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Evolution of Earing during Drawing and Ironing Processes

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A single cupping operation usually does not produce a cup deep enough for most rigid packaging applications. The can diameter may be further reduced and the wall height increased by redrawing. Furthermore, if ironing (wall thinning) is employed, a more uniform wall thickness and increased cup height results. It is essential to understand the fundamental gain about the effect of the ironing process on earing for an advanced convolute cut-edge design. Today, there are still difficulties in applying FEM for the ironing analysis directly due to many numerical problems including double sided contact and frictional effects in addition to proper material behavior using an accurate anisotropic model. In the present work, a general analytical solution was proposed in an explicit equation form to predict earing considering both the drawing and ironing processes. In the approach, the r-value and yield stress directionalities were considered by using the incompressible condition and the shear deformation mode. AA 3104 RPDT control coil was used for the experimental verification. It is shown that this approach is very useful for the prediction of the earing profile of a drawn & ironed cup.

Keywords: *Earing, R-value, Yield stress, Ironing, Analytical Approach*

1. Introduction

Generally, r-value and stress directionalities are the key input parameters for phenomenological constitutive models. These anisotropies are directly related to earing of a drawn cup. Compared to the finite element method, there have been few studies on prediction of the earing profile based on analytical approaches for a single step cup drawing. Hosford and Caddell [1] and Chung et al. [2] provided a quantitative trend between the r-value anisotropy and the earing profile in a mild steel and an aluminum alloy, respectively. Using a different approach, Barlat et al. [3] attempted to correlate the stress anisotropy (not r-values) to the earing trends. Recently, an analytical approach considering the r-value directionality as a main contributor to the earing profile was derived by Yoon et al. [5]. The method provides a simple tool for the prediction of the earing profile using, as input, basic information including the r-value directionality, the initial blank size and the cup radius. However, the method did not consider the stress directionality. Yoon et al. [6] simply combined Yoon et al. [5] and Barlat et al. [3] to consider both r-value and yield stress directionalities on earing prediction. Mulder and Nagy [4] further improved Yoon et al. [6] considering non-uniform strain in the flange and the process effects.

Commercial beverage canmaking processes include drawing, redrawing and several ironing operations. It is experimentally observed that during the drawing and redrawing processes earing develops, but during the ironing processes earing is reduced. The ironing processes typically decreases the degree of earing. A more uniform height (ie., less pronounced earing) results. Ironing is controlled by the clearance between the punch and the die land. It increases the total punch force, but does not affect the drawability. During the manufacturing of two-piece beverage cans, multiple ironing steps increase the wall height by about a factor of 3. There is, of course, a limiting reduction for a single ironing stage. Friction on the ironing ring wall opposes the flow of material, whereas friction on the punch side trends to draw the material in the direction of punch travel. Therefore, the opposing frictional forces produce severe transverse deformation through the thickness which makes it difficult to use a normal FE analysis for the process. This is because of the difficulties in handling both anisotropy and double-sided contact with conventional solid elements under severe transverse shear deformation. A large amount of CPU time is also required by using multi-layered solid elements. Therefore, no one has reported in detail the evolution of the earing profile during the ironing processes using finite element method.

In this work, a new analytical method simultaneously uses both r-value and yield stress effects to predict earing profile during both drawing and ironing operations. This method is relatively accurate and uses only seconds of CPU time. A new closed form equation is based on the exact integration of the logarithmic strain. Especially, the earing mechanism has been explicitly explained from the directionalities by demonstrating the contribution from each factor to the cup height profile. For verification purposes, the method has been investigated using the example of the AA 3104 control coil.

