

# An Experimental and Numerical Investigation of Non-isothermal Cup Drawing of a 7XXX-T76 Aluminum Alloy Sheet

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**Abstract.** The 7000-series of aluminium alloys are an attractive material for anti-intrusion components in the car body-in-white due to their high specific strength and lower density. The limited room temperature formability of these alloys can be overcome through elevated temperature forming while controlling heat exposure to prevent changes to the microstructure such as over-aging. The present work details a comprehensive characterization of a developmental alloy, 7xxx-T76, for non-isothermal warm forming of a cylindrical deep drawn cup. Material anisotropy and a non-associated constitutive model were developed with the hardening response as a function of temperature and strain-rate. Friction was characterized at elevated temperature using a Warm Twist Compression Test apparatus developed at the University of Waterloo. Significant material anisotropy was observed in the tensile characterization results and during warm forming with the formation of eight ears in the deep drawn cups for a drawing ratio of 2.25. The predictions of the forming model were evaluated in terms of the earring profile, punch force, and surface strains from optical strain measurements using ARGUS.

## 1. Introduction

In light of the governmental legislative requirements to reduce carbon dioxide emissions and fuel economy standards, lightweight materials such as the 7000-series aluminum alloys have gained interest for the body-in-white due to their high strength-to-weight ratio [1]. Compared to the medium-strength 5000-series work-hardenable aluminium alloys, the 7000-series alloys exhibit higher strength levels from precipitation processes that, at the same time, bear a risk of over-aging (coarsening of precipitates) if exposed to high temperatures as noted by Hui *et al.* [2]. While the strength-to-weight ratio of the 7000-series aluminium alloys is comparable to 1500 MPa ultra high strength steel, their limited formability at room temperature requires multi-step forming processes that contribute to a lengthy and costly process [3]. Warm forming at temperatures that are both low enough to prevent changes to the microstructure (over-aging) and high enough to benefit from the gain in formability, could represent an attractive alternative to conventional die quenching operations. The use of finite element models greatly facilitates the development of new forming technologies assuming that accurate material models and process parameters, such as friction, are adopted. The 7000-series of aluminium alloys often exhibit significant plastic anisotropy and strain-rate sensitivity at elevated temperatures that require detailed characterization to accurately predict material response in the forming simulations.



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The aim of this paper is to demonstrate the importance of a combined approach to characterize the constitutive behaviour and warm friction of a strongly anisotropic developmental 7000-series aluminum alloy in an over-aged temper, herein referred to as 7XXX-T76.

## 2. Material

The developmental alloy studied in this paper, 7XXX-T76, was supplied in a nominal sheet thickness of 2 mm and in an over-aged temper with the aim to improve the corrosion resistance. The composition of this alloy is given by Omer *et al.* [16] and has lower Cr and high Zr additions compared to AA7075, for example. For characterizing the material anisotropy, stress ratios (ratio between the stress at a certain orientation and the rolling direction (RD) at the same plastic work level) and R-values (ratio between the plastic strain in the width and thickness direction) were obtained from quasi-static tensile tests. Recent work by Omer *et al.* [4] has shown that tensile anisotropy characterized using the stress ratios and R-values for this 7xxx-T76 alloy was not sensitive to temperature and the room temperature characterization is valid for warm forming temperatures. Figure 1 serves to visualize the negligible stress anisotropy in contrast to the significant plastic anisotropy for 7XXX-T76.

