

Research Article

One-step Inverse Forming Simulation on Hot Forming Process of High-strength Food-can Tinplate

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Abstract: Hot stamping process is a complex process and the performance of food-can tinplate under high-temperature state is completely different from at room temperature. It will bring out some difficulties for the application of incremental method in early stages of food-can product design. In this study, it is the first time to put forward that the Finite Element Method of One-Step Inverse Forming can be used in hot stamping process of High-Strength food-can tinplate, which can evaluate the high temperature formability of sheet metal. The results show that: One-Step Inverse Forming FEM of High-Strength food-can tinplate is suitable for the initial die design stage because of its simple simulation method and high speed and is used to evaluate the high temperature formability of food-can tinplate.

Keywords: Finite Element Method (FEM), high-strength food-can tinplate, one-step inverse forming

INTRODUCTION

With the rapid development of food-can industry and the increasing demands for environmental protection and food-can tinplate safety. The application of High-Strength Boron steel in the field of food-can making can satisfy both the food-can making lightweight and improving the food-can material safety. The cold stamping forming of High-strength steel has higher efficiency, but has greater spring back and it's difficult to guarantee the forming accuracy. In contrast, the advantages of hot stamping forming technology of steel is reflected in:

- Sheet at high temperature has smaller deformation resistance and better plasticity.
- High-Strength food-can tinplate after hot forming has higher mechanical properties and better crashworthiness.
- Its dimensional accuracy is higher. So in recent years, it has been widely used in actual production.

Hot stamping technology is a complex process, it involves the problems such as geometric nonlinearity, material nonlinearity and contact nonlinearity etc. And it can be affected by thermodynamic parameters varied with the change of temperature conditions. So only by using the method of analyzing experiment, it is hard to solve problems of hot stamping technology encountered in actual production. Finite Element Method (FEM) is widely used in the simulation of sheet metal forming, Incremental Algorithm and One-Step Inverse Forming are the main methods. Many scholars have simulated

hot stamping process with Incremental Algorithm. Among them, (Naderi *et al.*, 2008a) simulated the thermal coupling process of hot stamping on High Strength food-can tinplate with the business software ABAQUS. Ma *et al.* (2011) had a simulation for hot forming of High-Strength steel with Static Explicit algorithm. Guo *et al.* (2013) simulated the hot forming process on front bumper beam of auto and anticipated its formability. Liu *et al.* (2010) and Zhou (2007) also had the simulation with Incremental Algorithm. The advantage of Incremental Algorithm is high precision, but it costs a lot time and needs a lot of staff's experience and technology in the calculation process, which brings out some difficulties for the application of incremental method in the early stages of food-can product design. One Step Inverse Forming Algorithm based on plastic deformation theory will have the calculation according the reverse order in contrast with the actual forming, which is from the final configuration of forming part inverse to the corresponding initial configuration. Just considering the initial blank and the end deformation, not the intermediate state of the deformation, so compared with the incremental algorithm, One Step Inverse Forming Algorithm needs less time to finish simulation (Bao *et al.*, 2010). At present, One Step Inverse Forming Algorithm is usually used to evaluate the formability of cold forming food-can tinplate, no any literatures produce its application on hot forming. In this study, firstly put forward using One Step Inverse Forming Algorithm to evaluate the high temperature formability of boron steel 22 MnB5 roughly, which can be used in

the initial stage and play a guiding role for subsequent design.

MATERIALS AND METHODS

The basic equation of one step inverse forming method: Basic idea of One Step Inverse Forming (Bao, 2004): Starting from the product's shape 'C', which is the middle section of product at the end of deformation, it needs to determine the position 'P0' in initial blank 'CO' corresponding to each node 'P' of the part under certain boundary conditions by using Finite Element method and it can get the distribution of strain, stress and thickness of the part. In the final configuration C, according Principle of Virtual Work, for any virtual displacement, the following formula can be gotten:

$$W = \sum_e W_{int}^e - \sum_e W_{ext}^e = 0 \quad \forall \{u^*\} \quad (1)$$

The above formula can also be further expressed as:

$$W = \sum_e (\int_{v_e} \langle \varepsilon^* \rangle \{ \sigma \} dv - \int_{v_e} \langle u^* \rangle \{ f \} dv) = 0 \quad (2)$$

Among them, is Virtual Displacement, is Virtual Strain, is Cauchy Stress and is Equivalent Force.

