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Comparison of Drawability between Warm Forming and Cold Forming of Aluminum 6xxx Alloys

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Abstract. The automotive industry has significant interests and material applications involving multiple aluminum alloys (5xxx, 6xxx, and 7xxx) for light weighting. However, the industry experiences a rather lengthy development time for utilizing aluminum alloys and the need for standard approaches. This paper compares the drawability of various aluminum 5xxx, 6xxx, and 7xxx alloys among cold forming and warm forming processes. A warm forming (WF) test cell was established to conduct warm forming tests with real-time monitoring and controlling the heating and forming temperatures of aluminum blanks during heating, part transferring and stamping. For cold forming trials, a 300-Ton servo press was used for obtaining the maximum drawability. A cross-form die was used to compare the aluminum drawability between cold and warm forming processes. Increased drawability varied with different aluminum 6xxx alloys. The warm-forming process window was determined for different aluminum alloys. This paper also compares finite element (FE) prediction results of the forming process between advanced material yield function model, Barlat 2000, and a conventional model, Hill 48. The Barlat 2000 model gave a superior correlation to both cold and warm forming experimental results compared with the Hill 48 model.

1. Introduction

The automotive industry is vigorously pursuing light-weighting of vehicles due both to customer demand for increased fuel economy as well as US CAFE regulations, which require that manufacturers' fleet fuel economy average reach up to 50 miles per gallon for light trucks and SUVs and up to 60 miles per gallon for passenger cars by 2025. Even in the midst of the rapid adoption of electric and hybrid vehicles, additional weight savings in traditional structures will be required for vehicle performance, electric range, and to offset the increased mass of batteries. High strength aluminum alloys, 5xxx, 6xxx, and 7xxx series alloys, have sufficient strength, stiffness, and ductility to replace the use of various steel alloys in traditional vehicle body design while enabling significant mass savings [1] and also have a large supply chain that is continuing to grow with demand.

6xxx series aluminum alloys have demonstrated use in the frames and skins of closure parts, e.g. hoods/bonnets, doors, and fenders, however, major technical challenges still exist in increased draw depth, springback, and relatively large radii achievable with current cold forming methods when compared to similar corresponding steel parts. In addition to material limitations in cold forming, modelling of the forming process itself is often inaccurate due to insufficient material property data and the impact of room temperature aging of some 6xxx series alloys creating variability between new and old stock raw material.

Increasing the temperature of the aluminum alloy during forming can increase maximum strain to failure while reducing the yield strength and elastic modulus, thereby addressing the previously cited issues in cold forming. However, excessive or insufficient heating can lead to wrinkling or strain localization and part cracking. In addition, elevating the temperature of 6xxx series aluminum can cause or increase the rate of precipitate formation, resulting in an overaged alloy in the final part, degrading its mechanical properties and causing the component to behave in a manner contrary to the intended design.

This study investigates the forming behaviour of two 5xxx series, three 6xxx series, and one 7xxx series aluminum alloys under typical cold forming conditions and determines optimal warm-forming process windows governed by blank temperature and Blank Holder Force (BHF). Mechanical properties and Forming Limit Diagrams (FLD) are experimentally determined at various temperatures to construct material models for use in FEA modelling of both alloys in cold and warm forming processes. A laboratory-scale test die was used for model verification and forming window definition.

2. Background

An extensive literature review on warm forming of 5xxx, 6xxx, and 7xxx Al alloys was conducted [2]. Warm forming (WF) trials on aluminum alloys have indicated a preferred temperature range, although specific temperatures and control parameters are undefined in existing publications. Considerable research has been conducted in North America in WF (around 250 to 400°C) of non-age hardenable 5xxx series alloys. Studies covered determination of material properties, lubrication, tool prototyping, and FE analysis. In addition, various forming methods such as Quick Plastic Forming developed by GM and development of WF cells were investigated [3,4]. Automotive parts, mostly closures (door and hood), have been warm formed in modest production quantities. In a major study conducted by U.S. Automotive Materials Partnership (USAMP), extensive investigations and prototype trials were conducted in the WF of Al 5xxx and 6xxx series alloys, mostly on 5182-O. In all these studies, sheet material was formed at around 275°C while the dies were heated in some cases and, in the most recent studies, were kept at room temperature [4, 5]. WF has been widely applied to form outer or inner panels with 5xxx and 6xxx Al alloys. In WF, blanks are pre-heated to less than 350°C.

