SPRINGBACK OF HOT STAMPING AND DIE QUENCHING WITH ULTRA-HIGH-STRENGTH BORON STEEL

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Abstract:

Hot bending and die quenching for U-shaped parts with ultra-high-strength boron steel were experimented and simulated to study the effect of die geometric parameters on springback and its mechanism. The results indicate that through hot contact bending and die quenching, bending parts with higher strength than that of cold stamping can be achieved, the tensile strength of which can reach 1500MPa. The springback angle of hot bending part increases by increasing the die radius, by increasing the gap between the punch and the die. Springback is mainly negative caused by/due to different cooling rate and the impact of thermal restoring moments. This provides a basis for the control of the hot stamping process applied in the production of complicated shape parts.

1 Introduction

In order to realize the sustainable development of human society, stricter requirements for automotive products have been put on safety, environment protection and energy-saving. In this context, there has been a general trend that body parts of automobile reduce weight by using thinner (and thinner) ultra-high-strength steel. However, when material strength is increased, the formability decreases greatly so that the traditional stamping process at room temperature can hardly guarantee the quality and shape precision of the forming part. As a result, a novel hot stamping process for ultra-high-strength boron steel has been proposed. It is a new process of heating boron steel to a proper temperature above the recrystallization temperature, at which the boron steel plate is in austenitic state and then of forming parts in hot stamping die, and finally of cooling and quenching the part with die cooling system, resulting in ultrahigh strength. The greatest difference drawn between new hot stamping technology and common hot stamping technology is that after hot forming of sheet material, the rapid quench(ing) cooling of the part is realized with die casting cooling system instead of air or water cooling to obtain martensite, namely, to achieve stamping parts with tensile strength about 1500MPa or above [1, 2]. In recent years, research into the development of ultra-high-strength boron steel and hot stamping technology has been actively carried out by automobile industry and steel industry in different countries throughout the world. Major auto manufacturers in Europe, America, and Japan as well as in China have started using the hot stamping technology to produce the ultra-high strength boron steel parts for the production of side door beams, bumper beams, A, B, C columns, etc. [3, 4]. The method of hot forming is an effective way to improve formability of ultra-high-strength steel and to reduce deformation resistance as well as the amount of springback [5]. In order to examine thermo-mechanical flow properties of UHSS sheet metal in the process of hot forming, the model for describing the relationship between

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flow stress and temperature, strain as well as strain rate were established through experiments [6]. Since hot stamping with ultra-high-strength boron steel is a complex forming process related to material nonlinearity, heat effect, geometric nonlinearity, it is difficult to predict the results by means of analytical and experimental methods [7, 8]. Due to its ultra-high-strength, hot stamped parts can hardly be changed after being hot stamped. Therefore, hot stamped parts are required to have smaller springback. In this paper, research into the influence of die parameters on springback of heat contact bending is carried out, and the springback mechanism of hot bending analyzed. The purpose of this research is to obtain higher precision of complex parts with ultra-high-strength boron steel.

2 Experimental and numerical models for hot bending

The diagram of hot bending die is shown in Fig. 1, wherein, the width of the blank is 300 mm and its length 440 mm; the thickness of the material is 2.0 mm. The material is ultra-high strength boron steel. The depth of punch press is 90 mm, and the flange width is 80 mm. The clearance between the punch and the die is 2,4 mm. Punch radius is 5 mm, and dies radius is 8 mm. The definition of various parts of obtained hot bending parts is shown in Fig. 2. When the blank is formed to the given depth, the bottom of the U-shaped piece is clamped between the punch and the die, an external force is exerted on the bottom of parts by the punch to make a tight contact with the die.

