Forming Analysis of High Strength Boron Steel in Hot Punching Process

Xiaoda Li[1, 2]

[1]*School of Automotive Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China*
[2]*Zhuhai College of Jilin University, Zhuhai 519041, Guangdong, China*

Xiangkui Zhang

School of Automotive Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China

Ping Hu*

School of Automotive Engineering, Dalian University of Technology, Dalian 116024, Liaoning, China
*Corresponding author

Abstract
High-strength boron steel used in auto body can not only achieve automobile lightweight, but also improve the crashworthiness. Hot punching process is the advanced manufacturing technology for forming high strength steel. At high temperature, it can improve the formability of sheet metal, reduce the spring back of forming part, and ensure the forming precision. With the finite element numerical simulation, it can effectively predict the forming process of sheet metal, and can greatly reduce high costs and long development cycle of traditional 'trial' method. In the paper, taking the B pillar of a car with '22MnB5' for example, had the thermal-mechanical coupling analysis for it. And then, the temperature distribution in sheet metal forming process and the change rate of thickness and thickness distribution after sheet forming were obtained. Having the simulation for hot forming products with thermal coupling conditions can provide effective help for the product design and process design of the punching die.
Key words: BORON STEEL, HOT PUNCHING, SHEET METAL, HIGH TEMPERATURE, THERMAL-MECHANICAL COUPLING ANALYSIS, HOT FORMING

1. Introduction

Hot punching technology is the most suitable and advanced manufacturing technology for forming high strength punching part. It integrates traditional forging stamping and quenching process and is the most appropriate and reliable means of production for forming parts with high strength steel such as front/rear bumpers of automobile, A/B/C pillars, roof framework. It has broad application prospects in the automotive industry.

The hot punching process is as follows: Firstly, make hot forming steel heated above the recrystallization temperature, the microstructure will be in the state of 'Austenite', and then the heated sheet metal is fed into the punching die for being formed, in the end, the forming part is quickly cooled for being quenched with cooling system of punching die, so the microscopic structure will be changed from 'Austenite' to 'Martensite', and the high strength workpiece can be obtained. Hot forming process can make the formability of sheet metal better, reduce the spring back of forming part, and ensure the forming precision. There are two stages in hot punching process of sheet metal including the forming stage at a certain temperature and the cooling stage. In the punching process, there are interactions between heat and deformation, the temperature field of part will be changed by heat transfer and plastic deformation, and the temperature gradient of part will be formed. The hot forming stage needs only short time, so the forming part has little change in temperature. In the stage of hot forming, it needn't consider the impact of phase transition generally.

With the hot forming process gradually being applied, computer numerical analysis about hot punching technology also has been made significant development. Malek Naderi et al [1] had the analysis for the microstructure, surface hardness on '22MnB5' steel of three different thicknesses, and simulated the forming process of hot punching with coupled thermal simulation software. M. Naderia et al [2] measured the stress-strain relationship of '22MnB5' at different temperatures and strain rates, and demonstrated that the constitutive equation proposed by the KOCKS etc. can describe the plastic behavior of boron steels better. D. W. Fan et al studied the mechanical properties of '22MnB5 HPF' steel sheet under isothermal deformation conditions [3]. M. Nikravesha et al [4] studied the impact of plastic deformation and cooling rate on the transition temperature of 'Martensite' and 'Bainite'. Ma. N. et al did the simulation tests of High Temperature Tensile and Quenching on hot forming steel sheet, studied the constitutive model of thermal-mechanical and transformation coupling in hot punching process [5, 6, 7].

In the paper, firstly, the material properties of high strength boron steel '22MnB5' were analyzed. And then, taking the B pillar of a car for example, did the thermal-mechanical coupling analysis for the forming stage in the hot punching process. The analytical method of thermal-mechanical coupling were introduced. With the software 'Dynaform', the temperature changes of the B pillar were simulated in the forming stage, and the thickness and change rate of thickness distribution after sheet forming were gotten, which will provide help for the subsequent design of punching die.

