Comparative Investigation on Aluminum Material Modeling with applications to Springback Prediction

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Abstract. A comparative investigation on springback prediction of aluminum stampings has been completed using an industry-type “shotgun” die as the benchmark case. 5xxx aluminum alloy at a thickness of 1.5 mm was used for the shotgun die tryout. After stamping tryout, the formed panel was scanned to capture its sprung geometry. The studied aluminum alloy was characterized by means of uniaxial tensile test and hydraulic bulge test to determine the material isotropic hardening behavior and planar anisotropy. In order to determine the material kinematic hardening behavior, the exclusive Yoshida model fitting test was conducted in tension-compression (T-C) and compression-tension (C-T) loading modes with the one-cycle and three-cycle loading schemes. The shotgun benchmark case was simulated using FEA software LS-DYNA®. By comparing the simulation results with the tryout measurements, the accuracy of springback prediction was examined to evaluate the influence of material modeling, loading mode and loading cycle in the Yoshida model fitting test. Based on the current benchmark study, the best practice in springback prediction and compensation of aluminum stampings and in conducting the Yoshida model fitting test of aluminum alloys were summarized for industrial applications.

1. Introduction
Springback prediction and compensation are a challenging task for stamping die design and engineering, which is also one of the controlling factors for the die manufacturing cost. This is particularly true for automotive aluminum stampings, since aluminum alloys tend to have large springback resulting from the lower elastic rigidity. For aluminum autobody closures, springback phenomenon is far beyond simple open-angle springback and is more representative of the side wall curl distortions and twist springback. Springback complexity on aluminum stampings has become a major issue in maintaining a consistent part geometric performance out of the press lines. Springback is an inherent material response during a reverse deformation process, which is extremely affected by the Bauschinger effect. Apparently, considering the Bauschinger effect in springback analysis is a must. Up to date, the most widely accepted material model with the Bauschinger effect included in the stamping simulation software is the one developed by Yoshida and Uemori (Yoshida model) [1, 2]. This nonlinear kinematic hardening model provides a framework which can be incorporated with any types of anisotropic yield functions and has been proven to be able to significantly improve the accuracy of springback prediction. However, most of these published investigations targeted the sheet metals other than aluminum alloys [3-5]. The previous experimental study showed that aluminum alloys have
a strong cyclic strain hardening behavior, but comparatively weak Bauschinger effect [6]. So far, it is unclear to what extent the Yoshida model can improve the accuracy of springback prediction for aluminum stampings. With the increasing use of aluminum alloys in the automotive industry, it is of utmost importance to find a way leading to accurate springback prediction and thus reliable die compensation for aluminum stampings.

The current work was aimed to address those outstanding demands, based on the experimental investigations, physical die tryout and extensive springback simulations. In the experimental investigations, the targeted material of an AA 5000 alloy at a thickness of 1.5 mm was characterized by uniaxial tensile test and hydraulic bulge test for its isotropic hardening and planar anisotropic behavior. The same material was also examined with the Yoshida model fitting test to determine its kinematic hardening behavior under different loading conditions. In the physical die tryout, the studied material was stamped with the industry-type “shotgun” die [7] as the benchmark case to investigate the relationship between material modeling and the accuracy of springback prediction. Based on the current benchmark study, the best practice in springback prediction and compensation of aluminum stampings were summarized for industrial applications.

2. Material property testing
Two kinds of material property testing have been performed to characterize the material isotropic and kinematic hardening behavior as well as the material planar anisotropy. Uniaxial tensile test and hydraulic bulge test were carried out to determine the basic material property parameters, material anisotropic yielding and isotropic hardening behavior. The material kinematic hardening behavior was examined by using the Yoshida model fitting test. In Yoshida model fitting test, the sample material is continuously deformed under cyclic loading and reverse loading condition, providing the essential testing data to determine the Yoshida model parameters for springback simulations.

2.1 Uniaxial tensile and hydraulic bulge tests
The material isotropic strain hardening and anisotropic yielding behavior have been determined with these two tests for the studied 5000 aluminum alloy. Uniaxial tensile test was conducted by following the ISO 6892 standard with the type 2 sample geometry at room temperature. The testing samples were cut along the 0°, 45° and 90° relative to the rolling direction, in order to identify the planar anisotropy. Hydraulic bulge test was used to explore the material isotropic hardening behavior in a higher strain range, following the ISO 16808 standard. Digital image correlation (DIC) techniques were used for all the tests to record the deformation process.

