was 0.1 MPa; the stamping velocity was 40 mm/s; and the time for pressure maintaining was 15 s. Figure 12(a) shows the hot stamping die structure used in our application test, and Figure 12(b) shows the cooling system of the synchronous quenching process.

4.2.1. Microstructure and Hardness Test of the Formed Part. Several 10 mm × 10 mm samples (for microstructure and hardness tests) were cut down from the formed part, as shown in Figure 13. Then, the microstructure samples were grinded, polished, and corroded before being observed under NEOPHOT30 metallographic microscope. The hardness test samples were grinded until there was no scratch existing. After that, 25 test points were chosen on the hardness test samples, the interval of which was 2 mm. The test force for hardness was 1 kg, and the hold time was 10 s.

The microstructure of formed part's different positions is shown in Figure 14. The content and homogeneity of martensite after hot stamping justified the effectiveness of process conditions. During the hot stamping process, position B was the first place contacting the die which was followed by positions C and D. Position A was the last one contacting the die among the four positions, and martensitic phase transitions here were the most insufficient. The earlier the blank contacted the die, the more sufficient the martensitic phase transition was.

Figure 15 shows the results of hardness tests of positions A, B, C, and D, which reflected the hardness distribution

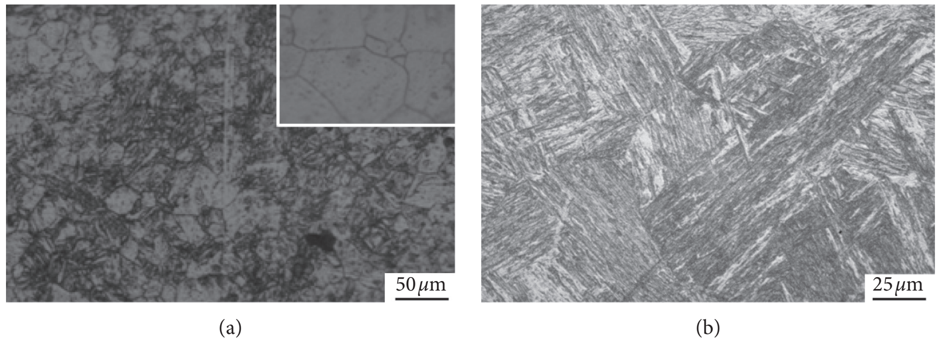

FIGURE 11: (a) Microstructure at 900°C; (b) microstructure after the synchronous quenching process.

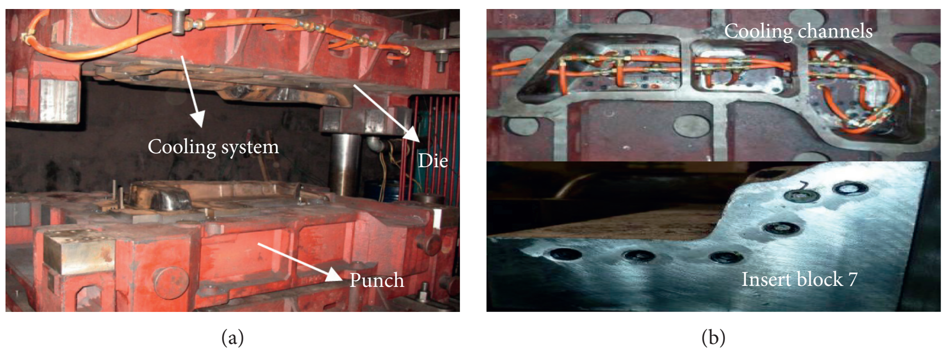

FIGURE 12: Die structure and cooling system of the synchronous quenching process: (a) die structure; (b) cooling system of the synchronous quenching process.

