Four Earing’s Prediction in Deep Drawing of AISI 1008 Steel Sheet Conical Product

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Abstract: Earing is a phenomenon that appears in deep drawing of parts produced using this process because of the anisotropic material properties. Most of, recent theories didn’t fully employ the mechanical materials properties, and ears number achieve depends on the FE simulation approaches. To anticipate the ears form issue in conical parts of AISI 1008 steel sheet deep drawing, in this work a new method is used to predict the earing formation during deep drawing. This method proposed combines the yielding limits and anisotropy r-values of the material to determine Hill48 yield criterion variables using several conical angles with several punch velocities. Equation for the value of yielding and anisotropy index for different orientation is used. AISI 1008 steel sheet is used as a case in this work, the zone of deformation or blank is partitioned radially to equal parts according to the anisotropic behavior. Hill48 yield function constants solved based on the material yielding point and anisotropy index together for the parallel deformed regions. A simulation using FE software for the process on the base of this method is executed to compare it results of lab work. and it noticed that Increasing speed may contribute slightly in decreasing the severity of anisotropy effect and this can be explained the process propagate the material need time to flow and if the speed increase this lead to increasing in strain hardening of the material\textsuperscript{[m]}. Increasing die angle shows that the different between the highest point to lowest point in the cup edge may increase. This work produces a conductive and dependable way to anticipate the forms of earing during cup drawing, which will have positive effective in manufacturing implementations and numerical outcomes and shows high agreement with lab work.

1. Introduction
The Von-Mises yielding criterion is the mostly used yielding isotropic function because of its simple equations. It’s appropriate for use in theoretic and FE computing. But, depending on the assumption of isotropic, the Von-Mises criterion of yielding not able to deal with or characterized material anisotropy, particularly processes related to sheets of metals. When sheets rolled for multi-stage and heat treated, metal, which has a particular texture by certain structure and approved orientation or direction, demonstrate distinct anisotropic manner \textsuperscript{[1]}[2]. Many approaches produced to verify this variance, which called anisotropy, in material behavior during deformation. The most popular one is the quadratic yielding criterion (Hill48 yielding function) suggested by Hill\textsuperscript{[3]} and it is used widely because of its easy to handle mathematical expression \textsuperscript{[4]}[5]. However results of unusual yielding behavior noticed in some applications which have sheet processed previously by rolling don’t explain.

Hence, the model isn’t satisfactory enough to exhibit actual process if conventional approach is used to calculate the factors. Using a another solving approach to obtain the parameters may, have a
contrasting influence on the yielding criterion efficiency[1][6][7]. Along with Hill’s criterion, numerous anisotropic yielding approaches suggested. Like, the plane stress criterion, Yld2000-2d, suggested by Barlat et al[8]. To explain anisotropic behavior when sheet deformed plastically, precisely for AL-alloy. The Yld2000-2d criterion include eight constants which can be found using yielding point and anisotropy index in 0°,45°,and 90°, associated with the biaxial tensile test[9]. But, the solid part, which is essential for thick sheets particularly when thickness stress in the sheet not ignorable, in finite element with Yld2000-2d yielding criterion cannot be used because plane stress variables only are considered[10].

Hill’s criterion is the most simple from all of the anisotropic yielding criterions. It includes four factors only, which make it suitable to utilize in this study. For isotropic conditions, the criterion reduces to the Von-Mises yield criterion [11][12]. The parameters of the Hill could be determined by the stress at yielding point or anisotropy index under different loading situations [1][7]. Researches have shown that yield point of metal and r- values have influence on the earings occur during drawing. But, the number and form of the ears cannot accurately describe using the Hill48 if stress of yielding or index of anisotropy only employed[1][13].

In this paper, an approach which used yield strength and anisotropy index both in consideration for parameters calculations of the Hill48 criterion is produced. The behavior of the AISI-1008 sheet anisotropy is debated and simulations of process tests exsiccated based on set of punch velocities and die angles to have a clear idea about the earing formed. The approach utilized the Hill48 yielding criterion to predict four ears forming during drawing tests of AISI-1008 steel sheet is supported using experimental results and compare it with traditional method using Lankford coefficient.