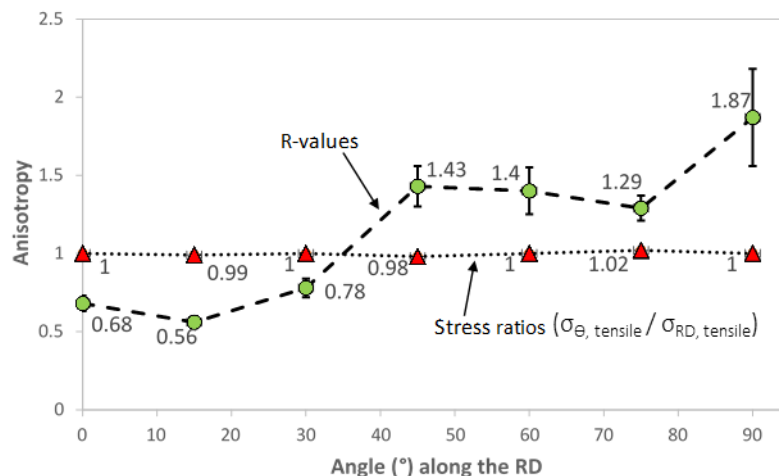


**Figure 1.** Tensile anisotropy of the 7xxx-T76 alloy at room temperature.

For characterizing the flow behavior of the 7XXX-T76 alloy, quasi-static tensile tests were performed at 150°C, 190°C, and 240°C. In order to explore the strain-rate sensitivity, tensile tests at 190°C were performed at two additional strain rates of 0.001 s<sup>-1</sup> and 0.1 s<sup>-1</sup>. For a more detailed description of the utilized test equipment, specimen geometry, and methodology, the reader is referred to Noder [5]. The experimentally-obtained stress-strain curves are represented by the solid curves in Figure 2 that confirm the expected drop in stress as a function of temperature. Interestingly, while there are no appreciable rate effects at room temperature, the yield stress measured at 190°C exhibits a significant dependence on the test speed. For calibrating the constitutive behavior, it is desirable to have hardening data at large strains that shed light into the choice of hardening model since the onset of UTS (diffuse necking) is observed in the tensile data below 10% strain. To this end, shear experiments were performed at room temperature and the measured shear stress *versus* shear strain data was converted into uniaxial equivalent values based on plastic work equivalence, using the method developed by Rahmaan *et al.* [6]. It is worth pointing out that the strain range from the shear experiments was five times larger than the strain levels from the tension test (represented by the red solid curve at 25°C).

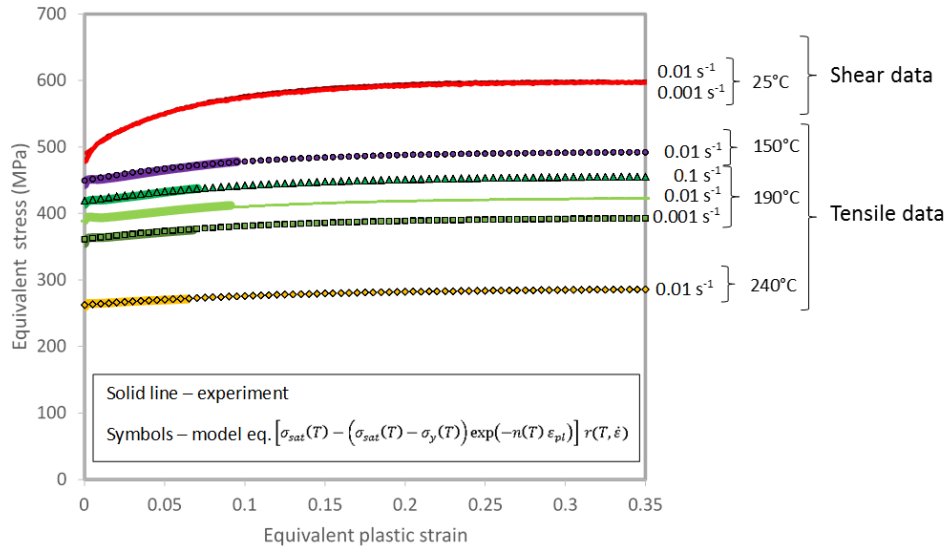


**Figure 2.** Stress-strain curves as a function of temperature and strain rate for 7XXX-T76 obtained from tensile tests and miniature shear experiments (at 25°C); Experimental data (solid lines) are compared to model predictions (symbols).

The observed flow behavior was well described through a modified Hockett-Sherby model [7] that was made temperature- and rate-dependent as shown in equation (1), where  $\sigma_{sat}$  represents the saturation stress,  $\sigma_y$  the yield stress,  $n$  the material hardening ability,  $\varepsilon_{pl}$  the plastic strain and  $r$  a multiplicative term that scales the flow stress at the reference strain rate as a function of the current strain rate. The reader is referred to Noder [5] for a more detailed description on the development of the constitutive model.

$$\sigma_{flow}(T, \varepsilon_{pl}, \dot{\varepsilon}) = \left[ \sigma_{sat}(T) - (\sigma_{sat}(T) - \sigma_y(T)) \exp(-n(T) \varepsilon_{pl}) \right] r(T, \dot{\varepsilon}) \quad (1)$$

