Development of Sheet Metal Forming Analysis Incorporating Phase-transformation Model for Hot Stamping

K Uenishi1, M Kubo2, T Suzuki1 and K Okamura1

1Steel Research Lab, Nippon Steel Corp., 1-8 Fuso, Amagasaki, Hyogo, 660-0891, Japan
2Nagoya R&D Lab., Nippon Steel Corp., 5-3 Tokaimachi, Tokai City, Aichi, 476-8686, Japan

Abstract. To predict the spring back after hot stamping of sheet metals, a user material routine incorporated with phase transformation effects has been developed and implemented in general-purpose commercial finite element software. The mechanical response of the metallographic structure incorporates variation of transformation plastic strain and transformation volume expansion. Additionally, the thermal response incorporates the dependencies of thermal properties and latent heat of phase transformation. The start timing of diffusive transformation was determined using Scheil’s law, and the Kolmogorov–Johnson–Mehl–Avrami equation was adopted for the progression of diffusive transformation. The Koistinen and Marburger equation was used for the progression of martensite transformation. Using the developed model, we considered the effects of phase transformation on shape fixability. We conducted experiments that focused on measuring the shape fixability of U-bend hot formed parts. In this study, we show that the spring back of the U-bend parts increases under conditions in which phase transformation occurs before formation has been completed. Furthermore, the spring back could accurately predict by using the developed model.

1. Introduction

In the automotive body parts, both improvement of collision safety performance and weight reduction to improve fuel efficiency are required. Against the background of these social demands, hot stamping (HS) parts made of ultra-high-strength steel with a tensile strength of 1.5 GPa class or more are used for automotive body parts. Furthermore, another feature of HS technology is that it can produce ultra-high strength parts with better shape fixability than cold forming parts. However, it is known that the shape fixability of HS parts is affected by changes in forming start temperature and material cooling conditions. It is important to include transformation plasticity in the constitutive equation to analytically predict the shape fixability, and the implicit stress integration method by the return mapping algorithm for this purpose was developed[1-3]. As a result, this analysis technique has been applied to HS.

Although previous studies reflect the effect of the grain size before forming on the calculation[5], and has also been applied to TWB, most of them use three-dimensional block elements despite plate forming[4-6]. This element is disadvantageous in terms of calculation time because it requires element division in the thickness direction. Additionally, there are reports of calculations using shell elements, and a problem of convergence and accuracy arises because they do not use the return mapping algorithm[7]. Therefore, applying these methods to efficiently verify mass production conditions of stamped parts is problematic.
In this study, we acquired physical property data through experiments and developed the analysis model that incorporated phase transformation and implemented the developed model as a general-purpose solver. The developed model enables analysis using the shell element model via the return mapping algorithm in the plane stress state and achieves both accuracy and calculation time. Additionally, by using the developed model, we considered the effects of phase transformation on shape fixability.

2. Numerical methods and material model

Figure 1 shows a conceptual diagram of the numerical analysis using in the developed model. The developed model implements user subroutines related to elastoplastic response and thermophysical properties that can accurately predict the phase transformation behavior during HS analysis using LS-DYNA. The subroutine umat for the mechanical response of a material considers the transformation plastic strain and the expansion or shrinkage due to thermal and/or phase transformation. The subroutine thumat for the thermal response considers latent heat and the variation of thermophysical material properties accompanying the phase transformation. The adaptability of the additive rule of the isothermal transformation in infinitesimal time period is assumed to calculate the diffusion-type phase transformation in continuous cooling. The start of phase transformation is determined by Scheil’s law[8], and the transformation rate is calculated by the Kolmogorov–Johnson–Mehl–Avrami (KJMA) equation[9].

\[
\xi = 1 - \exp\left[-a(T)t^{n(T)}\right],
\]

where the functions \(a(T)\) and \(n(T)\) are polynomials fit to the measured isothermal transformation curve. The volume fraction of the martensite \(\xi_M\) is calculated using the Koistinen and Marburger (KM) equation[10].

\[
\xi_M = 1 - \exp\left[-a(T - M_s)\right],
\]

where \(a\) is a material constant and \(M_s\) is the martensitic start temperature calculated by Kunitake’s empirical[11],

\[
M_s (°C) = 560.5 - 407.3(%C) - 7.3(%Si) - 37.8(%Mn) - 19.8(%Cr) - 19.5(%Ni) - 4.5(%Mo).
\]
The total strain increment $\Delta \varepsilon$ comprises elastic $\Delta \varepsilon_e$, plastic $\Delta \varepsilon_p$, thermo-metallurgical $\Delta \varepsilon_v$, and transformation plastic part $\Delta \varepsilon_{TP}$ under the assumption of additive decomposition.

$$\Delta \varepsilon = \Delta \varepsilon_e + \Delta \varepsilon_p + \Delta \varepsilon_v + \Delta \varepsilon_{TP}.$$  

(4)

The stress at the end of increment $t + \Delta t$ can be expressed as

$$\sigma^{t+\Delta} = \sigma^{t+\Delta} E : [\varepsilon^{t+\Delta} e + \Delta \varepsilon_v + \Delta \varepsilon_{TP}],$ $

(5)$

where the subscript on left side denotes time hereafter.