2. Performance of boron steel

Boron steel is widely used in hot punching process currently, the ingredient of the steel is characterized by adding boron which the mass fraction is about $(20\text{-}50)\times10^{-4}\%$ on the basis of the C-Mn steel. Boron can strengthen the steel because of the role of the solid solution, and for the lively chemical properties of Boron, Oxygen and Nitrogen, when adding Boron, it needs to add some elements forming oxide and nitride easily, such as Aluminum, Zirconium and Titanium. Solid solution Boron segregating at the Austenite grain boundaries delays nucleation of 'Ferrite' and 'Bainite', so it can improve the strength of steel.

The material in the article is the high strength steel '22MnB5' of hot forming, the basic performance includes chemical composition, microstructure and mechanical properties. Mechanical properties of materials depends mainly on the microstructure. The mass fraction of the chemical constituents on high strength steel '22MnB5' measured with X-ray fluorescence spectrometer 'LAB CENTER XRF-1800' is shown in table 1.

Table 1. Chemical composition (wt. %) of 22MnB5

Chemical composition	C	Mn	B	Al	Si	S	P
Mass fraction	0.23	1.26	0.0035	0.050	0.18	0.002	0.013

The original microstructure of hot punching boron steel is 'Ferrite' and 'Pearlite', the hardness is about 20HRC. After being heated, the microstructure of the sheet is 'Austenitic' which has high plasticity, small deformation resistance. The forming process is mainly happened in the state of 'Austenitic'. In the end, the steel is quenched and the microstructure becomes 'Martensite' which has high strength about 1500Mpa, and high hardness about 50HRC.

Hot forming is a complex thermal-mechanical coupling process, the temperature changing range of the sheet is relatively larger from about 800 ºC before forming to room temperature after cooling. The change of temperature will greatly affect the microstructure of material, mechanical properties, thermal properties. So in the process of building the Finite Element model, it needs to consider the impact of the temperature change on the properties of material adequately [8, 9]. The Stress-strain curves of the hot forming steel sheet '22MnB5' at different temperatures is shown in figure 1. Young's modulus and Poisson's ratios at different temperatures is shown is figure 2. Thermal conductivity and specific heat at different temperatures is shown is figure 3.

