Influence of material modeling on simulation accuracy of aluminum stampings

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Abstract
The best practice in modeling material yield, strain hardening and anisotropic behavior in plastic deformation has been analyzed for an AA 6016 aluminum alloy. The investigation was based on the extensive material property testing, stamping benchmarking and AutoForm simulations. For the material property testing, both the uniaxial tensile test and the hydraulic bulge test were conducted. The elliptic punch test and the cross die test served as the benchmarks to validate the simulation results. In the simulations, the material characteristics was modeled with the combinations of four strain-hardening models and three yield criteria. By comparing the simulation results with the experimental measurements, the influence of material modeling on aluminum stamping simulation accuracy was evaluated. It was concluded from this study that the yield criterion is the key factor in controlling the simulation accuracy. The simulation with the BBC2005 yield model predicts the most accurate results. It was also shown that the combined Swift/Hockett-Sherby strain-hardening model is most suitable to describe aluminum strain hardening behavior.

1. Introduction
Aluminum alloys have been increasingly used in the automotive industry as the favoured solution for vehicle weight savings. Since aluminum alloys are typically less formable than steels, it is often a challenge to make aluminum parts with the steel kind features. This is especially true for the outer panels where the outlook styling with distinguished sharper features is highly desired. In order to meet this challenge within a limited design-to-market time, stamping die engineering and process development are heavily relying on stamping simulations for guidance. The critical role the stamping simulations are playing is based on the simulation accuracy which is mainly given by the material modeling. Over the past several decades, numerous advanced material models have been developed to describe the material characteristics and implemented into the commercial CAE software \cite{1}. These efforts improved the predictive accuracy of the stamping simulations and have greatly expanded the simulation applicability. While those models are available for selection, it is essential to understand the limitations of those models and the associated accuracy levels they can provide in aluminum stamping simulations. So far, there are few publications available to address these issues. Thus it is of great importance to develop the best practice in material modeling, to benchmark the material model for its applicability and to understand the relationship between the material model and simulation accuracy level.
The current work was aimed to address these urgent industrial demands, based on the systematical experimental investigations and the extensive numerical analyses. In the experimental investigations, the testing material of Aleris Ecolite™ 160 ST (an AA 6016 alloy) at the thickness of 1.7 mm was characterized by the uniaxial tensile test and the hydraulic bulge test. The same material was also used for the elliptic punch test [2] and the cross die test. These two benchmarks were simulated with AutoForm software. In the simulation analysis, the material characteristics was modeled with the combinations of four strain-hardening models and three yield criteria. By comparing the simulation results with the experimental measurements from the benchmark studies, the simulation accuracy was evaluated. The effect of the material anisotropy on the simulation accuracy was also examined.

2. Material characterization
In this investigation, two types of material testing have been carried out. The basic material property testing was done by using uniaxial tensile tests and hydraulic bulge tests, providing the fundamental data for material modeling. The simulative stamping testing was conducted with the elliptic punch test and the cross die test, serving as benchmarks to evaluate the simulation accuracy.

2.1 Uniaxial tensile test
The material strain hardening and anisotropic behavior have been determined by using this test for the studied aluminum alloy. The test was conducted by following the ISO 6892 standard with the type 2 sample at the room temperature. The testing samples were cut along the 0°, 45° and 90° relative to the rolling direction in order to identify the effect of anisotropy. The digital image correlation (DIC) system was used for all the tests to record the deformation process. For each of the sample directions, the testing was repeated three times. In addition to the basic material property parameters and the stress-strain curves, the material coefficients of plastic anisotropy (r-value) were measured by the ISO 10113 standard.

2.2 Hydraulic bulge test
This test is necessary to model the material strain hardening behavior in the larger plastic strain range. More importantly, this test can provide the yield stress ($\sigma_y$) and coefficient of plastic anisotropy ($r_{xy}$- value) in the equibiaxial stress state which are critical for material modeling. The testing was performed by following the ISO 16808 standard for three square samples of 250x250 mm with the DIC system.

