

Influence of material modeling on earing prediction in cup drawing of AA3104 aluminum alloy sheet

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Abstract. In-plane biaxial tension and combined tension-compression tests are carried out for AA3104 aluminum alloy sheets. Linear stress paths are applied to cruciform specimens to measure the contours of plastic work in the stress space and the directions of plastic strain rates at each stress path. Coefficients $\alpha_1 - \alpha_8$ and exponent M of the Yld2000-2d yield function are determined to minimize the mean square error of the analytical yield locus from a measured work contour. The values of the weighting coefficients in the evaluation of the error are varied to check the effect of a specific stress state on the earing behavior. The effects of the combinations of the weighting coefficients on the accuracy of earing prediction in the cup drawing process are discussed.

1. Introduction

For aluminum beverage can body stock, a low level of earing during cup drawing is required. A sheet forming simulation, especially for earing prediction in the cup drawing process, is required to avoid difficulties in the drawing and ironing process. In the simulation, it is necessary to use a material model capable of accurately reproducing the deformation behavior of the aluminum sheet.

Determining the anisotropic coefficients of yield functions by a biaxial test is effective for obtaining accurate material models. Kuwabara et al. [1] developed a biaxial tensile testing method using a cruciform specimen for sheet metals. It is necessary to consider the effect of shear stress σ_{xy} , where x and y are the axes of in-plane plastic anisotropy, because the axis of principal stress is not always identical with the axis of plastic anisotropy. Yoon et al. [2] predicted the earing profile very accurately by employing a material model that reproduced the r -value and the yield stress directionalities precisely. In the cup drawing process, the stress state in the flange area is the in-plane tension-compression combined state. Therefore, it is necessary to reproduce the deformation behavior at the 2nd and 4th quadrants on the 2D stress plane accurately in order to predict the earing precisely. However, no studies have yet reported the plastic deformation behavior of aluminum beverage can body stock measured under the in-plane combined tension-compression stress states when the axes of principal stresses are not identical with the axes of anisotropy.

In this work, in-plane uniaxial tension, biaxial tension and combined tension-compression tests [3] were carried out for an AA3104 aluminum alloy sheet to measure the successive contours of plastic work in the stress space and the directions of plastic strain rates under linear stress paths. The angles made by the axes of principal stresses and the axes of plastic anisotropy were varied in uniaxial



tension and combined tension-compression tests to measure the experimental data including shear stress σ_{xy} . Anisotropic coefficients $\alpha_1 - \alpha_8$ and exponent M of the Yld2000-2d yield function [4] were determined to minimize the mean square error of the analytical yield locus from a measured work contour. The values of the weighting coefficients in the evaluation of the error were varied to check the effect of a specific stress state on the earing behavior. The effects of the combinations of weighting coefficients on the accuracy of the earing prediction in the cup drawing process are discussed.

2. Experimental

2.1. Test material

An AA3104 aluminum alloy sheet for an aluminum can body of 0.4 mm thickness was used in this work. The uniaxial tensile mechanical properties in the rolling direction are listed in Table 1. Hereinafter, the rolling, transverse and thickness directions are defined as the x, y and z axes, respectively.

Table 1. Tensile properties measured parallel with rolling direction.

$\sigma_{0.2}$ / MPa	c^a / MPa	n^a	α^a	r^b
258.9	629.3	0.303	0.0504	0.420

^a Approximated using $\sigma = c(\alpha + \varepsilon^p)^n$ for a logarithmic plastic strain range of $0.002 \leq \varepsilon^p \leq 0.035$.

^b Measured at uniaxial nominal strain $\varepsilon_N = 0.04$.

2.2. Procedure of biaxial tensile tests

Biaxial tensile tests were employed using cruciform specimens, the geometry of which is standardized in ISO 16842 [5]. 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 θ made by the axes of principal stresses and the axes of plastic anisotropy were varied as $0, 22.5, 45, 67.5$, and 90° .

The contour of plastic work associated with $\varepsilon_0^p = 0.003$ in the stress space was determined in order to quantitatively evaluate the biaxial deformation behavior of the test material, where ε_0^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. Cup drawing test

A cup drawing test was carried out using a cylindrical punch of 33 mm diameter. 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 earing profile of the drawn cups was measured.