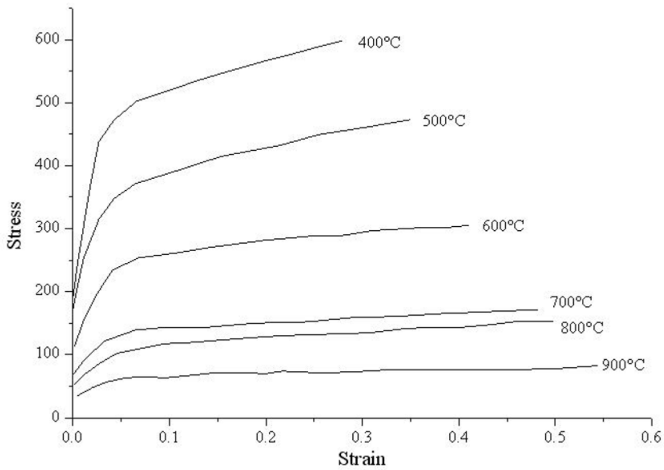

Figure 1. Stress-strain curves at different temperatures

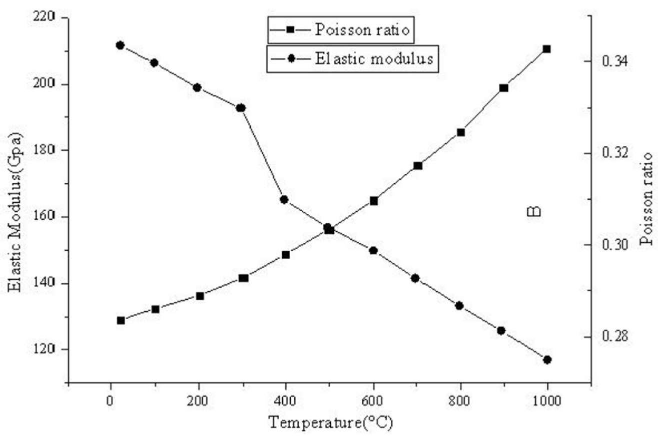

Figure 2. Young's modulus and Poisson's ratios at different temperatures

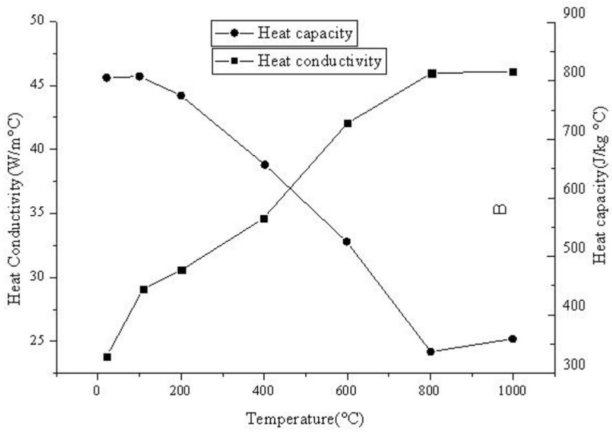

Figure 3. Thermal conductivity and specific heat at different temperatures

3. Thermal-mechanical coupling Analysis

There exists the temperature-related material behavior in hot punching process, so it needs to consider thermal process when being simulated and combine Finite Element (FE) module for thermal calculations and FE model for force calculations. In hot punching process, the convective heat transfer is happened between the sheet metal and surroundings, the contact heat transfer is happened between the sheet metal and the punching die. At the same time, the sheet metal deformation is also occurred. Hot punching is a typical thermal-mechanical coupling process, the heat transfer and the action of force will occur simultaneously [10].

In hot forming process of high strength steel, the plastic deformation and the heat transfer of the workpiece occur in the same space and time domains. But the physical properties of deformation and heat transfer problems are different, the deformation problem is described as elastoplastic boundary value problem, and the heat transfer belongs to transient heat conduction problem, so it is difficult to solve the corresponding field variables simultaneously. In the thermal-mechanical coupling simulation of explicit dynamics, the mechanics solution is by using time central difference integral formula of mass matrix, and the heat transfer equation can be obtained with step-by-step integration of forward difference. When forward difference and central difference are all explicit integrations, the heat transfer and mechanics solution can be obtained simultaneously by explicit coupling mode [11, 12].

Time integral formula of forward difference used in heat transfer equation is:

$$T^{N}_{(i+1)} = T^{N}_{(i)} + \Delta t_{(i+1)} \dot{T}^{N}_{(i)} \qquad (1)$$

In the formula, T^N is the temperature value of

Node 'N', the subscript 'i' is the increment during integration.

When using lumped heat capacity matrix and without the need for solving equations, forward difference is explicit integration. The temperature value of each step is obtained by $\dot{T}_{(i)}^{N}$ of the previous step, $\dot{T}_{(i)}^{N}$ can be obtained by the formula 2 in the beginning of calculation.

$$\dot{T}_{(i)}^{N} = (C^{NJ})^{-1}(P_{(i)}^{J} - F_{(i)}^{J}) \quad (2)$$

C^{NJ} is lumped heat capacity matrix, P^{J} is heat flux vector of outer heat source, F^{J} is internal heat flux vector.

Central difference integral formula of lumped mass matrix used in mechanics solution is:

$$\dot{u}_{(i+1/2)}^{N} = \dot{u}_{(i-1/2)}^{N} + \frac{\Delta t_{(i+1)} + \Delta t_{(i)}}{2}\ddot{u}_{(i)}^{N} \quad (3)$$

$$u_{(i+1)}^{N} = u_{(i)}^{N} + \Delta t_{(i+1)}\dot{u}_{(i+1/2)}^{N} \quad (4)$$

In the formula, u^{N} is the freedom of Node 'N', the subscript 'i' is the increment during integration. When the motion state of the node is obtained by $\dot{u}_{(i-1/2)}^{N}$ and $\ddot{u}_{(i)}^{N}$ of the previous step, central difference is explicit integration.

If forward difference and central difference are all explicit integrations, the analysis of the heat transfer and the mechanics solution can be solved by the explicit coupling method.

4. Thermal-mechanical coupling simulation of the automotive B pillar

B pillar can not only hold up the roof of the cockpit, but also protect the members of the cockpit. When the vehicle is involved in a rollover or overturning, B pillar can effectively avoid the cockpit being compressed to deformation and play an important role for vehicle safety. For cars, B pillar plays a supporting role, also plays the role of the door frame, so B pillar needs high strength material.

