Characterizing the Constitutive Properties of AA7075 for Hot Forming

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Abstract
The work presented herein investigates the constitutive properties of AA7075 as it undergoes a hot stamping/die quenching process. Tensile specimens were solutionized inside a heated furnace set to 470°C. Once solutionized, the samples were quenched to an intermediate temperature using a vortex air chiller at a minimum rate of 52°C/s. Tensile tests were conducted at steady state temperatures of 470, 400, 300, 200, 115 and 25°C. This solutionizing and subsequent quenching process replicated the temperature cycle and quench rates representative of a die quenching operation. The results of the tensile test were analyzed with digital imaging correlation using an area reduction approach. The area reduction approach approximated the cross-sectional area of the tensile specimen as it necked. The approach allowed for the true stress-strain response to be calculated well past the initial necking point. The resulting true stress-strain curves showed that the AA7075 samples experienced almost no hardening at 470°C. As steady state temperature decreased, the rate of hardening as well as overall material strength increased. The true stress strain curves were fit to a modified version of the extended Voce constitutive model. The resulting fits can be used in a finite element model to predict the behaviour of an AA7075 blank during a die quenching operation.

Keywords: Die Quenching; AA7075; solutionizing; quenching; area reduction; digital image correlation

Introduction
In the ongoing effort to improve fuel economy, the automotive industry is continually investigating new metal forming techniques and new alloys to increase strength and reduce weight. One such technique is the hot forming process, also known as die quenching (DQ). The DQ process is well-documented for ultra-high strength steels [1]–[3] and 5xxx and 6xxx-series aluminum alloys [4]–[7]. A more recent topic of research pertains to applying this technique to 7xxx-series aluminum alloys. For such alloys, the DQ process consists of first heating the blank to its solutionizing temperature, typically 470°C [8]. The blank is then transferred from the furnace into a chilled die set where it is simultaneously formed into a desired shape and rapidly quenched. The rapid quenching will force the blank to enter into a state of supersaturated solid solution (SSSS). The formed part is subsequently subjected to an artificial aging treatment.
The purpose of this paper is to determine the stress-strain properties required to model AA7075 as it undergoes a DQ operation. The published literature contains several studies that have characterized this alloy isothermally, wherein the AA7075 sample is taken in its T6 temper and heated in an oven to some desired temperature at which it is tested. Example of such studies can be found in [9]–[11]. The results produced by these studies are not applicable into a DQ operation since the material is not tested in a SSSS condition. The work presented in this paper outlines an experimental methodology used to replicate the temperature cycle of a DQ operation and also the data processing technique to obtain true stress-strain curves. The stress-strain curves were fit to a generalized Voce model.

**Experimental Setup**

All tensile tests in this work were conducted on a screw-driven MTS Criterion 49 machine incorporating high temperature hydraulic grips. The tensile machine accommodates an MTS 651 furnace, as shown in Figure 1. Testing was conducted at the following temperatures: 25, 115, 200, 300, 400 and 470°C. A temperature of 115°C was selected because the quenching apparatus was unable to quench to 100°C at a sufficient quench rate. Each temperature was tested at three strain rates: 0.01 s⁻¹, 0.1 s⁻¹ and 0.5 s⁻¹. The higher strain rate of 0.5 s⁻¹ corresponds to the upper limit (under control) of the tensile machine. The specimen geometry for the 0.01 s⁻¹ and 0.1 s⁻¹ rates followed the full-sized ASTM-E8 standard [12]. The specimens tested at 0.5 s⁻¹ utilized a sub-sized ASTM-E8 geometry. Thee repeats were conducted at each strain rate and each temperature.