Al 5xxx and 6xxx alloys showed a 20 to 60 percent increase in elongation when the forming temperature increases from 20 to 300°C. Logarithmic strains of 0.6, indicating high formability, are achievable near the 200°C forming temperature. USAMP conducted projects to develop techniques to stamp production parts, such as door inner panels, lift gates, and deck lids in heated die sets.

Ford Motor Company conducted a study to investigate the low-cost hot forming process of aluminum 5182-O [5]. The study includes FE simulations and experiments. A non-isothermal forming process was conducted in two different cases such as cold die/warm blank, and warm die/hot blank. The results were compared with the part formed at room temperature as the baseline. The FE simulations were performed at room temperature and at elevated temperature with isothermal assumptions. The forming temperatures ranged from 200 to 300°C. The blank was heated in the furnace for 180 seconds and the average time for transformation of the sheet from the furnace to the forming stage was about 15 seconds. Results showed a non-isothermal WF process (i.e., heated blank and cold die) demonstrates a low-cost approach to forming aluminum that is consistent with existing conventional stamping practices [5].

3. Objective

The objective of this study is to evaluate the effectiveness of warm forming and servo-controlled cold forming processes in deep drawing of the cross shape part with selected aluminum alloys.

4. Warm Forming (WF) Test Cell

EWI-FC designed and fabricated a custom-built linear transfer system (LTS) and integrated it with the infrared heating furnace and a 160-Ton Minster hydraulic press to create the WF test cell, as shown in Figure 1. The LTS was expected to give the cycle time of about 10 seconds. This is much faster than an industry robot that usually gives a cycle time between 15~20 seconds. LTS also has four thermocouples embedded into its gripper. Therefore, when the gripper picks up the blank, the temperature of the four corners of the blank is monitored during the part transfer from the furnace to the press/tooling. The detailed information of the LTS is available in a prior publication [2].

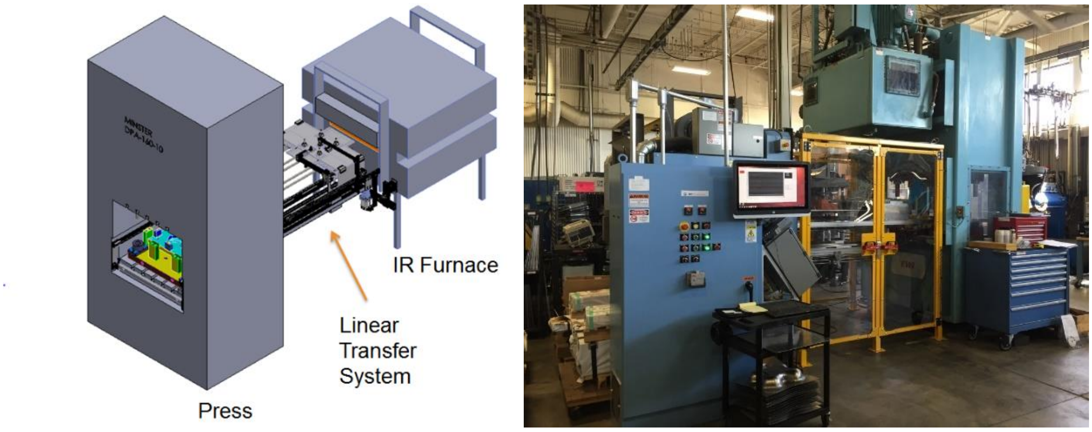

Figure 1. The WF Test Cell Available at EWI-FC.

5. WF Tests with Selected Aluminum Alloys

Three different aluminum alloys, AA6016-T4, AA6022-T4, and AA7075-T6 were selected for WF tests. These materials were selected based upon the interest of the participating industry partners. To evaluate the effectiveness of the forming temperature and blank holder force, EWI-FC and Tooling System Group (TSG) developed the Cross-Form Test tooling, as shown in Figure 2. The maximum punch draw depth is 96 mm. The initial flat square blank is 470 × 470 mm. The press can deliver a maximum 100-Ton blank holder force (BHF). Figure 2 illustrates the test tooling installed at the press.

Figure 2. Cross-Form Test Tooling at a 160-Ton hydraulic press (left), 300-Ton servo press (middle) and a tested part (upper right), and RD/TD directions on the cross shape punch (bottom right).

