

Research Article

Thermomechanical-Phase Transformation Simulation of High-Strength Steel in Hot Stamping

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The thermomechanical-phase transformation coupled relationship of high-strength steel has important significance in forming the mechanism and numerical simulation of hot stamping. In this study a new numerical simulation module of hot stamping is proposed, which considers thermomechanical-transformation multifield coupled nonlinear and large deformation analysis. In terms of the general shell finite element and 3D tetrahedral finite element analysis methods related to temperature, a coupled heat transmission model for contact interfaces between blank and tools is proposed. Meanwhile, during the hot stamping process, the phase transformation latent heat is introduced into the analysis of temperature field. Next the thermomechanical-transformation coupled constitutive models of the hot stamping are considered. Static explicit finite element formulae are adopted and implemented to perform the full numerical simulations of the hot stamping process. The hot stamping process of typical U-shaped and B-pillar steel is simulated using the KMAS software, and a strong agreement comparison between temperature, equivalent stress, and fraction of martensite simulation and experimental results indicates the validity and efficiency of the hot stamping multifield coupled constitutive models and numerical simulation software KMAS. The temperature simulated results also provide the basic guide for the optimization designs of cooling channels in tools.

1. Introduction

In order to meet the demands for reducing weight and improving safety, the hot stamping of high-strength steel, a new modern forming technology, has attracted more and more attention in the automobile industry [1]. The steel specimen produces martensitic microstructure and exhibits strong hardening abilities after hot stamping. The final yield strength and ultimate tensile strength can reach up to about 1000 MPa and 1500 MPa, respectively.

With comparison to the traditional cold stamping process, which has been thoroughly studied by scholars throughout the world [2–5], in the standard hot stamping process a steel blank is heated in a furnace to a certain high temperature (880–950°C). The matrix organization and mechanical behavior change with the thermal effect. The austenite transformation is distributed uniformly in the blank [6]. Then the heated blank is transferred into the tools (stamping molds) with water-cooled channels and formed and quenched simultaneously for a short time (less than 10 seconds). The phase transformation behavior from austenitic to martensitic state in the material causes an increase of the tensile strength up to 1200–1500 MPa. Throughout the entire stamping process, coupling thermomechanical characteristics are exhibited. The accurate control of temperature and final martensite rate play an important role in the final qualities of the molded parts [7].

The difficulty of hot stamping simulation is far beyond that of traditional cold forming. The thermodynamic properties of materials are affected by the changing of the microstructure, especially in the phase transform phase. The strong rate-dependent constitutive behaviors and temperature sensitivities are significant throughout the entire stamping process. Thermal contact and heat transfer between the tools and the blank surface must be considered with accuracy. The numerical modeling of the full process requires thermomechanical coupled material descriptions for the type of steel considered.

Bergman and Oldenburg implemented the numerical simulation of hot forming [8]. Eriksson et al. investigated the temperature and strain rate dependence of hot forming material [9]. Naderi, Bleck, and Merklein researched the plastic flow criterion and material parameters under high temperature [10, 11]. The theoretical analysis, numerical simulations, and experimental studies of hot forming were presented by Ma and Hu, who provided a new method for hot forming die design and technical process design [12, 13].

At present, most of the forming software programs available perform simplifications by using the rigid shell element to simulate the 3D tools in the hot forming modeling. Such assumption causes difficulties in simulating the temperature transport process. In 2012, Jiang, Wu et al. presented a numerical frame to simulate the thermal transport process by using a thick shell element of tools [14, 15]. It can simulate the simple components, such as U-shaped steel, with high accuracy. However, for the majorities of autopanels, the numerical simulations of temperature domain with complex 3D tool surfaces still face many difficulties and challenges.

In this paper, a fully coupled 3D thermomechanicalphase transformation finite element simulation of the hot stamping process is developed. The rate-dependent thermal constitutive model is implemented in the present software framework. In terms of general shell finite element and the 3D tetrahedral finite element analysis method related to temperature, a coupled thermal transport modeling for contact interaction between blank and tools is proposed. The hot stamping process of benchmark typical U-shaped steel and B-pillar steel is simulated by the present numerical program. Strong agreements of temperature, equivalent stress, and fraction of martensite between the simulated and experimental results indicate the validity and efficiency of the present multifield coupled numerical model in simulating the hot stamping process for the automobile industry.