$\Delta\theta_{11}$ and $\Delta\theta_{12}$ are set respectively as the springback angles of bending parts at the corner of the die, $\Delta\theta_{21}$ and $\Delta\theta_{22}$ are set respectively as the springback angles of bending parts at the corner of the punch. Springback angle $\Delta\theta_{ij}$ (i、j=1～4) can be expressed as

$$\Delta\theta_{ij} = \theta_{ij} - 90^{\circ} \tag{1}$$

If $\Delta\theta_{ij} > 0$, it shows that the springback in this position results in a positive springback, whereas in some other cases, in a negative one. The entire process (including bending, quenching and springback) of hot bending were simulated with ABAQUS software. Because of its symmetry, 1/2 of the blank was simulated and half of the die was

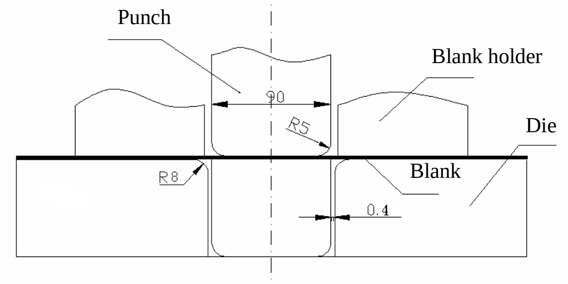


Figure 1. The sketch of the hot stamping bending dies.

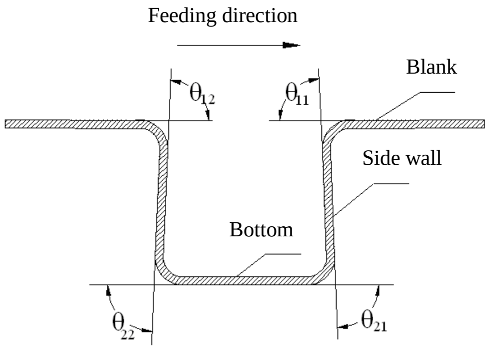


Figure 2. The definition of various parts at the hot stamping pieces.

modeled (shown in Fig. 3). Consequently, the numerical model was simplified to reduce the calculation time and to improve /calculating efficiency . The type of mesh used in the numerical model is selected as CPE4RT, and penalty method is employed to treat the contact between tools and blank. Based on the above approach, a numerical model is developed to carry out numerical simulations.

Hot tensile tests are performed at 600, 750 and 850℃and strain rates of 0,01, 0,1 and 1,0 s^{-1} to investigate flow properties of ultra-high-strength boron steel with the Gleeble 3500 testing system. First, the specimens are austenitized at 900 ℃ for 180 s, and then subjected to a 40 ℃/s cooling rate to avoid the bainite transformation. Once the chosen testing temperature is reached, uni-axial tensile tests are carried out. A multi-variant linear regression based on least square methodology is used to describe rheological behavior of materials as a function of strain, strain rate and temperature by fitting experimental datum through software Origin, and the constitutive equation of the sheet metal is obtained and expressed as

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m}\exp(\beta / T) \tag{1}$$

where K = 15,23, n = 0,429, m = 0,1479, and β= 3509,2.

In order to build the numerical model of hot-stamping process, heat conductivity, thermal expansion and specific heat of ultra-high-strength boron steel should be determined exactly at different temperatures. In this paper, heat conductivity, thermal expansion and specific heat are determined through thermal tests and are listed in Table 1, 2, and 3, respectively.

Table 1. Coefficients of heat conduction at different temperatures

Temperature [℃]	100	200	300	400	650	800	900
Heat Conduction W/m·K	10,8	9,97	9,49	8,58	5,32	5,53	5,43

Table 2. Specific heat at different temperatures

Temperature [℃]	100	200	300	400	850	900	950
Specific heat J/Kg·K	471	466	459	479	987	1019	1062

Table 3. Coefficients of thermal expansion at different temperatures

Temperature [℃]	100	200	300	400	850	900	950
Thermal expansion /℃ $\times 10^{-5}$	1,93	1,97	2,12	2,17	2,62	2,78	3,08

The quenchable steel is heated in the furnace to austenitic phase, then stamped in the die equipped with water-cooling system and then martensite is gotten/obtained through quenching. High strength steel sheet stamped parts in the high temperature are shown in Fig. 4. The microstructure that is composed of homogeneous small martensitic grains is shown in Fig. 5. Therefore, after hot stamping, the tensile strength of the material is improved by 2,5 times more than that before being hot stamped, which reaches /gets up to approximately 1500MPa.