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Table 1 shows the WF test matrix with three selected aluminum alloys. Three samples were repeated for each testing condition. Six different forming temperatures were used for WF tests based on the references of the literature and basic material formability tests at EWI to obtain flow stress and forming limit diagram (FLD) for each high temperature. Temperature change between the furnace and press forming was monitored using multiple thermocouples installed inside the furnace and LTS grippers in WF tests from the preliminary testing trials and temperature measurements. The cross-form die and punch were not heated and maintained in room temperature for warm forming tests. The blank holder force (BHF) was programmed to be constant as the die stroke increased. Four different draw depths were set with tool steel stoppers on the lower die to obtain exactly the draw depth. Forge Ease Al 278 recommended by Fuchs was used for most WF tests, with selected aluminum sheet materials. The lubricant was manually sprayed on the die before the heated blank was taken from the furnace and dropped on the tool. The new lubricant was sprayed on the die for each test.

Table 1. Test Matrix for WF Tests.

Grade	Thickness (mm)	Testing Temperature (°C)	Blank Holder Force (kN)	Draw Depth (mm)	Lubricant
AA6016-T4	0.9	100, 125, 150, 175, 200, 275	20 ~ 120 Constant or variable BHF determined via testing trials depending on temperature and thickness	58/70/83/96	Fuchs, Forge Ease Al 278 (with 1:3 mixed ratio of water)
AA6022-T4	1.0				
AA7075-T6	1.5				

From experiments, both wrinkling failure and cracking were observed when the temperature and/or BHF are inappropriate for the material formability. As the blank temperature varied, insufficient BHF resulted in severe flange wrinkling. When the material temperature was relatively high, excessive BHF resulted in horizontal cracking while vertical cracking was observed when the material temperature was relatively low, as shown in Figure 3. The WF process window was identified for selected aluminum alloys, as shown in Figure 3.

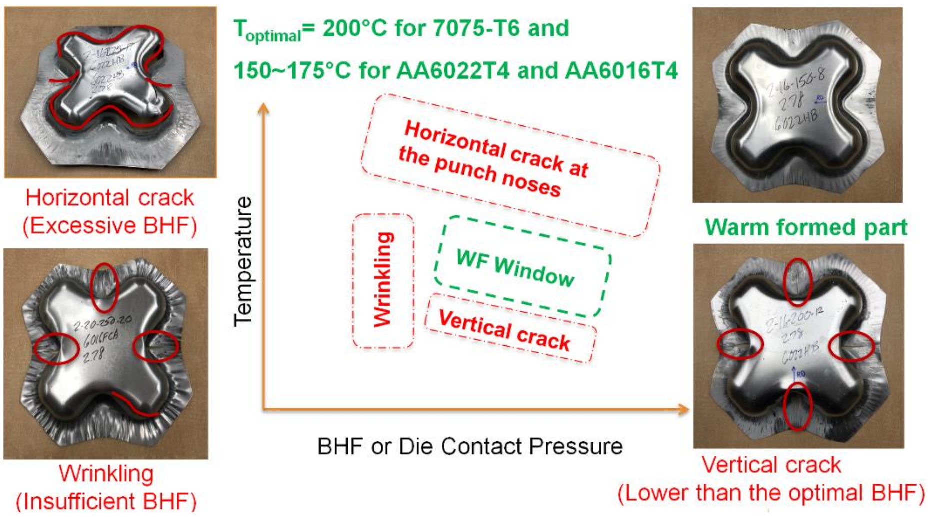

Figure 3. Warm Forming Process Window.

6. Cold Forming Tests with Selected Aluminum Alloys

In this study, a mechanical-servo press was used for cold forming tests. The cross form die was installed at a 300-Ton AIDA servo press for cold forming tests as shown in Figure 2. Five different aluminum alloys were selected for cold forming tests. Table 2 shows the detailed test matrix for cold forming. Three samples were repeated for each testing condition. To evaluate the effect of anisotropy on drawability, two different orientations of the blank were considered, one with the Rolling Direction (RD) aligned with the lobes of the cross and the second with the RD oriented 45 degrees from the lobes of the cross as illustrated in Figure 2. Blank holder force (BHF) was set to be either constant force of 50-kN or variable to investigate the effect of BHF on drawability. Four different lubricants were used for selected aluminum alloys because industry partners requested to use their approved lubricants to test their supplier aluminum alloys. All the wet lubricants were applied on both sides of the aluminum blank using the automated lubricator, UNIST. The amount of coating was programmed on the UNIST system to be around 2-3 gram/m^2. The coating amount of the dry film lubricant (DFL) is known to be around 1-gram/m^2 or less.

