Prediction of Eight Ears in Drawn Cup Based On a New Anisotropic Yield Function

J.W.Yoon (1), F. Barlat (1), R.E.Dick (1), S. Choudhry (2)

1 Materials Science Division, Alcoa Technical Center, PA 15069-0001
2 MSC Software Corporation, 500 Arguello St, Redwood City, CA 94063
Instability in Sheet Metal Forming Processes

Tensile Instability  Compressive Instability

Defects in Products
Source of Anisotropy

* Deformation modes
  - Dislocation glide, Twinning

* Microstructure
  - Grain structure, Dislocation structures, Second-phases, Solutes

Θ' precipitates

Dislocation structures

1050-O

1μm

<111>

6022-T4

1μm

<111>

Al-3%Cu

<010> <100>

1μm
Yld2004 (Barlat et al. (2004)) Prediction for AL 5019

\[ \phi = \phi(\Sigma) = \left| \tilde{S}'_1 - \tilde{S}''_1 \right|^a + \left| \tilde{S}'_2 - \tilde{S}''_2 \right|^a + \left| \tilde{S}'_3 - \tilde{S}''_3 \right|^a + \]

\[ + \left| \tilde{S}'_2 - \tilde{S}''_1 \right|^a + \left| \tilde{S}'_2 - \tilde{S}''_2 \right|^a + \left| \tilde{S}'_3 - \tilde{S}''_3 \right|^a + \]

\[ + \left| \tilde{S}'_3 - \tilde{S}''_1 \right|^a + \left| \tilde{S}'_3 - \tilde{S}''_2 \right|^a + \left| \tilde{S}'_3 - \tilde{S}''_3 \right|^a = 4\bar{\sigma}^a \]
- Stress Update
  \[ \Delta \sigma = C \Delta \varepsilon = C \Delta \varepsilon - \Delta \varepsilon \]

- Consistency Condition
  \[ \Phi \sigma \bar{\varepsilon} = \bar{\sigma} \sigma - \rho \bar{\varepsilon} = \]

- Stress-Strain Relation
  \[ \rho \bar{\varepsilon} = \varepsilon + \bar{\varepsilon} \]

- Multi-Step Return Mapping
  \[ \Phi \gamma = = \bar{\sigma} \sigma - \rho \bar{\varepsilon} = \Phi \]
  \[ \Phi \gamma = \bar{\sigma} \sigma - \gamma C m - \rho \bar{\varepsilon} + \gamma = \Phi \]
  \[ \Phi \gamma = \bar{\sigma} \sigma - \gamma C m - \rho \bar{\varepsilon} + \gamma = \Phi = \]

- Stable Convergence for Large Step Increment
### Basic patch tests for yield function and stress integration method

#### One element test

<table>
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<tr>
<th>Angle from Rolling Direction (Deg.)</th>
<th>EXP</th>
<th>Yld2000-2d</th>
<th>Yld96</th>
<th>Yld91</th>
<th>Hill’s (1948) Yld.</th>
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</tbody>
</table>

#### Tensile bar test

![Tensile bar specimen diagram](image_url)
Mini Die Drawing with Yld2004: Thickness Contour for AL 5019
Earing Profile (shell vs. solid): Yld2004 Prediction for AL 5019

Comparison between Yld2004/Shell and Yld2004/Solid

EXP  Yld2004/Shell  Yld2004/Solid

Normalized flow stress

Exp. r value

Exp. stress

Yld2004-18p

5019A-H48 (S.No. 765217)

Cup Radius (In.)

Angle from Rolling (Deg.)

0 10 20 30 40 50 60 70 80 90
The relationship between r-value and earing

\[ r = \frac{\varepsilon_w}{\varepsilon_t} \quad \rightarrow \quad r_{\theta+} = \frac{\varepsilon_r}{\varepsilon_t} = -\frac{\varepsilon_r}{\varepsilon_r + \varepsilon_{\theta}} \]

\[ \varepsilon_{\theta} \quad \varepsilon_r \quad \varepsilon_t \quad \theta = - r_{\theta+} + r_{\theta+} \]

\[ \varepsilon_r \theta = \frac{E_{r\theta+}}{r_{\theta+}} + \text{where} \quad \varepsilon_{\theta} = \frac{R_{\text{cup}}}{R_{\text{blank}}} = -E \]

\[ h_{\theta} \propto \varepsilon_r \quad \rightarrow \quad h_{\theta} \quad K = \frac{r_{\theta+}}{r_{\theta+} + } \]

r-value plot \( \leftrightarrow \) (Mirror Image) \( \rightarrow \) Cup Radius or Height
6 Ears Prediction for AL 2090 based on Yld2004

- **Normalized stress vs. Tensile direction**
- **Normalized shear stress contours**
- **Earing for AL2090**

Graphs showing experimental and predicted stress values for different directions and angles.
8 Ears Prediction based on Yld2004

- Stress input
- r value input

Normalized stress vs. r value

Stress input: Yld2004-18p
r value input: Yld2004-18p

Normalized stress (yy)

FM8 material

Normalized stress (xx)
Earless Target Cup Design?