2. Hill48 Yield Criterion (Using Flow Rule)

The equation of the Hill48 criterion is shown in Eq. (1):

\[ f = F\left(\sigma_{yy} - \sigma_{xx}\right)^2 + G\left(\sigma_{zz} - \sigma_{xx}\right)^2 + H\left(\sigma_{xx} - \sigma_{yy}\right)^2 + 2L\sigma_{xy}^2 + 2M\sigma_{zz}^2 + 2N\sigma_{yy}^2 = \sigma^2 \]  

Where x, y, z are the orthotropic anisotropic directions, F, G, H, L, M, and N are independent anisotropic constants obtained from various material tests. \( \sigma \) is the equivalent stress. When \( 3F=3G=3H=L=M=N \), Eq. (1) transform the Von-Mises criterion for defining an isotropic material. Eq. (1) is suitable for finite element simulation where a solid element used so the stress through thickness direction not ignored. The metal sheet is generally in a plane stress state during the forming, that is, \( \sigma_{zz}, \sigma_{xy}, \sigma_{xz} \) is 0 and then, Eq. (1) can be simplified to:

\[ f = (G + H)\sigma_{xx}^2 - 2H\sigma_{xx}\sigma_{yy} + (H + F)\sigma_{yy}^2 + 2N\sigma_{yy}^2 = \sigma^2. \]  

Eq. (2) is convenient for the simulation with shell type elements which the plane stress is taking in account only, but it’s not convenient for solid elements where the stress through thickness is considered important.

3. Determining Hill48 Yield Criterion Parameters

3.1. Formula of Yield Stress and Anisotropy for Various Directions

According to Hill48 equation (Eq. (2)) in the state of plane stress, the x and y are the rolling and transverse directions respectively. The rolling direction considered as the reference direction, and the yield stress in the rolling direction \( \sigma_0 \) considered as the reference stress. Therefore:

\[ \sigma_{xx} = \sigma_0 = \bar{\sigma}. \]  

According to the transformation formula, the stresses are written as:

\[ \begin{align*}
\sigma_x &= \sigma_1 \cos^2 \alpha + \sigma_2 \sin^2 \alpha - 2\tau_{xy} \cos \alpha \sin \alpha, \\
\sigma_y &= \sigma_1 \sin^2 \alpha + \sigma_2 \cos^2 \alpha + 2\tau_{xy} \cos \alpha \sin \alpha, \\
\sigma_{xy} &= (\sigma_1 - \sigma_2) \cos \alpha \sin \alpha + \tau_{xy} (\cos^2 \alpha - \sin^2 \alpha),
\end{align*} \]  

\[ \ldots..(4) \]
Where $\sigma_1$ act as, the stress in direction of angle $\alpha$ about the reference or rolling direction, $\sigma_2$ act as, the stress normal to $\sigma_1$ path, and $\tau_{xy}$ is the shear stress in the direction of angle $\alpha$. These stresses and their directions are shown in Figure 1.

The uniaxial tensile stress at $\alpha^\circ$ to the rolling path is assigned as $\sigma_2$ then, $\sigma_1 = \sigma_a$, $\sigma_2 = 0$, $\tau_{xy} = 0$. Thus, from Eq. (4), the stress components in $x,y$ plane are [14].

$$
\begin{align*}
\sigma_{xx} &= \sigma_a \cos^2 \alpha, \\
\sigma_{yy} &= \sigma_a \sin^2 \alpha, \\
\sigma_{xy} &= \sigma_a \sin \alpha \cos \alpha.
\end{align*}
$$

The tensile yield stress at angle its value is $\alpha^\circ$ to reference direction could be obtained in the bases of Eqs. (2), (3), and (5):

$$
\begin{align*}
\sigma_\sigma &= \sqrt{A + B + C}, \\
A &= (G + H) \cos^4 \alpha, \\
B &= (F + H) \sin^4 \alpha, \\
C &= 2(N - H) \sin^2 \alpha \cos^2 \alpha.
\end{align*}
$$

According to the flow function, the yield criterion in Eq. (2) is considered a plastic potential functions also. The plastic strains $d\varepsilon_x$, $d\varepsilon_y$, and $d\gamma_{xy}$ depending upon the Hill48 criterion can be determined using Drucker’s formula [15]:

$$
\begin{align*}
d\varepsilon_{xx} &= d\varepsilon \left[ 2(G + H)\sigma_{xx} - 2H\sigma_{xy} \right], \\
d\varepsilon_{yy} &= d\varepsilon \left[ 2(F + H)\sigma_{yy} - 2H\sigma_{xx} \right], \\
d\gamma_{xy} &= 4d\lambda \sigma_{xy}.
\end{align*}
$$