3. Finite element simulation

Finite element (FE) simulations using LS-DYNA v971 R6.1.2 were carried out for the cup drawing test. Due to the orthotropic anisotropy of the sheet, one quarter of a circular blank was analyzed. All dies and punch were assumed to be analytical 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 was used in the FE simulations. Anisotropic coefficients $\alpha_1 - \alpha_8$ and exponent M of Yld2000-2d were determined to minimize the mean square error of the analytical yield locus from the measured work contour. Combinations of weighting coefficients of evaluation function (1) were changed for four cases, (a) to (d) shown in Table 2, to check the effect of a specific stress state on the earing behavior.

$$f(\alpha_i, M) = \sum_{j=1}^N w_{j,\sigma} (\delta_{j,C} - \delta_{j,M})^2 + \sum_{k=1}^O w_{k,\beta} (\beta_{k,C} - \beta_{k,M})^2 \quad (1)$$

Here, $w_{j,\sigma}$ and $w_{k,\beta}$ are the weighting coefficients for the stress points forming a work contour and the directions of plastic strain rates $\delta_{j,C}$ and $\delta_{j,M}$ are the distances from the origin to the calculated and measured stress points, and $\beta_{k,C}$ and $\beta_{k,M}$ are the calculated and measured directions of the plastic strain rates. The calculations of the plastic strain rates are based on the normality rule.

Table 2 Experimental data for calculating parameters of the Yld2000-2d yield function.

	Uniaxial test				Biaxial test		
	$\sigma_0, \sigma_{45}, \sigma_{90},$	$\sigma_{15}, \sigma_{30},$ σ_{60}, σ_{75}	$r_0, r_{45}, r_{90},$	$r_{15}, r_{30},$ $r_{60}, r_{75},$	Quad. I	Quads. II, IV $\sigma_{xy} = 0$	Quads. II, IV $\sigma_{xy} \neq 0$
(a)	X		X		X ^a		
(b)	X		X		X		
(c)	X	X	X	X	X	X	
(d)	X	X	X	X	X	X	X

^a Equibiaxial tensile properties (σ_b, r_b), only.

4. Results and discussion

Figure 1 compares the measured deformation behavior of the test material and the behavior predicted by using Yld2000-2d (a)–(d). Figure 1(a) reproduces the yielding behavior under uniaxial tension precisely, whereas the reproducibility in the biaxial stress state and, in particular, that at the 2nd and 4th quadrants on the 2D stress plane is not accurate. In (b), no significant differences are observed from (a). In (c), the reproducibility is improved at the 2nd and 4th quadrants, whereas the accuracy under uniaxial tension has decreased. In (d), the reproducibility at the 2nd and 4th quadrants is the best in this study, whereas the accuracy under uniaxial tension has decreased further.