Table 2. Test Matrix for Cold Forming Tests.

Grade	Thickness (mm)	Blank Orientation	Blank Holder Force (kN)	Draw Depth (mm)	Lubricants
AA5052	1.0	RD and TD (RD: rolling direction along the cross punch and TD: transverse direction along the cross punch)	50	58/70/83/96	Fuchs Anticorit wet lubricant and OEM production wet lubricant
AA5754	1.2				
AA6016-T4	0.9				
AA6022-T4	1.0				
AA6016-T4	1.0				Zeller Gmelin's Dry film lubricant

Figure 4 compares the maximum draw depth of the cross form part with selected aluminum alloys and lubricants. Only AA6022 and AA6016 alloys were selected for both cold and warm forming tests with the cross form die. With the same wet lubricants, as expected, both AA5052 and AA5754 showed the larger maximum draw depth compared to AA6022 and AA6016. However, AA6016 DFL showed better drawing performance when compared to the AA6016 and AA6022 tested with wet lubricants while showing a similar maximum draw depth with AA5052 and AA5754.

Being high-formable alloys, AA5052 and AA5754 were only tested under cold forming conditions. AA5052 showed slightly increased drawability with Fuchs wet lubricant compared to AA5754 with the same lubricant. AA6022 showed the increased formability (+13-mm) with the Fuchs wet lubricant compared to the OEM baseline lubricant at room temperature.

In warm forming conditions, AA6022 showed further increased drawability (+13-mm) compared to cold forming test results. This clearly indicates the benefit of warm forming over cold forming. However, AA6016 did not show any further increase of the drawing depth regardless of lubricants and forming temperatures as shown in Figure 4. AA6016 with DLF showed similar maximum drawing depth of warm forming of AA6022. This is a result of the low die friction with the DFL. AA7075 has limited drawability at room temperature and it was tested only at the warm-forming condition. It showed a maximum drawing depth of 45-mm with the Fuchs Forge Ease 278 lubricant.

Cold forming of AA7075 was attempted, however, due to the alloy's low ductility, the minimum draw depth of 25.4 mm caused cracking and failure of the part. Warm forming AA7075 enabled crack-free parts at a maximum draw depth of 45.2 mm.

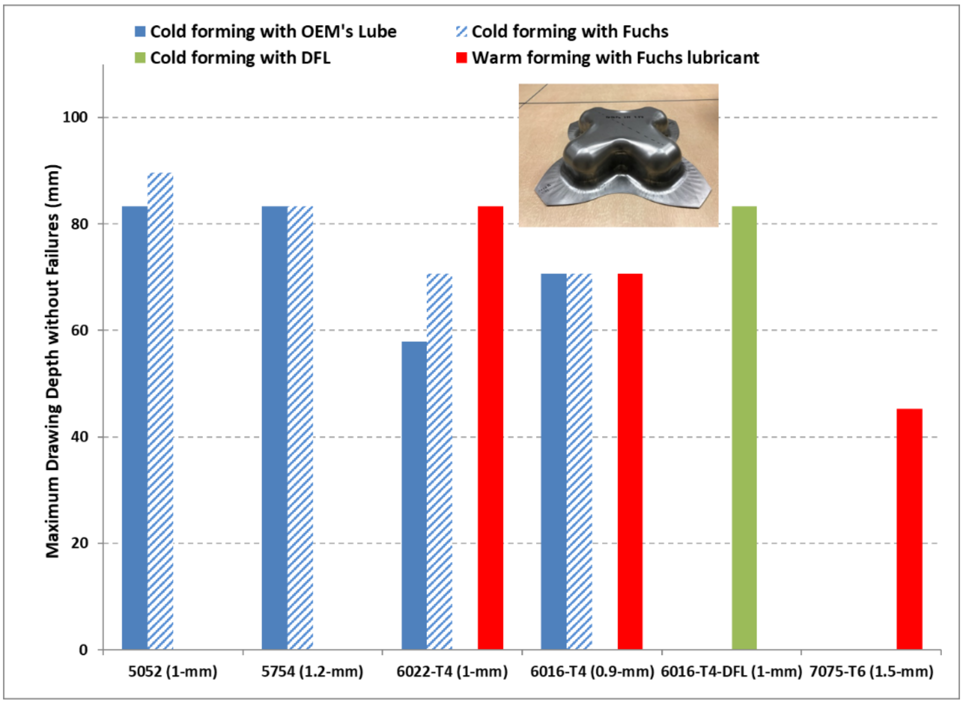

Figure 4. Comparison of the maximum draw depth for different aluminum alloys for cold and warm forming.