Then, with Eqs. (5) and (7) we have

$$
\begin{align*}
d\varepsilon_{xx} &= d\varepsilon \left[ 2(G + H)\sigma_{xx} \cos^2 \alpha - 2H\sigma_{xy} \sin^2 \alpha \right], \\
d\varepsilon_{yy} &= d\varepsilon \left[ 2(F + H)\sigma_{yy} \sin^2 \alpha - 2H\sigma_{xx} \cos^2 \alpha \right], \\
d\gamma_{xy} &= 4d\lambda \sigma_{xy} \sin \alpha \cos \alpha.
\end{align*}
$$

According to strains in Mohr circle, we get,

$$
\varepsilon_\alpha = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2} \cos 2\alpha + \frac{\gamma_{xy}}{2} \sin 2\alpha.
$$
Then, the strain increments \( \Delta \varepsilon \) in longitudinal or loading direction and \( \Delta \varepsilon_{90} \) in width direction [13] become:

\[
\begin{align*}
\Delta \varepsilon_{\alpha} &= d\varepsilon_{xx} \cos^2 \alpha + d\varepsilon_{yy} \sin^2 \alpha + d\gamma_{xy} \sin \alpha \cos \alpha, \\
\Delta \varepsilon_{\alpha+90^\circ} &= d\varepsilon_{xx} \sin^2 \alpha + d\varepsilon_{yy} \cos^2 \alpha - d\gamma_{xy} \sin \alpha \cos \alpha.
\end{align*}
\]

And depend on the hypothesis of constant plastic volume, we get:

\[
\begin{align*}
d\varepsilon_x + d\varepsilon_y + d\varepsilon_z &= 0, \\
d\varepsilon_z &= -(d\varepsilon_x + d\varepsilon_y) = -2\left(G \cos^2 \alpha + F \sin^2 \alpha\right) \sigma_0 \Delta \lambda.
\end{align*}
\]

From the index of anisotropy definition, it undergoes uniaxial tension in the direction of \( \alpha \) could be found by:

\[
r_{\alpha} = \frac{d\varepsilon_{\alpha+90^\circ}}{d\varepsilon_z} = \frac{H + (2N - F - G - 4H) \sin^2 \alpha \cos^2 \alpha}{F \sin^2 \alpha + G \cos^2 \alpha}.
\]

3.2. Solution of local Parameters

The tensile yield stresses at 0°, 45°, and 90° directions are set as \( \sigma_0 \), \( \sigma_{45} \), and \( \sigma_{90} \) and the \( r \)-values (anisotropic indexes) are set as \( r_0 \), \( r_{45} \), and \( r_{90} \), respectively. The area partitioning of the blank are shown in Figure 2, where (X) is rolling direction (0° direction), and (Y) is perpendicular or transverse to rolling direction (90° direction). Because of the anisotropy, the properties of materials changes with loading directions. Also, stress and deformation anisotropy both are essential part in characterizing the anisotropic behavior during deformation [1]. According to the partitions shown in Figure 2, more detailed data about the material will be taken in account and the FE results should be more precise.

3.2.1. Yield Stress and \( r \)-values Along Various Directions

In Sect. 3.1, the relation of \( \sigma \) with \( r \)-value is found. That means the yield stress \( \sigma \) and \( r \)-value at any direction could be solved. Then, set \( \alpha \) be equal to 0°, 45°, and 90°, respectively. The relationship between Hill48 parameters and the anisotropic indexes (yield stresses and \( r \)-values) are being determined using:

1. When \( \alpha = 0^\circ \)

\[
G + H = 1, \quad r_0 = \frac{H}{G}.
\]

2. When \( \alpha = 45^\circ \)

\[
F + G + 2N = \frac{4\sigma_0^2}{\sigma_{45}^2}, \quad r_{45} = \frac{F + G - 2N}{2(F + G)}.
\]

3. When \( \alpha = 90^\circ \)

\[
F + H = \frac{\sigma_{90}^2}{\sigma_0^2}, \quad r_{90} = \frac{H}{F}.
\]
3.2.2. Calculation of the Hill48 Parameters at Each Part

1. Part I (0°–45°)
   For the first part, properties of uniaxial tensile (yield stresses and r-values) in 0° and 45° directions are used because tensile deformation direction in part (1) is between 0° and 45°. In Eqs. (14) – (17), using these equations and Eq (16) to obtain the parameters G, H, N, and F for this part.

\[
H = \frac{r_0}{r_0 + 1}, \quad \text{equation (21)}
\]

\[
N = \frac{(2r_{45} + 1)\sigma_0^2}{(r_{45} + 1)\sigma_{45}^2}, \quad \text{equation (22)}
\]

Using these equations and Eq (16) to obtain the parameters G, H, N, and F for this part.