High strength boron steel '22MnB5' is used for the B pillar of an automotive, the model is shown in figure 4. Based on the software 'DYNAFORM', Select 'MAT-106' model for the material, that is the thermal viscoplastic material, and the thickness of material is 2mm. Use 'B-T' shell element in the calculation. To carry on the hot stamping simulation analysis of automotive B pillar, it needs the Finite Element modeling including Die, Punch, Binder and Blank. According the actual situation, use 'Single Action' drawing forming, that is, the punch is stationary, the die is moved downward along the punching direction, and the blank is rested on the blank holder. When the die is contacted with the blank, the plastic deformation of the blank is happened. When the punch and the die is completely closed, the forming process ends. During the simulation, the blank holder force is 200KN, and the punching rate is set to 50mm/s. The initial temperature of the sheet is set to 750 ºC, and the initial temperature of the die is 50 ºC. Adding graphite lubrication, Friction coefficient is set to 0.17.

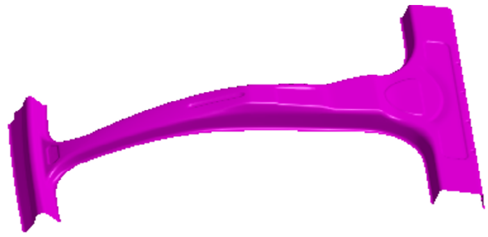

Figure 4. The model of the automotive B pillar

Figure 5 shows the temperature distributions of the sheet at different times, the initial temperature is 750 ºC. During the sheet forming, the total stroke is 195mm from the die being contacted with the blank at the beginning to the die and the blank holder being closed, that is the closing process. And then, the die continues to move along the punching direction, until the die and the punch is completely matched, the stroke is 75mm and the forming process is completed. With the die constantly moving, the forming degree of sheet metal will increase, at the same time, the temperature of the sheet will gradually be reduced. But due to the difference of time being contacted with the mold, the temperature decrease rate of the blank is also different, which make the temperature field distribution of the sheet asymmetrical. In addition, with the die constantly moved, the degree of contact between the die and the sheet gradually is increased, heat conduction can be conducted more sufficiently, at this time the temperature of the sheet will be dropped rapidly.

There are two major reasons for the local high temperature of the sheet:

(1). Deformation work produced due to plastic deformation, the heat generated in the friction process make the temperature of sheet raised. And the greater the deformation, the higher the temperature.

(2). Due to the different degree of deformation, the contact between the sheet in the positions with large deformation and the die is relatively poor, the heat transfer will be restricted and the local temperature of the sheet be decreased slowly.

Figure 6 shows the thickness distribution of the sheet after forming, and Figure 7 shows the thinning rate distribution of the sheet after forming. As we can see from the pictures, 'A' is the position that the thickness is increased most seriously, the thickness is about 2.103 and the increasing rate of thickness is 5.142%. In the positions of part of flange edge, the thickness is about 2.011~2.072mm and the increasing rate of thickness is about 2.087~3.615%. At the positions 'B', 'C', 'D' 'E' and the sidewall with greater drawing depth, the thickness of the sheet become thinner, the thinning rate on the whole is about 7~14%. There is the greater thickness change only in the position 'B', the minimum thickness is 1.492mm and the thinning rate is 25.492%, which can be improved by increasing lubricity of the sheet. From the calculation result, the size distribution of the part is better after forming, and under the process conditions, the part has better formability.

