Performance Evaluation of Planar Anisotropy Yield Criteria for Aluminum Sheet Forming Analysis

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Abstract. The present work aims making a step by identifying a set of standardized accuracy measures based on laboratory experiments. Uniaxial tension, plane strain tension, hemispherical dome, and square cup tests were conducted for a 6000 series aluminum sheet used as automotive panels. Principal strain distribution, punch height at fracture, draw-in, and wrinkling were measured and compared with numerical simulation predictions. The performance of the five yield criteria, Barlat89, BBC2005, Hill48, Vegter2017, and YSD6 (Yoshida 6th order polynomial function) was measured and evaluated using the conventional accuracy index and the proposed accuracy indexes that represent manufacturing defects encountered in practice. It is found that state of the art material models such as BBC2005, Vegter2017 and YSD6 are fully able of representing standardized material test results, which is also well reflected in the predictive accuracy of simulated hemispherical dome and square cup tests. Because earlier models such as Hill48 and Barlat89 lack in capturing a high number of experimentally determined data points, they should be used with caution even Barlat89 shows good performance in the hemispherical dome tests.

1. Introduction

The quality of yield criteria is evaluated based on their ability to capture a possibly high number of experimentally determined data points. This performance measure, however, only covers a limited and isolated set of stress/strain states which are hardly representative of the full complexity arising in real stamping applications. At the current state of the art, there is no objective and standardized base for validating material models under industrial conditions. The present work aims making a step in this direction by identifying a set of standardized accuracy measures based on laboratory experiments. In this study, uniaxial tension, plane strain tension, hemispherical dome, and square cup tests were conducted for a 6000 series aluminum sheet (afterthat A6xxx-T4) used as automotive panels. Directional material properties, forming limit curve, principal strain distribution, punch height at fracture, draw-in, and wrinkling were measured and compared with numerical simulation predictions. The performance of the five yield criteria, Barlat89, BBC2005, Hill48, Vegter2017, and YSD6 (Yoshida 6th order
polynomial function) was measured and evaluated using the conventional accuracy index and the proposed accuracy indexes that represent manufacturing defects encountered in practice.

2. Numerical formulations

Five yield criteria, Barlat and Lian [1] in 1989, Banabic et al. [2] in 2005, Hill [3] in 1990, Vegter [4] in 2017, and Yoshida et al. [5] in 2015, are introduced. Yoshida et al. proposed a constitutive model that describes the evolution of anisotropy with increasing plastic strain as the form of

\[
\varphi(\sigma) = C_1 \sigma_1^3 - 3 C_2 \sigma_2^2 \sigma_3 + 6 C_3 \sigma_2^4 + 7 C_4 \sigma_2^2 \sigma_3^2 + 6 C_5 \sigma_2^2 \sigma_3^2 - 3 C_6 \sigma_3^2 \sigma_3 + C_7 \sigma_3^3 + C_8 \sigma_3^6 + 9(C_9 \sigma_4^3 - 2 C_9 \sigma_3^2 \sigma_4) + 3 C_{10} \sigma_3^2 \sigma_4^2 - 2 C_11 \sigma_3 \sigma_4^2 + C_12 \sigma_4^3 \tau_{x y}^2 + 27(C_{13} \sigma_5^2 - C_{14} \sigma_3 \sigma_5) + C_{15} \sigma_5^2 \tau_{x y} + 27 C_{16} \tau_{x y}^2 = C_7 \sigma_3^6
\]

where \( C_i \) is the material parameters to be determined by directional yield stresses and \( r \)-values.

The performance of the yield criteria can be evaluated by comparisons with experimental measurements and mathematical predictions in general. In order to have a comprehensive evaluation tool, the CERTETA research team have developed a global accuracy index [6]. The accuracy index CA (Conventional Accuracy index) includes the errors calculated as the universal form of

\[
CA = \sum_i \frac{\delta_i^{\text{exp}} - \delta_i^{\text{sim}}}{\delta_i^{\text{exp}}} \times 100 \%
\]

where \( \delta \) can be directional stresses and \( r \)-values, stress sets on yield surface.