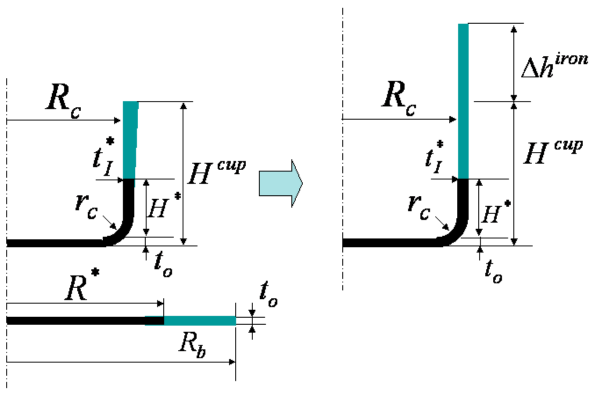

Figure 1. Analytical approximation of cup drawing & ironing processes

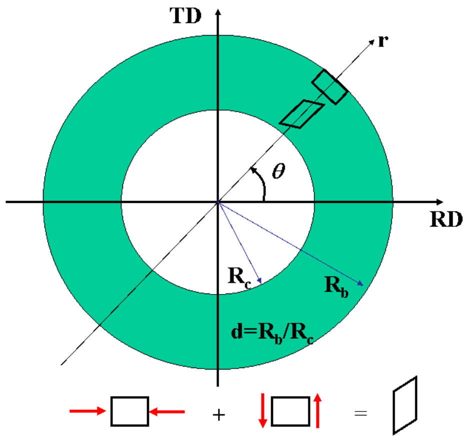

Figure 2. Deformation of an element which is initially located at the rim.

2. Theory

2.1 Cup Height After Drawing

A completely drawn cup as shown in Figure 1 is examined. In this case, it is assumed that no deformation of the sheet occurs at the flat punch head. Only the cup wall deformation is considered. First, for the cup wall the average circumferential strain is defined as:

$$\varepsilon_\theta^{ave} = \ln(\frac{R_c}{R}) \text{ for } R_c \le R \le R_b . \tag{1}$$

In Eq.1, the subscripts "*c*" and "*b*" refer to the cup wall and blank, respectively.

The blank of a cup can be viewed as a ring (Figure 2), the inner edge of which being drawn into the inside cavity under uniform displacement boundary control. When the ring begins to draw-in, different levels of compressive strains are generated circumferentially due to planar anisotropy. The corresponding radial strains contributing to the cup height profile (earing profile) result from the incompressibility condition under a plane stress condition. Assuming that, for a given direction, uniaxial tension and compression lead to identical r-values, these can be expressed as a function of the strains at the rim of the ring :

$$\varepsilon_\theta : \varepsilon_r : \varepsilon_t |_\theta = -(r_{\theta+90}+1) : r_{\theta+90} : 1 . \tag{2}$$

where the subscripts r, θ, t correspond to the radial, circumferential, and thickness directions, respectively. From [7], the total radial and circumferential strains which consider both r-value and yield stress anisotropy become

$$\varepsilon_r = -\frac{r_{\theta+90}}{1+r_{\theta+90}}\ln\left(\frac{\sigma_\theta}{\sigma_{ref}}\frac{R_c}{R}\right) = \ln\left(\frac{\sigma_{ref}}{\sigma_\theta}\frac{R}{R_c}\right)^{\frac{r_{\theta+90}}{1+r_{\theta+90}}} , \tag{3-a}$$

$$\varepsilon_\theta = \varepsilon_\theta^{ave} + \varepsilon_\theta^{stress} = \ln\frac{R_c}{R} - \ln\frac{\sigma_{ref}}{\sigma_\theta} = \ln\left(\frac{R_c}{R}\frac{\sigma_\theta}{\sigma_{ref}}\right) . \tag{3-b}$$

The total height of a cup can be obtained from the logarithmic integral of Eq.(3-a) as follows :

$$H^{cup}(\theta) = t_o + r_c + \int_{R_c}^{R_b} \exp(\varepsilon_r) dR \tag{4}$$

The integrated form of Eq.(4) can be expressed as

$$H^{cup}(\theta) = t_o + r_c + R_b\left(\frac{1+r_{\theta+90}}{2r_{\theta+90}+1}\right)\left(\left(\frac{R_b}{R_c}\right)^{\frac{r_{\theta+90}}{(r_{\theta+90}+1)}} - \frac{R_c}{R_b}\right)\left(\frac{\sigma_{ref}}{\sigma_\theta}\right)^{\frac{r_{\theta+90}}{(r_{\theta+90}+1)}} . \tag{5}$$

In Eq.(5), σ_{ref} can be defined as $\sigma_{ref} = \sigma_{ave} = \sum_i^n \sigma_i / n$.