Setting the node's virtual displacement in global coordinate system, expressed as ' \cdot ', it can be gotten:

$$W = \sum_e (\int_{v_e} \langle \varepsilon^* \rangle \{ \sigma \} dv - \int_{v_e} \langle u^* \rangle \{ f \} dv) = 0 \quad (3)$$

For triangle element of constant strain, in the above formula is:

$$\langle U_n^* \rangle = \langle U_i^* \quad V_i^* \quad W_i^* \rangle \quad (i = 1,2,3) \quad W_i^* = 0 \quad (4)$$

With the method 'Newton-Raphson (N-R)' to solve the formula and assemble together the internal and external forces of all nodes, it can be obtained a whole residual force vector:

$$\{R(U)\} = \sum_e (\{F_{ext}^e\} - \{F_{int}^e\}) \quad (5)$$

In the iteration step 'i', its approximate initial solution is, it can be obtained:

$$\{R(U^i)\} = \{F_{ext}(U^i)\} - \{F_{int}(U^i)\} \neq \{0\} \quad (6)$$

According N-R method, is done a Taylor expansion at, Retain first linear term and omit higher order term, it can be gotten:

$$\begin{cases} \left[-\frac{\partial \{R(U)\}}{\partial \{U\}} \right]_{U=U^i} \{ \Delta U^i \} = \{ R(U^i) \} \\ \{ U^{i+1} \} = \{ U^i \} + \{ \Delta U^i \} \end{cases} \quad (7)$$

Define tangent stiffness matrix:

$$[K_T^i] = \left[-\frac{\partial \{R(U)\}}{\partial \{U\}} \right]_{U=U^i} \quad (8)$$

The above tangent stiffness matrix can be had the limited central difference method to be solved for residual force vector with perturbation technique. That is:

$$K(i, j) = \frac{1}{2\delta} [R_i(U^i + \delta e_j) - R_i(U^i - \delta e_j)] \quad (\delta = 10^{-6} \sim 10^{-10}) \quad (9)$$

where, δ is the slight displacement perturbation of the node, is the unit vector in global coordinate system.

Material model of hot stamping: As can be seen in Fig. 1 (Bariani *et al.*, 2008), the principle of Hot Stamping technology is to heat the Boron steel sheet to Austenite's temperature range in the oxidation furnace and its microstructure can be transformed from Ferrite and Pearlite to Austenite and heat for some time to get full uniform Austenite. Then transfer the high temperature sheet to the hot stamping die with cooling waterways by manipulator or other equipment and finish the stamping and packing quenching of the sheet. Sheet metal stamping at high temperatures can be ensured its formability and forming precision. The microstructure of sheet metal after hot stamping is transformed from Austenite to lath martensite.

Figure 1 shows that the hot forming of Boron steel mainly includes two stage: high temperature forming and packing quenching in the die. In the high temperature forming stage, the blank is Austenite state, so the formability of the part mainly depends on the performance of the sheet in the austenite phase. In this case, mechanical properties of material will undergo fundamental changes compared with the state at room temperature. In the heat transfer process and forming process, the temperature range of austenitic material will be changed from 950 to 550°C and its properties will change with the temperature change greatly. Stress-strain curve of Boron steel 22 MnB5 at high temperature is shown in Fig. 2.

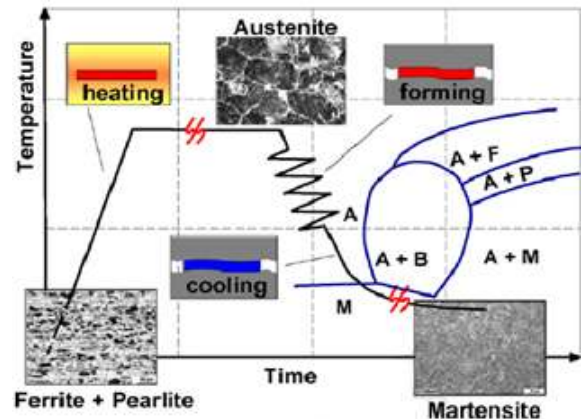


Fig. 1: The principle of hot stamping process

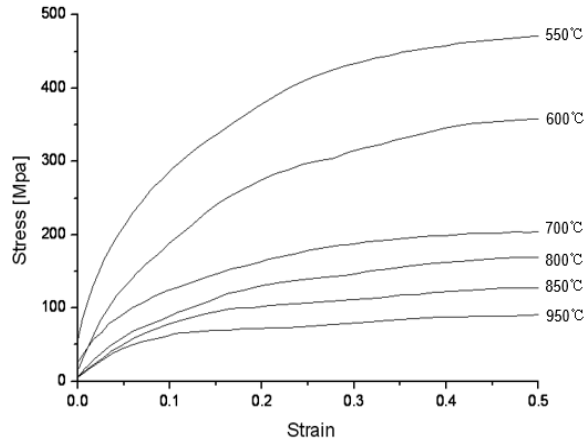


Fig. 2: Stress-strain curves at different evaluated temperature ranging from 550 to 950°C