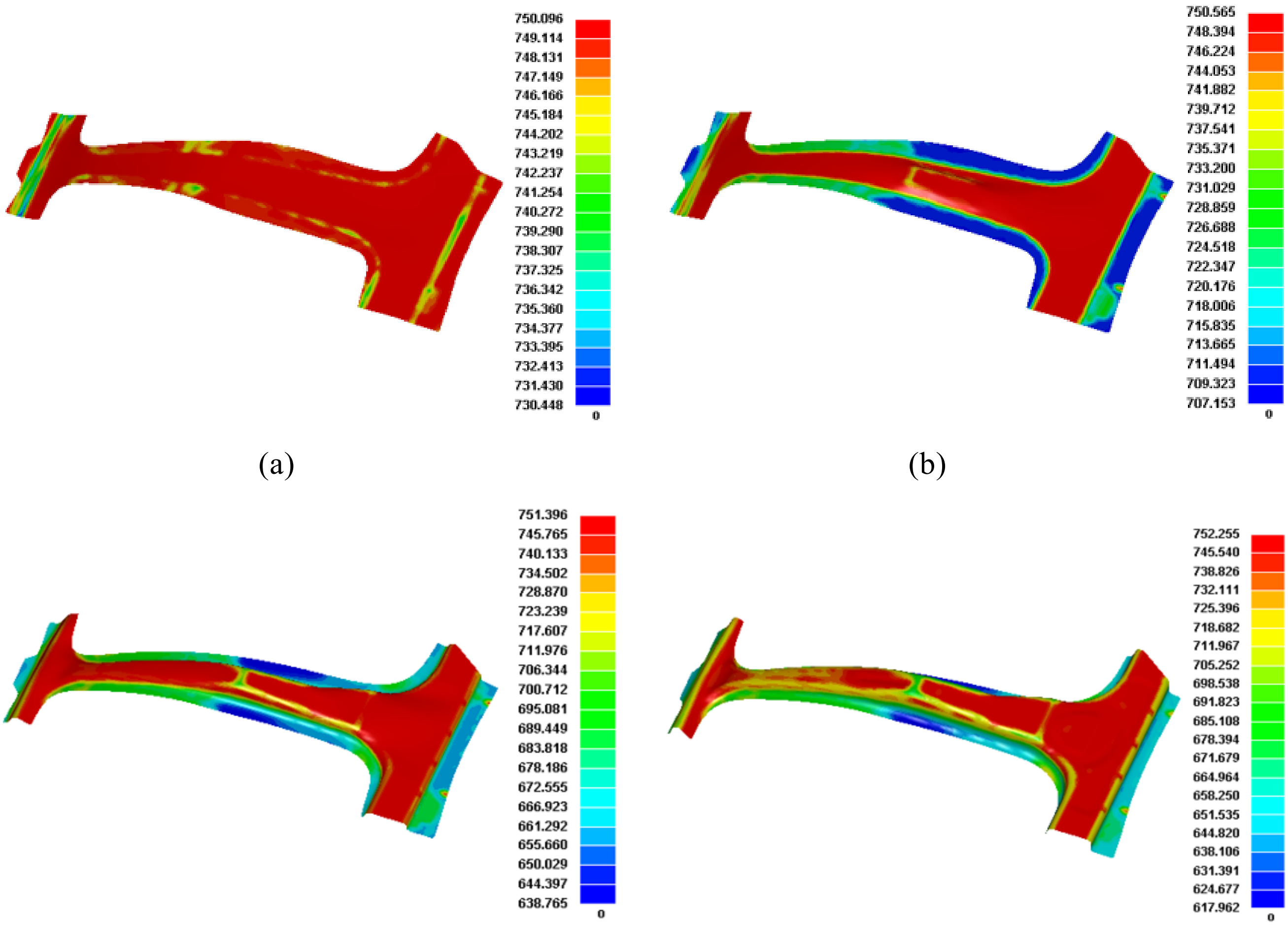

Figure 5. The temperature fields of the sheet at different times
(a) t=0.098500s (b) t=0.102968s (c) t=0.109993s (d) t=0.114500s