2.3 Elliptic punch test
The elliptic punch test consists of a set of five forming tests with five exchangeable punches [2]. Figure 1 shows the schematic view of the testing tool setup and five different punch profiles. As illustrated in Figure 1(a), the blank is held under pressure between the die and the blank holder during the testing. With the punch moving up, the blank is deformed to the defined punch head shape. Figure 1(b) shows the punch profiles being developed in this testing method. By changing the punches in the tests, the blanks can be deformed from the pure deep drawing mode with the flat head punch to the drawing combined with utmost intensive biaxial stretching mode with the hemisphere head punch while three other different drawing-stretching combination modes in between.

For the current study, the elliptic punch test was carried out for the deep ellipse, hemisphere, flat ellipse and cylinder punches. During the testing, two types of the lubricants - mill oil and Teflon film were applied to all the contact areas between the tools and the blanks. For the testing with the hemisphere, flat ellipse and cylinder punches, the circular blanks at the diameters of 180 mm, 190 mm, 200 mm, 210 mm and 220 mm were used. For the deep ellipse punch test, the diameters of the circular blanks were 140 mm, 150 mm, 160 mm, 170 mm and 180 mm. By combined the blank size with two different lubricants, a total of 70 tests have been completed under different binder holder forces. For all of the tests, the DIC system was used to measure the major and minor strain distributions on the outer surface of the samples. As an example, Figure 2 shows the measured major strain distributions for a flat ellipse sample. The major strain distributions along the 0°, 45° and 90° sections relative to the rolling
direction are available for the simulation comparisons. Additionally, the blank holder force (BHF) and the maximum punch force were recorded for each case. After testing, the blank draw-in values were measured along the $0^\circ$, $45^\circ$ and $90^\circ$ directions marked as location 1, 2 and 3 in Figure 3(a).

Figure 1 (a) Elliptical punch test setup and (b) punch profiles.

Figure 2 (a) Flat ellipse testing sample and (b) DIC measurement of major strain.

Figure 3 Draw-in measurement locations (a) elliptic punch test and (b) cross die test.

2.4 Cross die test
Different from the elliptic punch tests described above, the cross die test identifies the material deformation behavior at a more complicated stress state. The cross die geometry used in this study is shown in Figure 4. The square blanks of 260x260 mm, 270x270 mm, 280x280 mm, 290x290 mm and 300x300 mm were tested with different BHFs applied. The Teflon film was applied to all the contact areas between the blank and the tools. A total of ten tests have been completed. For this testing, the DIC system was also used to measure the major and minor strain distributions (Figure 5). After testing, the blank draw-in values were measured at the locations as illustrated in Figure 3(b).

Figure 4 Cross die test setup and tooling dimensions.

Figure 5 DIC measurement of minor strain.

Figure 6 Comparison of yield surfaces.
3. Material modeling

In sheet metal stamping simulations, material plastic deformation behavior is described by the material yield criterion and strain hardening model. With the advances in understanding material behavior in plastic deformation, numerous advanced yield criteria have been developed. It is well known that all of these criteria have their assumptions about material characteristics and therefore their limitations for applications. Regarding the strain hardening modeling, the true stress-true plastic strain relationship during plastic deformation should be well defined until the true plastic strain of 1.0 for stamping simulations. Since this curve cannot be experimentally measured to reach that amount of true plastic strain, it is necessary to extrapolate the testing data by using the strain hardening model.