Then, $\Delta \varepsilon_v$ can be calculated from the change of density and given as

$$\Delta \varepsilon_v = \Delta \varepsilon_v I = \frac{1}{3} \left(\frac{\rho(T, \xi)}{\rho(t, \xi)} - 1\right) I,$$

(7)

where the density can be approximated by linear mixture rule, and the density of each metallic part can refer to Miettinen [12] and Okamura [13].

Unknown variables in the equation (5) are $\Delta \varepsilon_p$ and $\Delta \varepsilon_{TP}$. According to the associated flow rule and using the isotropic yield function $f(\sigma)$, the plastic strain increment $\Delta \varepsilon_p$ is given as

$$\Delta \varepsilon_p = \Delta \varepsilon_p I = \Delta \rho \frac{\partial f(\sigma)}{\partial \sigma} = \Delta \rho \frac{3^{t+\Delta} s}{2^{t+\Delta} \bar{\sigma}},$$

(8)

and $f(\sigma) = \bar{\sigma} - Y(\bar{\sigma}^p, T, \xi), \quad \bar{\sigma} = \left(\frac{3}{2} s : s\right)^{\frac{1}{2}},$

(9)

where $\Delta \rho$ is a plastic multiplier that is equal to the equivalent plastic strain increment, $s$ is deviatoric stress, $\bar{\sigma}$ is equivalent stress, and $\bar{\sigma}^p$ is equivalent plastic strain, $Y(\bar{\sigma}^p, T, \xi)$ is flow stress approximated using the linear mixture rule. For the $\Delta \varepsilon_{TP}$, the formula by Denis et al. [14] is adopted as

$$\Delta \varepsilon_{TP} = \sum_{I=1}^{N-1} 3 K_I \xi_A \Delta \bar{\varepsilon}^{t+\Delta} I = \Delta h^{t+\Delta} s,$$

(10)

$$\xi_A = 1 - \sum_{I=1}^{N-1} \xi_I, \quad \Delta h = \sum_{I=1}^{N-1} 3 K_I \xi_A \Delta \bar{\varepsilon}_I,$$

(11)

where $K_I (I = 1, \cdots, N - 1)$ is the transformation plasticity coefficient from austenite to $I$th phase, and $\xi_A$ is the volume fraction of untransformed austenite. The value of $\Delta h$ is known at the start of increment. Substituting Eqs. (8) and (10) in (5) leads to

$$\sigma^{t+\Delta} = \sigma^{(T)} - \Delta \rho \frac{3^{t+\Delta} s}{2^{t+\Delta} \bar{\sigma}} + \Delta h^{t+\Delta} s.$$
The normal stress to shell surface must be zero. The elastic modulus in equation (4) must be replaced with the plane stress one \( E' \) and can be rewritten in matrix form as

\[
\{ \sigma \} = \{ \sigma^{(T)} \} - \left( \frac{3\Delta p}{2\sigma} + \Delta h \right) E' \{ s \},
\]

(13)

\[
\{ \sigma \}^T = (\sigma_{11}, \sigma_{22}, r_{12}, r_{23}, r_{31}), \quad \{ s \}^T = (s_{11}, s_{22}, 2s_{12}, 2s_{23}, 2s_{11}).
\]

(14)

By introducing the deviation operator matrix \( \{ P \} \), which works as \( \{ s \} = [P] \{ \sigma \} \), and multiplying the orthogonal operator matrix \( \{ Q \} \) (\( [Q][Q]^T = [I] \)), Eq.(13) leads to

\[
\{ Q \}^T \{ \sigma \} = \{ Q \}^T \{ \sigma^{(T)} \} - \left( \frac{3\Delta p}{2\sigma} + \Delta h \right) [E'] [P] \{ \sigma \},
\]

(15)

\[
\{ \sigma^* \} = \{ \sigma^{(T)*} \} - \left( \frac{3\Delta p}{2\sigma} + \Delta h \right) [Q]^T [E'] [Q]^T [P] [Q] \{ \sigma^* \},
\]

