Analysis of earing behaviour in deep drawing of ASS 304 at elevated temperature

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Abstract. Earing tendency in a deep drawn cup of circular blanks is one the most prominent characteristics observed due to anisotropy in a metal sheet. Such formation of uneven rim is mainly due to dissimilarity in yield stress as well as Lankford parameter (r-value) in different orientations. In this paper, an analytical function coupled with different yield functions viz., Hill 1948, Barlat 1989 and Barlat Yld 2000-2d has been used to provide an approximation of earing profile. In order to validate the results, material parameters for yield functions and hardening rule have been calibrated for ASS 304 at 250°C and deep drawing experiment is conducted to measure the earing profile. The predicted earing profiles based on analytical results have been validated using experimental earing profile. Based on this analysis, Barlat Yld 2000-2d has been observed to be a well suited yield model for deep drawing of ASS 304, which also confirms the reliability of analytical function for earing profile estimation.

1. Introduction
Accurate prediction of plastic deformation in metal forming depends upon the proper selection of yield function and hardening rule [1]. Substantial work on development of anisotropic yield has been reported by researchers in the past few decades [2]. For example, Hill in 1948 extended von misses yield criterion to consider plastic anisotropy by including four additional material parameters. Although the criterion does not predict r value with respect to orientation from rolling direction with fair accuracy, this criterion has been extensively used in the industry due to the simplicity involved in calibrating the function using simple uniaxial tensile test [3]. Barlat and Lian proposed a non-quadratic yield function for anisotropic sheet metal and characterized r value accurately. But the accuracy in prediction of r-value and yield strength with respect to orientation from rolling direction strongly depended upon addition material parameter in the yield function which has to be evaluated iteratively [4]. Barlat et al. [5] suggested anisotropic yield function with eight constants and successfully predicted the r-value and yield strength directionality with excellent accuracy to confirm its applicability for metal forming.

The deformation behavior of austenitic stainless has been studied extensively to access the formability at elevated temperatures. Jong et al. constructed forming limit diagram using conventional M-K (Marciniak–Kuczyński) model and modified PMC (Parmar–Mello–Chakrabarty) model and proved modified PMC model to be suitable since it captures the effect of surface roughening which substantially affects metal formability [6]. Stachowicz et al., for an austenitic stainless steel, investigated the effect of the forming temperature on yield strength, ultimate strength, uniform elongations and strain
hardening and on spring back in V-bend test [7]. Nevertheless, it is important to note that earing is one of the important characteristics in deep drawing since it is associated with the anisotropy in the sheet. Therefore, it is necessary to estimate prediction capability of the yield function in terms of $r$-value, yield strength directionality for earing profile prediction. Yoon et al. [8] formulated an analytical function to predict earing profile by taking tool dimensions, blank dimensions, yield function and Lankford parameter into account.

In the present study, deep drawing experiment has been conducted at $250^\circ$ C and cup height is measured with respect to orientation from rolling direction. Anisotropic yield models, viz., Hill 1948, Barlat 1989, Barlat Yld 2000-2d have been calibrated for ASS 304 to predict earing profile using analytical function suggested by Yoon. The results obtained from analytical function and simulations are compared with experimental data.

2. Analytical function for Earng profile
Yoon et al. proposed an analytical function to predict cup height with respect to orientation from rolling direction [8]. The function considers the contributions of the both of $r$-value anisotropic and yield strength anisotropy in cup height. The analytical function is given in Equation 1.

$$H_{cup}(\theta) = t_0 + R_c + \frac{R_b}{A_{\theta+90} + 1} \left( d^{A_{\theta+90}} - \frac{1}{d} \right) (B_\theta)^{A_{\theta+90}}$$

Where, $\theta$ is orientation from rolling direction, thickness of the blank: $t_0 = 1\text{ mm}$, punch corner radius: $R_b = 36\text{ mm}$, cup corner radius: $R_c = 19\text{ mm}$.

$$A_{\theta+90} = \frac{r_{\theta+90}}{1 + r_{\theta+90}}, B_\theta = \left( \frac{\sigma_{ref}}{\sigma^Y(\theta)} \right)^\beta$$