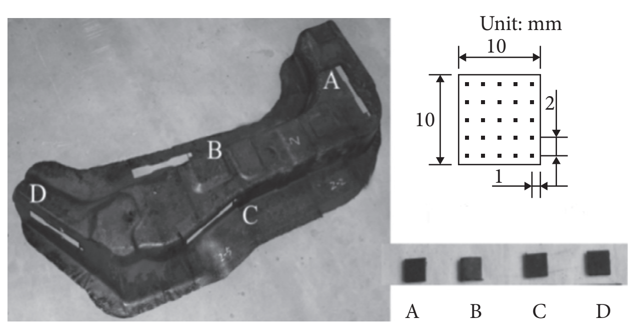

FIGURE 13: The formed part and samples for microstructure and hardness tests.

vividly. The average hardness value of positions A, B, C, and D was 463.1 HRV, 491.2 HRV, 473.5 HRV, and 486.7 HRV, respectively. Position B belonged to the highest hardness value among these four positions because of its highest content of martensitic phase. Although positions C and D had good material flow at corners, they contacted the blank holder a little later than position B, which made their hardness lower than that of position B. Position A was the last place contacting the die, and it had the lowest hardness value. Overall, the hardness distribution was approximately uniform, which was consistent with the homogeneity of martensitic phase transitions.

5. Conclusions

(1) By simulating the temperature distribution of formed part, the cooling channels should be arranged at the top of punch and the water velocity of each insert block should be rationally designed to control the uniformity of martensitic phase transitions.

(2) The structure of insert hot stamping die was designed, and the parameters of cooling channels were calculated. The number of cooling channels was 16, and their diameter was 10 mm firstly.

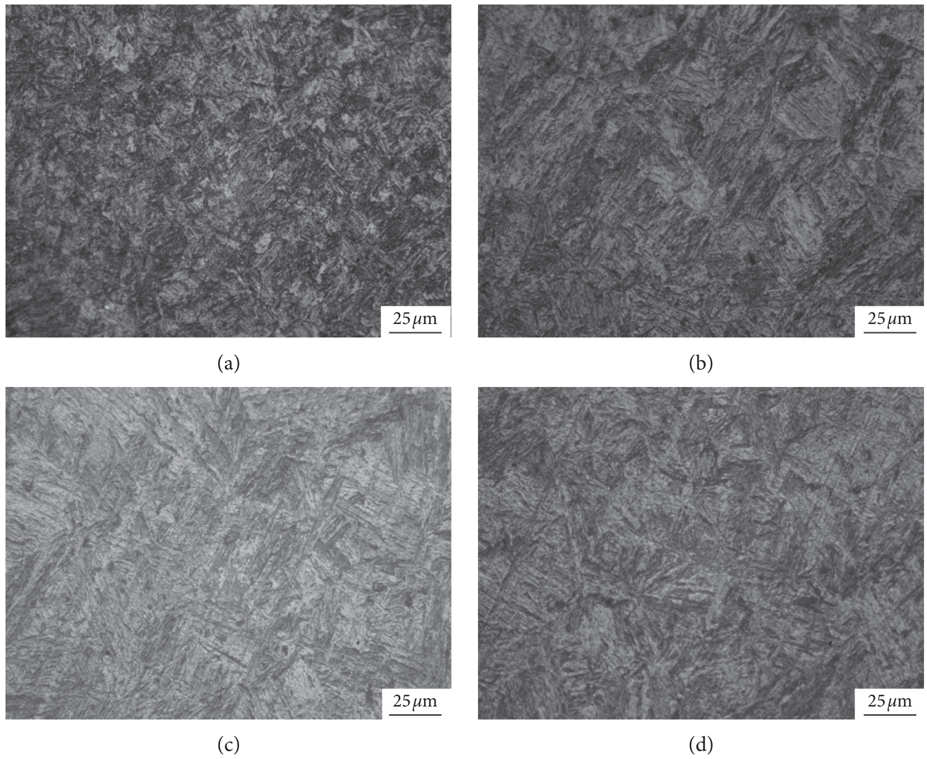

Figure 14: Microstructure of positions A, B, C, and D.