Referring to Figure 1, isotropic yield functions like von Mises or Hosford are not suitable to adequately capture the measured material behavior. In the scope of the current work, the more advanced Barlat [8] YLD2000-2d yield criterion was utilized in combination with an associative (AFR) and a non-associative (NAFR) flow rule with a yield exponent of 8 that is conventionally adopted for FCC materials. The calibration results are visualized in Figure 3 along with the anisotropy coefficients  $\alpha_1$ - $\alpha_8$  in Table 1. The mild stress anisotropy was well captured by both flow rules whereas the strong directionality in the R-value was poorly described by the AFR. Even though the NAFR was generally capable of describing the trend in the R-values, some discrepancies were present between 45° to 90°. One of the reasons for this observation might be enforcing the additional shear constraint, as described by Abedini *et al.* [9], that removes one degree of freedom from the plastic potential and reduces flexibility.

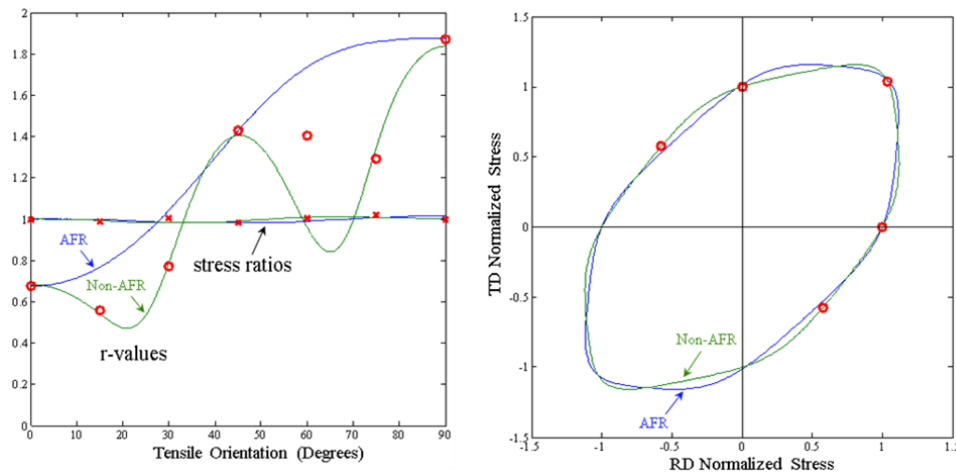


**Figure 3.** Calibrated yield surfaces for Barlat YLD2000-2d with AFR (blue) and NAFR (green). Symbols represent experimental data.

**Table 1.** Anisotropy coefficients for Yld2000-2d in its associated and non-associated form.

|                                | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ | $\alpha_9$ |
|--------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| <b>AFR</b>                     | 0.8376     | 1.1344     | 1.0503     | 0.9424     | 0.9880     | 0.8253     | 1.0360     | 1.0443     |
| <b>NAFR: Yield function</b>    | 1.2698     | 0.6131     | 1.9426     | 0.5602     | 0.3226     | 1.9306     | 1.0371     | 0.9926     |
| <b>NAFR: Plastic potential</b> | 0.6859     | -0.7087    | 0.8257     | 0.0627     | -0.076     | 0.6709     | 0.4637     | 0.4540     |

### 3. Experiments

#### 3.1. Circular Cup Drawing

Non-isothermal deep drawing of a cylindrical cup was examined as a representative forming operation due to its long sliding distances, large deformations, and the potential manifestation of anisotropy in the formed cup flange (earring). A tool set consisting of a binder, die, and 100 mm diameter punch with a die entry/punch profile radius of 12 mm and an effective clearance of 4.4 mm for the studied alloy, was installed in a servo-hydraulic press. Forming over a temperature gradient (with the punch at approximately 100°C and both the die and binder at 200°C) facilitated drawing of 228.6 mm (9") diameter blanks to a target depth of 75 mm that corresponded to a drawing ratio of 2.25. Note that these settings produced cups with a 20 mm flange with the intention to aid extraction of the formed part and for scanning the flange draw-in for post-processing purposes. A punch speed of 1 mm/s was selected and the material flow was controlled through a 100 kN binder load. Unfortunately, DIC strain measurement techniques are not amenable to cup drawing since the cameras cannot image the deformation within the flange and sidewall. Therefore, the GOM optical 3D measurement system, ARGUS, was kindly provided by Natural Resource Canada–CanmetMATERIALS where the strains after forming can be measured based upon the deformation of a grid etched onto the blanks prior to forming.

