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Hot Stamping Die Design for Vehicle Door Beams using Ultra-High Strength Steel

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The energy saving and safety is the eternal theme of development of automobile industry. Ultra-high strength steel automotive body structures of hot stamping have been widely used with these dual advantages that reducing vehicle weight while enhancing safety performance at the same time. The forming and quenching integration die was investigated in this paper with a vehicle door beam as an example, especially the whole die structure and hot stamping process were optimized through numerical simulation of die strength, cooling pipe arrangement and other related factors, and beam samples with tensile strength 1550Mpa, elongation rate 6.5% and shape accuracy of ±0.3mm were produced by this die. Moreover, the stiffness increased by 2.2 times than the original tube beam and 3.8 times of the intensity, which led to full score in C-NCAP Crash Test. By reducing the thickness cross section and the depth of drawing comparing with the original tubular beam, door beam weight could be reduced by 9.32%, which had effective energy-saving and emission-reduction effect.

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NOMENCLATURE

R_m = tensile strength
$A_{11.3}$ = percentage elongation

1. Introduction

Light weight auto-body and passive safety of passengers become trend of automotive industry, while energy saving and environment protecting deeply wised. Application of ultra-high strength steel with dual advantages of weight-light and safety improvement performance grows rapidly, also with characteristics of both high-strength and high-precision, has become a industry hotspot.

On one hand, the forming process parameters are the key points of hot stamping technology, on the other hand, hot stamping die needs to set cooling system to ensure the die function of stamping and quenching, which is quite different from the common stamping mold. The main parameters including heating temperature, holding time, forming speed, impulse pressure, holding time, open mold temperature, flow velocity and etc., should be optimized during hot stamping process primarily for guaranteed high-intensity and high-precision of forming parts. Taking a Chinese independent brand car door beam as an example, ultra-high strength steel hot stamping technology and lightweight design were studied in this paper.[1-3]

2. Development of hot stamping die for ultra-high strength steel door beam

2.1 Material optimization of hot stamping die

During hot stamping process, phase transformation strengthening of parts after forming is completed through the dies, so the dies require creation of cooling pipes inside to realize a cooling quenching function.[4,5] From the point of view for material properties, die material must have high thermal conductivity coefficient in order to achieve rapid and uniform cooling effect, better thermal fatigue performance and high heat strength to work under long-term alternation of heating and cooling state, strong wear-resistance to bear thermal friction of high temperature blank and its oxidation skin.[6-8]

Hot working die steel material of HHD containing high chromium in the composition (shown in Table 1) to enhance its corrosion-resistance was used. Under normal temperature, the

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Table 1 Composition of HHD (wt-%)

C	Cr	Mo	Ni	V	W	Si	Mn
0.2~0.35	8.0~13.0	1.0~2.0	0.7~1.3	0.4~1.0	0.3~1.0	0.7~1.3	0.2~1.0

Fig. 1 Door beam

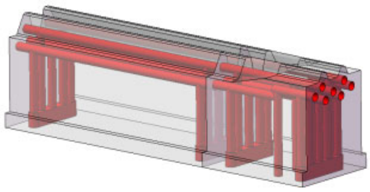

Fig. 2 Internal cooling pipes

hardness of HHD was above HRC48, which could keep as HV 498.2 at 600℃, showing high strength and good thermal stability at high temperature. And the material sh ows excellent wear-resistance at high temperature, which is less than a third of that of ASSAB8407.

Table 2 Parameters of cooling pipe

Depth from die surface to cooling pipe(mm)	5	10	15	20	25
Spacing between pipes (mm)	15	20	25	30	35
Dia. of cooling pipe (mm)	10	12	15	17	20