2. Key Technologies for Thermomechanical-Phase Transformation Coupled Behavior

2.1. Constitutive Laws of High-Strength Steel. 22MnB5 boron steel is the most common steel used for hot stamping. A brief introduction to the thermomechanical-phase transformation coupled constitutive relationship for high-strength steel is presented in the following section. Detailed descriptions can be found in [13].

In order to model the thermal-elastic-plastic response during the hot stamping process, an additive decomposition of the total strain increment ($\dot{\varepsilon}_{ij}$) is utilized [13, 14]. The total stain ε_{ij} can be expressed with the decomposition rate form as follows:

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} + \dot{\varepsilon}_{ij}^{\text{th}} + \dot{\varepsilon}_{ij}^{\text{tr}} + \dot{\varepsilon}_{ij}^{\text{tp}}, \tag{1}$$

where $\dot{\varepsilon}_{ij}^{e}$ is the elastic strain increment, $\dot{\varepsilon}_{ij}^{P}$ is the plastic strain increment, $\dot{\varepsilon}_{ij}^{\text{th}}$ is the thermal strain increment, $\dot{\varepsilon}_{ij}^{\text{tr}}$ is the isotropic transformation strain increment, and $\dot{\varepsilon}_{ij}^{\text{tp}}$ is



FIGURE 1: Stress-strain curves at different evaluated temperature from 500°C to 800°C.

the transformation induced plasticity increment. $\dot{\varepsilon}_{ij}^{\text{tr}}$ and $\dot{\varepsilon}_{ij}^{\text{tp}}$ play an important role in hot forming and are expressed as (2) in the traditional quenching treatment:

$$\dot{\varepsilon}^{\rm tr} = \beta \xi, \tag{2}$$
$$\dot{\varepsilon}^{\rm tp} = k \left(\overline{\sigma} \right) \overline{\sigma} \left(1 - \xi \right) \dot{\xi}, \tag{2}$$

where ξ is the fraction of martensitic transformation, β is the phase transformation volume coefficient, and *k* is the phase transformation plastic coefficient related to equivalent stress $\overline{\sigma}$.

The sensitivity of temperature on the forming behavior of 22MnB5 is investigated [16]. The flow curves shown in Figure 1 indicate that the temperature has a strong influence on the forming behavior of quenchable steel. Temperature increasing leads to an appreciable reduction of stress level and a decreased work hardening exponent.

For temperature variation from 500°C to 800°C, representative true stress-strain curves are displayed for an exemplarily strain rate of 1 s^{-1} . Other curves under different temperatures are obtained by quadratic interpolation using the existing experimental curves, such as the curves of 600°C and 700°C, as shown in Figure 1.

2.2. Martensite Phase Transformation. For the martensite phase transformation, the relationship between temperature and phase change is modeled using the equation proposed by Ma et al. [13], which can be written as follows:

$$\xi = 1 - \exp\left[-\theta\left(\overline{\sigma}\right)\left(M_s\left(\overline{\sigma}\right) - T\right)\right],\tag{3}$$

where ξ represents the fraction of martensitic transformation, M_s represents the martensite transformation's beginning temperature, θ represents the material parameter which reflects the austenite-martensite transformation rate, $\overline{\sigma}$ represents equivalent stress, and T represents temperature.



FIGURE 2: Relationships of the martensite start temperature M_s and material parameter θ with the variation to equivalent stress $\overline{\sigma}$.

The corresponding relation between the equivalent stress $\overline{\sigma}$ and starting temperature of martensite transformation M_s and the relationship between material parameter θ and equivalent stress $\overline{\sigma}$ are shown in Figure 2.

In general, the martensite start temperature M_s rises with increasing tensile and compressive normal stresses as well as shear stresses. The hydrostatic component always decreases the martensite start temperature. In the present paper, (3) is used to model the austenite to martensite reaction.

3. Nonlinear Large-Deformation FEM Formula of Hot Forming

Hot stamping is a coupled thermomechanical forming process with intended phase transformation. During the solidstate phase transformations, heat is released, which then influences the thermal field. Furthermore, both the mechanical and thermal properties vary with the temperature variation and deformation. Consequently, a realistic FE model for full process numerical simulation must consider the interaction among the mechanical, thermal, and microstructural fields.