General cup shape after drawing

Earless target cup (?)
Optimum Blank Design

Optimization Technology

Current Technology

Direct Design Method

Analysis code (FEM)

Experimental Trial
Example: Travel from Seoul to Busan

- Seoul
- Taejon
- Busan

Direct Design Method
Analysis Method
Iterative Blank Design using Inverse Method and Analysis Code

Combination strategy for optimum blank design:

1. Ideal Forming design code for initial estimation
2. Analysis for detail modification with deformation path method

Product Design

Initial Blank Design

FEM Analysis

Blank Modification

Shape Error < $\delta$

Precision Blank

Formability Evaluation (FLD)

Optimum Condition Check

Stop
Blank Modification Algorithm for Analysis Code

Modified blank shape

\[ L : \text{summation of element lengths in radial direction} \]

\[ L_I : \text{for initial geometry} \]

\[ L_F : \text{for final geometry} \]

\[ L_T : \text{for target geometry} \]

\[ L_M : \text{for modified initial geometry} \]

\[ L_I = L_F \rightarrow L_T \approx L_M \]

\[ \therefore L_I = L_M \]
Earless Cup Design Result

Mini Die Drawing

Earless cup design

Initial Blank Shape

- Original circular blank
- Blank from Ideal Forming
- Modified blank

Target cup height (0.55 inch)
- Cup height with circular blank
- Cup height using Ideal Forming blank
- Cup height after blank modification

X-Coord. (inch)

Y-Coord. (inch.)

Cup height profile (inch.)

Angle from rolling (deg.)
Earless Cup Design Result

Mini Die Drawing

h = 0.55 inch
Polycrystal model based on
incremental deformation theory

\[ F = RU \]

\[ \begin{align*}
D &= D + D = R \\
D &= \sum \dot{\gamma} - (b \cdot n) + n \cdot b = \sum \dot{\gamma} P \\
b &= R \cdot b \quad \text{and} \quad n = n \cdot R
\end{align*} \]

* Grain Level Stress

\[ \dot{\sigma} = C \cdot D - D = C \cdot D - \sum \dot{\gamma} P \]

* Slip System Level Stress

\[ \tau_{+\Delta} = \tau + \Delta \dot{\tau} \]

where

\[ \tau = \sigma \quad P \quad \dot{\tau} = CP : D = CP : D - D = CP : D - \sum \dot{\gamma} P \]

* Hardening in Slip System Level

\[ \tau = \begin{pmatrix} \dot{\gamma}_1 \\ \vdots \\ \dot{\gamma}_s \end{pmatrix} \quad \dot{\gamma} \]

Nonlinear Equilibrium Equation

\[ \dot{\gamma} = \tau_{+\Delta} - \tau = \]
Shear Test Simulation with Polycrystal Approach

45º shear

90º shear

Grip ends

3 mm

60 mm

15 mm

Shear zone

TD → RD

3 mm

60 mm
Numerical Results based on Polycrystal Plasticity

**AL 6022**

(111) pole figure for 6022-T4

(111) pole figure for 1050-O

**AL 1050**

90° shear, $\gamma = 0.35$

90° shear, $\gamma = 0.30$

Graphs showing Shear Stress vs. Shear Strain for 90 degree and 45 degree orientations.
Numerical Results based on Yld2004

**AL 6022**

- 3.995e+002
- 3.876e+002
- 3.747e+002
- 3.619e+002
- 3.580e+002
- 3.479e+002
- 3.300e+002
- 3.211e+002
- 3.112e+002
- 3.012e+002
- 2.893e+002

**AL 1050**

- 1.934e+002
- 1.446e+002
- 1.357e+002
- 1.206e+002
- 1.003e+002
- 1.091e+002
- 9.140e-001
- 8.285e-001
- 7.369e-001
- 6.483e-001

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Graph showing shear stress vs. shear strain for AL 6022 and AL 1050 under simple shear conditions.
Comparison between Polycrystal plasticity and Yld2004

Crystal plasticity

Yld2004

Simple shear
FE & crystal plasticity

Shear strain $\varepsilon_{12}$

Shear stress (MPa)

Simple shear
FE & Yld2004-18p

Shear strain $\varepsilon_{12}$

Shear stress (MPa)
Phenomenological models

Microstructural models