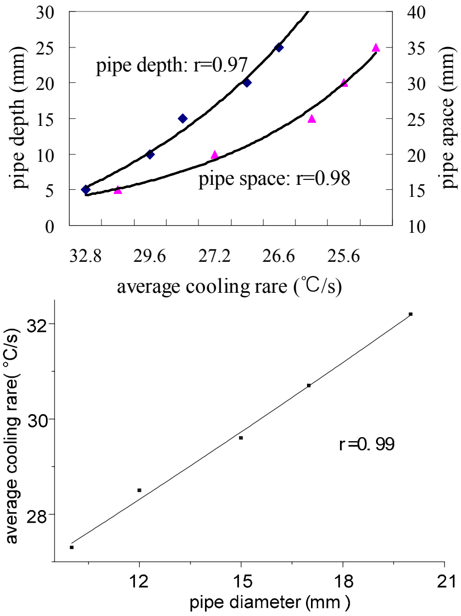

Fig. 3 Influence of cooling parameters

2.2 Development of ultra-high strength steel door beam and stamping die cooling system

Tubular beam including seamless tube and seam is a kind of door beam, among which the seam welded pipes with a maximum tensile strength of about 400MPa were manufactured by welding steel plates after being bent into pipes, and seamless steel pipes manufactured by drawing process had the tensile strength up to 600MPa, rare hardened tube got a tensile strength of 1400MPa. These door beams had simple structure and low manufacture cost, but relatively poor protection performance. Another kind of anti-collision door beam known as hat-shape beam was mainly divided into single-cap shape (U-type) and double-hat shape (W-type), whose tensile strength could reach above 1500MPa and get higher safety performance through hot stamping process, more widely used in European and American cars.

A door beam was optimized from seamless pipe to two-hat shape (thickness of 2mm, length of 1071mm, and width of 99.9mm) with the following shape shown in Fig. 1.

Cooling pipes were arranged in even distribution to maintain good cooling efficiency, as shown in Fig. 2, bolt seal method was used on the end of die and O-shape sealing rings were used at the bottom to prevent leakage of high-speed cooling water circulation. The cooling rate was guaranteed by water velocity regulated according to production cycle, and the appropriate temperature of cooling water was selected.[9,10]

2.3 Design of cooling parameters

Cooling system of hot stamping die influences not only the completion of forming and quenching but also final properties of the parts. The parameters include such three aspects as depth from die surface to cooling pipe, spacing between pipes (pipe center distance) and the diameter of cooling pipe, that is, location, arrangement and pipe shape.

Pre-condition for a numerical simulation as initial die temperature of 20℃, initial blank temperature of 890℃, cooling water flow rate of 1m/s, and other cooling parameters are given in Table 2. The simulation results were shown in Fig. 3.

As shown in Fig. 3, with increasing of depth from die surface to cooling pipe and space between pipes, the average cooling rate decreases; with increasing of pipe diameter, the average cooling rate linearly increases. And the greatest influence factor on cooling effectiveness is depth of pipe from the surface, followed by pipe spacing, and finally pipe diameter, that is, calculative determination of depth from die surface to cooling pipe should be considered first during design of die cooling system, and it is also the basis of the reasonable design of pipe spacing and pipe diameter. The depth from die surface to cooling pipe of 10mm, pipe spacing of 15mm and pipe diameter of 10mm was the optimized result of the simulation.

The design of cooling pipe should make sure that the die could keep ensuring sufficient strength during hot stamping process, so the overall strength intensity of the die needs to be checked firstly. The next numerical simulation boundary conditions were as friction coefficient of 0.03, forming speed of 50mm/s, the stress field and force were shown in Fig. 4. The results showed that there was no damage on die because the maximum deformation was only 0.027mm, which was in the elastic deformation range.

The stress simulation results showed that the stress is far less

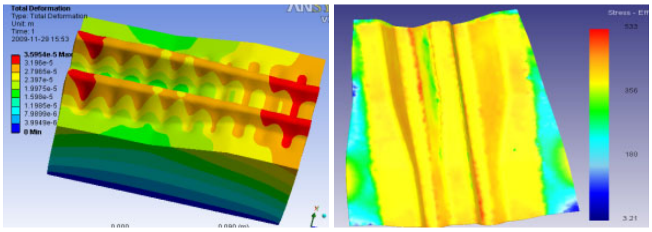

Fig. 4 Strain field simulation of hot stamping die

Fig. 5 Hot stamping die with different design of cooling system

than that of the blank mechanical strength, cracking phenomena would not happen. The corresponding door beam die entities was shown in Fig. 5.