2.2 Cup Height After Ironing

As can be seen in Fig.1, it is assumed that the ironing starting height H^* (a constant value defined by process) is given as an input value and the corresponding initial radius of H^* is defined as R_θ^*, which is located at $R_x < R_\theta^* < R_b$, where R_θ^* is not constant with respect to θ. R_θ^* can be determined by an iterative procedure when H^* is given (will be discussed later). The corresponding ironed thickness at H^* is also defined as t_I^*, which is located on the cup wall. The cup height after ironing can be derived from the volume constancy as follows [7] :

$$\varepsilon_\theta^{Total} = \ln\left(\frac{R_c}{R}\frac{\sigma_\theta}{\sigma_{ref}}\right) \quad \text{(from Eq.(3-b)} \quad \text{and } \varepsilon_t^{Total} = \ln\left(\frac{t_I^*}{t_o}\right) . \tag{6}$$

Then,

$$\varepsilon_r^{Total} = -\varepsilon_\theta^{Total} - \varepsilon_t^{Total} = -\ln\left(\frac{R_c}{R}\frac{\sigma_\theta}{\sigma_{ref}}\right) - \ln\left(\frac{t_I^*}{t_o}\right) = \ln\left(\frac{R}{R_c}\frac{\sigma_{ref}}{\sigma_\theta}\frac{t_o}{t_I^*}\right) . \tag{7}$$

The total cup height after ironing is

$$H^{Iron}(\theta) = H^* + \int_{R_\theta^*}^{R_b} \exp(\varepsilon_r^{Total}|_\theta) dR = \int_{R_\theta^*}^{R_b}\left(\frac{t_o}{t_I^*}\right)\left(\frac{\sigma_{ref}}{\sigma_\theta}\right)\left(\frac{R}{R_c}\right) dR . \tag{8}$$

Integrating Eq.(8) leads to

$$H^{Iron}(\theta) = H^* + \left(\frac{\sigma_{ref}}{\sigma_\theta}\frac{t_o}{t_I^*}\right)\frac{\left(R_b^2 - (R_\theta^*)^2\right)}{2R_c} . \tag{9}$$

In Eq.(9), R_θ^* is still unknown. This value can be determined from an iterative procedure as follows :

$$f(\theta) = H^{cup}(R_\theta) - H^* = 0 . \tag{10}$$

By the linear approximation,

$$f(\theta)+\frac{df(\theta)}{dR_\theta^*}\Delta R_\theta^* = 0 \;\rightarrow\; \Delta R_\theta^* = -f(\theta)/\frac{df(\theta)}{dR_\theta^*}\ . \tag{11}$$

$$R_\theta^* = R_\theta^* + \Delta R_\theta^*\ . \tag{12}$$

3. Application to Drawing and Ironing

For the verification, a cup drawing example was evaluated using AA 3104 control coil. The yield stress and r-value data are given in Figure 3. The specific dimensions of the tools are given as follows:

Punch diameter: D_p = 35.560 mm
Punch profile radius: r_p = 2.286
Die opening diameter: D_d = 36.576 mm
Die profile radius: r_d = 2.286 mm
Blank radius: D_b = 76.123 mm
Sheet Thickness : t = 0.457 mm

The AA 3104 control coil exhibits eight ears in the experimemtal cup drawing process. To predict the evolution of the earing profiles during drawing and ironing processes, the additional information shown in Fig. 1 is required. In this study, the target wall thickness and the starting height of ironing are set to t_I^*=0.508 mm (0.02 inch) and H^*=12.7 mm (0.5 inch), respectively. The value H^*(=12.7 mm) produces the R_θ^* based on Eq.(12). The values are summarized as

R_0^*	R_{15}^*	R_{30}^*	R_{45}^*	R_{60}^*	R_{75}^*	R_{90}^*
31.981	32.032	32.037	31.941	31.991	32.212	32.214

(unit : mm)