If the material is perfectly isotropic, a circular cup profile is expected. In contrast, for the studied 7XXX-T76 alloy, the flange exhibited a total of eight clearly defined ears as illustrated in Figure 4.

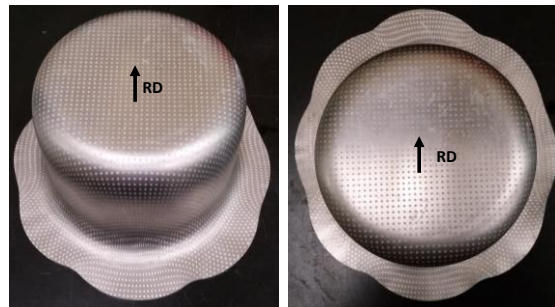
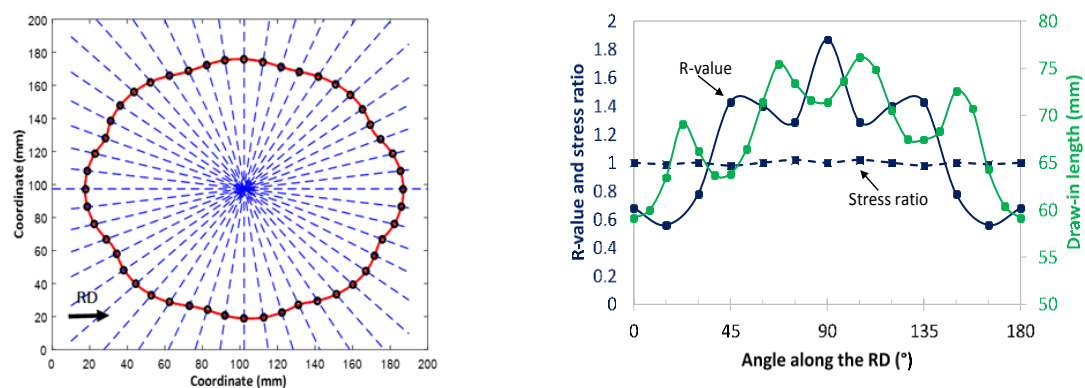


**Figure 4.** Earring profile of the 7XXX-T76 cup drawn to a target depth of 75 mm under non-isothermal conditions with Teflon film lubrication.

In order to study the relationship between the earring profile and the material anisotropy found by Yoon *et al.* [10] and van den Boogaard [11] the cup flange was scanned and the draw-in length (difference between the initial to the as-formed flange diameter) evaluated with a custom MATLAB script that imports the scanned flange profile and computes the draw-in length in  $7.5^\circ$  increments (see Figure 5a). The computed draw-in (green curve) is plotted together with the stress ratio and the R-values (blue curves) in Figure 5b that were both mirrored about the  $90^\circ$  symmetry line for visualization purposes. Assuming an orthotropic material, slight asymmetry in the earring profile was found for the ear in  $45^\circ$ ; this may be attributed to minor misalignment during forming or scanning of the profile. A good correlation between the R-values and the earring profile in the same direction rotated by  $90^\circ$  was observed. The high R-value in the TD, hence the increased resistance to thinning, resulted in less material flow in the RD.



a) Post-processed flange profile

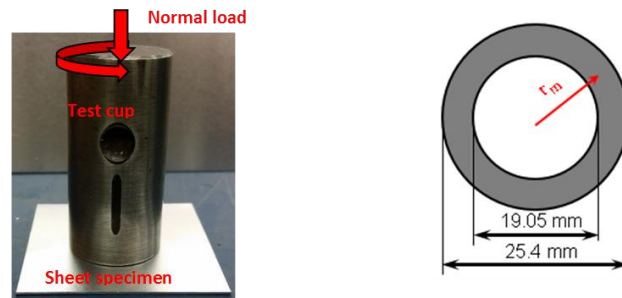
b) Correlation of draw-in length with anisotropy

**Figure 5.** Evaluation of the draw-in for correlation with the material anisotropy.

### 3.2. Elevated Temperature Friction

Warm friction was studied utilizing a modified Twist Compression Test (TCT) apparatus that facilitates testing at temperatures up to  $430^\circ\text{C}$ . Figure 6 serves to illustrate the test methodology developed by Schey [12]; an annular test cup is pressed onto a clamped sheet specimen and starts rotating at a constant sliding speed. Adopting Coulomb's friction law, the complex nature of friction is simplified to a non-dimensional number, the coefficient of friction (COF). It is important to note that solely relying on the COF can be misleading and that the evolution of the COF and lubricant breakdown are equally important to consider.