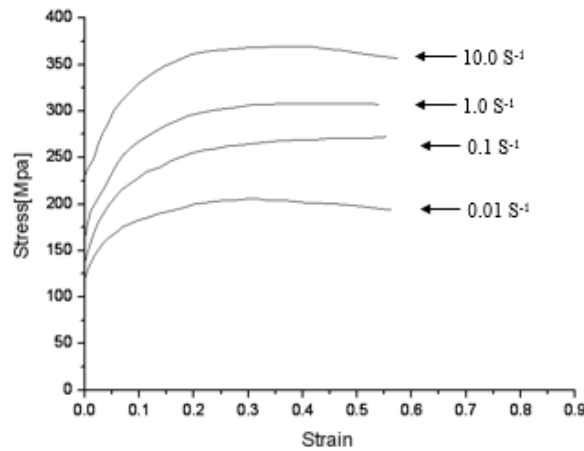


Fig. 3: Stress-strain curves of hot forming steel at different strain rate (T = 700°C)

As can be seen from Fig. 2, in hot forming process, the mechanical properties of austenite strongly depends on the temperature, the higher temperature, the smaller flow stress. And the influence of the strain rate on material properties of high-temperature forming is shown in Fig. 3. As can be seen, when the tensile strain rate increased from 0.01 to 10/sec, that is, the strain rate improved 1000 times, the yield strength of the material is increased by 2 times. In hot forming process, the strain rate is usually less than 1.0/sec.

Constitutive equations of high temperature on boron steel is the indispensable mathematical model in numerical simulation of hot stamping, it can reflect the relationship of the flow stress and strain, the strain rate and the temperature. From the view of some domestic and foreign literatures published on hot forming of high-strength boron steel, (Naderi *et al.*, 2008b; Hongsheng *et al.*, 2011; Huiping *et al.*, 2013) had all built the constitutive equations of high temperature austenite on high strength boron steel, which reflects the influence of strain, strain rate and temperature on boron steel's plastic deformation.

Table 1: Material parameters of flowing stress

K/MPa	β	b	n_0	c_n	m_0	c_m
41.54	38.93	0.011	0.2167	0.0033	0.012	0.0031

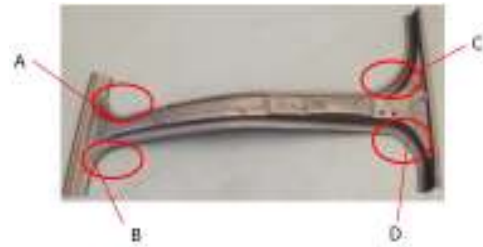


Fig. 4: The hot stamping product: B pillar

In this study, using the modified 'Norton-Hoff' formula to express the macroscopic flow stress at austenite stage of high temperature, as shown in formula (10):

$$\begin{cases} \sigma(\varepsilon, \dot{\varepsilon}, T) = K(b + \varepsilon)^{n(T)} \dot{\varepsilon}^{m(T)} \exp(\beta/T) \\ n(T) = n_0 \exp(-c_n(T_i - T_0)) \\ m(T) = m_0 \exp(-c_m(T_i - T_0)) \end{cases} \quad (10)$$

In the formula, K is Intensity Coefficient, b is Strain Correction, β is Temperature Coefficient, n_0, c_n, m_0, c_m are Hardening material parameters, the above parameters are all constants, obtained by high temperature tensile test, as shown in Table 1 (Ma, 2011).

RESULTS AND DISCUSSION

For verifying the effectiveness of One Step Inverse Forming to evaluate the formability of high-strength steel sheet at high temperature, select the B-pillar of a car to have the simulation, as shown in Fig. 4. The material used is 22 MnB5, the thickness is 2 mm. Build the 3D model of product and mesh it, with the triangular mesh when using One Step Inverse Forming method and with quadrilateral B-T (Belytschko-Tsay) element when using incremental method. When simulating, the two methods are all used the above material parameters and the same process parameters. Among them, the forming temperature is set to 750°C, the stamping rate is 0.1/sec. As is shown in Fig. 4, the draw beads are placed at the locations A, B, C and D. The friction coefficient is 0.17 and no use the blank holder. After completing the calculation, compare the results of the thickness distribution using two different methods, as shown in Fig. 5a and b. And two simulation results show basically the same thickness distribution, Table 2 shows the comparison of the average thickness in several key positions. Therefore, One Step Inverse Forming method is effective to roughly estimate the high temperature formability of high strength steel sheet.

