Formability study on stamping an engine hood with aluminum alloy sheet

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Abstract. The formability of stamping an engine hood with aluminum alloy sheet was examined in the present study. In the stamping process, except that aluminum alloy would crack easily, a small elastic modulus makes the aluminum alloy easier to produce a significant springback defect, which would lead to variation of accuracy and is hard to grapple with. In the present study, the cyclic tension-compression reversal tests were first conducted to obtain the stress-strain relations and the Bauschinger effect exhibited in the aluminum alloy sheet was noted. The finite element simulations were then preformed for V-bending and U-hat drawing of aluminum alloy sheet, and the results of springback and side-wall curl were compared with those obtained from experiments. It is concluded from the comparison that the material model which includes the Bauschinger effect renders a more consistent result with the experimental data. In order to investigate the difference of forming characteristics between conventional steel and A6181-T4 in the stamping process of an engine hood, the effects of process parameters on the stamping formability were systematically analyzed by the finite element simulations. The finite element simulation results were validated by the production engine hood and the characteristics of A6181-T4 formability investigated in this study were confirmed.

1. Introduction
In recent years, due to the demand for lightweight, aluminum alloys have received more attention from the industry, and the range of the application has also increased. However, when aluminum alloy sheets are used in the stamping process, the forming defects, such as crack and springback, are prone to occurring. The academic has in-depth research on the various properties of aluminum alloys and their applications. In terms of material models, Barlat et al. [1-3] proposed a new material model theory, and successively explored the yield surface, experiments, and materials, indicating that the Barlat yield criterion has better accuracy than Bishop and Hill model. In terms of materials, Zhang and Shivpuri [4] demonstrated the importance of material parameters and adjusted the process parameters to achieve a better formability of A6181. As for springback research, Samuel [5] used aluminum, mild steel and stainless steel materials to compare the springback presented in the U-hat experiments conducted. It was found that aluminum has the largest amount of springback. As the radius of the punch increases, there is an increasing tendency for sidewall curl, and as the radius of the die corner increases, the sidewall curl decreases. Jr [6] conducted U-hat experiments using isotropic materials with similar material properties and non-isotropic materials as specimens. He found that the springback of anisotropic materials is more serious than that of isotropic materials. Regarding research on formability, Lange [7] proposed a simulation test method to evaluate the formability of sheet metal materials. In the research of automobile engine hood forming, Karima [8] used the finite element software FAST-3D to simulate
the outer cover of the hood, and also set the forming conditions for whole and local die geometries. Qiu et al. [9], under the premise of not modifying the shape design of the remaining addendum, explored the influence of the shape of the sheet on the stamping formability and designed the best sheet shape in the stamping simulation of the hood.

In the present study, the formability of an engine hood with aluminum sheets was investigated. The tension-compression reversal tests were first conducted to obtain the stress-strain relations and the material constants used in an anisotropic hardening model with Bauschinger effect considered for the A5083-O and A6181-T4 aluminum sheets. The formability of stamping an engine hood with A6181-T4 aluminum sheet was then investigated. And the difference of forming characteristics between conventional steel and A6181-T4 in the stamping process of an engine hood was also examined.

2. Material properties tests

Two kinds of aluminum alloy sheets, A5083-O and A6181-T4, were investigated in the present study. Aluminum alloy A5083 is often used for the lightweight parts requiring high corrosion resistance. In the past, the A5083 was mostly manufactured using the plate numbered H116. However, the relatively small elongation limits its application in manufacturing complex parts. Compared to A5083-H116, A5083-O has a lower initial yield strength and a larger elongation, as shown in Fig. 1 of the stress-strain curves obtained from the uniaxial tension tests, resulting in a better formability than A5083-H116. As for A6081, it is popularly used in the automotive industry.