In analogy to the deep drawing process, Teflon film with a sheet thickness of 0.1 mm was utilized and a minimum of three repeats per condition were considered. TCT was performed at an interface pressure of 25 MPa, a sliding distance of 50 mm, and a sliding speed of 5 mm/s. These process parameters, obtained from pre-tests and FE simulations for a warm forming process of the studied alloy, were concluded to adequately replicate the studied deep drawing process.



a) Methodology                      b) Geometric dimensions of the test cup

**Figure 6.** Twist Compression Test apparatus.

The evolution of the COF over the sliding distance is recorded for 25°C and 170°C in Figure 7a and Figure 7b, respectively. In order to demonstrate the effectiveness of the Teflon film, its performance is plotted along with the COF for the lubricant Forge Ease AL278 (blue curve), referred to as Fuchs [13], that is utilized for high-volume production in industrial applications. The improved lubricity at 170°C can be explained through the presence of EP additives for the Fuchs and the temperature induced drop in the shear stress for the Teflon film [14].

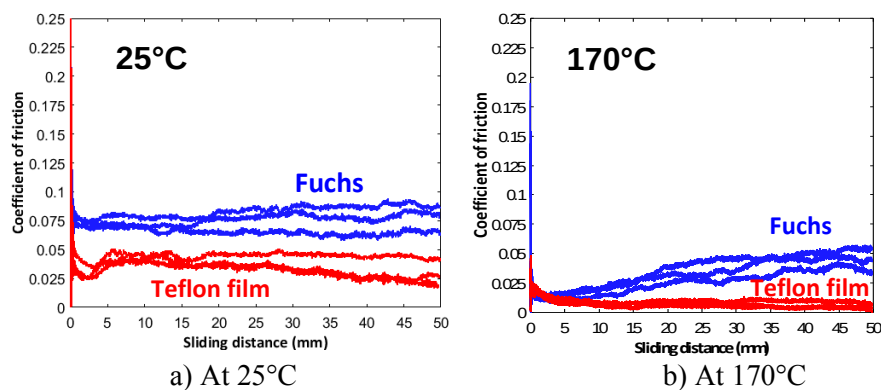


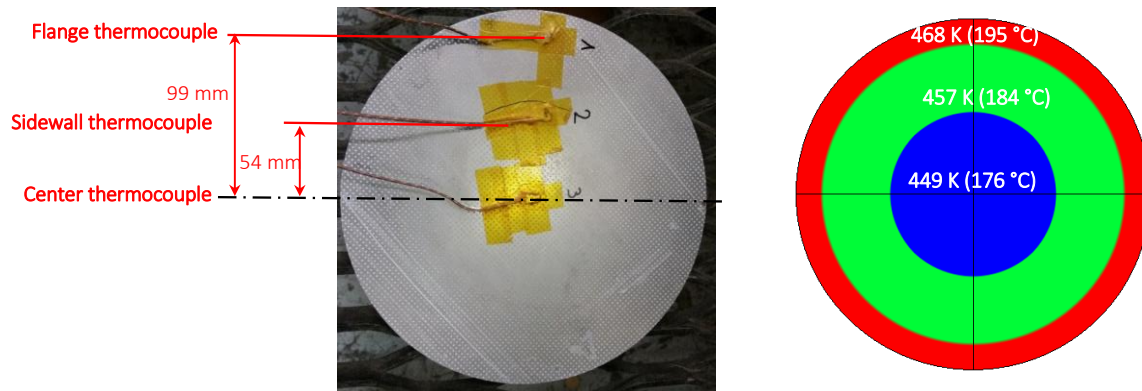
**Figure 7.** Evolution of the COF over the sliding distance with Teflon film (red curves) and Fuchs (blue curves).

In accordance with the ASTM G115 Standard Guide for Measuring and Reporting Friction Coefficients [15], the steady-state COF for Teflon film was found to be 0.037 (Std. dev  $\pm 0.007$ ) and 0.007 (Std. dev  $\pm 0.002$ ) at 25°C and 170°C, respectively. Additional details on the TCT tests and friction characterization under different test conditions such as contact pressure and velocity can be found in Noder [5].

