

## Hot Forming Simulation of Boron Steel Based on Deformation Theory

**Xiaoda Li<sup>1,2</sup>**

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

**Weijie Liu**

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

**Xianghui Zhan**

*Zhuhai College of Jilin University, Zhuhai 519041, Guangdong,  
China*

## Abstract

High-strength Boron steel is used in automotive field, and as some important structural parts of automobile body for its light weight and high strength. But Boron steel sheet's formability is not well and it is prone to have punching defects at room temperature, so it needs to be heated for being improved its formability which is called hot stamping process currently. Using numerical simulation to study hot stamping process of steel sheet can greatly reduce development cycle of stamping die and reduce costs. Especially in the initial design stage of hot stamping die, it needs a simulation tool which can quickly simulate the formability at high temperatures according the shape of the workpiece, and which does not require much tooling information. In the paper, with one-step inverse forming method based on deformation theory, the formability of BH1500 Boron steel was firstly simulated in the state of austenite at high temperature, the main calculation formulas and method was proposed. And the simulation results were compared with the experimental values. The results shows that the simulation and experimental results are basically the same, and the method can evaluate the formability of boron steel in high temperature conditions with only little die information effectively and quickly. It plays an important role in the early stages of stamping die design.

Key words: BORON STEEL, BH1500 STEEL, DEFORMATION THEORY, ONE-STEP INVERSE FORMING, HOT FORMING, HOT STAMPING

## 1. Introduction

It is a global concern issue on reducing energy consumption and emissions of vehicles. Almost each country has introduced various laws and regulations to specify the emissions standards. The key techniques for reducing vehicle fuel consumption are the followings: reducing vehicle weight, reducing drag coefficient through improving vehicle appearance, and improving the thermal efficiency of the engine etc. Among them, automotive lightweight is an important and effective way to solve the problem.

High Strength Steel (HSS) is widely used in automobile industry for its light weight and high strength, and it can greatly reduce weight of auto body and improve crash safety of vehicle. With the rapid development of modern metallurgical technology, Ultra High Strength Boron Steel is developed. But it's hard to be formed at room temperature, and prone to have punching defects such as cracking, spring back, and other defects, at the same time, the abrasion of die is more serious and its life is greatly reduced. Hot stamping (also called hot forming) is one of the key technologies to solve the above problems, which combines traditional hot forging technology and cold stamping technology. And it is an advanced manufacturing technology specifically for forming high strength boron steel and it is used to output some auto body parts like front/rear bumper, A/B/C pillar, roof frame, channel framework, and anticollision-beam of automobile door.

With the development of some basic subjects like numerical analysis, plastic forming, and computer technology etc. Computer Aided Engineering (CAE) technology has been obtained a breakthrough achievement. After the finite element numerical simulation being introduced in stamping, it has greatly

reduced the tryout time, and effectively solved problems such as the stamping die scrapped, the unreasonable process, and the poor forming quality. In the field of hot stamping simulation on Boron steel, P. Ravier [1], G. Bergman [2], D. Lorenz [3], M. Naderi [4] et al studied constitutive relation of thermal-mechanical coupling, the choice of material parameters and typical parts' trial with hot stamping. Hoffmann H [5] and Arthur B Shapiro [6] simulate the hot forming respectively using the software Abaqus and LS-DYNA. Ma N et al [7, 8] studied coupled models of hot forming with Static Explicit method. The finite-element (FE) method on the sheet metal forming simulation mainly includes incremental method based on flow theory and deformation theory. Currently the simulation technologies mentioned in literatures for hot stamping are all belong to incremental method.

Finite-element analysis technology based on incremental method needs all stamping process parameters to calculate, needs engineers have rich experience of using analysis software and hold enough knowledge on stamping process, and it often takes much more time. But the FE technology based on deformation theory: one step inverse forming, can simulate quickly without any information about stamping die, which has been widely used in the initial design phase of stamping die and product. FLECHE, Simex, AutoForm/OneStep, FAST3D, HyperForm et al are all the representative software. However, one step inverse forming method is only used in traditional stamping process at room temperature at present.

In this paper, one step inverse forming FEM based on deformation theory is firstly used to simulate the forming of Boron steel BH1500 in the state of austenite at high temperature, and get the thickness distribution of the reinforcing beam of B pillar after



4. Basic equation of one step inverse forming

4.1 Logarithmic strain

Using linear triangular membrane unit to divide the initial sheet and final configurations of part, logarithmic strain can be expressed as shown in Formula 1.

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{xy} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} = [M][\varepsilon_1][M]^T \quad (1)$$

Among them,  $[\varepsilon_1]$  is logarithmic main strain matrix,  $[\varepsilon_1] = \text{diag}(\ln\lambda_1, \ln\lambda_2, \ln\lambda_3)$ ,  $[M]$  is conversion matrix.

$$[M] = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta$  is the angle between spindle strain and x-axis.

