Nonisothermal Warm Deep Drawing Behavior of Automotive Grade Aluminum Alloy Sheets

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Abstract. In this work, thermomechanical FE modeling of nonisothermal warm deep drawing of automotive grade AA5754 and AA6082 aluminum alloy sheets were performed. The deformable blanks were modeled using temperature dependent Cowper-Symonds constitutive equation along with Barlat-89 yield criterion. The predicted cup heights, earing, % thinning and surface strain distributions were successfully validated within acceptable error of 5%. The development of earing profile, cup thinning pattern and surface strains along 0°, 45° and 90° from rolling direction (RD) were plotted using the validated data. The ear profile developed in AA5754 cups was prominent compared to AA6082 due to relatively higher anisotropy at elevated temperatures. Thickening was more prominent along 45° to RD for AA5754, whereas thinning was higher in this direction for AA6082 material. The strain states developed at cup corner along plane strain condition was lower than the FLD0 values of materials. Thus there was uniform surface strains at cup corner indicating the improved ability of material to withstand more deformations. Comparatively, AA5754 exhibited relatively better formability compared to AA6082 material.

Keywords: FE modeling, warm deep drawing, aluminum alloys, anisotropy, strain distribution

1. Introduction
Lightweighting is a key method under consideration in automotive sector to cope with the stringent emission rules [1]. Aluminum alloys have potential application in this regard owing to its high strength-to-weight ratio and excellent corrosion resistance. Typically, AA5754 and AA6082 series alloy sheets are used due to their moderate strength properties, and decent weldability [2]. Deep drawing process is an important process followed to produce both shallow and deep cup shaped components used for different automotive components such as automotive door panels, fender, valve enclosures, round enclosure, slender cups, spring seat, filters, fuel tanks, wiper motor housing, cartridge case, lids, containers, etc. [3,4]. As aluminum alloy sheets displays poor formability, techniques such as warm forming has to be adopted to improve the drawing limit window of aluminum alloy sheets. This process is considered because of the easiness in modification of an existing setup to accommodate heating arrangements with reduced installation investments while stamping complex components [3,5].
Moreover, the deep drawing process with differential temperature gradient, i.e. nonisothermal warm deep drawing, was reported to produce significant improvement in part depth [3,6].

The formability studies using computer aided finite element (FE) methods are necessary to predict the warm forming behavior implementing temperature dependent material properties, anisotropy, strain hardening, and strain rate sensitivity [7]. The FE analysis helps to significantly reduce the material wastage during expensive experimental trial and error tooling tryouts [8,9]. The proper identification of a constitutive model to incorporate temperature dependent stress-strain behavior and yield function is vital in accurate formability predictions using FE methods [8]. Generally, forming limit diagrams (FLD) are used as the failure criteria to define the necking/failure strains in sheet metal forming processes [10,11].

In this regard, a comparative study into the temperature-dependent deformation behavior of automotive grade thin aluminum alloy sheets under nonisothermal warm deep drawing conditions is important. Hence, in this study, thermomechanical FE modelling of this nonisothermal process for such as AA5754 and AA6082 was developed using temperature-dependent Cowper-Symonds coefficients and Barlat89 yield parameters. The FE predicted data was first validated with experimental measurements, and correspondingly, the deformation behavior was studied in terms of earing, thinning and surface strain development.

2. Methodology

2.1. Material selection and characterization

Two automotive grade aluminum alloy sheets selected in the present work were the strain hardened AA5754 and precipitate hardened AA6082 of 1mm thickness. These aluminum alloy sheets are usually used in manufacturing thin-walled components including panels and hoods of lightweight automotive cars. The AA5754 material is a strain hardened alloy having moderate strength and elongation, but produces undesirable stretcher marks while deforming. Hence, these sheets are used for inner panels. The AA6082 is a heat-treatable alloy that attains strength with heat treatment post forming, and hence applicable for exterior panels.