#### 4. Finite Element Model

Modelling of the non-isothermal deep drawing process was performed using LS-DYNA with explicit time integration. For computational efficiency, use of the quarter-symmetry was made and both the tooling (punch, binder, and die) and the blank were discretized with fully integrated (Type 16) shell elements. With the aim to adopt a temperature- and rate-dependent hardening model in combination with the Barlat YLD2000-2d yield function, a user-defined material subroutine (umat) was utilized that accommodates the plastic potential being same as the yield function (AFR) or different from the yield function (NAFR). Note that simulations using the (i) AFR and (ii) NAFF Barlat YLD2000-2d function were run, as well as simulations using a (iii) NAFF Hosford yield function with a Barlat YLD2000-2d flow potential. The geometric boundary conditions such as position constraints, punch speed and clamping load were applied in analogy to the experimental process conditions. Contrary to the physical drawing process, where the blank was heated in closed tooling prior to forming, in the FE model, the

resulting steady-state temperatures were assigned to different blank sections as visualized in Figure 8. These temperatures were obtained from thermocouples attached to sections corresponding to the as-formed flange, sidewall, and cup center.



a) Thermocouples attached during forming      b) Assigned temperature in the FE model

**Figure 8.** Temperature measurements in the non-isothermal deep drawing process.

With the intention to speed up simulation times, the following simplifications were adopted. Use of time and mass scaling was made by utilizing a punch speed of 500 mm/s instead of 1 mm/s while scaling thermal properties and strain rates accordingly. A lower bound of the explicit time step was prescribed to  $10^{-6}$  s. Finally, instead of computing the heat transfer between the blank and the tooling, a time-dependent thermal history was prescribed to the blank. These thermal conditions were obtained from the computed thermal history of a thermo-mechanical analysis with a von Mises material model. Resulting temperatures in the respective flange, sidewall, and hat section were averaged and prescribed to the blank in the form of a time-dependent temperature evolution that allowed simplification of the analysis to a structural instead of a thermo-mechanical analysis. For a more detailed description of the model set-up, prescribed temperature curves, and the umat, the reader is referred to Noder [5].

## 5. Results and Discussion

The predicted earring profiles for the studied yield functions and flow rules are summarized in Figure 9. Note that for visualization purposes, the quarter-model was mirrored to represent a full cup. As expected, the isotropic Hosford yield function with a yield exponent of 8 predicted a perfectly circular cup whereas the associative Barlat YLD2000-2d yield function in Figure 9b predicted the presence of four ears. Both non-associative configurations exhibited the experimentally observed eight ears. The deviation between model prediction and experiment for the associative Barlat YLD2000-2d was to be expected in light of the limited number of calibration parameters to describe both the stress and strain anisotropy. It is important to note that the peak plastic strain values for some elements in the flange section were caused by severe element distortion.

