Enhancement of Edge Crack Predictability for Automotive High-Strength Thick Steel Sheets Considering the Pressure Effect

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Abstract. This paper deals with the prediction accuracy of edge crack of automotive high-strength thick steel sheets according to the numerical simulation method. The mechanical tests under tension, tension/compression and loading-unloading conditions were performed to evaluate anisotropy, hardening behaviour and elastic modulus change, respectively. Edge stretchability was evaluated by the HER(hole expansion ratio) test according to the hole processing method. Based on the measured data, three simulation methods were constructed with respect to the material model and the element type. The half dome test was selected for verifying edge crack predictability according to the simulation method. The simulation results show that the pressure effect along the thickness direction has significant effect on prediction accuracy of edge crack for high-strength thick steel sheets used for automotive chassis parts.

1. Introduction
The use of advanced high-strength steel sheets has been accelerating for the vehicle weight reduction and the crashworthiness improvement. Recently, this trend is spreading to automotive chassis parts considering their structural stiffness. For the weight reduction of automotive chassis parts, steel companies are developing new materials with improved strength and formability. Figure 1 shows edge crack examples of automotive chassis parts when using high-strength thick steel sheets[1-2]. This phenomenon becomes a serious problem due to the lower edge stretchability of high-strength steels. Therefore, it is very important to predict edge crack phenomenon by numerical simulation in the early manufacturing process design stage in order to reduce the development time and cost.

(a) Support bracket  
(b) Wheel disk  

Figure 1. Examples of edge crack phenomenon in automotive chassis parts.
This paper suggests a more reliable simulation method for automotive thick steel sheets to increase the edge crack prediction accuracy. For the numerical simulation, various mechanical tests were performed to construct an advanced material model specialized for the sheet metal forming process. Three simulation methods were established according to the material model and the element type. The half dome test was employed for evaluating the simulation methods. The comparison result shows that the advanced material model and the pressure-dependent element are important for improving edge crack prediction accuracy.

2. Material characterization
Advanced high-strength steels have been actively adopted for the weight reduction of an auto-body. Recently, automotive companies are trying to employ 780 MPa grade thick steel sheets for the automotive chassis parts, such as sub-frame, control arm and wheel disk. Therefore, PO780CP 3.24t and PO780FB 3.30t are selected for studying the edge crack prediction accuracy by the numerical simulation. The mechanical tests were performed and material models are constructed for the numerical simulation.

2.1. Mechanical testing
In this study, three mechanical test results under tension, tension-compression, loading-unloading conditions are employed in order to use an advanced material model in sheet metal forming simulation[3]. The tensile and loading-unloading tests were conducted with MTS universal testing machine. As shown in Figure 2, DIC (Digital Image Correlation) system was utilized to measure the strain distribution and r-value during the tensile test. KS-5 standard specimen was used for tension and loading-unloading tests. The tension-compression test was performed with the reversal strain of 5 %. The specimen shape for the tension-compression test was specially designed for increasing the test range without buckling[4]. As shown in Figure 2(b), a laser extensometer was installed additionally in order to measure the strain at the gauge section between upper and lower anti-buckling devices. The strain rate of all mechanical tests was 0.001 /sec.

2.2. Test results and material modeling
Anisotropic tensile properties and kinematic hardening phenomenon was investigated from three mechanical tests. Figure 3(a) shows the stress-strain stress curves according to the material and loading angle. The yield point elongation was observed for PO780CP and PO780FB. Table 1 shows the anisotropic mechanical properties of two materials. The hardening curve was approximated by Swift/Hockett-Sherby model as follows:

(a) MTS + DIC system  
(b) Tension-compression testing machine

Figure 2. Testing machines for the mechanical testing.
\[ \sigma = (1 - \alpha) \left\{ C (\varepsilon_p + \varepsilon_0)^m \right\} + \alpha \left\{ \sigma_{sat} - (\sigma_{sat} - \sigma_i) e^{-\alpha \varepsilon_p} \right\} \]  