The present work proposes a set of standardized accuracy measures based on laboratory experiments, tailored to represent manufacturing defects. Both the tests and the measures should be chosen to strike a balance between proper representation of the real situation and a manageable experimental complexity. The accuracy index PA(Proposed Accuracy) includes the errors calculated as the universal form of

\[
PA = \sum_j \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{sim}}}{\beta \sigma_i^{\text{exp}}} \times 100 \%
\]

where \( \alpha \) can be principal strains, fracture, draw-in, wrinkling, dimensional accuracy, etc. and \( \beta \) is a special reference factor to normalize \( \alpha \) properly. In this study, uniform elongation (0.21) and specified length (10mm) are used as \( \beta \) for strain and wrinkling PA.

3. Experimental tests

3.1. Uniaxial tension test

Uniaxial tension tests were conducted along the rolling (RD), 45° to the rolling (DD), and transverse to the rolling (TD) directions by the standard of JIS (Japan Industrial Standards) 13B using ZWICK ROELL (Z100) machine. The tension tests based on the displacement control were conducted with the constant crosshead speed of 1mm/min for all specimens during the uniform deformation. The true and engineering stress-strain curves along the three directions are shown in Fig. 1(a) where the test specimens before and after the tests are shown. The directional yield stresses and \( r \)-values are 140.6MPa, 134.6MPa, 132.0MPa, 0.6310, 0.3567, and 0.5533 along RD, DD, and TD directions respectively. It is found that the yield stress along RD direction is the highest one and the three directional \( r \)-values are lower than unity.

3.2. Hemispherical dome test

The experimental determination of the FLC was conducted by hemispherical dome test with various specimen widths for the A6xxx-T4 aluminum sheet. Fig. 2(a) shows the schematic geometry of the hemispherical dome tools. The punch velocity was set to 80mm/min. The strains on the specimen surface
are measured using the ASAME GPA system to analyze the deformation of the square grids (2mm X 2mm). The strains corresponding to failed and safe grids (the set of the failed grids include both the crack and neck ones) are plotted in the FLD. Fig. 2(b) shows the specimens after the dome tests. Six different specimen widths were used to derive the sheet split at different strain paths (uniaxial, near plane strain, biaxial, and equi-biaxial strains).

3.3. Plane strain tension test
Plane strain tension tests were conducted by using ZWICK ROELL (Z100) machine. The specimen in Fig. 1(b) was designed where plane strain status under 1% longitudinal extension was shown for uniaxial tension loading. The loading conditions are the same as the uniaxial tension test except for the specimen design. The plane strain stress is measured as 156.1MPa.

3.4. Square cup test
The square cup drawing tests were performed using a hydraulic press machine (1000 tons) composed of a die, a blank holder, and a punch. Fig. 3(a) presents the schematic representation of the tools and dimensions. The gap between the die and the punch is 30mm to make sufficient wrinkling in the wall region. A blank holder force of 250kN is used to guarantee a part without necking or crack. The tests were conducted for a punch velocity of 5mm/s where 2.03g/m² of lubricant oil was applied to the blank sheet. The strains on the specimen surface were measured using the ARGUS system and plotted along three directions, RD, DD, and TD. Fig. 3(b) shows a specimen after the test.

![Fig. 1 (a) stress-strain curves and test specimens after tensile test (JIS13B), (b) plane strain test specimen](image1)

![Fig. 2 (a) schematic diagram of hemispherical dome test, (b) formed specimens after the test](image2)
4. Numerical simulations and accuracy indexes

Based on the measured material data, the conventional accuracy index is evaluated including directional stresses, r-values, and yield surfaces. For the numerical simulations of the hemispherical dome and the square cup tests, the commercial stamping simulation softwares, AutoForm [7], AutoForm_Sigma [7], and TriboForm [8], were used. The performance of yield criteria is evaluated based on deviations between experimental measurements and numerical predictions for principal strains, fracture height, draw-in, and wrinkling shape. Swift/Hockett-Sherby hardening equation for A6xxx-T4 sheet is used to describe the extrapolation of the mechanical behavior predicted from the uniaxial tensile test shown in Fig. 4(a). In Fig. 4(b), the error of yield stress and absorbed energy is calculated as 0.8% and 0.7% by Swift/Hockett-Sherby equation and 2.6% and 1.4% by Swift equation. In order to evaluate the performance of yield criteria, the five yield criteria, Barlat89, BBC2005, Hill48, Vegter2017, and YSD6 were used and each simulation was done respectively. The measured forming limit curve was used for necking detection in the simulation.