3.1 Yield criterion

As the dedicated simulation tool for this work, AutoForm has implemented three yield criteria - Hill48 [3], Barlat89 [4] and BBC2005 models [5]. Figure 6 compares these three yield criteria in the principal stress plane with respect to the initial yield stress measured. It is obvious from Figure 6 that the BBC2005 model fits all those three testing data points very well, while other two models fit only one of the testing data points. Compared to the BBC2005 model, the Hill48 model has the biggest difference while the Barlat89 model has the smallest difference in the equibiaxial stress state. Away from the equibiaxial stress state, the Barlat89 model has significant difference to the BBC2005 model in describing aluminum yielding behavior. For the Hill48 model, its significant difference to the BBC2005 model exists for almost all the biaxial stress states. As stated by Dorel Banabic etc. [1], the BBC2005 model has the flexibility of exactly taking eight measured material mechanical property parameters - three uniaxial yield stresses ($\sigma_0$, $\sigma_{15}$, $\sigma_{90}$), three uniaxial coefficients of plastic anisotropy ($r_0$, $r_{45}$, $r_{90}$), the biaxial yield stress ($\sigma_b$) and the biaxial coefficient of plastic anisotropy ($r_b$). For this study, those eight parameters were experimentally measured and directly input into the BBC2005 model. The Hill48 model uses only four material mechanical property parameters ($\sigma_0$ or $\sigma_{15}$ or $\sigma_{90}$, and $r_0$, $r_{45}$, $r_{90}$) to determine its yield function. As a result, it can only match one testing data point as seen in Figure 6. In addition, the Hill48 model cannot use the same number of yield stresses and $r$ values in the identification procedure. This is a significant drawback for materials like aluminum whose mechanical property parameters may vary a lot. The Barlat89 model also does not give accurate predictions of the biaxial yield stress and biaxial coefficient of plastic anisotropy. It is seen from Figure 6 that the Barlat89 model cannot simultaneously capture the planar variation of the uniaxial yield stress and uniaxial coefficient of plastic anisotropy. These phenomena would be well examined by the elliptic punch tests where the material is deformed under different biaxial stretching conditions.

3.2 Strain hardening model

There are several strain hardening models available in AutoForm. For this comparative study, four models implemented have been analyzed namely Swift, Ghosh, Hockett-Sherby (H-S), and combined Swift/Hockett-Sherby (S/H-S) models. The formula of these models are listed below for reference.

**Swift:**

$$\sigma = C \ast (\varepsilon_{pl} + \varepsilon_0)^m$$  \hspace{1cm} (1)

**Ghosh:**

$$\sigma = C \ast (\varepsilon_{pl} + \varepsilon_0)^m - D$$  \hspace{1cm} (2)

**Hockett-Sherby:**

$$\sigma = \sigma_{sat} - (\sigma_{sat} - \sigma_i)e^{-ae_{pl}}$$  \hspace{1cm} (3)

**Combined S/H-S:**

$$\sigma = (1 - \alpha) \left\{ C \ast (\varepsilon_{pl} + \varepsilon_0)^m \right\} + \alpha \ast \left\{ \sigma_{sat} - (\sigma_{sat} - \sigma_i)e^{-ae_{pl}} \right\}$$  \hspace{1cm} (4)

where $\sigma$ is the equivalent stress and $\varepsilon_{pl}$ the equivalent plastic strain. All others are material parameters.
In order to accurately model the material strain hardening behavior, the testing data from both the uniaxial tensile test and bulge test were used. With the internally developed curve fitting methodology, the parameters in each of those four models were derived. Figure 7 demonstrates the results of the four models compared with the testing data. It is seen that both the H-S and combined S/H-S models give better representations over the testing data. For the strain range over 0.6, the H-S model predicts little strain hardening while combined S/H-S model shows a very small strain hardening trend. For the strain range less than 0.2, the combined S/H-S model gives better description than the H-S model. Both the Swift and Ghosh models, however, predict much stronger strain hardening behavior in the strain range over 0.6 (Figure 7(a)) and in the small strain range (Figure 7 (b)). Therefore, it can be concluded that the combined S/H-S model is most suitable to describe aluminum strain hardening characteristics.