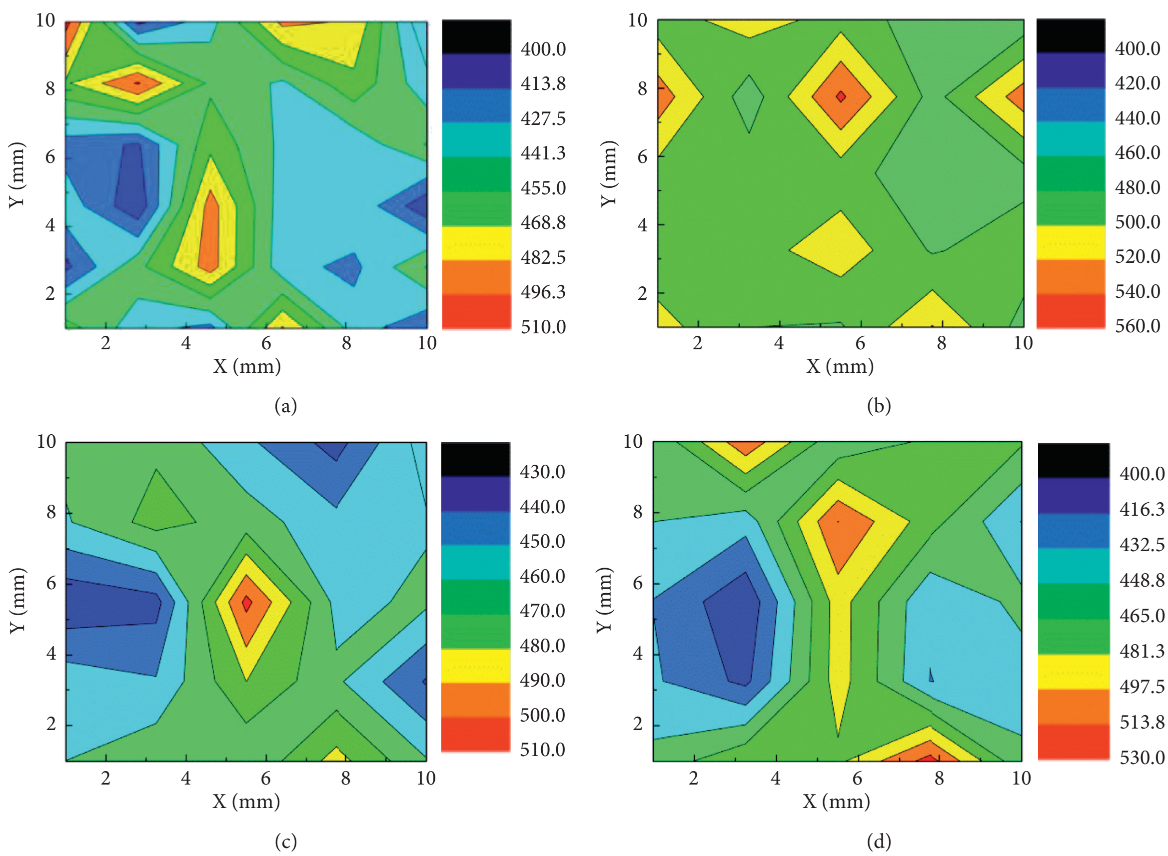

Figure 15: Hardness distribution of positions A, B, C, and D.

(3) Optimization design of the cooling system in punch and die was conducted based on FEM simulation. The diameter of the four channels at corners of punch and die was increased from 10 mm to 12 mm. The maximum temperature of punch and die after forming experienced a decrease of 15°C and 12°C, respectively.

(4) The phase transitions of ultrastrength steel during the hot stamping process were studied, which mainly included the microstructure change in the heating and the quenching process. The microstructural uniformity control of martensitic phase transitions in the synchronous quenching process was also researched.

(5) Application test was done, and four important positions were chosen to conduct the microstructure and hardness tests. The microstructure tests proved the sufficiency and homogeneity of martensitic phase transitions. The hardness tests demonstrated the uniformity of different places' hardness, which justified the effectiveness of the process conditions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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