3.1. Thermal Transport Model and FE Formulae

(i) Basic Formula of Heat Transfer in the Hot Forming Process. The equation of heat conduction in an isotropic solid is as follows:

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v - \rho c \frac{\partial T}{\partial t} = 0, \qquad (4)$$

where ρ is the mass density, *c* is the specific heat, *k* is the thermal conductivity, and q_v is the internal heat generation rate per unit volume. q_v includes external heat sources as well as transformation heat (q^{tr}) and heat generated by plastic deformation (q^p) as:

$$q^p = a\sigma'_{ij}\dot{\varepsilon}_{ij},\tag{5}$$

where σ'_{ij} is the deviatoric stress tensor and $\dot{\varepsilon}_{ij}$ is the strain increment.

The latent heat q^{tr} can be defined by the following equation [16, 17]:

$$q^{\rm tr} = \rho L \frac{\partial \xi}{\partial t},\tag{6}$$

where *L* is the latent heat of fusion (J/kg). ξ is the volume fraction martensite transformation.

The heat transfer processes between the contacted surfaces were considered by using the following convection boundary conditions:

$$-k\frac{\partial T}{\partial n} = h\left(T - T_a\right),\tag{7}$$

where T_{α} is the temperature at the contacted surface and *h* is the heat transfer coefficient.

(ii) Governing Equation for 3D Transient Heat Conduction Process. The finite element formulation for 3D transient heat conduction is as follows:

$$C^e \dot{T}^e + K^e T^e = F^e, \tag{8}$$

where C^e is the heat capacity matrix, K^e is the heat conduction matrix, and \dot{T}^e and T^e are the derivatives of element nodal temperature with respect to time and element nodal temperature, respectively. F^e is the nodal temperature load vector. Their components are as follows:

$$C_{ij}^{e} = \int_{V_{e}} \rho c N_{i} N_{j} dV,$$

$$K_{ij}^{e} = \int_{V_{e}} k \left(\frac{\partial N_{i}}{\partial x} \frac{\partial N_{j}}{\partial x} + \frac{\partial N_{i}}{\partial y} \frac{\partial N_{j}}{\partial y} + \frac{\partial N_{i}}{\partial z} \frac{\partial N_{j}}{\partial z} \right) dV,$$

$$F_{i}^{e} = \int_{V^{e}} N_{i} q_{\nu} dV + \int_{\partial V^{e}} N_{i} \overline{q} dA,$$
(9)

where \overline{q} is the distributed heat flux per unit area and N_i refers to the shape function.



FIGURE 3: Quadrilateral temperature shell element.

(*iii*) 3D Thermal Shell Element. The basic equation of temperature shell elements, as shown in Figure 3, was developed by Wang and Tang [18]. The temperature shell elements adopt the $\xi_1\xi_2\xi_3$ curvilinear coordinates, with ξ_1, ξ_2 in the neutral plane and ξ_3 perpendicular to the neutral plane. Assume that the inner element temperature field changes in second order along the ξ_3 direction:

$$T(\xi_{1},\xi_{2},\xi_{3},t) = T_{0}(\xi_{1},\xi_{2},t) + T_{1}(\xi_{1},\xi_{2},t)\xi_{3} + T_{2}(\xi_{1},\xi_{2},t)\xi_{3}^{2},$$
(10)

where $T_0(\xi_1, \xi_2, t)$ represents neutral surface temperature and $T_1(\xi_1, \xi_2, t)$ and $T_2(\xi_1, \xi_2, t)$ can be determined by the boundary condition on $\xi_3 = \pm 1/2$.

(*iv*) 3D Thermal Tetrahedral Element [19]. The 3D tetrahedral element is implemented in the heat conduction simulation of tools. It is assumed that temperature is a linear transformation function with the coordinates (x, y, z):

$$T = a_1 + a_2 x + a_3 y + a_4 z, \tag{11}$$

where a_1, a_2, a_3 , and a_4 are the undetermined coefficients, unit four coordinates of the nodes *i*, *j*, *m*, and *l*.

As shown in Figure 4, the shape function of the tetrahedral element is obtained as follows:

$$N_{\xi} = \frac{1}{6V_e} \left(a_{\xi} + b_{\xi} x + c_{\xi} y + d_{\xi} z \right) \quad (\xi = i, j, m, l), \quad (12)$$

where V_e is the volume of the tetrahedral element and a_{ξ} , b_{ξ} , c_{ξ} , and d_{ξ} are the coefficients related to the node locations.

