Influence of hardening functions on earing prediction in cup drawing of AA3104 aluminum alloy sheet

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Abstract. The accuracy of cup drawing simulation of aluminum alloy sheets strongly depends on the hardening and yield functions used in the simulation. In this study, stress-strain curves for an AA3104 aluminum alloy sheet were measured by uniaxial tensile and rolling tensile tests to identify parameters for various hardening functions. In addition, in-plane uniaxial tensile, biaxial tensile, and combined tension-compression tests were carried out to measure the successive contours of plastic work in the stress space and the directions of plastic strain rates under linear stress paths. The anisotropic coefficients, $\alpha_1-\alpha_8$, and exponent $M$ of the Yld2000-2d yield function were determined so that the mean square error of the analytical yield locus from the measured plastic work contour was minimized. Finite element simulations of cup drawing of the aluminum alloy sheet were carried out using the determined parameters for hardening functions and the Yld2000-2d yield function implemented in LS-DYNA. By comparing the simulation results with the results of cup drawing experiments, the effects of the hardening functions on the accuracy of earing profile prediction were investigated.

1. Introduction

To form an aluminum beverage can body, a low level of earing during cup drawing is required. A sheet forming simulation, especially for earing prediction during the drawing of the cup, is required to avoid difficulties in the drawing and ironing process. Thus, the simulation requires a material model capable of accurately reproducing the deformation behavior of the aluminum sheet. In Yoon et al. [1] it was shown that the Yld2004-18p anisotropic yield function[2] is capable for predicting earing behavior during drawing of aluminum alloy sheets, and a simplified analytical approach that relates the earing profile to the $r$-value directionality was presented.

The hardening function is one of the important components of phenomenological material models as well as the yield function. In a practical industrial analysis, an isotropic hardening model is used for simplicity, and the hardening function is usually obtained from a uniaxial stress-strain curve. However, if the strain level in the forming process under consideration is larger than the uniaxial tensile elongation, the hardening curve for a larger strain is given by extrapolation of the hardening function. For example, the strain level at the flange during drawing of an aluminum can would be about 0.5 or more, while the tensile elongation in the typical aluminum can body is one-tenth of that.
To measure the stress-strain relationship at strains larger than the tensile elongation, the rolling tensile test [3] has been proposed. In this simple method, it is assumed that the strain in the tensile test produces the same work hardening as the equivalent strain by rolling. Thus, the material is pre-strained by cold rolling to various thickness reductions. After each reduction, tensile specimens are cut and tested, and stress-strain curves for each reduction increment are made. The curves are set up at the abscissa of each pre-strain, and then the outer range of stress-strain curves of the material is regarded as the envelope for all the individual stress-strain curves. An applied example of rolling tensile test for 5000 series aluminum sheet was reported by Kazaoka et al.[4]; therefore, it is promising that this method be applied to 3000 series aluminum sheet to measure the outer range of the stress-strain curve.

In this study, stress-strain curves for AA3104 aluminum alloy sheet were measured by uniaxial tensile and rolling tensile tests to identify parameters for various hardening functions. In addition, in-plane uniaxial tensile, biaxial tensile,[5] and combined tension-compression tests [6] were carried out to measure the successive contours of plastic work in the stress space and the directions of plastic strain rates under linear stress paths. The anisotropic coefficients, α₁-α₈, and exponent M of the Yld2000-2d yield function [7] were determined so as to minimize the mean square error of the analytical yield locus from the measured plastic work contour. Finite element (FE) simulations of cup drawing using the aluminum alloy sheet were carried out using the determined parameters for hardening functions and the Yld2000-2d yield function implemented in the LS-DYNA. By comparing the simulation results with the results of experimental cup drawing tests, the effects of the hardening functions on the accuracy of earring profile prediction were investigated.

2. Experimental

2.1. Test material
This study used AA3104 aluminum alloy sheet for an aluminum can body 0.4 mm thick. The rolling direction (RD), transverse direction (TD), and thickness direction were defined as the x, y, and z axes, respectively.

2.2. Hardening functions
2.2.1. Approximate expression for hardening curve
In the simple isotropic hardening model, it is assumed that the yield surface retains its shape while it expands. In this case, we assume that the yield condition is expressed as

\[ \sigma = H(\varepsilon^p), \]  

where \( \sigma \) is the Cauchy stress, \( \sigma \) is the effective stress, and \( H(\varepsilon^p) \) is the material hardening function, which is a function of the effective plastic strain \( \varepsilon^p \). The following equations can be used as the hardening function \( H(\varepsilon^p) \):