The uniaxial tensile testing was performed at various temperatures ranging from 30°C-250°C as detailed in previous work of the authors [5,12,13]. Tensile tests were performed under the strain rates of 1x10^-3 s^-1, 1x10^-1 s^-1 and 1.6x10^-1 s^-1 to evaluate the strain rate sensitivity of the materials [12,13]. Lankford anisotropy parameters (r values) along rolling direction (0°), 45°, and 90° at different temperatures were evaluated at all the investigated temperatures [5,13], and the respective values are enlisted in Table 1. The widely used Cowper-Symonds model (Eq.1) was used to evaluate the strain rate sensitivity of the materials at different temperatures.

$\bar{\sigma}(\dot{\varepsilon}, \dot{\varepsilon}) = K \bar{\varepsilon}^n \left[ 1 + \left(\dot{\varepsilon}/C\right)^{1/p} \right]$  \hspace{1cm} (1)

Here, $\bar{\sigma}$ = effective flow stress at a particular temperature, $K$ is strength coefficient, $n$ is strain hardening exponent, and $C$, $p$ are Cowper-Symonds strain rate sensitive parameters. These parameters evaluated at different temperatures were correlated to develop temperature dependent material flow properties. The variation in $K$ value and $n$ value is depicted in Fig. 1a, and the variations of $C$ and $p$ are also shown separately in Fig. 1b and Fig. 1c respectively. The decreasing trend of $K$ and $n$ values with temperature as observed from Fig. 1a showed that the materials are thermally softened with rise in temperature. The exponential reduction in $C$ value in Fig. 1b demonstrated the increasing strain rate sensitivity of materials. However, $p$ values showed a polynomial decrement nature with temperature (Fig. 1c).

The Barlat89 yield criterion [14] represented in Eq. 2 was used in FE model and this model was referred as *MAT_036 in LSDYNA solver.
Table 1 Experimental $r$-values ($r_0, r_{45}, r_{90}$), average anisotropy value ($\bar{r}$) and planar anisotropy value ($\Delta r$) evaluated for AA5754 and AA6082 sheets at 30-250°C

| Material | AA5754 | AA6082 |
|----------|--------|--------|
| Temperature (°C) | 30 | 100 | 175 | 200 | 250 | 30 | 100 | 175 | 200 | 250 |
| $r_0$   | 0.71  | 0.74  | 1.02 | 1.13 | 1.23 | 0.60 | 0.64 | 0.69 | 0.78 | 0.93 |
| $r_{45}$ | 0.56  | 0.59  | 0.91 | 1.00 | 1.12 | 0.68 | 0.72 | 0.79 | 0.89 | 0.99 |
| $r_{90}$ | 0.79  | 0.81  | 1.12 | 1.17 | 1.28 | 0.56 | 0.61 | 0.66 | 0.75 | 0.91 |
| $\bar{r}$ | 0.65  | 0.69  | 0.99 | 1.08 | 1.19 | 0.63 | 0.67 | 0.74 | 0.83 | 0.96 |
| $\Delta r$ | 0.19  | 0.18  | 0.15 | 0.14 | 0.13 | -0.09 | -0.09 | -0.12 | -0.13 | -0.07 |

* $\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4}$

** $\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2}$

Figure 1 Temperature dependent variation with respective curve fitting equations of (a) $K$, $n$ values, (b) $C$ value, and (c) $p$ value

$$\psi(\sigma_{xy}) = a|\beta_1 + \beta_2|^M + a|\beta_1 - \beta_2|^M + c|2\beta_2|^M = 2\sigma^M$$ (2)

Here, $\sigma$ = yield stress of the material, $M=8$ for aluminum alloy; $\beta_1, \beta_2 =$ stress invariants expressed in terms of terms of $\sigma_x, \sigma_y, \sigma_{xy}$ (plane stress components in orthotropic axis) as shown in Eq. 3.

$$\beta_1 = \frac{\sigma_x + l\sigma_y}{2}, \text{ and } \beta_2 = \left[\frac{(\sigma_x - l\sigma_y)^2}{2} + (q\sigma_{xy})^2\right]^{1/2}$$ (3)
The Lankford anisotropy coefficients evaluated along three directions \((r_0, r_{45}, r_{90})\) were also made temperature dependent with a third order polynomial curve fitting method. Further, according to these variations in \(r\) values, the temperature dependent values of Barlat89 anisotropy coefficients \((a, c, l\) and \(q\)) were calculated after solving a set of non-linear equation following the steps as detailed in [10,13]. The variation in Barlat89 yield locus of both the sheets at 100°C, 175°C, and 200°C are compared in Fig. 2. It was observed that the size of yield locus was decreasing, as the blank material possessed lower stress levels at elevated temperatures. The shrinkage of yield locus of was more in case of AA6082 compared to AA5754 material.