![Figure 1. MTS Criterion 49 tensile machine, incorporating an MTS 651 furnace (left). Also shown (right) are the quenching nozzles and the hydraulic grips in which the specimen is held.](image)

To replicate the thermo-mechanical history during the DQ process, all tensile specimens were first heated to 470°C and then quenched to one of the aforementioned temperatures and tested at said temperature. The quenching was performed within the furnace using cold pressurized air that was fed from a vortex chiller. The exit temperature of the air from the chiller was 4°C. Three quenching nozzles were placed behind the tensile specimen, along the gauge length of the sample, as shown in Figure 1. The pressure on each nozzle was adjustable, ensuring a constant cooling rate throughout the gauge length of the tensile samples. Thermocouple measurements are shown in Figure 2 for an AA7075 sample quenched to 300°C. The figure shows that the gauge length of the specimen cooled at a uniform rate of 60°C/s and that the temperature gradient was only 7°C along the length. In general, the quench rate was never
below 52°C/s and the temperature gradient never above 9°C for any of the tensile tests conducted.

**DIC Processing**

Strains were measured during tensile testing using a stereo digital imaging correlation (DIC) setup with two Point Grey GRAS-50S5M-C cameras. A pair of Nikon AF Micro 180 mm lens were attached to the Point Grey cameras. All DIC analysis was done using Vic-7 [13], which is a commercial stereoscopic DIC software package.

The tensile tests at elevated temperatures experienced diffuse necking at quite low strain levels, always before 4% elongation. Therefore, the standard formulas usually used to convert engineering stress and strain to true stress and strain could not be used, as they are valid only up to the point of necking. This work, instead, utilized an area reduction technique. In this technique, the cross-sectional area of the neck in the tensile specimen is approximated using the data extracted from the DIC software.

**Figure 2.** Temperature-time profile in the gauge section of the tensile sample as it is quenched using the setup in Figure 1.

A line slice was drawn across the neck in the tensile specimen, as shown in Figure 3a. From this line slice, the x, y and z coordinates across the width of the sample were extracted and also the major and minor strains. The line slice yielded 200 data points along the sample width at every time step during the test.
Figure 3. (a) Line slice drawn on the necking zone of an AA7075 sample tested at 470°C and (b) illustration of the area reduction method, showing the initial cross-section and a profile of the deformed section as determined by the DIC. The area reduction method divides the deformed section into trapezoidal segments and individually calculates their area.

The data extracted from the line slice was used to construct the profile of the deformed cross-section of the neck, as shown in Figure 3b. The area reduction method divided the deformed section into several segments and approximated the area of each segment using the trapezoidal rule. The instantaneous area of the deformed section was calculated by summing the areas of each individual segment:

\[ A_{inst} = \sum A_i = \sum w_i \times t_i \]  \hspace{1cm} \text{equation (1)}

From this instantaneous area, \( A_i \), the true stress and strain were calculated:

\[ \varepsilon_{true} = \ln \frac{A_0}{A_{inst}} \]  \hspace{1cm} \text{equation (2)}

\[ \sigma_{true} = \frac{F_{inst}}{A_{inst}} \]  \hspace{1cm} \text{equation (3)}

To calculate \( w_i \) in equation (1), the average distance between each segment was calculated:

\[ w_i = x_{i+1} - x_i \]  \hspace{1cm} \text{equation (4)}

The average instantaneous thickness, \( t_i \), was calculated by integrating the through-thickness strain, \( \varepsilon_3 \), along the width of the specimen:

\[ t_i = t_0 \times \exp \left( \frac{\varepsilon_{3i} + \varepsilon_{3i+1}}{2} \right) \]  \hspace{1cm} \text{equation (5)}

In equation (5), \( \varepsilon_3 \) was determined using the law of volume conservation:
\[ \varepsilon_3 = -\varepsilon_1 - \varepsilon_2 \]

\textit{equation (6)}

where \( \varepsilon_2 \) is the strain in the width direction and \( \varepsilon_1 \) is the strain in the longitudinal direction. Both variables were extracted from the line slice.