7. FE Simulations

A FE model for the cross forming was developed as shown in Figure 5 using PAM-STAMP. Three steps, including gravity drop of the blank, BHF holding, and die motion, were simulated sequentially. The blank holder applies the constant BHF force at the same values as used in the experiments. Two different anisotropic yield functions, Hill 48 and Barlat 2000 (Figure 5), were used to define material anisotropic yield function in PAM-STAMP. Temperature and strain rate dependent material model was developed from the standard tensile tests and the model used for the blank model in FEA.

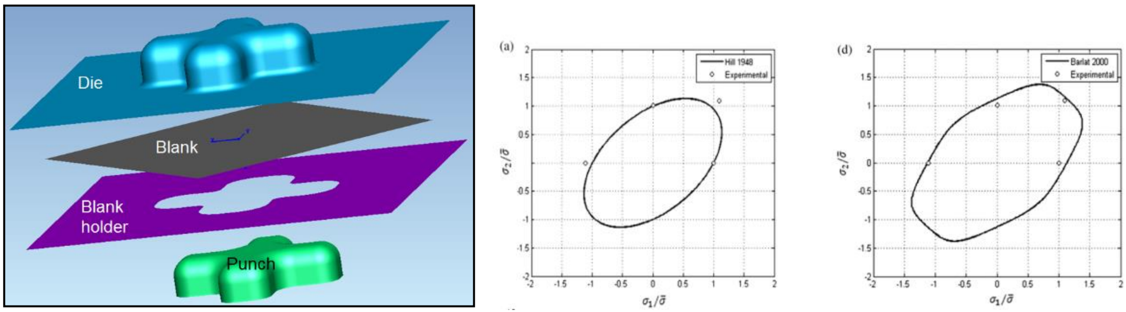

Figure 5. FE Model of the Cross Forming Using the PAM-STAMP (left), Hill 48 anisotropic yield function (middle) and Barlat 2000 anisotropic yield function for elevated temperatures (right).

The selected warm-formed parts were cut in both straight and diagonal directions with respect to the cross to measure the thinning distribution. Barlat 2000 yield function showed the more accurate prediction of thinning distribution of the cross formed parts in both cold and warm forming conditions compared to the Hill 48 yield function. Figure 6 compares the thinning distributions of the straight-cut section of AA6022-T4 warm-formed part between experiment and simulation while Figure 7 shows a similar comparison of the thinning distribution of the diagonal-cut section. In both cases, thinning predictions with the Barlat 2000 model showed good correlations with experimental measurements. Similar comparisons were made for AA7075-T6 warm formed parts. The detailed results are available in [2].

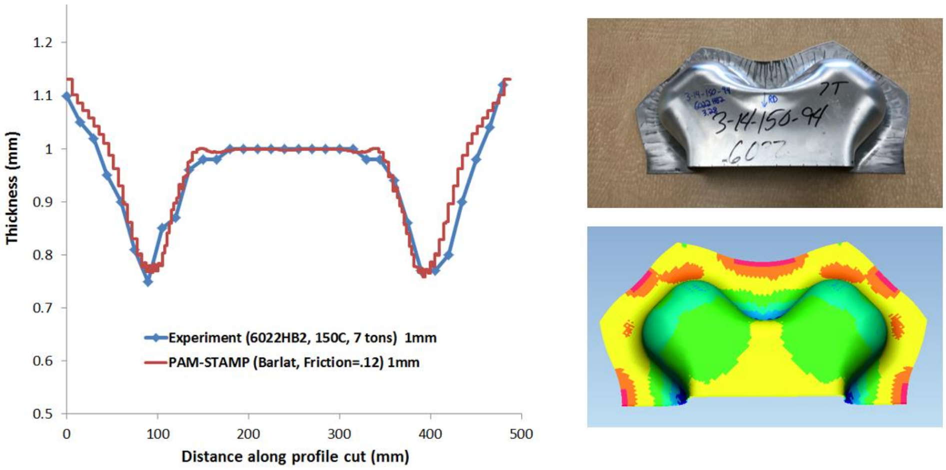

Figure 6. Comparison of thinning distribution on the straight-cut-cross-section of the AA6022 warm-formed part with 83 mm drawing depth and FE prediction at BHF 70 kN and COF of 0.15.