3. Hot stamping process applications

3.1 Hot stamping simulation

Hot stamping process mainly concerns on high temperature deformation behavior of sheet, which is closely related to optimization of process parameters. In this paper, Baosteel hot-rolled BR1500HS (compositions shown in Table 3), with hardness of HV193, tensile strength of 666MPa, microstructure of ferrite and pearlite was in experimental measurement. From CCT curve (Fig. 6), it could be seen that, AC_3 was 811℃, AC_1 was 736℃, critical cooling rate of 15℃/s, martensite start point was between the 350~380℃, the end point of was of 280~300℃.

Experiments were conducted using Gleeble-3800 thermal simulator to study the rheological behavior. Sample part was heated to 950℃ under 15℃/s speed, persevered at this temperature for 5 minutes to obtain homogeneous austenite organization, then quickly cooled to experiment temperature under speed of 70℃/s to complete isothermal tension test. During process of data analysis, Norton-Hoff's law was used to build the models:

$$\sigma = 50.12\varepsilon^{0.31}\dot{\varepsilon}^{0.07}\exp(2542/T) \qquad (1)$$

Numerical simulation of hot stamping was done according to property parameters and material model, and the results were shown in Fig. 8. Since most region of the anti-collision beam was bending and minority belonged to stretch, most zones had the same thickness. The material flowed quickly in zone A Fig. 7 and had big deformation, therefore there was the biggest thinning ratio of 20% and the maximum stress which would be easy to generate stress concentration. The material flow was extrusion at zone B, which had the highest temperature and increased thickness, for it was the last place touching the die. The lowest temperature was at sides, which cooled obviously for the greatest pressure here and first contacting with die.

Table 3 Composition of BR1500HS (wt-%)

C	Mn	B	Si	Cr	S	P
0.21	1.35	0.0033	0.28	0.23	0.004	0.0055

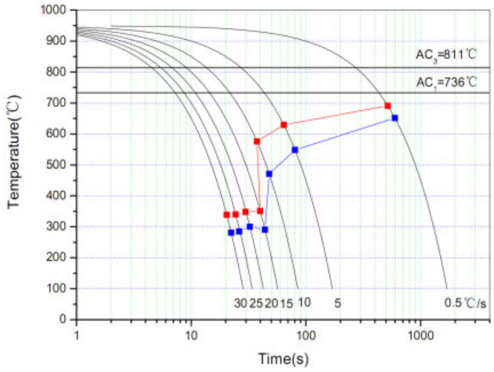

Fig. 6 BR1500HS CCT curves (from Baosteel)

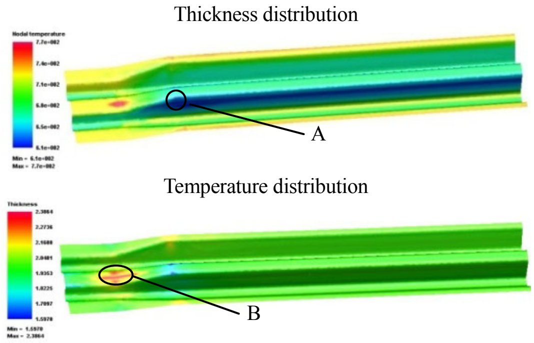

Fig. 7 Results of numerical simulation

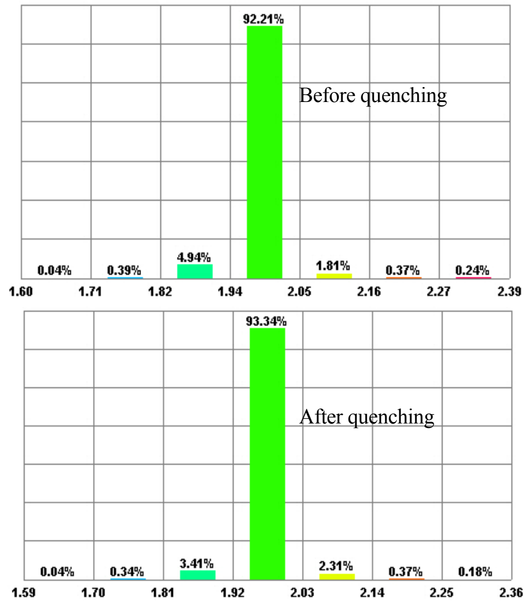

Fig. 8 Thickness of deformed parts

The lowest temperature of the part was above 600℃ according to the simulation results, which could meet requirements of martensite transformation. The highest temperature of the die was under 200℃ during the whole process, then the temperature of the formed part was below 150℃ and the temperature of the die was