Linear equation:
\[ H(\varepsilon^p) = A + K\varepsilon^p, \]  
Swift’s equation:
\[ H(\varepsilon^p) = C(\alpha + \varepsilon^p)^n, \]  
Voce’s equation:
\[ H(\varepsilon^p) = a - be^{-cep}, \]  

where A, C, α, n, a, b, and c are material parameters determined by the uniaxial stress-plastic strain curve. When Voce’s equation is used, the equivalent stress converges to a certain value with increasing equivalent plastic strain, while the equivalent stress increases infinitely with increasing equivalent plastic strain when using Swift’s equation.
2.2.2. Parameter determination for hardening functions

i) Determination by uniaxial tensile test.
A true stress–true plastic strain curve measured by uniaxial tensile tests over a plastic true strain range of 0.002–0.035 was used to determine the hardening functions parameters in the (a) linear, (b) Swift, and (c) Voce equations.

ii) Determination by rolling tensile test.
Pre-strain was applied to the test material by cold rolling to reductions of 10, 25, 40, and 50%. The amount of applied pre-strain was estimated from reduction $R$ by the following equation assuming plane strain compression state with invariable sheet width and von Mises yield condition:

$$\bar{\varepsilon} = \frac{2}{\sqrt{3}} \ln \left( \frac{1}{1-R} \right).$$

Uniaxial tensile tests were carried out to obtain true stress–true plastic strain curves for the pre-strained materials, and then the amount of applied pre-strain was added to the tensile true plastic strain of each tensile result. All the individual stress-strain curves were plotted on the same graph so that the outer range of stress-strain curves of the material was obtained as a bounding envelope by Voce’s equation. Hereinafter, Voce’s hardening curve obtained by rolling tensile tests is referred to as (d) Voce-RT.

2.2.3. Comparison of obtained hardening curves
The parameter values determined for hardening functions are shown in Table 1, and the hardening curves calculated by each function are shown in Figure 1. Curve (a) determined by the uniaxial tensile test and linear function produced the highest strain hardening, followed by curve (b) of Swift and curve (c) of Voce. Curve (d) of Voce-RT determined by rolling tensile tests produced the lowest hardening.

| Table 1 Parameters of hardening functions determined by (a), (b), and (c) uniaxial tensile tests and (d) rolling tensile test. |
|-----------------|-----------------|-----------------|-----------------|
| Function        | Determined by   | Parameter       |
| (a) Linear      | Tensile test    | $A$ 254.8 MPa   |
|                 |                 | $K$ 1182 MPa    |
| (b) Swift       | Tensile test    | $C$ 802.8 MPa   |
|                 |                 | $\alpha$ 0.08367 |
|                 |                 | $n$ 0.4627      |
| (c) Voce        | Tensile test    | $a$ 428.8 MPa   |
|                 |                 | $b$ 174.4 MPa   |
|                 |                 | $c$ 8.436       |
| (d) Voce-RT     | Rolling tensile test | $a$ 320.4 MPa |
|                 |                 | $b$ 65.16 MPa   |
|                 |                 | $c$ 24.89       |

2.3. Yield functions

2.3.1. Procedure for biaxial stress test
Biaxial tensile tests were performed using cruciform specimens, the geometry of which is standardized in ISO 16842 [8]. Seven linear stress paths, $\sigma_x: \sigma_y = 4:1$, 2:1, 4:3, 1:1, 3:4, 1:2, and 1:4, were applied to the cruciform specimens. Combined tension-compression tests were also performed. Six linear
stress paths, $\sigma_x : \sigma_y = 1:2, 1:1, 2:1, -1:2, -1:1$, and $-2:1$, were applied, and the angles $\theta$ made by the axes of principal stresses and the axes of plastic anisotropy were varied as $0, 22.5, 45, 67.5$, and $90^\circ$. The contour of plastic work associated with $\varepsilon_p^P = 0.003$ in the stress space was determined to quantitatively evaluate the biaxial deformation behavior of the test material, where $\varepsilon_p^P$ is the logarithmic plastic strain measured in the uniaxial tensile test along the RD, and was employed as a reference datum for the plastic work per unit volume.

2.3.2. Parameter determination for Yld2000-2d yield function

Anisotropic coefficients $\alpha_1 - \alpha_3$ and exponent $M$ in the Yld2000-2d function were determined so that the mean square error of experimental results of uniaxial and biaxial stress tests and the values calculated by Yld2000-2d under the same stress paths was minimized. Corresponding experimental results were as follows:

i) Uniaxial yield stresses and $r$-values at $0, 15, 30, 45, 60, 75$, and $90^\circ$ from the RD.
ii) Biaxial stress values and directions of plastic strain rates at all stress paths.

Figure 2 compares the measured deformation behavior of the test material and the behavior predicted by Yld2000-2d, which reproduced the work contour of the material accurately.