3 Influence of die radius on springback of hot bending parts

Under the same test conditions, hot-stamping was numerically simulated after changing only die radius, which was 5 mm, 6 mm, 8 mm and 10 mm

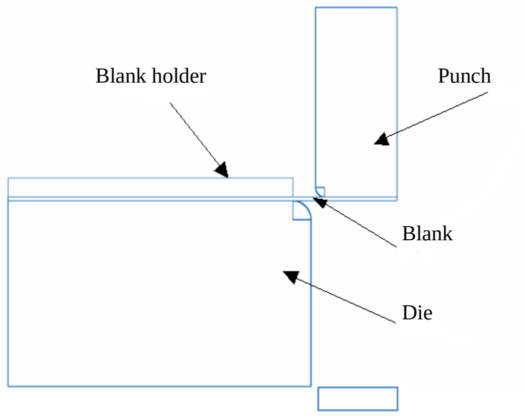


Figure 3. The geometric model of the U-shaped parts achieved by hot contact bending.

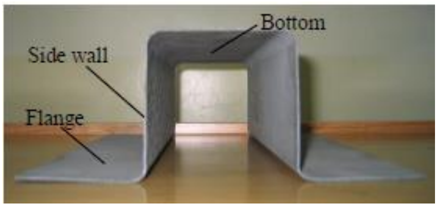


Figure 4. Ultra-high-strength boron steel stamping parts under high temperature.

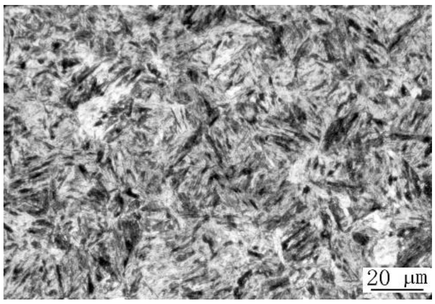


Figure 5. Microstructure of ultra-high-strength boron steel stamping parts.

respectively, and angles were measured to calculate the springback. The relationship obtained by simulations and experiments between die radius (R_d) and its springback angle ($\Delta\ \theta_1$) is shown in Fig. 6. According to Fig. 6, by increasing the die radius, the absolute value of springback at the die fillet 1 and fillet 2 of U-shaped parts is increased. The cause for such a negative springback is that in the hot stamping process, the internal side of sheet material is in contact with the die at fillets, and the external side is in contact with airso that cooling rate is fast on the internal side and low on external side. In the quenching process however,, the sheet material at fillets withstands certain thermal shrinkage stress so that the phenomenon of negative springback occurs. By increasing the fillet radius of the die, the sheet material at external side of fillet contacted with the air is increased. So, thermal shrinkage stress withstood by die fillet 1 and 2 of U-shaped parts is increased, and the absolute value of springback is also accordingly increased.

4 Influence of die clearance on springback of hot bending parts

Under the same condition other tests are performed, the die clearance is changed by adjusting the thickness of clearance the block on the die is adjusted, and bending with different gaps, which were 2,15mm, 2,35mm, 2,5mm and 2,75mm respectively, is carried out. The angle of the obtained hot bending part is measured, and the springback angle calculated. Since the absolute value of springback angle of the testing part is relatively small, the change of the angle value caused by the change of die gap should be considered in the calculation. t For instance, the value of the actual angle minus the sum of the change of the angle value caused by the change of die gap and 90°, will be the real obtained springback angle. The change value of theoretical angle α that is caused by the change of die gap, i.e., the wedge angle formed by the sheet side wall and the side wall of the die when stamping is completed, is shown in Fig. 7. The obtained relationship through simulations and experiments between the die clearance (*s*) and the springback angles ($\Delta\theta_1$) is presented in Fig. 8.

It can be seen that the absolute values of the springback angle are raised by increasing die gap, and accordingly, the springbacks are all negative springbacks. The cause of the phenomenon of negative springback is that, at the die fillets, the internal side of the sheet metal is in contact with the die, and its external side is in contact with the air so that in the quenching process, the cooling speed of internal side is faster and that of the outer side is slower. The difference of internal and exter nal cooling speed results in the difference of their shrinkage quantity and velocity, and the sheet material at fillet of dies undergoes some thermal shrinkage stress, resulting in the phenomenon of springback. Besides, by reducing die gap, on the one hand, the temperature difference between the internal side and external side of the material sheet is decreased, and the negative springback is also decreased correspondingly. On the other hand, when die gap is reduced, the angle formed after the material sheet entered into the die cavity is also