Figure 3(b) shows the loading-unloading test results with a strain interval of 1%. In order to consider the elastic modulus change according to the plastic strain, the chord modulus model was utilized as follows:

\[ E = E_0 - (E_0 - E_0) \left\{ 1 - e^{-\xi \varepsilon_p} \right\} \]

Figure 3(c) shows the tension-compression test results with the reverse strain of 5% in order to observe the kinematic hardening characteristics. Recently, the Yoshida-Uemori model is widely-used to represent the kinematic hardening tendency [5-6]. This model is a two-surface approach using the inner surface (f) and the bounding surface (F). These surfaces can be expressed as follows

\[ f = \phi (\sigma - \alpha) - Y = 0 \]  
\[ F = \phi (\sigma - \beta) - (B + R) = 0 \]

(c) Tension-compression

Figure 3. Mechanical test results of hot-rolled thick steel sheets.
Table 1. Anisotropic mechanical properties of hot-rolled thick steel sheets.

| Material | Direction | Yield stress [MPa] | Tensile stress [MPa] | Uniform elongation [%] | Total elongation [%] | r-value |
|----------|-----------|--------------------|----------------------|------------------------|----------------------|---------|
| PO780CP 3.24t | RD | 700 | 781 | 12.15 | 21.93 | 0.66 |
| | DD | 691 | 760 | 12.76 | 25.72 | 1.51 |
| | TD | 731 | 801 | 9.87 | 19.66 | 1.00 |
| PO780FB 3.30t | RD | 746 | 810 | 12.15 | 22.79 | 0.68 |
| | DD | 784 | 816 | 11.36 | 24.59 | 1.70 |
| | TD | 804 | 849 | 10.10 | 18.99 | 1.39 |

Table 2. Material parameters of hot-rolled thick steel sheets for simulations.

| Parameter | Swift / Hockett-Sherby | Yoshida-Uemori | Chord modulus |
|-----------|-------------------------|----------------|---------------|
| K [MPa]   | PO780CP | PO780FB | PO780CP | PO780FB | PO780CP | PO780FB |
| e0        | 0.050 | 0.040 | 0.050 | 0.040 | - | - |
| Y [MPa]   | 390 | 355 | 390 | 355 | 210 | 210 |
| a0 [MPa]  | 330 | 450 | 330 | 450 | 140 | 155 |
| n         | 0.205 | 0.175 | 0.205 | 0.175 | - | - |
| σi [MPa]  | 702.6 | 747.2 | 702.6 | 747.2 | - | - |
| σsat [MPa]| 915.6 | 2795.0 | 915.6 | 2795.0 | - | - |
| C1        | 4000 | 4000 | 4000 | 4000 | - | - |
| C2        | 270 | 300 | 270 | 300 | - | - |
| m         | 11.0 | 7.1 | 11.0 | 7.1 | - | - |
| b [MPa]   | 80 | 120 | 80 | 120 | - | - |
| ξ         | 10 | 18 | 10 | 18 | - | - |
| Rsat [MPa]| 200 | 180 | 200 | 180 | - | - |
| h         | 0.60 | 0.10 | 0.60 | 0.10 | - | - |

where \( \alpha \) denotes the back stress of the inner surface (f) and its size(Y). \( \beta \) corresponds to the center of the bounding surface (F), which expands isotropically at a rate defined by R from the initial size B.