Fig. 9 Broken part

Table 4 Bumper beams best hot stamping process parameters

Heating temperature	heating time	pressing speed	pressing force	Holding time	Flowing rate
930℃	4.5min	75mm/s	7MPa	15s	1.1m/s

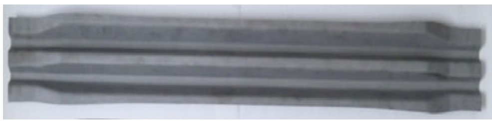

Fig. 10 Ultra-high strength steel door beam

below 60℃ after quenching time of 15s, and the parts were well-formed without wrinkle and crack.[11]

Quenching time was helpful for thickness distribution as same as martensite transformation of formed parts, and the results were shown in Fig. 8. It can be seen that the thickness was about 2mm (92.21%) after hot stamping, and the thickness was more uniformity (93.34% for 2mm) after quenching.

3.2 Hot stamping process and optimization

Tensile strength of steel plate at high temperature was just 100MPa, if there was blank holder force (BHF for short), the material flowed quickly and the parts was broken, since tensile strength of the parts could not be enough to sustain the friction resistance, and the phenomena could be seen from Fig. 9. Rarely wrinkling of hot stamping parts would emerge without BHF, since parts could stretch freely with low strength at high temperature.

Influence of heating parameters to micro-structural transformation was great according to experiments, so as the influence of forming parameters to mechanical properties of hot stamping parts. Since quenching time was significant for martensite transformation with reasonable cooling speed, and stamping force influent to shape of stamping parts. Besides, the transfer time of blank was an important factor, that is, with increasing of transfer time, initial deformation temperature decreased, and larger pressure was needed to finish stamping. Furthermore, martensite transformation would not be completed.[12]

Optimum processing parameters were summarized as Table 4, and excellent anti-collision beams quality was gotten in practice which was shown as Fig. 10.

3.3 Mechanical properties testing and analysis

The results of tensile tests, hardness tests, thickness tests, residual stress tests and accuracy tests were shown in Table 5, from which the following conclusions could be drawn that tensile strength achieved 1550MPa, 3.8 times of the cold bending beam pipe (about 400 MPa), the maximum thinning rate was 17% which meeting the stamping thickness requirements, white light scanning

Table 5 Hot stamping door beam performance parameters

HRC	Rm/MPa	$A_{11.3}$/%	Maximum thinning rate	Max residual stress (MPa)	Dimensional accuracy (mm)
48	1550	6.5	17%	264	±0.3

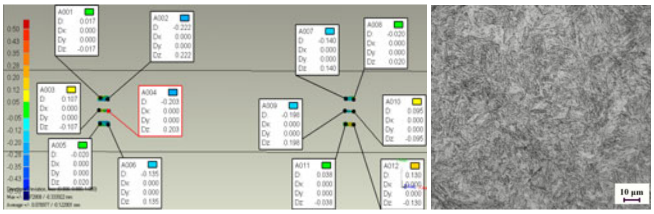

Fig. 11 Results of scanning test and uniform microstructure

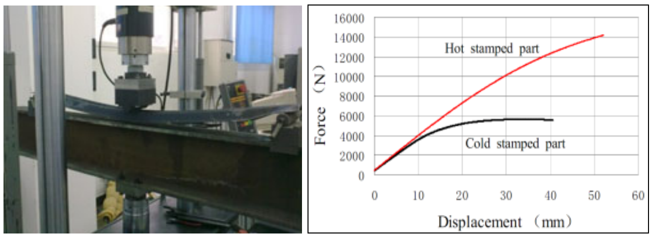

Fig. 12 Comparison of three-point bending test

Fig. 13 Vehicle side impact contrast of cold bending pipe (left) and hot forming door beam (right)

displayed that size accuracy of the welding surface at both ends of the beam completely satisfied requirement of welded assembly precision (± 0.5mm) shown as Fig. 11, and the microstructure displayed as uniform lath martensite.