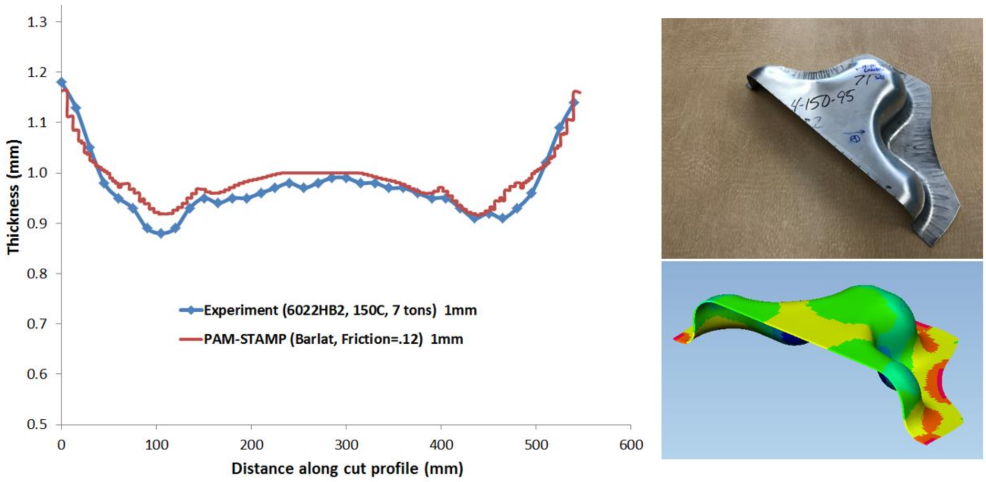

Figure 7. Comparison of thinning distribution on the diagonal-cut-cross-section of the AA6022 warm-formed part with 83 mm drawing depth and FE prediction at BHF 70 kN and COF of 0.15.

8. Findings and Conclusions

The following findings can be summarized from the study:

- The newly developed WF test cell was used to develop WF process conditions for 6xxx-7xxx aluminum alloys by emulating the production conditions, such as heating cycle, transfer time, lubrication, and press operation
- AA5052 and AA5754 showed larger maximum drawing depth compared to AA6016 and AA6022 in cold forming with wet lubricants.
- AA6016 DFL showed better drawing performance as compared to AA6016 and AA6022 tested with wet lubricants and showed similar maximum draw depth with AA5052 and A5754.

- AA6022-T4 was successfully drawn up to 83 mm at the 150°C target temperature (170°C furnace set temperature) without any defects. This indicates that the draw depth of AA 6022-T4 increased by 13 mm, up to a maximum of 70.6 mm, as compared to cold forming.
- AA6016-T4 was drawn up to 70.6 mm at the 175°C target temperature (195°C furnace set temperature) without any defects.
- The maximum draw depth of AA 6016-T4 was 70.6 mm in cold forming with DFL. There is no clear benefit in WF versus cold of AA 6016-T4 (0.9 mm).
- AA7075-T6 was successfully drawn up to 45.2 mm at the 200°C target temperature (230°C furnace set temperature) without any defects.
- Cold forming trials with AA7075-T6 resulted in severe cracking below the 25.4 mm minimum draw depth.

The following conclusions can be drawn from this performed study:

Warm forming showed increased drawability with AA6022 (1-mm thickness) compared to cold forming. Cold forming of a dry film coated AA6016 showed similar drawability with warm forming of AA6022 (1-mm thickness). This gives automotive stampers options to choose either warm forming of aluminum 6xxx series or cold forming with dry film coated aluminum 6xxx series alloys. Dry film lubricant for aluminum blanks is often not used by automotive OEMs due to compatibility issues with welding, adhesive bonding processes, and additional cleaning operations after forming. The cross-form test die can provide the warm forming process window in terms of temperature and BHF with respect to the maximum drawing depth. The developed process window can be applied in warm forming of component level prototype parts and further process optimization for production applications. Advanced yield function such as the Barlat 2000 model should be considered to accurately predict aluminum material behaviour in warm forming simulations.

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