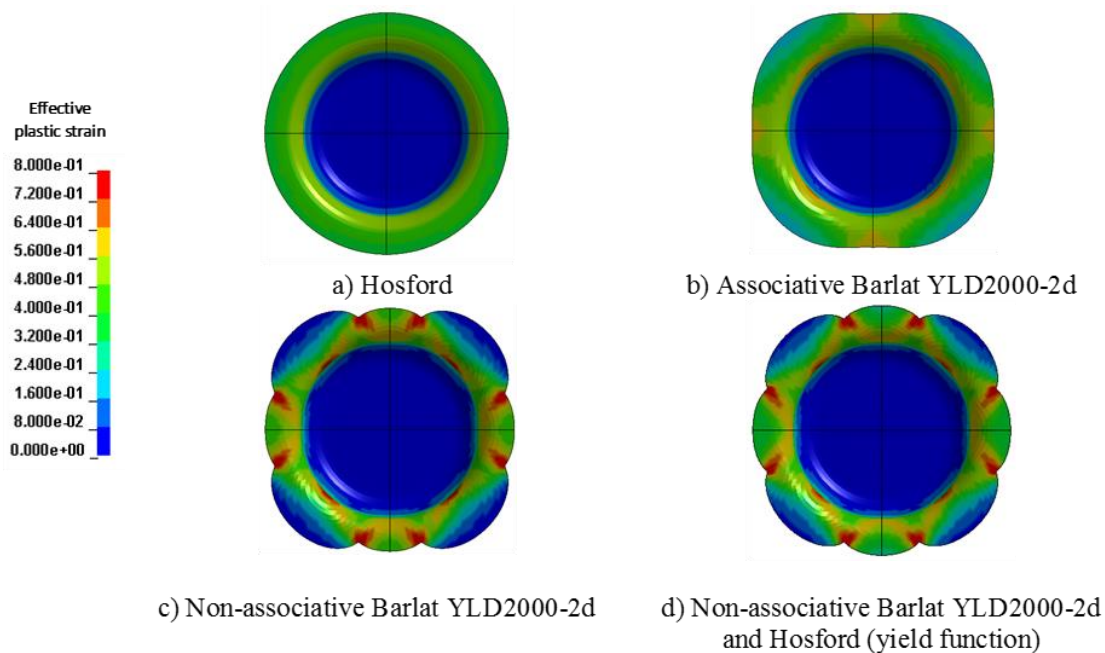


**Figure 9.** Predicted cup profile as a function of the adopted yield function and flow rule.

The predicted draw-in of the non-associative Barlat YLD2000-2d yield functions and the experimental measurements can be seen in Figure 10a. The predictions utilizing the Hosford (blue colour) for the yield stress function resulted in better correlation between model predictions and experiments (brown colour). Nevertheless, the draw-in was overestimated by both yield functions which could be due to the applied boundary conditions in the FE model. Figure 10b demonstrates that even though both lubricants have a very low COF (0.007 for Teflon film and 0.03 for Fuchs at 170°C), the effect of friction (lubricant selection) on the predicted draw-in is significant.

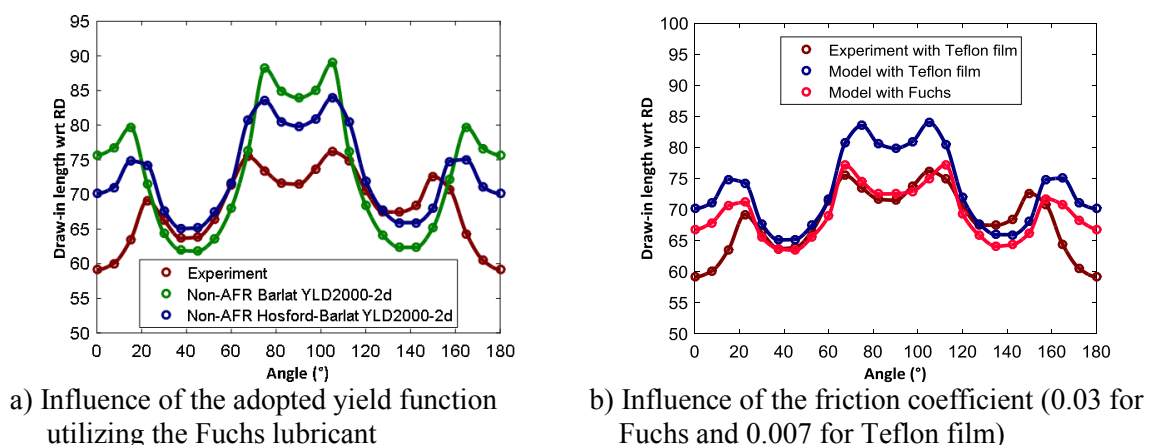


**Figure 10.** Effect of plasticity model and friction on the draw-in.

Since, among the studied yield functions and flow rules, the non-associative Hosford-Barlat YLD2000-2d captured the earring profile most accurately, the force displacement and surface strains are discussed for this plasticity model with the Teflon film lubricant. Figure 11 compares the forming force *versus* punch displacement and serves to illustrate the importance of a rate-sensitive constitutive model. In the absence of rate effects, the peak force was in very good agreement with model predictions (3% deviation) whereas the force was overestimated by roughly 11% when accounting for rate effects.

The somewhat different force evolution in the second stroke part is believed to be due to the adopted model simplifications in the previous section.