![Figure 7 Curve fitting results in (a) full strain range and (b) small strain range](image)

4. Simulation results
The simulations of the elliptic punch tests and the cross die test were carried out in AutoForm\(^\text{\textregistered}\)plus R6, using three node triangle elements with 11 layers, adaptive refinement and “Final Validation Accuracy” settings. The experimental process inputs – tool and blank geometries, blank holder force and travel were directly used in the simulation setup. The two different lubrications were simulated by varying the friction coefficient to match the measured draw-in values. The pressure and velocity dependent frictional model was selected for all the simulations. To investigate the influence of yield criterion on simulation accuracy, the three yield criteria were evaluated with the combined S/H-S model. The eight material parameters in the BBC2005 model were the experimental inputs. For both the Hill48 and Barlat89 models, the \(\sigma_b\) and \(r_b\) values were calculated from the \(\sigma_0, r_0, r_{45}\) and \(r_{90}\) values. To examine the strain hardening influence, all the four models were incorporated with the BBC2005 yield criterion.

4.1 Blank draw-in match
Matching the blank draw-in values in the simulations to the measurements is the first step before evaluating the simulation results. For each of the simulation cases, the best blank draw-in match was obtained by adjusting the base friction coefficient. Figure 8 compares the draw-in values predicted from the three yield models with the measurements for the deep ellipse sample which was formed with the circular blank of 160 mm in diameter, the mill oil lubrication and the BHF of 14 kN. It is found that the BBC2005 model has good correlation with the measurements at those three measurement locations and is overall the best prediction. The similar results were observed for the other ellipse punch tests and the cross die test as well. Since this model can take the mechanical property parameters measured at those three directions, it can accurately capture the material anisotropic behavior. Both the Barlat89 and Hill48 models show a good draw-in match at one or two locations, but not all the three locations. This phenomenon can be well explained by the limitations of the models as discussed before. It is worthy to mention that the Hill48 model cannot give a close draw-in match for the cylinder punch test with the Teflon film, no matter how to change the friction coefficient (Figure 9). The same is also found for the flat ellipse punch test with the Teflon film.
4.2 Influence of yield criterion

Figure 10 depicts the difference in the major and minor strain distributions between the measurements and the predictions from the three yield models along the 0° section of the deep ellipse sample formed with the circular blank of 160 mm in diameter, the mill oil lubrication and the BHF of 14 kN. For this case, the BBC2005 model gives the most accurate results for both the major and minor strains. Its maximum derivation is about 5% for the major strain and 2% for the minor strain. The Barlat89 model shows a good prediction of the major strain with the maximum derivation of about 6%. But its minor strain prediction is far away from the measurements. Figure 10 also proves that the Hill48 model gives the worst predictions for both the major and minor strains. Although this model can take the testing input at the 0° direction (Figure 6), its strain predictions are the least accurate ones.

The hemisphere punch testing case, as shown in figure 11, further validates the influence of the yield criterion on the simulation accuracy in which the circular blank of 190 mm in diameter was deformed with the mill oil lubrication and the BHF of 32.4 kN. By comparing the predicted major and minor strain distributions along the 45° section, it has been proven that the BBC2005 model has the best results, while the Hill48 has the worst ones even with the opposite major strain distribution pattern in the mid of the sample. The Barlat89 model demonstrates the relatively good agreements with the measurements for both the major and minor strains, except in the middle area of the sample.

Figure 10 Comparison between the simulation/experimental results of the major/minor strains for the deep ellipse sample along the 0° section

Figure 11 Comparison between the simulation/experimental results of the major/minor strains for the hemisphere sample along the 45° section

Figure 12 provides the extra evidence in confirming the simulation accuracy from using the BBC2005 model, where the predicted minor strain distributions along the 90° section of the sample...
formed with the cross die are compared with the measurements. For this case, the 270x270 mm blank was deformed with the Teflon film under the BHF of 1000 kN. It is again found that the Hill48 model predicts the least accurate strain values. Other industrial cases with the 5xxx and 6xxx aluminum alloys further validated these findings.