2.2. Finite element model

The nonisothermal warm deep drawing experiments were performed using cooling punch with water circulation which was maintained near to room temperature (30°C) while the dies were heated to 200°C. The schematic of the setup with dimensions is shown in Fig. 3a. The initial diameters of the blanks considered were 110 mm for AA5754 and 103 mm for AA6082 material. During warm deep drawing, flange materials were under thermally softened state at 200°C, whereas cup wall, corner and center was

![Figure 2](image-url)  
**Figure 2** Variation in Barlat89 locus of AA5754 and AA6082 materials under warm temperatures

![Figure 3](image-url)  
**Figure 3** (a) Schematic of the experimental nonisothermal warm deep drawing process (all dimensions are in mm.) and (b) FE model developed for nonisothermal process
under cooled conditions because of direct contact with the punch at 30°C (refer Fig. 4). The FE model of the nonisothermal warm deep drawing process was done using LSDYNA, and corresponding tooling and blank is shown in Fig. 3b. The tools were assigned as rigid bodies, and deformable blanks as four node quadrilateral Belytschko-Tsay shell elements of size 1mm×1mm. The overall computational time was reduced as quarter-symmetric model was considered. Both the punch and binder were allowed to move in –Z (downward direction) and die was assigned as fixed body. The blank was placed over the die and the blank holding force (BHF) of 1.5kN was applied. The initial temperature assigned for the die and binder was 200°C and that of punch was 30°C. All the relevant thermal and structural properties of steel tools and aluminum blank were taken from [15]. The punch was ramped up to 1000mm/s during the deformation stage to utilize the time scaling method which can reduce overall computational time. Accordingly, all the rate dependent properties were also scaled in the FE model. The coefficient of friction at the die-blank and punch-blank interfaces were assumed as 0.23 and 0.33 respectively [10]. The experimentally evaluated FLDs at 200°C of respective materials [5,13] were used as the failure criterion.

2.3. Background on deformation rate
During warm deep drawing, most of the critical plastic deformation occurred over the die profile to form the cup wall region. The flange materials were always maintained within the heated die, and the selected materials were strain rate sensitive at elevated temperatures. Hence, it was essential to understand the strain rate arising in the critical deformation zone. Fig. 4 represents the heat transfer and velocity of material flow during the nonisothermal warm deep drawing process. The material element in flange region first moved inward in the radial direction and reached at the position b. This element was prone to plastic bending and unbending when it flowed over the die profile radius to form the cup wall in the radial position x_i. The radial draw-in velocity (v_i) of the material at the entrance of the die cavity (at distance x_i) was assumed to be almost equal to the punch velocity (v_p = 20 mm/min). Also, assuming the flange deformation to be under plane strain condition, the effective plastic strain rate of the flange element (\dot{\varepsilon}_{flange}) located at a distance x (x_0 > x > x_i) was estimated according to Eq. 4 [16].

\[ \dot{\varepsilon}_{flange} = -\frac{2}{\sqrt{3}} \frac{v_i}{x} \]  

The \dot{\varepsilon}_{flange} of an element initially located at 3 mm inside the perimeter of the blank (i.e. at the radial distance of 52.0 mm for AA5754 and 48.5 mm for AA6082) was calculated using the above relation. It was found that \dot{\varepsilon}_{flange} increased from 4.96x10^{-3} s^{-1} to 9.99x10^{-3} s^{-1} during the sliding over the die. However, the \dot{\varepsilon}_{flange} of the material during drawing into the cavity over the die profile radius was almost

![Figure 4](image-url)
constant, i.e. 9.99×10^{-3} \text{ s}^{-1} to 13×10^{-3} \text{ s}^{-1}. Hence, the identification of Cowper-Symonds coefficients evaluated from the tensile test responses at the lowest initial strain rates (10^{-3} \text{ s}^{-1} and 10^{-1} \text{ s}^{-1}) could be able to provide a reasonable description of flow stress during thermomechanical FE modelling of the warm deep drawing process.