2. Part II (45°–90°)
   In similar way considering the Eqs. (16) – (19), using these equations and Eqs (16) and (17) to obtain the parameters G, H, N, and F for second part.

4. Using Traditional Hill Model Depending on Strain Ration
   In forming of sheet metal applications use of strain ration is common for characterization of materials (Lankford Coefficient) so, the ratios of strain in the direction of width to the strain in direction of thickness must be converted to Hill model with direction of rolling aligned with 11 direction, the anisotropic index in the rolling direction is:

\[
r_0 = \frac{d\varepsilon_{22}}{d\varepsilon_{33}} = \frac{H}{G}, \quad \text{equation (25)}
\]

And the r-values in the perpendicular direction is:

\[
r_{90} = \frac{d\varepsilon_{11}}{d\varepsilon_{33}} = \frac{H}{F}, \quad \text{equation (26)}
\]

The r-value in the direction is described in Eq (13). For sheet metal, the below relations can be derived for \( R_{ij} \) values that need in Hill model:

\[
R_{11} = 1, \quad \text{equation (27)}
\]

\[
R_{22} = \sqrt{\frac{r_0(1 + r_{90})}{r_{90}(1 + r_0)}}, \quad \text{equation (28)}
\]

\[
R_{23} = \sqrt{\frac{r_{90}(1 + r_0)}{r_{90} + r_0}}, \quad \text{equation (29)}
\]

\[
R_{12} = \sqrt{\frac{3 \times r_{90}(1 + r_0)}{(2r_{45} + 1)(r_{90} + r_0)}}, \quad \text{equation (30)}
\]

\[
R_{13} = 1, \quad \text{equation (31)}
\]

\[
R_{23} = 1, \quad \text{equation (32)}
\]
For each \( r \)-value \( r_0 \), \( r_{45} \), and \( r_{90} \), the mathematical mean is taken from experimentally measured Lankford Coefficients [16]. The material constants are demonstrated in Table 1.

### Table 1. Material constants of AISI-1008 steel sheet

| \( \sigma_0 / \sigma_0 \) | \( \sigma_{45} / \sigma_0 \) | \( \sigma_{90} / \sigma_0 \) |
|-------------------------|-------------------------|-------------------------|
| \( r_0 \)               | \( r_{45} \)             | \( r_{90} \)             |
| 1.02927                 | 1.0635                  |                         |
| 0.37583                 | 0.29023                 | 0.5343                  |

5. Obtaining Anisotropic Parameters

The anisotropy parameters for the Hill48 criterion solved using Eqs. (16)–(24) and their values documented in Table 1 and Table 2, and the part-specific parameters are demonstrated in Table 3. In Abaqus, anisotropic deformation behavior is produced based on the Hill48 yield criterion and six parameters are demanded to define the anisotropic properties of materials. But, only four parameters needed to be obtained under the state of plane stress. The parameters of Hill48 yield criterion under state of plane stress demonstrated in Eq. (32) [7]:

\[
\begin{align*}
F &= \frac{1}{2R_{12}} + \frac{1}{2R_{11}} - \frac{1}{2R_{13}}, \\
G &= \frac{1}{2R_{23}} + \frac{1}{2R_{22}} - \frac{1}{2R_{21}}, \\
H &= \frac{1}{2R_{31}} + \frac{1}{2R_{32}} - \frac{1}{2R_{33}}, \\
N &= \frac{1}{2R_{12}}.
\end{align*}
\]

Where \( R_{11}, R_{22}, R_{33} \) and \( R_{12} \) are four material parameters to apply Hill48 in Abaqus. There are other parameters, \( R_{13} \) and \( R_{23} \), whose assumed to be equal to one. Then, depending to Eq. (32), \( R_{ij} \) can be rewriten as Eq. (33). The results are demonstrated in Table 4.

\[
\begin{align*}
R_{11} &= \sqrt{\frac{1}{G + H}}, \\
R_{22} &= \sqrt{\frac{1}{G + H}}, \\
R_{33} &= \sqrt{\frac{1}{G + H}}, \\
R_{12} &= \sqrt{\frac{1}{N}}.
\end{align*}
\]

### Table 2. Material constants for strain ratios

| \( R_{11} \) | \( R_{22} \) | \( R_{33} \) | \( R_{12} \) | \( R_{13} \) | \( R_{23} \) |
|-------------|-------------|-------------|-------------|-------------|-------------|
| 1           | 1.2913      | 0.79596     | 1.09663     | 1           | 1           |