**Results**

The resulting true stress-strain curves are shown in Figure 4 as solid lines. The experimentally derived curves were fit to a generalized Voce model of the form:

\[ \sigma = A + (B + Ce)(1 - \exp(-D\varepsilon)) \]

\textit{equation (7)}

where \( A, B, C \) and \( D \) are phenomenological parameters, fit to the experimental curves using a Gauss-Seidel non-linear regression technique. Table 1 shows the values of these parameters, as a function of temperature and strain rate. Of the four parameters, \( A, C \) and \( D \) were functions of only temperature. Only the \( B \) parameter was found to be a function of both temperature and strain rate. The resulting stress-strain curves, as predicted by these parameters, are shown Figure 4 as dashed lines. The dashed curves matched the experimental stress-strain curves very well for temperatures at and above 200°C. For lower temperatures, the fit was not as good because the generalized Voce model is unable to capture the negative strain rate sensitivity exhibited by AA7075 in the SSSS condition below 200°C.

**Figure 4.** True stress-strain curves, obtained using the area reduction method, for AA7075 at six temperatures at three strain rates
Table 1. Parameters from equation (7) fit to the experimental stress-strain data for AA7075 and AA7085 where T is in Celsius. The R^2 value of the fits are also shown

| Parameter | AA7075 | R^2 |
|-----------|--------|-----|
| A (MPa)   | 144 + 0.00467T – 0.000477T^2 | 0.94 |
| B (MPa)   | 172 – 0.538T + 0.000378T^2 + 0.3017^\dot{\varepsilon} | 0.96 |
| C (MPa)   | 399 – 0.688T – 0.000337T^2 | 0.99 |
| D (s)     | 16 + 0.1T | 0.91 |

Discussion
The area reduction technique employed in this work is highly dependent on proper setup and calibration of the DIC system. To verify the accuracy of the method, the cross-sectional area of two tensile specimens were measured under an optical microscope: one tested at room temperature at 0.1 s\(^{-1}\) and another tested at room temperature at 0.5 s\(^{-1}\). The cross-section of the first specimen was measured to be 19.55 mm\(^2\), while the area reduction technique calculated 19.81 mm\(^2\). The initial cross-section area for this specimen was 25.15 mm\(^2\). The area of the second specimen was measured to be 9.35 mm\(^2\), while the area reduction calculated 9.24 mm\(^2\). The initial area was 12.65 mm\(^2\).

The percent error in measured area was 1% in both cases, indicating that this technique was accurate in calculating true stress. In terms of percentage in area change, the first sample experienced an area reduction of 26.1% based on the measured value, and a reduction of 27.0% based on the calculated value. The second sample experienced a reduction of 22.2% based on the measured value and 21.2% based on the calculated value. In both samples, the discrepancy between measurements and area reduction were equal to or less than 1%. Therefore, the area reduction technique was deemed accurate in calculating true strains as well.

The experimental stress-strain curves in Figure 4 were found to be experience softening with increasing temperature. For the temperatures 200°C and above, the curves were positive strain rate sensitive. For 115°C and below, they were negative rate sensitive. The evolution of strain rate sensitivity is caused by the Portevin-Le Chatelier (PLC) effect, which is well-documented in literature. Leacock et al. [14] observed the PLC serrations for AA7075 at room temperature. Rahmaan et al. [15] have made similar observations about the PLC effect causing negative rate sensitivity on AA5182. The extended Voce model was unable to capture this evolving strain rate sensitivity. While not ideal, this is not a significant issue for modelling the DQ process since, in a DQ operation, the blank is expected to be fully formed before it cools to below 200°C. Therefore, it is not crucial to perfectly capture the constitutive properties of AA7075 at cooler temperatures. If it is necessary to correctly characterize cooler temperatures, more computationally expensive models are available such as the one derived by Kabirian et al. [16].

Conclusions
The experimental and subsequent DIC analysis conducted in this work has yielded stress-strain curves that characterize AA7075 under conditions corresponding to a DQ forming operation. Temperature and strain rate dependent curves have been determined. The stress-strain curves were found to be positively strain rate sensitive for temperatures at or above 200°C. They were negative rate sensitive for temperatures below 115°C, likely due to the PLC effect. These experimentally-derived true stress-strain curves can be used to model an AA7075 blank under a broad range of temperatures and strain rates. The extended Voce
model presented herein provides a reasonably accurate fit to the experimental curves. Future work will see implementation of these curves into a finite element model.

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