3. Results and discussion

It was found that the maximum blank diameter drawn without failure during nonisothermal warm deep drawing process of AA5754 material was 110 mm, and that of AA6082 was 103 mm. The developed FE model was then successfully validated by comparing ear profile, thickness and surface strain distributions. Fig. 5a and b respectively show the FE predicted quarter section of completely drawn cups of AA5754 and AA6082 materials. Fig. 5c shows the experimentally drawn cups of both the materials. Minor wrinkling observed was also predicted well with the developed FE model.

3.1. Ear profile development

The ear profile developed during intermediate stages at similar flange diameters along rolling direction (RD) for both the materials with die internal radius as reference is shown Fig. 6a. The radial inward flow of flange materials through the die corner radius was not uniform at different angles from RD to transverse direction (TD). This was because of higher anisotropy experienced by flange material which is in contact with the die and binder maintained at 200°C. It was observed that the evolution of ear profile was different for both materials along diagonal direction (along 45° from RD). This waviness was better visible in the flange at an instantaneous cup depth of 30 mm, and in the completely drawn cups as shown in Fig. 6b. The average cup heights ($H_{avg}$) was slightly under predicted within 5% error, i.e. 40.4 mm and 34.6 mm against experimental values of 41.6 mm and 35.5 mm respectively for AA5754 and AA6082 cups. The ear profile was demonstrated in terms of % earing = ($h_i$ - $h_{min}$) / $h_{min}$, where $h_i$ is the instantaneous cup height, and $h_{min}$ is the minimum cup height. Fig. 6c demonstrates the % earing profile developed for both the materials. It was observed that peak of ear was developed along 45° for AA5754, whereas trough was observed at similar location for AA6082. This difference in peak location was mainly because of the corresponding positive and negative planar anisotropy ($\Delta r$) values of AA5754 and AA6082 respectively (Table 1). The ear profile was more pronounced for AA5754 as it showed relatively higher anisotropy response at higher temperatures compared to AA6082 material (Table 1).

3.2. Thinning development

The measured thinning profile of deep drawn cups along RD was matching very well with the FE predictions. Fig. 7 provides the thinning distributions of both the materials from cup center through corner, wall and towards the top of the cup. There was minor stretching of materials during the initial stages of deep drawing. With further increment in punch displacement, the material bends over the

![Figure 5](image-url) FE predicted deep drawn cups of (a) AA5754 and (b) AA6082 and (c) representative experimental deep drawn cups (arrow represents rolling direction (RD))
Figure 6 Comparison of earing profile development from FE simulations: (a) at similar flange radius along RD, (b) at an intermediate cup depth of 30mm (top view) and completely drawn cups, and (c) %earing developed in fully drawn cups.

Figure 7 Thinning developed along RD, DD, and TD in completely drawn cups of (a) AA5754 and (b) AA6082 materials with the experimental data along RD.

punch profile radius and bending and unbending happens simultaneously over the die profile radius. Hence, the flange sheet experiences radial tensile load. During the warm deep drawing test, the materials were always under heated conditions within the die (at 200°C) which results in lower strength property and r values. Generally, higher the r value, higher the deep drawability with enhanced resistance to thinning of sheet materials. AA5754 showed improved r at elevated temperature (Table 1). Thus more resistivity towards flow was offered along RD and TD, which resulted in increased thinning along these directions compared to that along 45° (DD). Such non-uniformity resulted in relatively more compressive hoop stresses to act towards DD. This resulted in about 110% thickening at the cup top along DD when compared to that along RD as observed from Fig. 7a. The converse was true for AA6082.
materials, and thus higher thickening was observed along TD and RD compared to that along DD. However, as observed from Fig. 7b, almost similar thinning pattern was observed for AA6082 in RD and TD. The thickening along DD was lesser by around 60% than that along RD. Negative thinning demonstrated increased thickening in the cup wall region. These variations in anisotropy and thickening also attributed to the variation in ear profile development in completely drawn cups (Fig. 6). It was observed that there was no abrupt thinning at cup corner region.