In addition to the examination of the major and minor strain predictions, the calculations of the maximum punch forces for the four elliptic punch tests were also evaluated with the experimental results as listed in table 1. The comparisons in table 1 demonstrate that the simulation results with the BBC2005 model have good agreements with the measurements for all of those cases. Both the Barlat89 and Hill48 models, however, over predicts the forces for all of the cases listed.

| Yield Model /Measurement | Deep Ellipse Φ160 mm blank Mill oil BHF=14.6 kN | Flat Ellipse Φ210 mm blank Teflon film BHF=44.4 kN | Hemisphere Φ190 mm blank Mill oil BHF=32.4 kN | Cylinder Φ210 mm blank Teflon film BHF=43.6 kN |
|-------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| BBC2005                 | 70.6                            | 123.5                           | 107.1                           | 123.9                           |
| Barlat89                | 77.5                            | 137.6                           | 113.8                           | 136.4                           |
| Hill48                  | 77.5                            | 117.3                           | 117.3                           |                                  |
| Measurement             | 61.1                            | 122.2                           | 106.7                           | 122.9                           |

*Figure 12* Comparison between the simulation/experimental results of the minor strains for the cross die sample along the 90° section

*Figure 13* Comparison between the simulation/experimental results of the major/minor strains for the flat ellipse sample along the 90° section

| Yield Model /Measurement | Deep Ellipse Φ160 mm blank Mill oil BHF=14.6 kN | Flat Ellipse Φ210 mm blank Teflon film BHF=44.4 kN | Cylinder Φ210 mm blank Teflon film BHF=43.6 kN |
|-------------------------|---------------------------------|---------------------------------|---------------------------------|
| Combined S/H-S          | 70.6                            | 123.5                           | 123.9                           |
| Hockett-Sherby          | 70.4                            | 121.8                           | 124.0                           |
| Ghosh                   | 69.6                            | 120.6                           | 123.0                           |
| Swift                   | 69.1                            | 120.7                           | 121.3                           |
| Measurement             | 61.1                            | 122.2                           | 122.9                           |

*Table 1* The experimental and predictive results of the maximum punch forces (kN) based on three different yield criteria

*Table 2* The experimental and predictive results of the maximum punch forces (kN) based on four different strain hardening models
4.3 Influence of strain hardening model

The influence of the strain hardening model on the simulation accuracy was investigated based on the BBC2005 yield criterion for the combined S/H-S, H-S, Ghosh and Swift models, as stated in section 3.2. Figure 13 shows the comparison between the simulation and experimental results of the major and minor strain distributions along the 90° section of the flat ellipse sample. The sample was formed with the circular blank of 210 mm in diameter and the Teflon film under the BHF of 44.4 kN. The simulation results from those four strain hardening models are overlay to each other without a distinct difference. Overall, the predicted strain values are in good agreement with the measurements with the maximum derivation of about 7%. The same phenomenon can also be observed from figure 14, where the predicted major strain distributions by using the four different models are compared with the measured values for the cross die sample. These indicate that the simulation accuracy is more controlled by the yield criterion, rather than the strain hardening model. For aluminum stamping applications, selecting the correct yield criterion is critical to obtain the desired simulation results.

![Figure 14 Comparison between the simulation/experimental results of the major strains for the cross die sample along the 0° section](image)

Table 2 lists the calculated maximum punch forces by using those four strain hardening models with the comparisons to the experimental results. Those calculated values are very close to each other and in good agreements with the measurements. Although no significant differences in simulation results are found in terms of the major/minor strain and maximum punch force, it can be seen from figure 7 that the combined S/H-S model better fits the testing data and is thus recommended for use.

5. Conclusions

The current investigation clearly demonstrates that for aluminum stamping simulations, the BBC2005 yield criterion gives the most accurate strain calculations and forming force predictions. In order to take the full advantages of the BBC2005 model, it is necessary to do both the uniaxial tensile test and the bulge test for determining the eight material property parameters. It is also validate that the combined Swift/Hockett-Sherby model is most suitable to describe aluminum strain hardening characteristics. For industrial aluminum applications, it is highly recommended to use these two models together.

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