3.2. FE Formula with Static Explicit Algorithm. Based on the continuum theory and virtual work principle [20], the static explicit finite element equation of coupled multifield is obtained by the following:

$$\left[K_{p}\right]\left\{\nu\right\}^{e} = \left\{\dot{f}_{p}\right\} + \left\{\dot{g}_{p}\right\} + \left\{\dot{f}\right\}^{e},$$
(13)



FIGURE 4: Temperature tetrahedral element.

where $\{v\}^e$ is the nodal velocity vector and $[K_p]$ is the mass matrix with the form of

$$\begin{bmatrix} K_p \end{bmatrix} = \int_e \left\{ [B]^T \left(\left[\widetilde{D}_{ep} \right] - [F] \right) [B] + [E]^T [Q] [E] \right\} d\nu,$$

$$\left\{ \dot{g}_p \right\} = \int_e [B]^T \left(\frac{\eta}{1+\zeta} \{P\} + \dot{T} \left\{ \beta' \right\} \right) d\nu, \qquad (14)$$

$$\left\{ \dot{f}_p \right\} = \int_{a_\sigma} [N]^T \left\{ \dot{\overline{p}} \right\} da + \int_e [N]^T \left\{ \dot{p} \right\} d\nu,$$

where p_i and \overline{p}_i (i = 1, 2, 3) are the body force and surface force vector, [B] is the strain element, and the force vector [F] takes the form of

$$F_{ijkl} = \frac{1}{2} \left(\sigma_{lj} \delta_{ki} + \sigma_{kj} \delta_{li} + \sigma_{li} \delta_{kj} + \sigma_{ki} \delta_{lj} \right).$$
(15)

4. Numerical Simulations of U-Shaped Steel and B-Pillar in Hot Stamping

Based on the above multifield models, FEM, and temperature field analysis, the numerical modeling of the hot stamping process is developed and implemented into independently developed CAE commercial software called KMAS for metal sheet forming. Two numerical examples are presented in this section to show the strong ability and feasibility of the present numerical framework to simulate the hot stamping process.

According to the three-dimensional temperature field characteristics of hot forming, the proprocessing of 3D tools typically follows the rules below.

- We must divide the 3D elements into internal and boundary elements. Different surfaces with different thermal boundary conditions must be defined.
- (2) The contact surfaces and cooling channel surfaces on the tools are separated to realize the contact interface simulation and treatment of the boundary conditions.



FIGURE 5: Relationships of yield stress and elastic modulus with increasing of temperature.



FIGURE 6: Relationships of heat conductivity and specific heat with increasing of temperature.

- (3) For the triangular elements on the boundary surfaces, the nodes should be organized with a certain order to guarantee the same normal direction.
- (4) We assume there is only one surface of each element at the border. The deal, to some extent, can meet the accuracy requirements of the thermal simulation.

4.1. Material Properties of 22MnB5 Steel. The materials of U-shaped steel and B-pillar steel are composed of 22MnB5 high-strength steel, and #45 steel is chosen as the material of the tools. Figures 5 and 6 show the major mechanical and thermal related properties of 22MnB5 steel with variation of temperature. We can see that the yield stress, elastic modulus, and thermal conductivity decrease, respectively, as the temperature increases. Also, as the temperature increases, the variation of specific heat reaches the maximum at 800 K and then remains constant.



FIGURE 7: Schematic diagram of FE model.

4.2. Numerical Simulation of U-Shaped Steel in the Hot Stamping Process. Figure 7 presents the finite element configurations of tools and blank for U-shaped steel. The thickness of blank is t = 1.6 mm. Heat transfer between the contact



FIGURE 8: Process of split surfaces from 3D tools.



FIGURE 9: Simulation temperature results on different element of blank.

interfaces takes place via conduction through the contacting spots, the conduction through the interstitial gas, and radiation across the gaps. The convection of blank and tools to the environment ($h_e = 3.6 \text{ W/(m^2 K)}$), convection from tools into cooling channels ($h_c = 4700 \text{ W/(m^2 K)}$), and heat transfer from hot blank to tools ($\alpha_c = 5000 \text{ W/(m^2 K)}$) are also considered, as shown in Figure 8. The changing of the contact situation between blank and tools leads to changing of blank temperature. Three periods can be summarized to describe the contact behavior.

(1) Stamping Phase (0–0.5 s): point 1 is not fully contacted with the tools due to being gently warped, and the temperature drops slowly. The temperatures of the other points decrease greatly.



FIGURE 10: Simulation temperature results of die (t = 0.5 s).



FIGURE 11: Simulation temperature results of punch (t = 0.5 s).



FIGURE 12: Simulation temperature results of blank holder (t = 0.5 s).



FIGURE 13: Experimental and simulated temperature results of blank.



FIGURE 14: Equivalent stress and fraction of martensite curve with different temperature.