4.1. Conventional accuracy index

In Fig. 4(c), the normalized directional yield stresses are compared with those of measurements. It can be seen that BBC2005, Vegter2017, and YSD6 predict the yield stresses of DD and TD directions well. However, in the prediction of Barlat89 and Hill48, there are bigger differences on the yield stress of DD direction. Although the yield stress predictions of RD, DD, and TD by BBC2005, Vegter2017, and YSD6 are almost identical to experimental measurements, the intermediate values are different slightly from each other. The comparison of directional r-values predicted by yield criteria is made for the five yield criteria. The five yield criteria predict the r-values of RD, DD, and TD directions well all. As in the case of directional yield stresses, the intermediate r-values are different slightly from each other. In Fig. 4(d), the predicted yield surfaces are compared to each other. The predictions of equi-biaxial and TD direction yield stresses are identical to the measurements well except for Hill48. YSD6 delivers the closest prediction, $\sigma_1 = 1.1226$, for the measured plane strain stress, $\sigma_4 = 1.1138$, followed by Vegter2017, $\sigma_4 = 1.0897$. This shows that the plane strain stress can be an additional index to compare the accuracy of yield surfaces. The conventional accuracy index are summarized in Table 1.

4.2. Hemispherical dome test

Additional simulation for hemispherical dome tests were conducted in order to evaluate the performance through the proposed accuracy index. The number of elements is 4325 for the half model considering the symmetry. The integration points are 11 through the thickness direction. Coulomb friction model is used for washing condition. The punch strokes are 24mm for W75 and 25mm for W150 respectively. The predictions and measurements of the principal strains along the center line and the fracture heights are compared in Fig. 5(a), 5(b) and 5(d). In the specimen width 75mm (W75), the plane strain mode is shown well in all yield criteria. In the specimen width 150mm (W150), the scatters around the pole region among the yield criteria are bigger than those of W75. Fig. 5(c) shows yield stress ratios of the
five yield criteria. The deviations in W150 is bigger than those of W75 among yield criteria. Fig. 5(d) shows the comparison of fracture heights and all yield criteria show good agreement under 4% error. Strain Index and Height Index are calculated and summarized in Table 2. Vegter2017 delivers the best Strain Index as 2.6% and Barlat89 shows the best Height Index as 1.3% although Barlat89 lack in capturing a high number of experimentally determined data points with lower conventional accuracy index.

4.3. Square cup test

The surface roughness of A6xxx-T4 sheet and the tools are 0.3μm and 0.5μm respectively. The TriboForm friction model was generated by considering sheet/tool surface roughness, pressure, strain, velocity, temperature, and lubricant amount and used in the simulation. This advanced friction model replaces the conventional Coulomb friction model in which a constant coefficient of friction is used to describe the frictional behavior. The number of elements is 45,293 for the full model. The integration points are 11 through the thickness direction.

![Fig. 4](image-url)

**Fig. 4** (a) hardening equations, (b) error (%), (c) directional yield stresses and r-values, (d) yield surfaces

| Table 1 Conventional Accuracy Index (CA) |
|-----------------------------------------|
| CA (Conventional Accuracy Index)        | BBC2005 | Vegter2017 | YSD6  | Barlat89 | Hill48 |
| CA1 [%]: Directional Yield Stress       | 0.0     | 0.0        | 0.0   | 3.5      | 4.3    |
| CA2 [%]: Directional r-value            | 0.0     | 0.0        | 0.0   | 0.0      | 0.0    |
| CA3 [%]: Yield Surface                  | 0.1     | 0.1        | 0.1   | 0.8      | 2.3    |
| Conventional Accuracy Index [%]         | 0.0     | 0.0        | 0.0   | 1.4      | 2.2    |
**Fig. 5 (a)** comparison of strain distribution of W75, **(b)** strain distribution of W150, **(c)** yield stresses at the pole, **(d)** punch heights at fracture