![Figure 1. Stress-Strain curves of A5083-O and A5083-H116.](image)

2.1. Cyclic tension-compression tests

It has been well known that the Bauschinger effect plays an important role in the springback phenomenon of stamping advanced high strength steel and aluminum alloy sheets, and an appropriate material model to describe the Bauschinger effect is necessary for the finite element simulations of stamping process. Quite a lot of models have been published. Among them the Yoshida-Uemori hardening model (Y-U model) [10,11], as given by equations (1)-(3), is popularly adopted in many commercial finite element codes. In order to find the material constants used in the Yoshida-Uemori hardening model, cyclic tension-compression tests [12] were conducted in the present study. The experimental machine used in this study is the MTS810 tensile testing machine, and the test specimen size is shown in Fig. 2. In addition, in order to avoid the buckling of the test specimen during the compression stage, the test piece is placed in the constraint jig shown in Fig. 3. During the experiment, the specimen is firstly stretched to 4% at a speed of 0.005 mm/s. When the set strain is reached, the force of the machine is unloaded, so that the test piece elastically recovered until the force returns to zero, and then the test piece is compressed in the reverse direction up to 8%. Figure 4 shows the cyclic stress-strain curves of A5083-O in the strain ranges of 4% and 8%, respectively. The Bauschinger effect is obviously observed in Fig. 4. The specimen was then unloaded and stretched in tension up to 6%. A smaller yield stress in tension than that in compression is noted in this second cycle. The subsequent third cycle began with unloading then compressed the specimen up to 4%. The stress-strain curve of the compression path does not conform with that generated in the first cycle and displays a slightly larger value. However, when the specimen was unloaded and then stretched again, the stress-strain path showed a trend that followed that given in the second cycle, as shown in Fig. 4. The cyclic loading paths
shown in Fig. 4 implies that the stress-strain curves may approach to a converged state after three loading-unloading-loading cycles in the tension and compression directions, respectively. It also can be inferred from Fig. 4 that an envelope curve may be formed if the subsequent cyclic loading tests continue to be implemented for A5083-O aluminum alloy sheet.

\[
\sigma_{\text{bound}}^{(f_{\text{low}})} = B + R + \beta = B + (R_{\text{sat}} + b)(1 - e^{-m\varepsilon_p}) \quad (1)
\]

\[
E_{\text{eav}} = E_o - (E_o - E_i)[1 - e^{-\mu \varepsilon_p}] \quad (2)
\]

\[
\sigma_{B_0}^{(p)} = 2\beta_0 = 2b (1 + e^{-m\varepsilon_i}) \quad (3)
\]

The material constants used in the Yoshida-Uemori model were then determined from the tension-compression cyclic loading tests and the values are showed in Table 1. In order to verify the correctness of the material constants determined in Table 1, the finite element analysis was performed using the PAM_STAMP software to simulate the tension-compression tests with those constants as part of material parameters input. The tension-compression test was conducted in a strain range of 10%. The stress-strain curves generated from the finite element simulation results and those obtained from the actual experiments are shown in Fig. 5. As seen in Fig. 5, both curves are close to each other and the difference is insignificant. The consistency between the actual test data and the finite element simulation results confirms the validity of the Yoshida-Uemori material constants of A5083-O established in the present study. The cyclic tension-compression tests were also conducted with A6181-T4 aluminum alloy sheet and the Yoshida-Uemori material constants were determined experimental results.
**Figure 5.** The simulation and experiment results of the tension-compression tests.

**Table 1.** Material constants of Yoshida-Uemori model.

|        | Y (MPa) | C (MPa) | B (MPa) | Rsat (MPa) | b (MPa) | m | h | E₀ (GPa) | Eₐ (GPa) | ξ |
|--------|---------|---------|---------|------------|---------|---|---|---------|---------|---|
| A5083-O| 137     | 600     | 142     | 193        | 15      | 16 | 0.5 | 75      | 65      | 70 |

**3. Springback analysis and experimental verification**

In this study, in order to investigate the springback phenomenon generated in the stamping of A5083-O and A6181-T4 aluminum alloy sheets, the actual V-bending and U-hat forming experiments were carried out. The V-bending experiment is equivalent to the so-called forming in the industry, mainly to test the phenomenon of springback after forming. And the U-hat experiment is equivalent to the so-called drawing in the industry, mainly to test the phenomenon of sidewall curl after forming. The finite element analysis was also conducted with the use of Hill 48, Hill 90, and Barlat 91 yield criteria, as well as with Hill48 incorporated with the Yoshida-Uemori hardening model. The finite element simulation results were then compared with the experimental data obtained from the V-bending and U-hat forming tests conducted in the present study.