(16)

where \( \{ \sigma^* \} = \{ Q \}^T \{ \sigma \} \) and \( \{ \sigma^{(T)*} \} = \{ Q \} \{ \sigma^{(T)} \} \). Because the matrixes \( [Q]^T [E'] [Q] \) and \( [Q]^T [P] [Q] \) are orthogonal, we can easily express \( \{ \sigma^* \} \) by \( \{ \sigma^{(T)*} \} \). After performing certain calculations, we have

\[
\bar{\sigma}^2 = \frac{1}{2} \left[ \frac{\sigma_{11}^{(T)*}}{1 + (\frac{3\Delta p}{2\sigma} + \Delta h) E' / 3(1-\nu)} \right]^2 + \frac{3}{2} \left[ \frac{\sigma_{22}^{(T)*}}{1 + (\frac{3\Delta p}{2\sigma} + \Delta h) 2G} \right]^2 \\
+ 3 \left[ \frac{\sigma_{12}^{(T)*}}{1 + (\frac{3\Delta p}{2\sigma} + \Delta h) 2G} \right]^2 + 3 \left[ \frac{\sigma_{23}^{(T)*}}{1 + (\frac{3\Delta p}{2\sigma} + \Delta h) 2G} \right]^2 + 3 \left[ \frac{\sigma_{31}^{(T)*}}{1 + (\frac{3\Delta p}{2\sigma} + \Delta h) 2G} \right]^2.
\]

(17)

Then, the plastic strain increment \( \Delta \varepsilon_p \) can be determined by solving \( \Delta p \) to satisfy the next equation

\[
g(\Delta p) = \bar{\sigma}^2 - Y(\varepsilon_p^* + \Delta \varepsilon_p, \varepsilon_p^{(T)} + \Delta \varepsilon_p, \varepsilon_p^{(T)} + \Delta \varepsilon_p)^2 = 0.
\]

(18)

The stress \( \{ \varepsilon + \Delta \varepsilon \} \) can be calculated by \( \{ \sigma \} = [Q] \{ \sigma^* \} \) after obtaining \( \{ \sigma^* \} \) by substituting \( \Delta p \) into Eq.(16).
3. Experimental methods

3.1 Verification of phase transition in thermal expansion behavior

The prediction accuracy of the phase transformation behavior in the developed model was verified using a simple model of the specimen size.

The test material used was steel sheet of 22MnB5 grade for HS. The thermal expansion behavior was experimentally measured by simulating the thermal history of HS. The specimen size was 1.6mm×20mm×200mm. The thermal history of HS was simulated by electric heating the specimen and applying feedback control to the temperature. The heating temperature was 950°C, and the heating time at the heating temperature was 120s. After that, it was cooled to 750°C at 15°C/s to simulate transfer and cooled to room temperature at 50°C/s to simulate die cooling. The thermal expansion behavior during this heat treatment was measured with a contact thermal dilatometer.

Figure 2 shows the analysis model. The analysis model simulating the shape of the specimen was created with a thick shell element. The thermal history measured in the experiment was given as the thermal boundary condition, and the strain change accompanying the temperature change was calculated.

3.2 Effect of phase transformation on part shape fixability

Using the U-bend molding model shown in Figure 3, the results of numerical analysis using the developed material model were compared with the experimental results, and the accuracy of the developed model was verified. This U-bend forming part has a shape in which slight changes in stress generated during molding are easily reflected in the amount of spring back, making it suitable for verification of shape fixability. The blank is placed on the pins of mold. Therefore, the temperature of the blank hardly decreases because it does not come into contact with the mold until the start of forming. Also, the effect of diffusion-type phase transformation and martensitic transformation on shape fixability was investigated by changing air cooling rate conditions during transportation. Under low cooling rate conditions, the blanks are air-cooled during transport to achieve a diffusion-type phase transformation. On the other hand, under high cooling rate conditions, the martensite phase transformation can be achieved by forced convection cooling of the blank during transport.

The experimental process of the U-bend forming test is shown in Figure 4, and the experimental conditions are shown in Table 1. Shape fixability was evaluated by measuring the change in the curvature radius $\Delta R$ of the U-bend parts.

Figure 5 shows the analysis process of the developed model. After each analysis process, the development model passes history variables (e.g., temperature, stress, and volume fraction of a phase) to the next analysis process. Table 2 shows the analysis conditions. The analysis conditions were set to correspond to the experiment.
Figure 3 Schematic of U-bend forming. (a) U-bend molding die. (b) Blank.