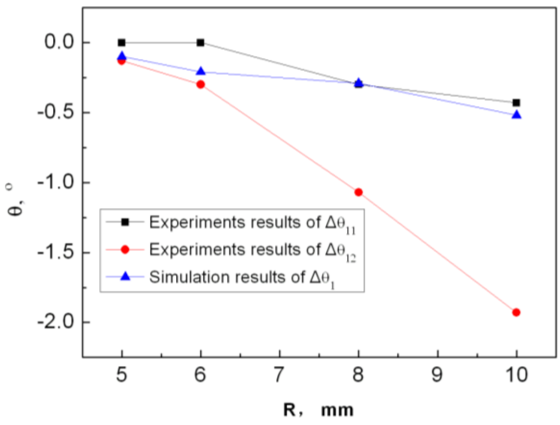


Figure 6. The relationship between the die radius and springback $\triangle\theta_1$.

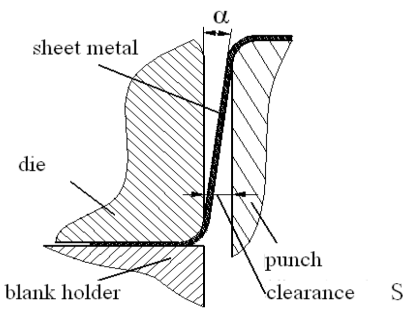


Figure 7. Diagram of the wedge angle α.

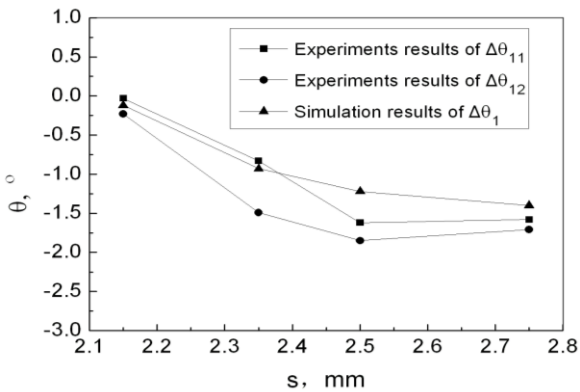


Figure 8. The relationship between the die clearance and springback.

reduced, and the wrap angle of the material at the punch fillets is increased, and the bending formation area is increased, thus the forming force is raised, resulting in the tensile stress /withstood/undergone by the material sheet when fillets are increased and this stress is reverse to/inversely proportional to the direction of thermal shrinkage stress in this position, reducing the effect of thermal shrinkage stress on the springback of material sheet. Therefore, by decreasing die gap, the value of springback angle is reduced.

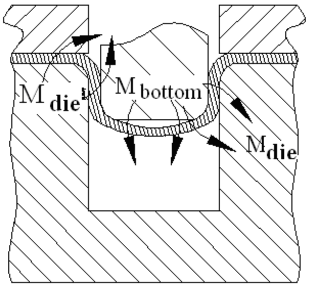
5 Mechanism of springback in hot stamping

As shown in Fig. 9, springback in hot stamping is caused by three main reasons:

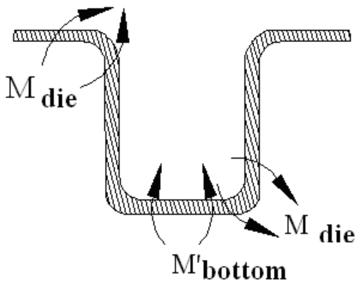
(1) Springback caused by forming force. Sheet metal at the die fillets withstands compressive stress in the internal side and tesile stress in the external side. The direction of the restoring moment M_{punch}, M_{die} generated after unloading at the die fillets is shown in Fig. 8.a). At the same time, the sheet metal below the punch bends to the cylindrical arc. The direction of the restoring moment M_{bottom} generated after unloading at the bottom is shown in Fig. 9 a).The restoringmoment M_{punch}, M_{die} and M_{bottom} will increase the angle at the corner of the punch and the die, which results in a positive springback.

(2) Springback caused by hot contact bending. At the end/After hot contact bending, the bottom of the U-shaped piece is clamped between the punch and the die in the reverse direction. The direction of the restoring moment M'_{bottom} generated after unloading at the bottom is shown in Fig. 9 b), which is in the positive direction to the M_{bottom}. The restoring moment M'_{bottom} will decrease the angle at the corner of the punch and die, which results in a negative springback.