**3.1. V-bending test**

The V-bending die is composed of a set of bottom die and punch with a bending angle of 90-degree, as shown in Fig. 6. During the test, the sheet specimen is placed on the die, and the punch moves down to bend the sheet metal. When the bent sheet specimen is taken out from the die, the angle between the ends of the sidewall of the specimen is no longer 90 degrees as the angle of the punch due to springback, and the difference between the angles before and after stamping is defined as springback, as shown in Fig. 7. When the specimen opens outwards, the springback is termed a positive springback; while if the specimen retracts inward, the springback is called a negative springback.

The experiment was first conducted with A5083-O (thickness of 3 mm) as specimens, and the springback value was obtained through the 3D Family optical measuring instrument after the test. The measured springback data were compared with those obtained from the finite element simulation results with the use of various yield criteria and hardening model, as shown in Fig. 8. It is observed that the springback phenomenon is not so significant. It may be attributed to the relatively large thickness of the aluminum sheet. It also can be found that the prediction of each yield criterion or material model has a certain accuracy, as shown in Fig. 8. It may be due to the deformation mode resulted from V-shaped bending being relatively simple compared to U-hat forming. It is noted as well in Fig. 8 that the simulation result obtained with the use of Barlat 91 yield criterion closes to that obtained by using Hill 48 yield criterion incorporated with Yoshida-Uemori hardening model. It reveals that the Barlat 91 yield criterion renders a better result in springback prediction than those predicted by Hill 48 and Hill 90 yield criteria. All the yield criterion constants used in the finite element simulations are shown in Table 2. The V-bending test was also conducted with A6181-T4 (thickness of 0.95mm) aluminum alloy sheet as
specimen. The test result reveals that the springback is more significant than that generated with A5083-O as specimen due to the large difference in sheet thickness.

**Figure 6.** V-bending test.

**Figure 7.** Definition of springback.

3.2. U-hat forming experiment

The die setup for conducting U-hat forming experiment is shown in Fig. 9. The U-hat forming experiment consists of a set of punch, die, and holder. In the experiment, blank holder force is set to 20kN, and drawing speed is 5m/s. After U-hat forming, the sidewall of sheet is no longer a straight line and is curled to a circular arc shape, as shown in Fig. 10, and the radius of curvature (mm) of the sidewall curl is adopted as an index to represent the amount of sidewall curl. Both A5083-O sheet of 3mm in thickness and A6181-T4 sheet of 0.95mm in thickness were used for specimens. The measured sidewall curl of A5083-O sheet was compared with those obtained from the finite element simulation results with the use of various yield criteria and hardening model, as shown in Fig. 11. Because the straight wall is subjected to tensile and compressive forces in the U-hat forming process, the Yoshida-Uemori hardening model considering this phenomenon is in good agreement with the experimental result, as shown in Fig. 11. It reveals that the Yoshida-Uemori hardening model could better describe the deformation mode subjected to clearly cyclic reverse loading condition.

**Figure 9.** U-hat forming experiment.

**Figure 10.** Definition of sidewall curl.

**Table 2.** Yield criterion constants used in FE simulations.

|            | Barlat |            |            |            |            |            |            |
|------------|--------|------------|------------|------------|------------|------------|------------|
|            | A      | B          | C          | F          | G          | H          | M          |
|            | 1.0575 | 1.0449     | 0.9602     | 1          | 1          | 0.9442     | 8          |
|            | Hill90 |            |            |            |            |            |            |
| α          | 3.730478| 0.090828   | -0.44451   | 1.05       |            |            |            |
| β          |        |            |            |            |            |            |            |
| γ          |        |            |            |            |            |            |            |
| m          |        |            |            |            |            |            |            |
|            | Hill48 |            |            |            |            |            |            |
| F          | 0.5688 |            |            |            |            |            |            |
| G          | 0.7042 |            |            |            |            |            |            |
| H          | 0.2958 |            |            |            |            |            |            |