2.2 Yoshida model fitting test
The test was performed with a sophisticated testing apparatus featuring a customized anti-buckling mechanism. By maintaining a real-time controlled side force, the testing specimens can be continuously...
deformed under either tension-compression (T-C) or compression-tension (C-T) loading cycles. Figure 1 compares the true stress-true strain curves measured with and without a side force applied. It is clear from Figure 1 that the applied side force has little effect on the testing measurements. For all the Yoshida model fitting tests, 3D DIC techniques were used in a real time mode for strain measurements. All the testing samples were cut along the sheet rolling direction and tested at a constant strain rate of 0.002/sec.

In order to evaluate the influence of the loading mode and loading cycle on the determination of the Yoshida model parameters and the resultant springback prediction accuracy, the tests were conducted under the following conditions: (1) one-cycle T-C test, (2) three-cycle T-C test, and (3) three-cycle C-T test. Each of these tests was repeated three times. For the one-cycle T-C test, the loading path followed (1) tension to 5% strain, (2) compression to -5% strain, and (3) tension to 0%. For the three-cycle T-C test, the loading path followed (1) tension to 2.5% strain, (2) compression to -2.5% strain, (3) tension to 5% strain, (4) compression to -5% strain and (5) tension to 0% strain. For the three-cycle C-T test, the loading path followed (1) compression to -2.5% strain, (2) tension to 2.5% strain, (3) compression to -5% strain, (4) tension to 5% strain and (5) compression to 0% strain. Figure 2 and 3 compare the true stress-true strain curves from the three-cycle T-C and C-T tests respectively. With these testing measurements, the Yoshida model parameters can be determined for the simulations.

3. Shotgun Panel Tryout
As detailed in [7], the industry-type “shotgun” draw die was specifically designed with the stake beads to provide a post-stretch force over the formed blank near the end of the drawing process. Figure 4 clearly shows that the use of the stake beads can greatly reduce the springback on the formed part.

![Figure 2. The true stress-true strain curves measured from the T-C test.](image1)

![Figure 3. True stress-true strain curves measured from the C-T test.](image2)

![Figure 4. The tryout panels formed with and without the steak beads.](image3)

![Figure 5. The scanned part geometry.](image4)
The details of the shotgun tryout die and its stake bead geometry can be found in [7]. For the current tryout, the B4H8 stake bead was adapted which has the bead radii of 2 mm and the bead height of 8 mm. A total of ten blanks were laser cut along the sheet rolling direction for the tryout. After tryout, two panels were selected for white light scanning to capture their springback geometries as shown in Figure 5. The scanned panel geometries also provided the blank draw-in boundaries for the simulations to match.

4. Springback Analysis and Evaluation
The forming simulation and springback analysis of the shotgun part were conducted with the commercial software LS-DYNA. Figure 6 depicts the tooling and blank setup in the simulations. The tooling surfaces used in the simulations were rebuilt from the scanned data of the real tryout tools. This practice can significantly reduce the CPU time and also improve the simulation accuracy. The blank was modelled with the fully integrated shell elements with 7 integration points along the sheet thickness direction. The binder clamping force and forming velocity were defined according to the tryout measurements.

The material models used for the current comparative study were MAT36: 3-PARAMETER_BARLAT, MAT226: MAT_KINEMATIC_HARDENING_BARLAT89, MAT37: TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC and MAT_125: MAT_KINEMATIC_HARDENING_TRANSVERSELY_ANISOTROPIC. MAT36 is the material model incorporating the Barlat89 planar anisotropic yield function, and MAT37 uses the Hill48 transverse anisotropic yield criterion. Both MAT36 and MAT37 are widely used in stamping simulations, and even in springback analysis when the testing data for using the Yoshida model are not available. MAT226 and MAT125 are the advanced material models of MAT36 and MAT37 respectively, being coupled with the Yoshida nonlinear kinematic hardening model. Based on the material property testing data detailed in the Section 2, all the parameters in these four models can be determined for forming simulations and springback analyses.

Springback prediction was evaluated by comparing the part geometries from the simulations with the scanned tryout part geometries. The tryout parts were scanned on their outer surfaces, while the middle surfaces of the blank were used in simulations. In order to have a reasonable comparison, the sprung middle surfaces of the blank in the simulations were offset with a half thickness. In all the springback calculations, the 3-2-1 constraints on the formed parts were defined along the edges of the blank location holes as shown in Figure 7. This would ensure the real constraining condition in the tryout be applied in the simulations.