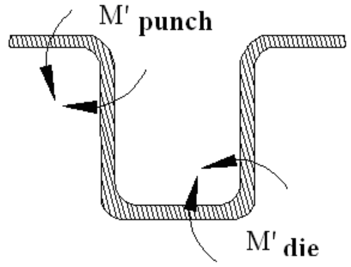
(3) Springback caused by quenching. The cause of the phenomenon of the negative springback is that, at the die fillets, the internal side of the sheet material is in contactwith the die, and its external side with the air. The cooling rate of internal side is thus faster and that of the outer side slower in the quenching process. The difference of internal and external cooling speed results in the difference of their shrinkage quantity and velocity. The direction of the restoring moment M'_{punch} and M'_{die} generated after unloading at the fillet, which is in the positive direction to the M_{punch} and M_{die}, is shown in Fig. 9 c).. It is worth noting that the moments M'_{punch} and M'_{die} result in a negative springback. In the hot stamping, sheet metal at elevated temperatures exhibit austenite state. Its yield strength and elastic modulus values are very low. This leads to small restoring moments at the fillet of the punch and the die, but also at the bottom of the punch. However, fast cooling rate of the sheet metal in hot stamping results in a greater impact of the restoring moments $M'_{punch}$and M'_{die}. Therefore, the springback of hot stamping part is generally negative.



a) Springback caused by the forming force



b) Springback caused by hot contact bending



c) Springback caused by quenching

Figure 8. Diagram of springback moments in cold and hot bending.

6 Conclusions

1) The effective quenching of hot formed parts of high strength steel can be realized in the designed die, which mainly forms the martensitic microstructure, with tensile strength up to 1500MPa or above, exceeding the tensile strength of original sheet material by more than 2.5 times.

2) The springback of a hot bending part is generally negative caused by different cooling rates and the impact of the thermal restoring moments;

3) The springback angle of a hot bending part is increased by increasing the die radius, and the gap between the punch and the die. The numerical simulation results of the springback in hot contact bending are well consistent with the experimental results, which verify the reliability of the simulation model.

As a result a novel hot stamping process for ultra-high-strength boron steel was proposed. During the process, stamping and quenching take place simultaneously, with tensile strength up to 1500MPa or above. The effect of die geometric parameters on springback and its mechanism in the hot stamping process has been studied by an experimental and simulation method. This provides a basis for the control of the hot stamping process, which is to be applied to the production of complicated shape parts.

References

[1] Bao, J.: *Hot Stamping and Simulation for Ultra High Strength Boron Steel* (Doctoral Dissertation), Harbin Institute of Technology, Harbin, China, 2008, 28-36.

[2] Karbasian, H. et al.: *A Review on Hot Stamping*, Journal of Materials Processing Technology, 210 (2010) 15, 2103-2118.

[3] Bok, H. H. et al.: *Comparative Study of the Prediction of Microstructure and Mechanical Properties for a Hot-stamped B-pillar Reinforcing Part*, International Journal of Mechanical Sciences, 53 (2011) 9, 744-752.

[4] Naderi, M. et al.: *Analysis of Microstructure and Mechanical Properties of Different High Strength Carbon Steels after Hot Stamping*, Journal of Materials Processing Technology, 211 (2011) 6, 1117-1125.

[5] Mori, K. et al.: *Warm and Hot Stamping of Ultra High Tensile Strength Steel Sheets Using Resistance Heating*, CIRP Annals Manufacturing Technology,54 (2005) 1, 209-212.

[6] Merklein, M. et al.: *Characterization of the Flow Properties of the Quenchenable Ultra High Strength Steel 22MnB5*, CIRP Annals Manufacturing Technology, 55 (2006) 1, 229-232.

[7] Hyunwoo, S. et al.: *An Investigation of the Blanking Process of the Quenchable Boron Alloyed Steel 22MnB5 before and after Hot Stamping Process*, Journal of Materials Processing Technology, 212 (2012) 2, 437-449.

[8] Naderi, M. et al.: *Analysis of Microstructure and Mechanical Properties of Different High Strength Carbon Steels after Hot Stamping*, Journal of Materials Processing Technology, 211 (2011) 6, 1117-1125.