### Table 3. Hill48 parameters of anisotropy

| Part | \( G \) | \( H \) | \( F \) | \( N \) |
|------|--------|--------|--------|--------|
| \( 0^\circ - 45^\circ \) | 0.6518 | 0.3483 | 0.81135 | 1.1563 |
| \( 45^\circ - 90^\circ \) | 0.82   | 0.241558 | 0.6428 | 1.15598 |

### Table 4. material parameters for Hill48 yield criterion in Abaqus

| Part | \( R_{11} \) | \( R_{22} \) | \( R_{33} \) | \( R_{12} \) |
|------|-------------|-------------|-------------|-------------|
| \( 0^\circ - 45^\circ \) | 0.999999 | 0.92862 | 0.82672 | 1.13897 |
| \( 45^\circ - 90^\circ \) | 0.971  | 1.06338 | 0.82654 | 1.139123 |
6. Experimental Procedure

In this study we used AISI-1008 steel sheet circular blank with diameter of 110 mm and 0.9 mm thickness as a sample to demonstrate and compare the difference between the theory used in this study and traditional way using strain ratio to predict the shape and number of earing in deep drawing of semi conical products. Three die’s angles were used 70°, 72°, and 74° from the x-axis as shown in Figure 3 drawn at three punch velocity 100, 150, and 200 mm/min the preparation presented in Figure 4 with constant BH force. Parameters of the process are shown in Table 5.

| Table 5. Deep drawing process variables |
|-----------------------------------------|
| Blank diameter | Blank thickness | Die profile radius | Punch profile radius |
| 110            | 0.9            | 10                | 8                  |

7. Finite Element Simulation of Deep Drawing

Based on the data stated above, the simulation of the AISI-1008 steel sheet is executed using Abaqus software 4.16 with meshing C3D8R type element and the process preformed with range of 0°-90° taking in consideration that drawn product is symmetrical Figure 5 shown the result of the simulation using Hill48 associated with the parameters obtained by the method used in this study along with product from the experimental work.

![Figure 3. Schematic of deep drawing (180° cut).](image)

![Figure 4. Die angle](image)

![Figure 5. (A) the simulation product obtained by the method in this study. (B) Experimental product result from the process.](image)

8. Results and Discussion

As mentioned earlier a comparison between experimental work and simulation results as demonstrated in Figures 6-8 A, B, and C shows the relation between the cup height and angle for die angle 70°, 72°, and 74° in different punch velocities and as noticed that increasing speed may contribute slightly in decreasing the severity of anisotropy effect and this can be explained the process propagate the material need time to flow and if the speed increase lead to increasing in strain hardening of the material and this cause restriction of material flow in die cavity and reduce the difference between ears height at cup lip[17]. Increasing die angle shows that the distance between the highest point to lowest
point at cup edge of ears apparently increased. As obviously the method followed in this study shows a good agreement with experimental in prediction of shape and number of formed ears while, traditional method give an acute earing effect and it is noticed during the preforming of experimental and simulation that the ears formed at the final stages of drawing opposite to the cylindrical sheet drawing and it started when the sheet pressured between the punch and die. Figure 9 demonstrate the comparison of simulation and experimental for some products and it’s seen that the using of traditional strain ratio show more sever effect of earing comparing with product produce from experiential procedure while for using method of this study it produce more smooth and more nearby result.

Figure 6 (A). relation between cup height for 70° at 100 mm/min

Figure 6 (B). relation between cup height for 70° at 150 mm/min
Figure 6 (C). relation between cup height for 70° at 200 mm/min

Figure 7 (A). relation between cup height for 72° at 100 mm/min

Figure 7 (B) relation between cup height for 72° at 150 mm/min
Figure 7 (C). relation between cup height for 72° at 200 mm/min

Figure 8 (A). relation between cup height for 74° at 100 mm/min

Figure 8 (B). relation between cup height for 74° at 150 mm/min
9. Conclusions

1. A new method was used to predict the four earing which happen during deep drawing of conical cups by dividing a quarter of circular blank to two equal sectorial areas, and employ the yield point and index of anisotropy at the same time to obtain the parameters in each area.

2. Increasing the number of divided areas provides more detailed information and produced more accurate prediction in the FE simulation.

3. Using the method suggested in this study a FE simulation of the deep drawing process preformed and four earing prediction is produced with satisfactory agreement with experiment work.

4. Increasing speed may contribute slightly in decreasing the severity of anisotropy effect and this can be explained the process propagate the material need time to flow and if the speed increases this led to increasing in strain hardening of the material[m]. Increasing die angle shows that the different between the highest point to lowest point in the cup edge may increase.
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