![Figure 6. Tooling setup in simulations.](image1)

![Figure 7. Constraints applied for springback evaluation.](image2)
5. Springback Results and Discussions

The shotgun part has three distinguished geometric regions (Figure 8). The material in the uniform channel region has a balanced stretch-bend deformation along the side walls during the forming process. The springback in this region is mainly attributed to the open-angle springback. In the transition region, the material undergoes a slightly unbalanced stretch-bend deformation at both the sides with the extra stretch at the top and also along the right-side wall curvature. Since the extra stretch is not significant, the springback in this region is still dominated by the open-angle springback plus a little side wall curl springback. The material in the aggressive region of the part has a strong unbalanced stretch-bend deformation at both the sides. The part cross sections are progressively enlarged toward the end of the part, resulting in an aggressively enhanced stretch forming at the top and along the right-side wall of the part. The springback in this region is dominated by the side-wall curl and twist springback. It is worthy to state that the springback difference in these three regions is mainly applied to the material at the right-side of the first blank-tooling contact line A-B (Figure 8). At the left side of the first contact line A-B, the open-angle springback is the major component due to the straight and uniform part geometry. In order to reflect the springback complexity on the part, the springback evaluation was performed based on the cross-section cuts in each of those regions as shown in Figure 9.

Figure 8. The geometric and springback characteristics of the shotgun part. Figure 9. The cross section cut scheme for springback comparison.

5.1 Influence of material kinematic hardening

To evaluate the material kinematic hardening effect, the five sprung cross-section profiles predicted using MAT226 and MAT125 are compared with the profiles predicted using MAT36 and MAT37, and also with the scanned profiles (Figure 10). It is found from Figure 10 that at the left side of the contact line A-B where the open-angle springback is dominated, the springback predictions using MAT125, MAT36 and MAT37 are very close to each other. They are also in excellent agreement with the scanned data, especially along the side wall and inside the drawbead area. In contrast, the material model MAT226 predicts the worst springback results among the studied four material models. The derivations between the predicted springback profiles using MAT226 and the scanned profiles are in the range of 2.0 to 4.0 mm with the maximum derivation of 3.9 mm at the cross-section cut #4. Overall, the material model MAT125 gives the best springback prediction at the left side of the contact line A-B.

At the right side of the contact line A-B where a complex springback is observed, the accuracy of springback prediction varies from the region to region. As shown in Figure 10(a), the predicted springback profiles using these four models are fairly close to each other and also in good agreement with the scanned profiles in the uniform channel region. In this region, MAT226 gives the improved springback results. Compared to the scanned data, the maximum derivation of MAT226 decreases from 1.9 mm at the cross-section cut #1 to 1.3 mm at the cross-section cut #2. Contrastingly, both MAT36 and MAT37 predict the worst springback results at the cross-section cut #2 with the maximum derivation of 1.9 mm. The improvement in springback prediction using MAT226 is highlighted in Figure 10(b), where the predicted sprung cross-section profiles are in excellent agreement with the
scanned profiles for both the transition and aggressive regions. For both MAT36 and MAT37, the difference between the predicted and scanned sprung cross-section profiles increases with the increase in the side-wall curl and twist springback. The maximum derivation reaches 5.8 mm and 7.1 mm inside and outside the drawbead area respectively at the cross-section cut #5.

![Figure 10](image_url)

(a) Sections in the uniform channel region  (b) Sections in the transition and aggressive regions

**Figure 10.** Springback comparison between the material models with and without kinematic hardening.

The testing data in Figure 2 and 3 indicate that aluminum alloys have weak Bauschinger effect and less kinematic hardening, as compared with other materials. The comparisons discussed above still demonstrate a moderate improvement in springback prediction using the advanced material models with the consideration of the Bauschinger effect and material kinematic hardening behaviour. In particular, a significant improvement has been observed in the aggressive region of the shotgun part where sophisticated deformation creates a complicated springback phenomenon. For aluminum autobody closures, springback is mainly dominated by twist springback. Based on the findings above, it can be concluded that the advanced material models should be used in order to obtain more accurate springback prediction and thus more reliable springback compensation.

![Figure 11](image_url)

**Figure 11.** Comparison in springback simulation results between MAT125 and MAT226.

### 5.2 Influence of yielding criterion

In aluminum stamping simulations, part formability evaluation and springback prediction are always associated with each other. Depending on testing data availability, the advanced material models of MAT125 and MAT226 may be used interchangeably. Even though both the models include the Yoshida nonlinear kinematic hardening rule, the yield criterion incorporated in the models are different. The influence of the Barlat89 and Hill48 models on springback prediction was investigated with the Yoshida model parameters derived from the three-cycle T-C tests. The associated springback results are compared with the scanned data as shown in Figure 11. Overall, the predicted cross-section profiles using these two models are close to each other and also to the scanned profiles. The difference in
springback prediction between these two models is underlined in the aggressive region where the open-angle, side-wall curl and twist springback are all encountered. Figure 11 clearly reveals that MAT125 has better springback predictions at the left-side of the first contact line A-B, while predicts the worse results at the right side of the line A-B. Since MAT226 can provide more accurate results in forming simulations, it is therefore recommended to use it for springback analysis of aluminum stampings having complex geometries.