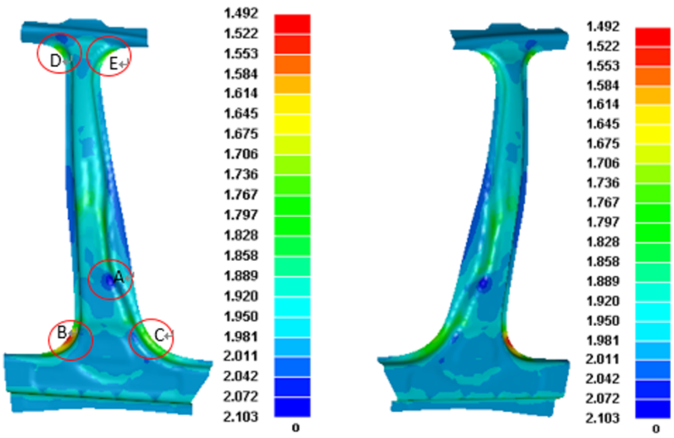

Figure 6. The thickness distribution of the sheet after forming

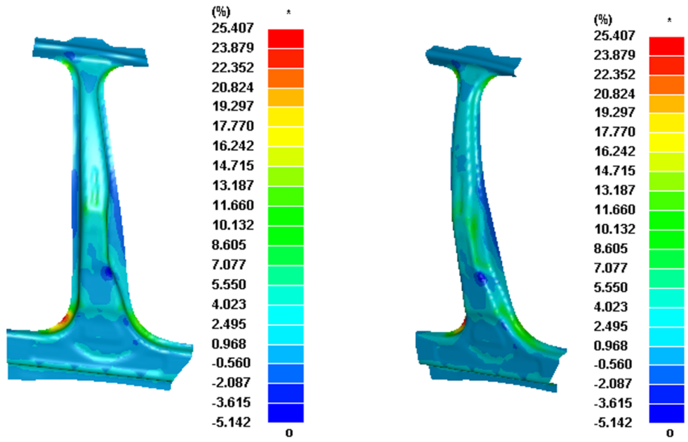

Figure 7. The thinning rate distribution of the sheet after forming

5. Conclusions

In the article, for the hot issue of research ‘hot punching process’ at present, it analyzed the basic properties of boron steel ‘22MnB5’, including the ingredients, the microstructure and the mechanical properties. Introduced the analysis process of thermal-mechanical coupling in the hot forming of boron steel. And taking high strength B pillar of a car for example, for the forming stage, had the thermal-mechanical coupling simulation under the process conditions with the software ‘Dynaform’. Discussed the temperature fields at different times in hot forming stage, the thickness distribution after sheet forming, and the thinning distribution. The results show that it can get the B pillar of uniform thickness and better deformation. Introducing the thermal-mechanical coupling condition to hot punching process, it has important implications for the subsequent hot stamping parts and hot stamping die design.

Acknowledgements

This work was supported by National Natural Science Foundation of China (No. 11472071).

References

1. Malek Naderi, Vitoon Uthaisangsuk, et al. (2008) A Numerical and Experimental Investigation into Hot Stamping of Boron Alloyed Heat Treated Steels. *Steel research int,* 79(2), p.p.77-84.
2. M. Naderia, L. Durrenberger, et al. (2008) Constitutive Relationships for 22MnB5 Boron Steel Deformed Isothermally at High Temperatures. *Materials Science and Engineering A,* 478, p.p.130-139.
3. D. W. Fan, B. C. De Cooman, et al. (2010) Influence of Isothermal Deformation Conditions on the Mechanical Properties of 22MnB5 HPF Steel. *Steel research int,* 81(4), p.p.292-298.
4. M. Nikravesha, M. Naderib,G.H. Akbari. (2012) Influence of Hot Plastic Deformation and Cooling Rate on Martensite and Bainite Start Temperatures in 22MnB5 Steel. *Materials Science and Engineering A*, 540, p.p.24-29.
5. Ma Ning, Hu Ping, Shen Guozhe, et al. (2009) Model and Numerical Simulation of Hot Forming. *International Symposium on Automotive Steel, ISAS conference Proceedings*, Dalian, China, p.p.362-367.
6. Ma N., Hu P., Shen G. Z., et al. (2010) Modeling, Testing and Numerical Simulation on Hot Forming. *AIP Conference Proceedings, Plenary lecture of NUMIFORM*, p.p.18-27.
7. Ma N., Hu P., Guo W. Et al. (2010) Coupled Constitutive Relation and Numerical Simulation of Hot Forming. *Steel Research International*, 81, p.p.937-943.
8. Yang Shiming. (1980) Heat Transfer Theory. *Higher Education Press*: Shanghai, China.
9. Zhu Chao. (2010) Hot Punching Die Design and Optimization of Ultra-high-strength Steel. *Jilin University*: Changchun, China.
10. Zhang xinming, Wu Yiping, Deng Yunlai, et al. (2011) Hot Deformation Constitutive Equation of Mg-Gd-Y-Zr Alloy. *Journal of Chinese Nonferrous Metals*, 21(12), p.p.12-19.
11. Yan Zhen (2013) Experimental Study of Thermodynamic Properties of High Temperature on Boron Steel and Hot Punching Simulation for Typical Parts, *Shanghai Jiao Tong University*: Shanghai, China.
12. Fan Guowen (2013) Numerical Analysis of Key Factors on Hot Stamping of Ultra-high-strength Boron Steel, *Jilin University*: Changchun, China.