4.2 Constitutive equation of Boron steel at high temperature

Before the sheet metal forming, it needs to be heated to above recrystallization temperature, and holding for some time, the microstructure of material ‘the mixture of ferrite and pearlite’ will be transformed to ‘austenite’. For the hot forming products, the final shape and size is mainly finished in the state of ‘austenite’. Hot forming Boron steel has following characteristics: Higher plasticity, lower deformation resistance, higher forming limit, and lower spring back, so it can be used to produce workpieces with complex geometry. During the hot forming process, high temperature constitutive equation of Boron steel

is the indispensable mathematical models, which is important for numerical simulation of hot forming, development of hot forming process and optimization of process parameters. And it reflects the relationship between the flow stress and strain, strain rate and temperature. Some researchers have studied performances of boron steels. For example, Naderi M et al [10] studied the effects of strain, strain rate, and temperature on the plastic deformation of boron steel through isothermal uniaxial compression test, and establish two equations to explain plastic deformation behavior of boron steels boron steels with ‘Voce-Kocks’ dynamic constitutive model and ‘Molinari Ravichandran’ model respectively. Liu H S et al [11] built flow stress model of boron steel based on strain, strain rate and temperature. Li H P et al [12] described the hot deformation behavior of Boron steel B1500HS in the state of ‘austenite’ with modified ‘Arrhenius’ equation, and it is used in the article, the constitutive equation is shown in Formula 2.

$$\sigma = \frac{1}{\alpha} \operatorname{arcsinh} \left[ \exp \left( \frac{\ln \dot{\varepsilon} - \ln A + Q/RT}{n} \right) \right] \quad (2)$$

$\sigma$ —Flow stress of material

$\dot{\varepsilon}$ —Strain rate

R—Molar gas constant (8.3145J.mol<sup>-1</sup>K<sup>-1</sup>)

T—Absolute temperature

Q—Deformation activation energy of material

A,  $\alpha$ , n are all material-related factor

4.3 Solution of one step inverse forming

According principle of virtual work, in final configuration ‘C’ of part, for any given virtual displacement  $\{u^*\}$ , virtual work of internal forces is equal to external virtual work, so

$$W = \sum_{\varepsilon} W_{int}^{\varepsilon} - \sum_{\varepsilon} W_{ext}^{\varepsilon} = \sum_{\varepsilon} (\int_{V^{\varepsilon}} \{\sigma^{\varepsilon}\} \{ \varepsilon^* \} dv - \int_{V^{\varepsilon}} \{u^*\} \{f\} dv) = 0 \quad \forall \{u^*\} \quad (3)$$

$\{u^*\}$  is virtual displacement,  $\{\varepsilon^*\}$  is virtual strain generated by virtual displacement,  $\{\sigma\}$  is Cauchy stress tensor,  $\{f\}$  is effective external force vector.

Solve the nonlinear equations with ‘Newton-Raphson’ method iteratively [13].

5. Simulation of B-pillar reinforcement beam

As B pillar reinforcement beam of an automotive for example, the material is B1500HS boron steel. The initial temperature of the sheet is 810 °C, blank holder force is 30KN, and the punching rate is 0.1s<sup>-1</sup>. Under the process conditions, through the experiment verification, it can get the product which has uniform thickness distribution, and there is no phenomenon of severe local thinning or severe wrinkling because of local thickening, which meet the requirements of formability.

With one-step inverse forming based on deformation theory, simulate the forming of B pillar reinforcement beam, and with the same process parameters. Figure 3 shows the simulation result, and Figure 4 is the test part. Select two typical sections to study the thickness distribution. Figure 5 and Figure 6 shows thickness distribution contrast of two sections between test values and the simulation, as we can see, the simulation results can be seen basically consistent with the experimental results, and the two groups of values have the same change trend. The thickness distribution of cross-section1 shows an increasing trend on the whole because the section is a corner. But the change of thickness is within the safe range, and without causing wrinkles. Cross-section2 have a greater depth, as we can see from the Figure 6, the side walls have a greater plastic deformation,

and have larger amount of thinning, but it also meets requirements of formability.