**Table 2** Proposed Accuracy Index (PA)

| PA (Proposed Accuracy Index) | BBC2005 | Vegter2017 | YSD6 | Barlat89 | Hill48 |
|-----------------------------|---------|------------|------|----------|--------|
| PA1 [%]: Strain Index (H Dome Test) | 3.8     | 2.6        | 6.0  | 6.7      | 22.4   |
| PA2 [%]: Height Index (H Dome Test) | 1.8     | 2.8        | 4.5  | 1.3      | 2.9    |
| PA3 [%]: Strain Index (SQ Cup Test) | 4.2     | 4.1        | 3.1  | 4.4      | 5.5    |
| PA4 [%]: Length Index (SQ Cup Test) | 0.8     | 0.7        | 0.6  | 0.7      | 0.7    |
| PA5 [%]: Wrinkling Index (SQ Cup Test) | 5.7     | 5.4        | 5.4  | 7.3      | 5.8    |
| Proposed Accuracy Index [%] | 3.3     | 3.1        | 3.9  | 4.1      | 7.5    |
| Normalized PA wrt BBC2005   | 1.00    | 0.96       | 1.20 | 1.25     | 2.29   |

Fig. 6(a) shows the predicted shape of the square cup by YSD6. In the wall region, it can be seen that much wrinkling is occurred as in the real product in Fig. 3(b). The major strain along RD, DD, and TD directions is compared in Fig. 6(b), 6(c), and 6(d) respectively. It can be seen that the four yield criteria except for Hill48 show good agreement in major strain distribution along RD and TD directions. The comparison of major strains along DD sections, show larger scatter among the modelling approaches. Also in this case advanced models such as BBC2005, Vegter2017 and YSD6 outperform classical approaches especially in predicting strain for the wall region. This confirms the common knowledge...
Fig. 6 (a) predicted formed shape using YSD6, (b) comparison of strain distribution along RD direction, (c) DD direction, (d) TD direction, (e) wrinkling shapes, (f) formed blank outlines
that Hill48 is inadequate to be used with materials with r-value smaller than unity. YSD6 shows the best Strain Index as 3.1%. Fig. 6(e) shows the section shape at the height=30mm from the punch top in order to compare the wrinkling shapes. The average deviations of wrinkling are 0.57mm (BBC2005), 0.54mm (Vegter2017), 0.54mm (YSD6), 0.73mm (Barlat89), and 0.58mm (Hill48) respectively. Wrinkling Indexes are 5.4% to 7.3% in the case of β=10mm. Fig. 6(f) shows the comparison of the length between the center and the outline after springback. The average deviations of length between the center and edge are 2.0mm (BBC2005), 1.8mm (Vegter2017), 1.5mm (YSD6), 1.8mm (Barlat89), and 1.8mm (Hill48) along 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° directions respectively. Length Indexes are all under 0.8%. The deviation of strain, punch height at fracture, draw-in, and wrinkling are proposed as new accuracy indexes for performance evaluation and summarized in Table 2. It is seen that Vegter2017, BBC2005, YSD6, and Barlat89 models deliver comparable performance remaining on Proposed Accuracy Index below 5%.

5. Conclusions
In assessing the accuracy of the results under complex forming process conditions can be a challenging task. The present contribution proposes a new set of objective criteria for discussing the effect of different factors on the process results and makes a step in this direction based on laboratory experiments. Specifically the role of material modeling is detailed.

State of the art material models such as BBC2005, Vegter2017 and YSD6 are fully able of representing standardized material test results, which is also well reflected in the predictive accuracy of simulated hemispherical dome tests. Earlier models such as Hill48 and Barlat89, lack information in this respect and should be used with caution even Barlat89 shows good performance in the hemispherical dome tests.

As far as the square cup simulations are concerned, it is seen that all models are principally capable of predicting strain, blank draw-in, and wrinkling accurately. This is primarily due to the fact that in the present geometry both situations fall in the vicinity of a uniaxial compressive stress state where the yield loci do not vary strongly. The comparison of major strains along DD sections, show larger scatter among the modelling approaches. Also in this case advanced models such as BBC2005, Vegter2017 and YSD6 outperform classical approaches especially in predicting strain for the wall region.

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