3.3. Surface strain distribution
The surface strain data obtained from FE simulations along RD, DD and TD for both the cups are plotted in Fig. 8. Both major and minor true strain trend was very well predicted and matched with that of experimental strains along RD. As relatively more stretching occurred in the cup wall region along TD and RD for AA5754 and along DD for AA6082, the major true strain distributions was higher in the respective directions. The maximum of major true strains developed along cup wall of AA5754 in DD was lesser by about 90% with that of RD. The trend shown by minor true strains along DD in the cup wall was also minimum. Conversely, the maximum of major true strain evolved was about 60% higher along DD compared to RD for AA6082 cup, and the minor true strains was also higher along DD. The lower C value of AA5754 material represented its relatively higher strain rate sensitivity [5] (Fig. 2b). The higher strain rate sensitivity indicated higher strain redistribution capability of the material [10]. Moreover, the enhanced resistance to thinning due to higher $r$ values also reflected the relative improvement in drawability of AA5754 compared to AA6082 material. The variations of strain values from general trend at cup top region was due to wrinkling and uneven thickening happened in these regions. The minor and major true strains evolved in completely drawn cup center, corner, wall and top regions captured from FE simulations consolidated for both the materials are given in Table 2. The positive major and minor true strains indicated marginal initial stretching which also resulted in minor thinning at cup center (Fig. 7). The minor true strains recorded at the cup corner were approximately

![Figure 8](image)

**Figure 8** Surface strain developed along RD, DD, and TD in completely drawn cups of (a) AA5754 and (b) AA6082 materials with the experimental data along RD

**Table 2** Minor and major true strains at different locations in completely drawn cup compared with FLD$_0$ at 200°C

| Location on the cup | AA6082 | AA5754 |
|---------------------|-------|-------|
| Major | Minor | Major | Minor | Major |
| Center | 0.004 | 0.006 | 0.014 | 0.017 |
| Corner | -0.008 | 0.085 | -0.006 | 0.079 |
| Wall | -0.279 | 0.279 | -0.383 | 0.368 |
| Top | -0.480 | 0.230 | -0.588 | 0.308 |
| FLD$_0$ (at 200°C) | 0 | 0.351 | 0 | 0.432 |
equal to zero, which signified that material deformation was under plane strain condition. Usually, the part failure happens in a deep drawing process when the necking/failure strains at cup corner exceeds the limiting strains in plane strain conditions. This particular strain state represented in forming limit diagram is represented as FLD_0. The FLD_0 of AA5754 and AA6082 sheet materials evaluated at 200°C is also given in Table 2. The major true strains at cup corner was very much lower than that at FLD_0 value, signifying the avoidance of sudden localization of thinning/necking.

4. Conclusions
In this study, thermomechanical FE modeling of nonisothermal warm deep drawing process of AA5754 and AA6082 materials was successfully developed incorporating temperature-dependent material properties. The Cowper-Symonds parameters and Barlat89 yield coefficients evaluated at different temperatures ranging from 30°C to 250°C were incorporated into the FE model. The FE predicted results showed good agreement with experimental ear profile, thinning and surface strain data. It was observed that cup height and ear profile developed in AA5754 cups was prominent due to higher planar anisotropy at elevated temperatures. The peak of earing was along the diagonal direction (DD) for AA6082 due to negative planar anisotropy. The highest thickening of approximately 110% was observed for AA5754 cups along DD at the cup top. This thickening resulted in about 60% reduction of maximum major true strain evolved at cup top region. Conversely, the maximum thickening in cup wall regions was 60%, and the corresponding maximum major true strains evolved was 60% lower along RD for AA6082. Most of the deformations were observed to be in the tension-compression mode. Non-localization of thinning and surface strains at cup corner indicated improved ability of materials to withstand more deformation without failure. The AA5754 showed comparatively better formability due to its higher temperature dependent rate sensitivity, yielding and anisotropy responses compared to that of AA6082 material.

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