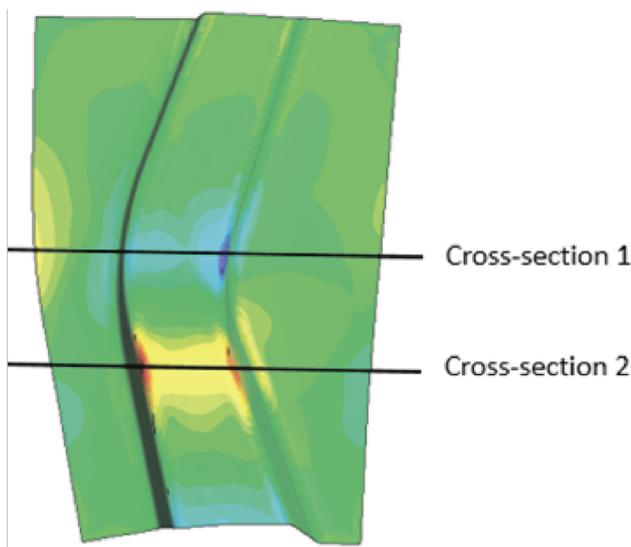


Figure 3. The simulation result with one step inverse forming



Figure 4. The test part of hot forming

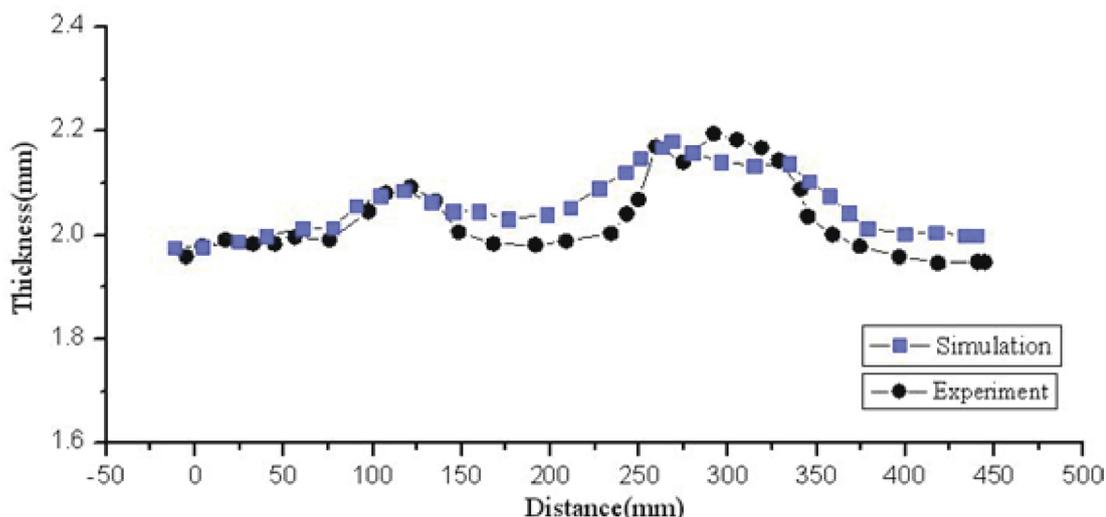


Figure 5. Thickness distribution contrast of cross section1 between test values and the simulation

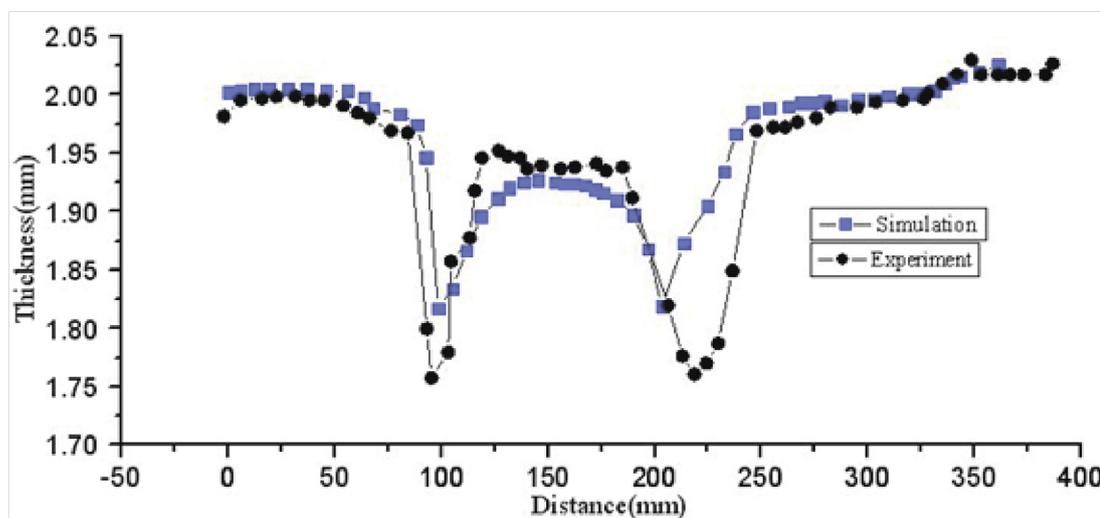


Figure 6. Thickness distribution contrast of cross section2 between test values and the simulation

## 6. Conclusions

Numerical simulation method of punching process can greatly reduce development cycle of stamping die and costs. One-step inverse forming method based on deformation theory is mainly used at the beginning of die design. It can evaluate the formability of sheet metal with only little die information quickly and play a guiding role for the subsequent design of the stamping die. At present, the method is mainly used in traditional cold punching process, in the article, the method is firstly used in hot stamping of Boron steel and can be used to simulate the formability of Boron steel in the state of 'Austenite' at high temperature. The paper also introduces hot forming process of HS Boron steel, and introduces basic principle of one step inverse forming, basic equations including logarithmic strain equation and constitutive equation of Boron steel at high temperature, and solution of one step inverse forming. In the end, taking a car's B-pillar reinforcement beam as an example, simulate the formability of the product at high temperature and compare thickness distribution simulated and experimental values. The results shows that the simulation results can be seen basically consistent with the experimental results, and the two groups of values have the same change trend. So the simulation effect of the method reaches the expected requirements. And the method is effective enough to evaluate high temperature formability of HS Boron steel sheet.

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