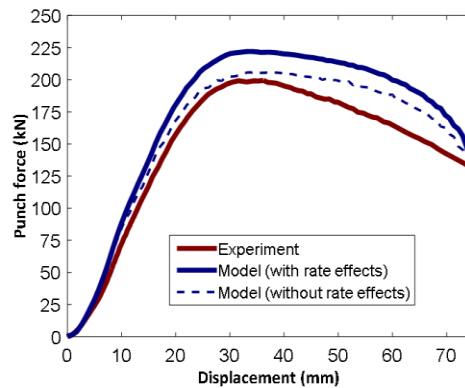
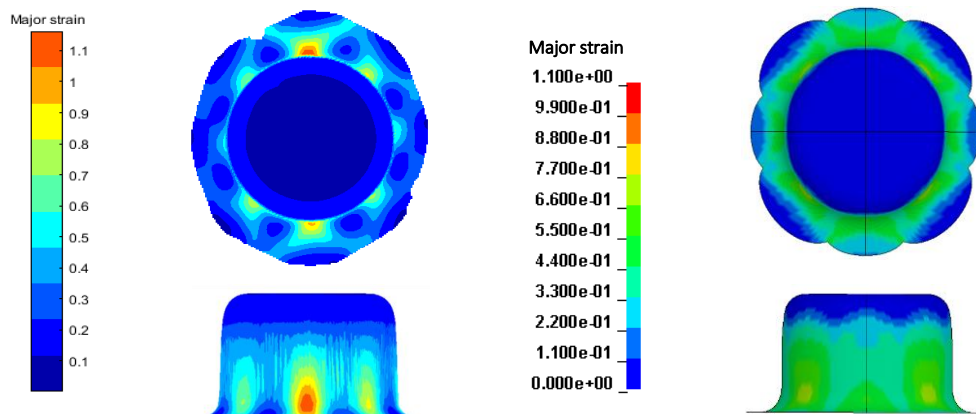


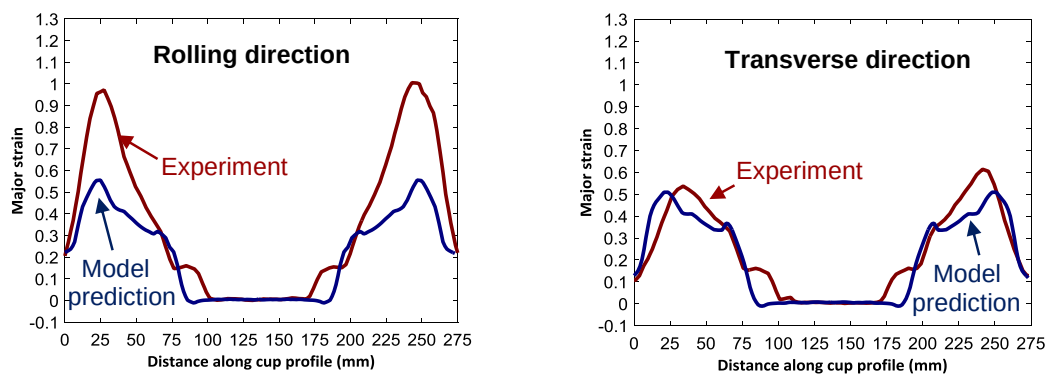
**Figure 11.** Comparison of the punch force between the experiment and the model prediction.

Figure 12 compares the surface strains obtained from the ARGUS optical strain measurements and model predictions. While acceptable agreement was observed for the major strain in the TD in Figure 13b, the strain distribution along the cup profile in the RD was somewhat underpredicted by the non-associative Hosford-Barlat YLD2000-2d model. Coupling the current mechanical analysis with the thermal solver could yield a more realistic temperature distribution in the blank profile that directly influences the friction and material flow behavior.



a) Experiment (ARGUS strain measurement)      b) Prediction (NAFR Hosford-Barlat YLD2000-2d)

**Figure 12.** Comparison of the major strain distribution in the 7XXX-T76 cup



a) In the rolling direction

b) In the transverse direction

**Figure 13.** Comparison the major strain distribution along the cup profile

## 6. Conclusion

The work presented in this paper demonstrates the need for a combined modelling approach, hence accurate description of the material model and friction characterization. The studied developmental 7XXX-T76 aluminum alloy exhibits a mild stress anisotropy and a planar strain anisotropy that was manifest in the presence of eight ears in non-isothermal circular cup draws. Among the tested yield functions and flow rules, the non-associative Hosford-Barlat YLD2000-2d for the yield stress and the plastic potential, respectively, predicted a draw-in that was in good agreement with the experiment whereas the friction coefficient was identified as a powerful parameter that requires a temperature-dependent implementation. The observed deviations in the force-displacement and predicted surface strains point to the need to couple the mechanical and thermal solver.

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