2.4. Cup drawing tests

Cup drawing tests were carried out using a cylindrical punch with diameter of $33$ mm. The punch and die clearance was set to avoid cup wall ironing. The blank holding force was $5$ kN. Beef tallow was applied to both sides of the blanks as a lubricant. The drawn cup is displayed in Figure 3. The earing profile of the drawn cups was measured.

3. Finite element simulation

Finite element simulations were carried out for the cup drawing test. Due to the orthotropic anisotropy of the sheet, one quarter of a circular blank was analyzed. The die and punch were assumed to be rigid bodies. Fully integrated shell elements were employed for the circular blank model. A friction coefficient of $0.05$ was employed for all contacts in the model. The Yld2000-2d yield function determined in Section 2.3.2 was used in the FE simulations.

4. Results and discussion

Figure 4 compares load-stroke curves predicted by FE simulations with those obtained by experiment. The relationship between hardening curves and predicted punch loads is observed. The hardening curve (d) of Voce-RT provided the most accurate load-stroke curve prediction in this study. Figure 5 compares the predicted and measured cup heights. The predicted cup height increased with increasing
magnitude of strain hardening (flow stress). Note that hardening curve (a) with the linear function produced the largest hardening and most accurate cup height prediction in Figure 5. Therefore, it is impossible to combine accurate cup height prediction with accurate punch load prediction within the hardening model used in this study.

The predicted and measured radial true strain distributions are provided in Figure 6. The predicted strain at the bottom of the cup with hardening curve (a) was larger than that with curve (d) and experimental results. If we apply a high degree of hardening like curve (a) to the hardening model, inflow resistance at the flange increases as the draw forming progresses. Therefore, the increased tension at the cup bottom and wall transmit forming force loaded from the punch to the flange, and increases the strain in this region. This increased strain results in the increased cup height.

The predicted radial strain in the cup wall was much smaller than that obtained by experiment for every hardening curve, meaning that prediction of the ratio of thickness strain to radial strain in the wall is not accurate. Anisotropy of uniaxial tensile r-values calculated with Yld2000-2d and experimentally measured are shown in Figure 7. Calculated r-values are much smaller than the experimental ones, indicating that thickness increase is overestimated, which then results in underestimation of the cup height.

5. Conclusion
i) Parameters for various hardening functions were determined for AA3104 aluminum alloy sheet using stress-strain curves measured by uniaxial tensile and rolling tensile tests. Determination of parameters for hardening functions by uniaxial testing caused overestimation of strain hardening.
ii) The predicted cup height increased with increasing magnitude of strain hardening. It was impossible to simultaneously achieve accurate cup height prediction and punch load prediction within the hardening model used in this study.

iii) When we applied a high magnitude of strain hardening, inflow resistance at the flange increased as the draw forming progressed. Therefore, the tension increased at the cup bottom and wall, which transmitted the forming force to the flange and increased the strain in this region, which in turn increased the cup height.

iv) Predicted radial strain in the wall was much smaller than the experimental result, which is why the model underestimated the cup height.

References

[1] Yoon J W, Barlat F, Dick R E and Karabin M E 2006 Prediction of six or eight ears in a drawn cup based on a new anisotropic yield function *Int. J. Plasticity* **22** 174-193

[2] Barlat F, Aretz H, Yoon J W, Karabin M E, Brem J C and Dick R E 2005 Linear transformation-based anisotropic yield functions *Int. J. Plasticity* **21** 1009-1039

[3] Ford H 1948 Researches into the Deformation of Metals by Cold Rolling *Proc. Inst. Mech. Eng.* **159** 115-143

[4] Kazaoka T, Natori K, Matsumoto R and Utsunomiya H 2015 Determination of flow stress equation of Al-Mg alloy for sheet metal forming analysis *J. Japan Inst. Light Met.* **65** 568-572 (in Japanese)

[5] Kuwabara T, Ikeda S and Kuroda T 1998 Measurement and Analysis of Differential Work Hardening in Cold-Rolled Steel Sheet under Biaxial Tension *J. Mater. Process. Technol.* **80/81** 517-523

[6] Kuwabara T, Horiuchi Y, Uema N and Ziegelheimova J 2007 Material testing method of applying in-plane combined tension-compression stresses to sheet specimen *J. Japan Soc. Technol. Plasticity* **48** 630-34 (in Japanese)

[7] Barlat F, Brem J C, Yoon J W, Chung K, Dick R E, Lege D J, Pourboghrat F, Choi S H and Chu E 2003 Plane stress yield function for aluminum alloy sheets – Part 1 : Theory *Int. J. Plasticity* **19** 1297-319

[8] ISO 16842: 2014 Metallic materials –Sheet and strip –Biaxial tensile testing method using a cruciform test piece