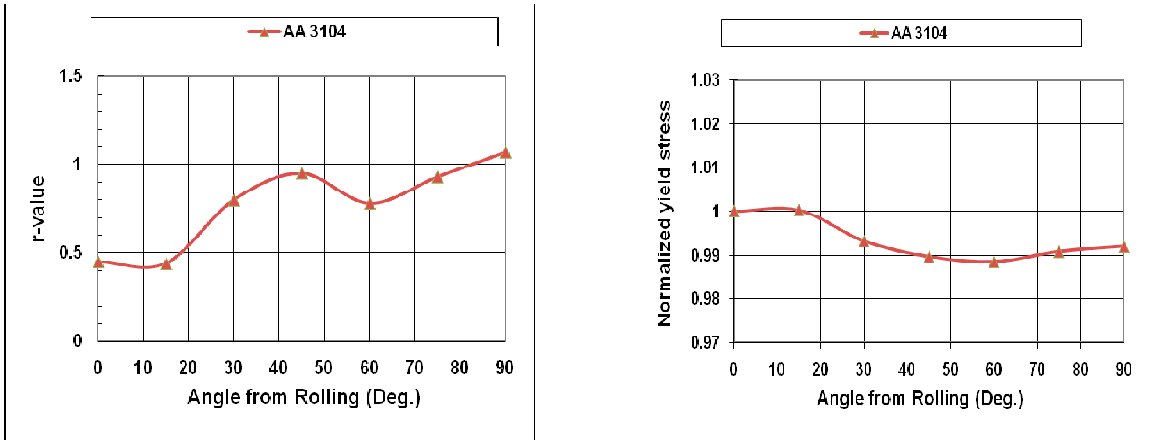

Figure 3. Anisotropic Properties : (a) r-value plot (b) yield stress plot

As can be seen in Figure 3, AA 3104 shows a complicated r-value shape, but the yield stress directionality is small compared to the other two alloys in the figure. In Figure 4(a), the earing profile after cup drawing was predicted using the analytical equation and it was also compared with the analytical solution of [5]. It was not possible to get a converged solution based on the finite element method due to the severe contact problem during the ironing procedure. Thus, the FE result is not available for comparison. In Figure 4(b), the contribution from the yield stress is much smaller than the one from the r-value. The results from the present theory and Yoon et. al [5] show similar predictions in Figure 4(a). In Figure 5(a), the comparison of the cup height profiles was made after ironing. The present theory shows excellent agreement with the experimental data. This is because the r-value distribution does not influence the cup height change for an ironing process as shown in Eq.(9). Unlike cupping and redrawing, ironing does not benefit from high r-values. This is because ironing is characterized by the same plane-strain flow, $\varepsilon_\theta = 0$ (where R_c is cup radius). The only influence of the r-value is its effect on the wall thickness changes before ironing. With a high r-value, there is less wall thickness in the initial drawing and redrawing steps, so less ironing is required to achieve the same final wall thickness. The metal flow in ironing can be regarded as similar to plane-strain drawing. Therefore, ironing can be treated as a uniform redistribution of metal volume in the cup sidewall. Although the yield stress contribution to the cup height is small as shown in Figure 3(b), it has a significant contribution to the change of the earing profile which leads to excellent agreement with the experimental data. Figure 5(b) shows the earing profiles after drawing and ironing. It is worth mentioning that the overall earing magnitude was reduced to one third after ironing. Also, the cup height at the 45 degrees is higher than the height at 0 degrees after ironing.