Three-point bending test as Fig. 12 showed that cold bending pipe beam could not continue to bear force above when the displacement was above 20mm, while hot stamping could bear greater force with good elasticity, which was 2.5 times of that for cold bending pipe beam.

According to automotive side impact standard of GB20071-2006, vehicle side impact contrast pictures with cold bending pipe and hot forming door beams were shown in Fig. 13. Under assessment in accordance with C-NCAP regulations, score of vehicle with cold bending pipe was 10.85 points, while score of vehicle with hot stamping door beam was 16 points (full marks). Ultra-high strength steel played an important role in enhancing the overall vehicle side impact safety performance and ensured that all indicators met the national standard collision.

Compared with the cold bending pipe parts, 2mm thickness W-type hot stamping door beam had a significant increase in safety performance, with weight increased by 38%. To meet the requirements for lightweight auto-body, two kinds of design

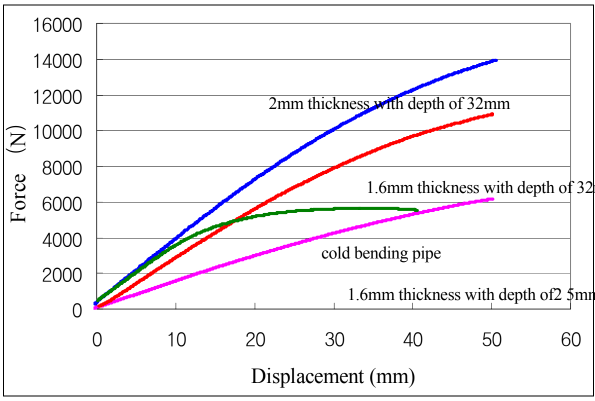

Fig. 14 Three-point bending test comparison curves of 4 kinds of door beam

optimization were developed on both depth and thickness of this kind of beam. While hot stamping steel sheet thickness reduction from 2mm to 1.6mm, weight of the beam increased 7.7% than that of the cold bending pipe; when keeping the length and the width dimension constant, while reducing the depth from 32 mm to 23.6 mm, weight of the beam decreased 9.32%, all led to energy conservation and emission reduction.

Three-point bending experiments of door beams (Fig. 14) showed that, with the reduction of sheet thickness or the reduction of depth, bending property of hot stamping beam reduced synchronously, and thickness of sheet metal played less important role on the bending property, so automotive parts could achieve more lightweight from thinning thickness while achieving weight loss purpose.

As shown as Fig. 14, the deformation of lightweight optimization door beam increases 15mm compared to 2mm that of thick 32mm deep door beam, 6.7% of the original deformation, the deformation increasing amount would have no effect on the automotive side impact test results, that was, the improved lightweight door beams satisfied double requirements of safety and lightweight.[13]

4. Conclusions

(1) The most influential factor on cooling effectiveness of pipe is depth of pipe from die forming surface, followed by pipe spacing and pipe diameter. Depth from die surface to cooling pipe should be basis of reasonable design of pipeline spacing and diameter.

(2) Hot stamping die developed with optimized system and process parameters could guarantee full martensite microstructure and excellent mechanical performance, with average tensile strength of 1550Mpa, elongation of 6.5%, shape accuracy of ±0.5mm; and the optimization process parameters were heating temperature of 930℃, holding time of 4.5min, forming speed of 75mm/s, punching pressure of 7MPa, quenching time of 15s, flow velocity of 1.1m/s.

(3) The ultra-high strength steel door beam was optimized to realize crash test full marks, with stiffness increased of 2.5 times, strength increased of 3.8 times, lightweight of 9.32% than that of original pipe, which achieved dual objectives of security and lightweight.

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