The relative kinematic motion \( \alpha_* \) of the yield surface and its evolution are expressed as follows:

\[
\alpha_* = \alpha - \beta \tag{5}
\]

\[
\dot{\alpha}_* = C \left[ \left( \frac{\alpha - \alpha}{Y} \right) (\sigma - \alpha) - \frac{\alpha}{\alpha_*} \right] \dot{\rho} \tag{6}
\]

\[
\bar{\alpha}_* = \phi(\alpha_*), \ a = B + R - Y \tag{7}
\]

where (') represents the objective rate, \( \dot{\rho} \) is the effective strain rate, and C is a material parameter that helps control the rate of the yield-surface translation. The increments in the size and kinematic motion of the bounding surface are defined as follows:

\[
\dot{R} = m(R_{sat} - R) \dot{\rho} \tag{8}
\]

\[
\dot{\beta} = m \left( \frac{2}{3} b (\sigma - \alpha) - \beta \dot{\rho} \right) \tag{9}
\]

where \( b \) is the saturation value of the bounding-surface translation, m is a material constant controlling the kinematic rate of the bounding surface, and \( R_{sat} \) is the saturation value for R. As shown in Figure 3(c), the Yoshida-Uemori model shows good approximation ability to capture the kinematic hardening of 780MPa grade hot-rolled steel sheets. Based on the test results, hardening models are constructed as shown in Table 2.
3. Edge stretching test

3.1. HER(Hole Expansion Ratio) test
The HER test is most widely-used experimental method to measure the edge stretchability of steel sheets according to the punch condition. Figure 4 shows the schematic diagram of the HER test[1]. After making the hole with the diameter of 10 mm, the conical punch expands the hole until the crack penetrates along the thickness direction. Figure 5 shows the HER test results of 780MPa grade hot-rolled steel sheets. Milling condition shows remarkable hole expanding performance comparing to the punching conditions. Between two punching conditions, the clearance increase slightly improve the HER value. The measured HER values can be used as an input for judging the edge crack in the sheet metal forming simulation.

![Figure 4. Schematic diagram of the HER test.](image)

(a) Test specimens (PO780FB)  (b) HER

![Figure 5. HER test results according to the hole making condition.](image)

3.2. Half dome test
The half dome test[7-8] was employed to evaluate the simulation accuracy according to the material model and finite element. As shown in Figure 6(a), 100 x 200 mm square-type specimen is deformed by the semi-spherical punch. In order to induce the early edge crack, the initial blank position was moved to 20 mm inside from the centreline. Specimens are manufactured by the milling process. From the test specimen, the edge crack was observed near the die shoulder of the upper die.
4. Numerical simulation for edge crack prediction
The half dome test was used to evaluate the simulation accuracy according to the material model and finite element in the edge crack prediction. The simulation software was Autoform R8. As shown in Table 3, three kinds of simulation models are established with the combination of the yield function, hardening model and finite element. In this paper, the thick shell was employed to take account of the contact pressure effect because the conventional shell element cannot calculate the thickness stress due to the plane stress assumption. Figure 7 explains the principal of the thick shell element how to calculate the thickness stress[9]. The friction coefficient was fixed as 0.15. Figure 8 shows the comparison of the limit dome height and the fracture location between experiment and simulation. The edge crack was judged with the criterion calculated from the HER value of the milling condition. All simulation methods can predict the same fracture location however the limit dome height is clearly different according to the simulation method. Figure 9 shows the force-displacement profile according to the simulation method. When the advanced material model was employed, the prediction accuracy of the edge crack was improved. And the force-displacement profile almost approaches to the experimental curve when the thick shell element is combined with the advanced material model. Table 3 presents the quantitative values of the limit dome height and the maximum punching force when the edge crack occurs. The prediction accuracy drastically enhances by using the advanced material model with the thick shell element. It means that selection of the material model and the element type is very important to obtain the accurate simulation result for the pressure-sensitive stamping problems of thick steel sheets.

Figure 7. Principal of the thick shell element to consider the contact pressure effect[8].

Figure 8. Comparison of the limit dome height according to the simulation method.
In this paper, three kinds of simulation methods were evaluated for predicting the limit dome height and the maximum punching force of the half dome test. The results support that the use of the advanced material model and the thick shell element is necessary to improve the prediction accuracy of the edge crack phenomenon when the contact pressure is not negligible. The simulation scheme established can be a useful tool to reduce the development time for the sheet metal forming process of high-strength chassis parts with hot-rolled thick steel sheets in the automotive application.

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