Figure 4 Experimental process.

Table 1 Experimental conditions

|                         |                |
|-------------------------|----------------|
| Blank material          | 22MnB5         |
| Blank size (mm)         | 1.4x190x40     |
| Austenitizing condition| 900°Cx240s     |
| Cooling rate during     | (a) Low cooling rate condition: -5°C/s  |
| transfer condition      | (b) High cooling rate condition: -32°C/s|
| Forming speed (mm/s)    | 100            |
| Forming start temp.     | (a) Low cooling rate condition: 700–550°C |
|                         | (b) High cooling rate condition: 250–650°C|
| Closed tool time (s)    | 15             |

Transfer the History variables(temperature, Stress) to next process

Table:| Heating | Air cooling | Forming | Die quench | Spring back |
|--------|------------|---------|-----------|------------|
| Developed model | — | ○       | ○        | ○          | ○          |
| Conventional model | — | —       | ○        | ○          | —          |

Figure 5 Comparison of conventional and development methods in the analysis process.
Table 2 Analysis conditions

| Element model                              | Thick Shell element (TSHELL) |
|--------------------------------------------|------------------------------|
| Number of integration points in the thickness direction | Temperature: 3 Stress: 7 |
| Mesh size (mm)                             | 1.4                          |
| Initial temperature (°C)                   | 900                          |
| Cooling rate during transfer condition     | (a) Low cooling rate condition: -5°C/s (b) High cooling rate condition: -32°C/s |
| Forming speed (mm/s)                       | 1000 (time scale = 10)       |
| Forming start temperature                  | (a) Low cooling rate condition: 700–550°C (b) High cooling rate condition: 250–650°C |
| Holding time at bottom dead center (sec)   | 0.30 (time scale = 100)      |

4. Results and discussion

4.1 Verification of phase transition in thermal expansion behavior

Figure 6 shows a comparison of the experimental and analytical results of the thermal expansion behavior. In addition to the thermal expansion behavior, the prediction of the martensite start temperature is consistent with experiments and analysis, indicating that the phase transformation behavior of HS can be accurately predicted using the developed model.

Figure 7 shows the comparison of the continuous cooling transformation (CCT) diagram between the simulation and experiment. The result shows that the developed model can accurately predict the onset of diffusion-type phase transformation (ferrite and bainite) and martensitic phase transformation could be predicted.

![Figure 6](image1.png)

**Figure 6** Temperature–strain relation under thermal history simulating the HS process.

![Figure 7](image2.png)

**Figure 7** Comparison of the CCT diagram between the simulation and experiment.
4.2 Effect of phase transformation on part shape fixability

Figure 8 shows the comparison of forming start temperature–shape fixability relation between simulation and experiment and the relationship between the forming start temperature and the phase fraction obtained from the analysis results. In the experiment of low cooling rate, the change in curvature radius increases as the forming start temperature decreases. Moreover, the results of analysis using the developed model show that the experimental results can be accurately reproduced. According to the analysis results, the forming start temperature at which shape fixability is reduced coincides with the temperature at which diffusion-type phase transformation occurs. On the other hand, under condition of high cooling rate, shape fixability decreases below the martensite start temperature.

Figure 9 shows the effect of fraction of martensite and transformation plasticity on shape fixability. Under the condition of analytically the transformation plasticity coefficient of martensite \( K = 0 \), the shape fixability is reduced. Therefore, the reason for the decrease in shape fixability is that when processed after phase transformation, residual stress does not decrease due to transformation plasticity, and the deformation resistance of the transformed phase is higher than that of austenite. It is considered necessary to form austenite to ensure the shape fixability of the HS parts.

![Figure 8](image1.png)

![Figure 9](image2.png)

**Figure 8** Comparison of the forming start temperature–shape fixability relation between the simulation and experiment, and the relationship between the forming start temperature and the phase fraction.

(a) Cooling rate during transfer is low. (b) Cooling rate during transfer is high.
Summary

In this study, sheet metal forming analysis technology incorporating a phase transformation model for HS was developed and verified. The findings obtained from this study are shown below.

1. Using the developed model, the thermal expansion behavior during the HS process caused by temperature change and phase transition can be accurately predicted.

2. At low forming start temperatures, the spring back of the part considerably changed after being released from the tools, and the analysis results agreed well with the experimental results. In other words, the suggestion was made that considering the phase transition behavior of the HS process was necessary.

3. To develop HS parts with good shape fixability, it is necessary to form them in the austenitic phase.

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Figure 9 Effect of the fraction of martensite and transformation plasticity on shape fixability.