5.3 Influence of loading mode in Yoshida model fitting test
Yoshida model fitting test is usually carried out in a cyclic T-C loading mode. Technically, the test can also be conducted in a cyclic C-T loading mode. This reverse loading mode imposes the Bauschinger effect in the tension with early re-yielding, permanent stress softening, and work-hardening stagnation as demonstrated in Figure 3. In real stamping operations, both T-C and C-T loading modes may simultaneously exist on a part at different locations. It is of great interest to investigate the influence of the loading mode on the determination of the Yoshida model parameters and further on springback simulation results. In the current study, the three-cycle T-C and C-T testing data were used to calibrate the Yoshida model parameters for springback simulations. The corresponding parameter values using these two sets of testing data are compared in Table 1. Apparently, the loading mode applied in the test has significant effect on calibrating the Yoshida model parameters.

| Table 1 Yoshida model parameters calibrated with the testing data from T-C and C-T loading |
|----------------------------------|---|---|---|---|---|---|---|---|
| Loading mode | CB (MPa) | Y (MPa) | SCI | K (MPa) | RSAT | SB (MPa) | H | C1 | C2 |
| T-C | 106.0 | 68.0 | 950.0 | 19.0 | 160.0 | 16.0 | 0.3 | 0.003 | 0.22 |
| C-T | 132.4 | 85.7 | 977.0 | 16.4 | 136.0 | 22.5 | 0.2 | 0.006 | 0.20 |

Figure 12 (a) and (b) compares the predicted sprung cross-section profiles with the tryout results for MAT125 and MAT226 respectively. It can be seen from Figure 12 that for the advanced material models of MAT125 and MAT226, little difference in springback prediction is observed with those two sets of the Yoshida model parameters. The notable difference may be found at the cross-section cut #5 for MAT125, where the maximum deviation in the predicted cross-section profiles between the T-C and C-T modes is 1.3 mm. Figure 12 (a) and (b) also proves that the predicted cross-section profiles using MAT125 and MAT226 with those two sets of the Yoshida model parameters are in good agreement with the scanned profiles. It can therefore be concluded that even though the loading mode in Yoshida model fitting test has big influence on the Yoshida model parameters, it has little effect on springback prediction.

![Figure 12](image-url)  
(a) MAT125 T-C vs. C-T  
(b) MAT226 T-C vs. C-T

Figure 13. Influence of loading cycles on springback prediction (MAT125)
5.4 Influence of testing data from single and multiple loading cycles

Yoshida model fitting test may be performed at single or multiple T-C loading cycles. For this study, the Yoshida model parameters derived from the single cycle and multi-cycle T-C tests are compared in Table 2. Figure 13 illustrates the difference in the springback simulation profiles using the parameters listed in Table 2 for MAT125. The comparison in Figure 13 clearly shows that there is no notable difference in springback prediction for all the profiles examined, even though a notable difference in the parameter values can be observed in Table 2. Since this benchmark part has open-angle, side-wall curl and twist springback altogether, it implies that a single cycle T-C test is good enough to fully characterize material kinematic hardening behavior for complex springback simulations.

| Loading cycle | CB (MPa) | Y (MPa) | SCI (MPa) | K (MPa) | RSAT (MPa) | SB (MPa) | H | C1 | C2 |
|---------------|---------|---------|-----------|---------|------------|---------|----|----|----|
| Single        | 101.25  | 90.0    | 911.0     | 19.5    | 146.7      | 28.4    | 0.3| 0.01| 0.32|
| Multiple      | 106.0   | 68.0    | 950.0     | 19.0    | 160.0      | 16.0    | 0.3| 0.003| 0.22|

6. Conclusions

The current benchmark study demonstrates that for aluminum autobody closures, a higher accuracy of springback prediction leading to better springback compensation can be obtained using the advanced material models considering the Bauschinger effect and material kinematic hardening behavior. It is highly recommended to use the advanced material model of MAT226 for forming simulation and springback analysis of aluminum stampings being subjected to complex deformation and springback. For simple shape parts having dominated open-angle springback, MAT125 is able to give accurate springback prediction. The investigations with the shotgun part proved that the Yoshida model parameters determined from the tension-compression test or compression-tension test have little influence on springback prediction. It was also observed from the study that a single cycle of tension-compression test can provide sufficient data to calibrate the Yoshida model parameters for springback analysis of aluminum stampings.

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