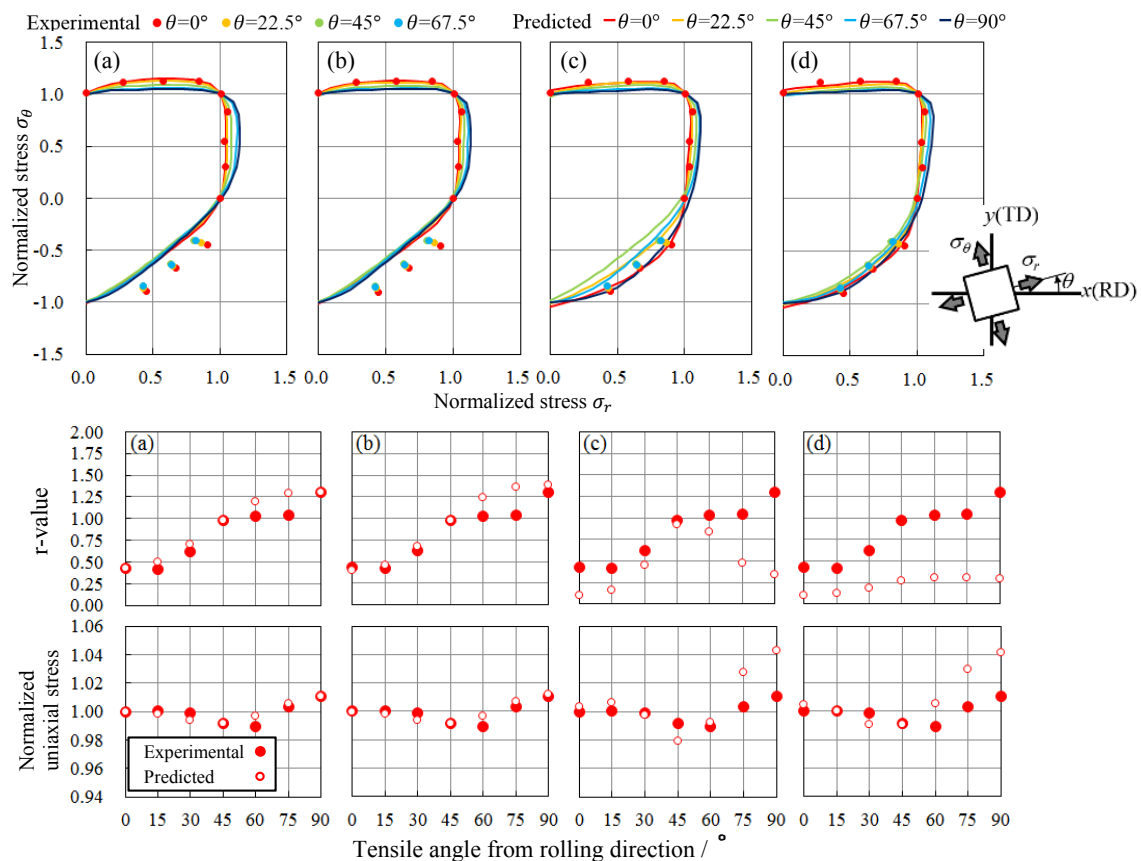


Figure 1 The deformation behavior measured experimentally and predicted by Yld2000-2d (a)–(d).

Figure 2 compares the measured cup height with the heights predicted using the Yld2000-2d yield function. The cup height is normalized by the average cup height. Figure 2(d), which reproduces the yielding behavior at the 2nd and 4th quadrants in the stress space, provides the closest agreement with the measurement. In a previous study [6] of the relation between the shape variation of the contour of plastic work according to θ and the predicted earing profile, it was reported that the cup height becomes relatively higher when the shape of the work contour at the 2nd and 4th quadrants is relatively shrunk. In our study, the same feature is observed in (a)–(d); namely, the shape of the work contour at the 2nd and 4th quadrants is relatively shrunk at $\theta = 45^\circ$, and the predicted earing profile indicates four ears at 45° from the rolling direction. Furthermore, the relation between the earing amplitude and the magnitude of the expanded/shrunk difference of the shape of the work contour at the 2nd and 4th quadrants is observed; namely, the low magnitude of the expanded/shrunk difference results in the low amplitude of the earing in (a) and (b); on the other hand, the high magnitude of the expanded/shrunk difference results in the high amplitude of the earing in (c).

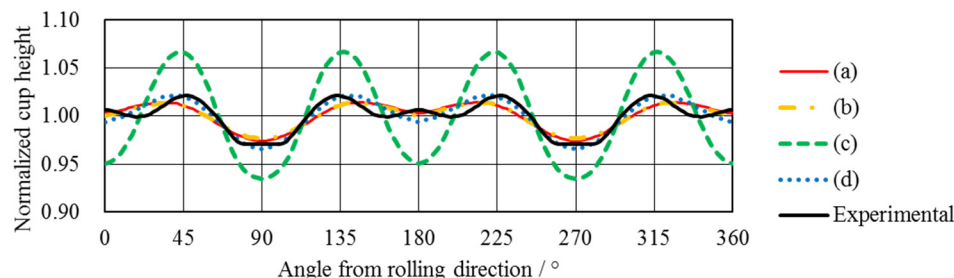


Figure 2 Comparison of the measured cup height with those predicted by Yld2000-2d (a)–(d).

5. Conclusion

In-plane uniaxial tension, biaxial tension and combined tension-compression tests were carried out for AA3104 aluminum alloy sheet, and the contour of plastic work and the directions of the plastic strain rates (r -values) at $\varepsilon_0^p=0.003$ were precisely measured. The predicted earing profile changed depending on the focused stress state used to determine the anisotropy coefficients of the Yld2000-2d yield function. In this work, case (d), which reproduces the yielding behavior at the 2nd and 4th quadrants of the stress space, provides the closest agreement with the measurement. It was observed that the magnitude of the difference in the expanding/shrinking rate of the work contour shapes at the 2nd and 4th quadrants affects the earing amplitude.

References

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