Where, $0.5 \leq \beta \leq 1$, $d = \frac{R_b}{R_c}$

$$\sigma_{ref} = \left( \int_0^{2\pi} \sigma^Y(\theta) d\theta \right) / 2\pi$$

In order to calculate earing profile, $\sigma^Y(\theta)$ is substituted by yield strength obtained by anisotropic yield function for different orientations. For this purpose, yield functions namely Hill 1948, Barlat 1989 and Barlat Yld 2000-2d are calibrated for ASS 304. The required material properties for the yield criteria development have been determined using uniaxial tensile tests at $250^\circ$C. The calculated material properties are mentioned in Table 1. The detailed procedure was mentioned for material parameter determination by Kotkunde et al. [2]. The obtained material constants from above three yield criteria are mentioned in Table 2. Figure 1 (a), (b) and (c) shows the yield loci for ASS 304 at $250^\circ$C. Figure 2 (a) and (b) shows yield stress variation and Lankford coefficient variation respectively.

| Yield model         | Material parameters |
|---------------------|---------------------|
| Hill 1948           | $F$ | $G$ | $H$ | $N$ |
| Barlat 1989         | $a$ | $c$ | $h$ | $p$ | $m$ |
| Barlat Yld 2000-2d  | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a$ |

| Material properties for ASS 304 alloy at 250$^\circ$C |
|---------------------------------------------------------|
| $\sigma_0$ (MPa) | $\sigma_{45}$ (MPa) | $\sigma_{90}$ (MPa) | $r_0$ | $r_{45}$ | $r_{90}$ |
|-------------------|----------------------|----------------------|-------|-----------|-----------|
| 176.16            | 161.06               | 167.05               | 0.758 | 0.946     | 0.753     |
3. Result and Discussion

Deep drawing experiments on ASS 304 have been performed at 250°C with 72 mm blank diameter and 1 mm thickness sheet, and the earing profile is measured using dial gauges. The details of the setup are given in previous work by Kotkunde et al. [3]. Figure 1 (a) (b) & (c) show the yield loci plotted by Hill 1948, Barlat 1989 and Barlat Yld 2000-2d yield criteria. It is clear from the figure that yield locus plotted by Hill 1948 and Barlat 1989 yield functions are not able to predict the bi-axial yield point. But, these yield loci captures in plane yield stress asymmetry in a fairly accurate manner. However, for Barlat Yld-2000-2d yield function, the locus passes very well through uniaxial tensile yield points in rolling and transverse direction along with the biaxial yield stress point. This confirms suitability of Barlat Yld 2000-2d for representation of the yield curve for ASS 304.

It is also important to compare the prediction capability of yield stress and $r$-value directionalities with experimental results. Since yield functions have a key role in evaluating the plastic strains using flow rule. Figure 2 (a) & (b) show the variation of yield stress and $r$-value with respect to orientation from rolling direction. It can be observed from Figure 4 (a) that Hill 1948 yield function does not capture yield stress variation with respect to rolling direction but it predicts $r$-value directionality accurately. In case of Barlat 1989 yield function, a good agreement is observed for yield stress and $r$-value only for two orientations and significant discrepancy with experimental data for remaining one direction. This depends on the directionality equation of yield stress or $r$-value for which parameter $p$ is calculated iteratively. On the contrary, Barlat Yld 2000-2d calculates the yield strength and $r$-value directionality with excellent accuracy which also shows Barlat Yld 2000-2d to be suitable for calculating material response than that of the other two models.

Furthermore, the experimental cup height is compared with analytical model and it is represented in Figure 3. It is observed from Figure 3 that the analytical earing profile predicted by Hill 1948 and Barlat 1989 yield functions over-estimates cup height. On the other hand, Barlat Yld 2000-2d predicts the
analytical cup height precisely with a minimum error of 1.01% and 0.96 correlation coefficient. It guarantees Barlat Yld 2000-2d to be a well suitable for calculating the cup height analytically.

Figure 3 Comparison of Analytical and experimental earing profile

4. Conclusions
Analytical equation with three anisotropic yield functions was used in this work to provide an approximation of earing profile of deep drawn cup. The main conclusions from this study are:

Accuracy of earing profile predictions critically depends upon the proper selection of yield function. Since the anisotropy in both yield stress as well as $r$-value contributes to earing in the deep drawn cup. Hill 1948 and Barlat 1989 yield functions are not accurate enough in characterizing $r$-value and yield stress directionality. Whereas, Barlat Yld 2000-2d predicts these directionalities precisely. As a result, analytical equation coupled with Barlat Yld 2000-2d yield function provides an excellent approximation of the earing profile in agreement with experimental data.

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