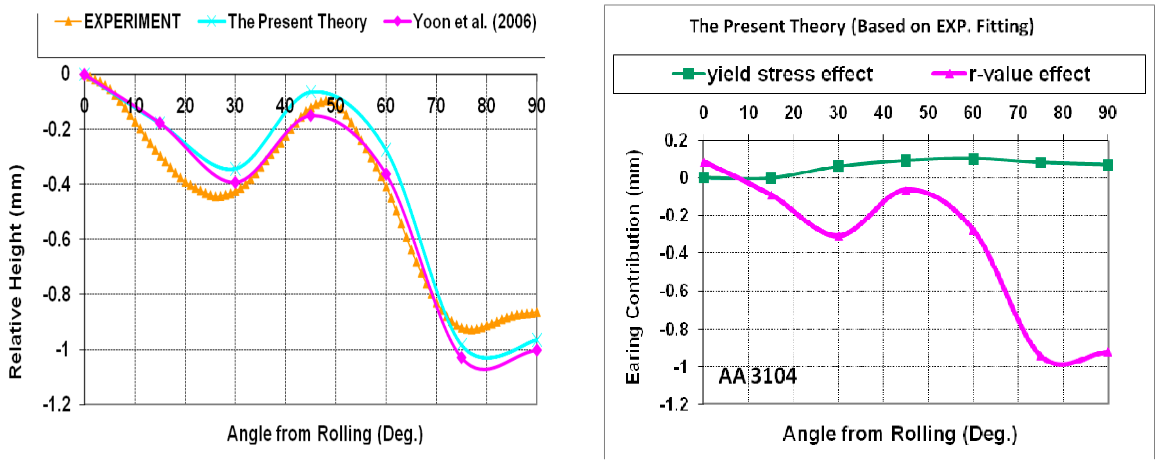

Figure 4. (a) Earing profiles after drawing (b) Effects of r-value and yield stress on earing profile

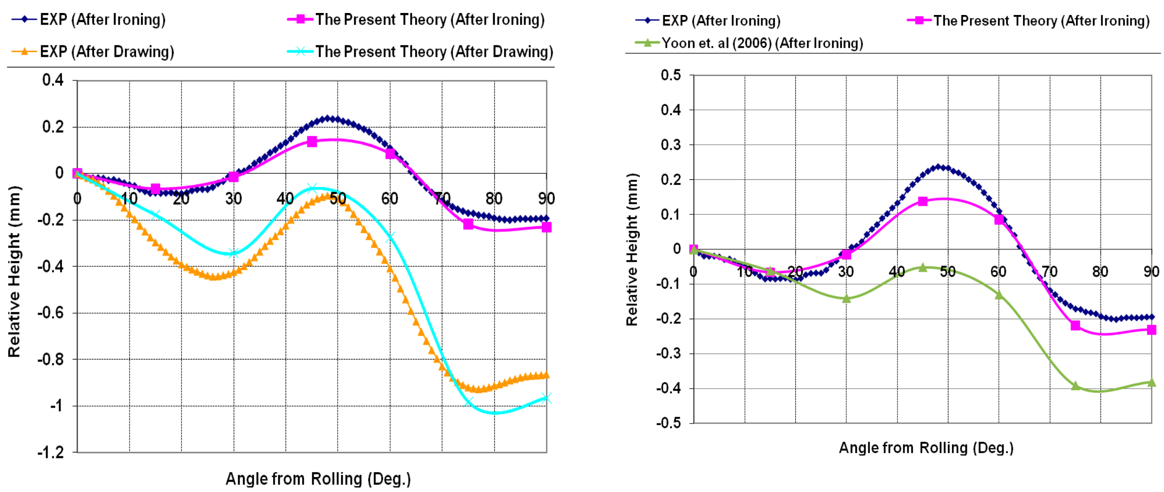

Figure 5. (a) Comparision of the predicted earing profiles with experiment after drawing and ironing (b) Comparision of the earing profile after ironing with [5]

4. Conclusion

Analytical equations were derived in this work to provide an approximation of the earing profile of drawn & ironed cups. The analytical model considers both the r-value and yield stress directionalities simultaneously. The earing mechanism is explained based on the proposed theory. The theory is consistent with the results from FEM and experiments. It was found that the yield stress contribution is important to predict the correct earing trend and the r-value has no contribution to earing in the ironing process. The earing progression during cup drawing and ironing can be easily traced from the analytical equations. The developed formula can be efficiently used for a convolute cut-edge design by considering both the drawing and ironing operations.

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