**Figure 8.** Springback values of V-bending simulations and experiment.

**Figure 11.** Sidewall curl values of U-hat forming simulations and experiment.
4. Forming an engine hood with aluminum alloy sheet

Through conducting actual experimental tests and the finite element analysis, the formability characteristics of A5083-O and A6181-T4 aluminum alloy sheets used in the stamping process has been figured out. In the present study, the stamping of an engine hood with aluminum alloy A6181-T4 sheet was also investigated. The original die design was for the stamping process with a 340 MPa grade steel as the sheet blank. The finite element simulations were performed first to examine the validity of the die design. In the simulations, the yield criterion adopted is Hill 48, blank holder force being 400kN for aluminum alloy sheets and 750kN for steel sheets, and drawing speed is 2m/s. The simulation results reveal that the 340 MPa steel sheet is less likely to cause defects in the forming process, such as a smaller value of thinning shown in Fig. 12. The actual production part without any defect, as shown in Fig. 13, also confirmed that the engine hood formed by 340MPa steel can be successfully developed with the original stamping die design. However, if the material was replaced with aluminum alloy A6181-T4 sheet, cracking defects were likely to occur, as a much larger value of thinning was noted in the finite element simulation result shown in Fig. 14. The actual forming process was implemented as well using the original stamping dies with aluminum alloy A6181-T4 sheet. Crack defect was presented, as shown in Fig. 15, and the location of crack is consistent with that predicted by the finite element analysis. It implies when different materials pass the same die, the aluminum sheet would be greatly stretched at the part and could not be spread easily, thus being prone to cracking when the thinning rate is higher than 20%.

Since the material properties could not be changed for A6181-T4 aluminum sheet, the stamping process parameters including original stamping die shapes were modified to eliminate the crack defect occurred in the production part. The finite element simulations were also performed to analyze the effect of each parameter on the formability of A6181-T4 aluminum engine hood. The sensitivity of process parameters, such as friction coefficient, blank-holder force, and die corner radii, on the formability was examined by the finite element analysis. Through the analysis of the finite element simulation results, an appropriate blank-holder force was determined and several corner radii were slightly modified to avoid the occurrence of crack defect. With the modified process parameters, a sound production engine hood with A6181-T4 aluminum alloy sheet was manufactured, as shown in Fig. 16.

![Figure 12. Thinning analysis result of traditional steel hood.](image1)

![Figure 13. Actual production of traditional steel hood.](image2)

![Figure 14. Thinning analysis result of aluminum alloy hood.](image3)

![Figure 15. Crack defect on aluminum hood.](image4)
5. Concluding remarks

The cyclic tension-compression tests conducted in the present study reveal that both A5083-O and 6181-T4 aluminum alloy sheets exhibit significant Bauschinger effect. The Bauschinger effect thus affects the accuracy of the finite element simulations in the prediction of springback occurred in the V-bend and U-hat forming tests. The comparison of the springback and sidewall curl between the simulation results and the experimental data indicates that the finite element analysis with Yoshida-Uemori hardening model renders a better result in springback prediction. It is also noted that for sheet blank being subject to a clearly cyclic tension-compression loading condition during the forming process, such as in U-hat forming, the finite element analysis with Bauschinger effect considered is better applied in order to describe the springback phenomenon more accurately.

In the forming of an automotive engine hood, both the finite element analysis and the actual stamping operation confirm that the tooling suitable for the forming process with a 340 MPa grade steel as the sheet blank may not be applicable to the forming process with 6181-T4 aluminum alloy sheet, due to significant variations in material properties. In order to investigate the feasibility of using the same tooling with acceptable minor modifications to form the engine hood with 6181-T4 aluminum alloy sheet, the finite element analysis was performed systematically to examine the effects of process parameters on the formability of the stamping process. Through the analysis of the finite element simulation results, it is found that an appropriate blank-holder force and slightly modifications on several corner radii could eliminate the crack defect. With the modified process parameters, a sound production engine hood with A6181-T4 aluminum alloy sheet was manufactured and the finite element analysis is also validated.

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