FIGURE 15: Typical microstructure of sample.

Mathematical Problems in Engineering



FIGURE 16: Schematic diagram of tools model.



FIGURE 17: Simulation temperature results of blank.

- (2) Quenching Phase (0.5–6.5 s): due to the effect of the cooling channels on the inner surface of the tools, the cooling rate of the blank is high (about 300 K/s) at the beginning of the quenching phase.
- (3) Latent heat of phase transformations is released and thus affects the blank thermal history. We observed that the temperature curve fluctuates at around the time of 1.5 s.

(*i*) *Results for Thermal Field.* Tools with water channels were designed to make the temperature distribution homogeneous with efficiency. The temperature distributions of the 3D tools, slices surfaces, and cooling channels surfaces are shown in Figures 9–12.

Thermocouples were installed and utilized to measure the temperature variations during the prototype hot forming. The experimental and simulation results are shown in Figure 13. A high consistency can be observed for the entire stamping process. Table 1 presents the maximum temperature values located at the die, punch, and blank holder.

(ii) Results for Equivalent Stress and Fraction of Martensite. In the process of hot stamping, temperature and deformation at the shoulder (a position with large curvature) largely affect the steel forming performance. Two character points are selected to present the variation of equilibrium stress and fraction of martensite with temperature, as shown in Figure 14. The presence of an applied or internal stress affects both the martensite start temperature M_s and the fraction



(c) Temperature distributions of die with water channels

FIGURE 18: Simulation temperature results of die (t = 0.56 s).

Maximum temperature of tools				
Tools	Time	Position	Value	Channel value
Die	0.5 s	Point 2	460 K	316 K
Punch	0.5 s	Point 2	370 K	312 K
Blank holder	0.5 s	Point 1	390 K	312 K

TABLE 1: Maximum temperature of tools.

of martensite formed as a function of the cooling below M_s . When $\overline{\sigma}$ changes within a certain range, M_s increases with the increase of $\overline{\sigma}$.

It can be seen from Figure 14 that, when quenching begins, there is no martensite transformation. The amount of martensite transformation increases as time increases (Figure 14(a)). 6 s later, the martensite volume fraction of the blank reaches above 90% (Figure 14(b)).

The optical microscopy images of the blank related to the same position as that in Figure 14(a) are presented in Figure 15 after quenching in the final condition. Ferrite appeared as white, bainite appeared as light gray, and martensite appeared as black lath-shape. The average martensite volume fraction was 75.9%.

4.3. Numerical Simulation Results of B-Pillar Steel. B-pillar steel stamping is chosen as the second example. The tool model design for B-pillar is shown in Figure 16 and the 3D finite element model in Figure 17. The quenching stages of B-pillar are also simulated by KMAS software.

The beginning temperature of the quenching of the blank is 873 K. Five character points are selected (Figure 18(a)) in



(c) Temperature distributions of punch with water channels

FIGURE 19: Simulation temperature results of punch (t = 0.56 s).

the surface of the die tool. The temperature curves shown in Figure 18(b) present the temperature changing process of each point. We can see from the temperature curve that point 2 does not fully contact with the tools, due to a gentle warp, and the temperature drops slowly. The temperatures of the other points decrease greatly. Similar with the die, as shown in Figure 19, four character points on the punch surface are selected.

The maximum temperatures of the tools and cooling channel appear within a short time after quenching begins. Then, due to the continuing cooling effect of the water channel, the temperature of the tools decreases at a rapid speed. Figure 20 presents the final B-pillar products by the hot stamping process. The martensite volume fraction of the blank reaches above 90%, as shown by the optical microscopy image test.



FIGURE 20: High-strength B-pillar steel with hot stamping technique.

5. Conclusion

(1) During the stamping phase, the blank slides along the tool wall lead to an increase in the tool temperature.

At the end of this phase, the tools reach the maximum temperature at the shoulder.

- (2) The temperature of a cooling duct placed closer to the tool surface in a convex area is higher than that in a concave area. Most of the surfaces of the cooling channels remain at a low temperature in the quenching process.
- (3) Due to the ignorance of the flow velocity and pressure of water, the temperature distributions on the different slices surfaces are almost the same.

It can be concluded that the efficient cooling is most desired in convex areas, that the geometry of cooling ducts is restricted due to constraints in drilling, and that the ducts should be placed but sufficiently far from the tool contour to avoid any deformation. A more accurate contacted condition and flow analysis for hot stamping remains to be studied.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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