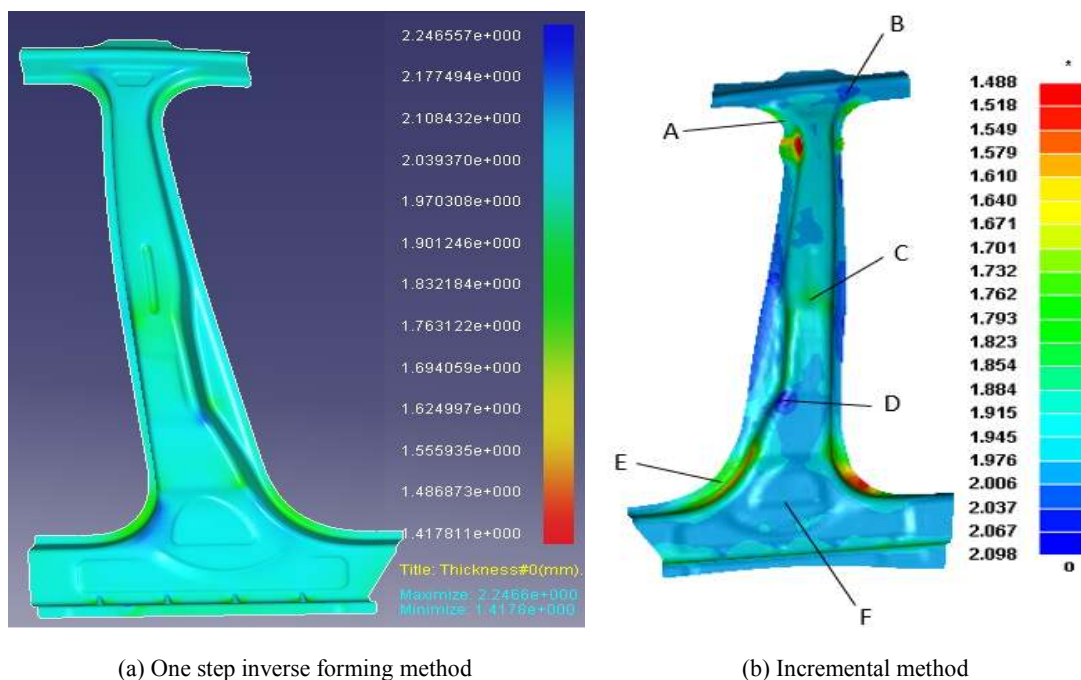


Fig. 5: Thickness distribution

Table 2: The comparison of the average thickness in several key positions

	A	B	C	D	E	F
Incremental method	1.850	2.037	1.823	2.098	1.854	2.006
One step inverse forming	1.860	2.108	1.901	2.130	1.870	2.003

CONCLUSION

- It is the first time to use One Step Inverse forming method to simulate the hot stamping of high-strength steel sheet in this study and to forecast the high temperature formability of high strength steel sheet. And taking the B pillar of a car for example, compare the thickness distribution results with the paper's algorithm and incremental method. The results show that One Step Inverse forming method to simulate the hot stamping has a fast computing speed and before computing, it needs only few process parameters. And the last thickness distribution simulated using the paper's method is consistent with that using the incremental method. So the method can be used in the initial stage of die designing and can roughly evaluate the high temperature formability of high-strength steel sheet.
- In the thermoplastic forming process of metal sheet, Constitutive Equation as the model describing the relationship of the thermodynamic parameters, is very important for researchers to use FEM simulation technology to anticipate, formulate and optimize the parameters of forming process. So, it is a key to get the correct material's constitutive relation of high temperature austenite

and the precision of constitutive models has a greater impact on the accuracy of the One Step Inverse Forming simulation.

- At present, the algorithm of the study is only used to evaluate the high temperature formability of high strength steel sheet in the state of different temperature and different stamping rate. In the further, the algorithm will be used to assess the shape and size of blank more exactly, which can reduce the amount of machining for the hard cutting steel sheet because of its high hardness after quenching.

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