Strain Rate and Temperature Dependent Plastic Response of AA7075 during Hot Forming

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Abstract. High strength 7xxx series aluminum alloys are being increasingly considered for automotive applications due to their superior specific strength compared to 6xxx series alloys. Complex structural components made from 7xxx series alloys need to be manufactured through warm forming or hot stamping due to their low ductility at room temperature. For hot stamping, the AA7075 blanks are heat treated to above 480°C, yielding a supersaturated solid solution, corresponding to a W temper state. The preheated blanks are then simultaneously formed and rapidly quenched using cooled dies. The entire forming process takes place in the W temper condition. The stamped parts are further subject to an artificial aging heat treatment to achieve the desired temper through precipitation hardening. Therefore, understanding the strain rate and temperature dependent plasticity behavior of AA7075-W is critical to establish optimum design parameters for the hot stamping process. The present work is concerned with the strain rate and temperature dependent plastic response of AA7075 in the W temper state. In particular, the results from a comprehensive experimental program on uniaxial tension specimens are presented. High temperature experiments are carried out at strain rates ranging from 0.001-2/s in a universal testing machine. An induction heating system with infrared high speed imaging is used to span the entire temperature range from 180°C to 480°C, over the full range of strain rates considered. Based on the experimental results, a candidate plasticity model with an empirical mixed Swift-Voce hardening law and a Johnson-Cook type strain rate and temperature dependence is calibrated.

1. Introduction

In recent years, one of the primary challenges facing the automotive industry is to meet government regulations on fuel economy and vehicle safety. Towards this objective, lightweighting of structural components using precipitation hardenable aluminum 7xxx series alloys has been considered as a viable alternative to advanced high strength steels. AA7075, an Al-Zn-Mg-Cu series aluminum alloy, possesses excellent mechanical properties such as high specific strength, high fracture toughness and resistance to stress corrosion cracking, leading to its wide use in the fabrication of aerospace components. However, low room temperature formability and high processing cost has limited the automotive applications of AA7075.

In order to improve the formability of AA7075, several sheet forming processes at elevated temperatures have been studied, which may be used in place of conventional cold forming methods. Among them, one of the most promising being hot stamping/die quenching. For hot stamping, the AA7075 blanks are solution heat treated to above ~480°C (solidus temperature of the material), yielding
a supersaturated solid solution, corresponding to a W temper state. The preheated blanks are then simultaneously formed and rapidly quenched using actively cooled dies. The entire forming process takes place in the W temper state. The stamped parts are further subject to an artificial aging heat treatment to achieve the desired T6 temper through precipitation hardening [1]. The hot stamping process has the potential to be cost effective to manufacture automotive components from AA7075, since it can be implemented using existing high temperature processing technology for boron steels. Harrison and Luckey [2] demonstrated the feasibility of manufacturing a B-pillar outer panel from AA7075 through hot stamping. They showed that hot stamping followed by artificial aging treatment produced a high strength component with material properties equivalent to the T6 temper. Ilinich and Luckey [3] used a non-isothermal coupled thermomechanical model to predict the strain and thickness distributions after hot forming of the panel. They identified a need to obtain experimental stress-strain data for solution heat treated AA7075 over a temperature range of 200-480°C, and strain rates from 0.01-10/s.

During hot stamping, metals and alloys undergo complex thermomechanical loading histories. Understanding the strain rate and temperature dependent plasticity behavior of materials during hot stamping is critical to establish optimum design parameters for sheet metal forming. Since the hot stamping process takes place entirely in the solution heat treated W temper condition, only the experimental stress-strain data obtained from tests on AA7075-W can be considered to be representative of the forming process. There are very limited studies on the plasticity behavior of AA7075-W. Xiao et al. [4, 5] performed hot uniaxial tensile tests on solution heat treated AA7075 using a Gleeble 3500 thermomechanical simulator in the temperature range of 300-450°C and strain rates from 0.1-10/s. They proposed a constitutive model considering recrystallization, dislocation recovery, grain size and damage. A good agreement of experimental results and predictions was obtained. Omer et al. [6] investigated the plastic response of AA7075-W by performing uniaxial tensile tests using a heated furnace for solution heat treatment and a vortex air chiller to quench the specimen to the target temperature. They conducted tensile tests for target temperatures from 25-470°C and strain rates of 0.01-0.5/s. They used 3D DIC with an area reduction approach to estimate the true stress-strain response of the material beyond the initial necking point. They proposed an extended Voce constitutive model to predict the plasticity behavior of AA7075-W.

Studies on other important factors essential for hot stamping applications have been performed such as evolution of yield strengths, anisotropy and hardening behavior of AA7075 during natural aging [7], optimization of processing parameters for AA7075 during hot stamping [8], prediction of forming limit curves [9], investigation of the deformation and post-formed strength for different hot forming processes [10] and evaluation of the interfacial heat transfer coefficient for hot forming of aluminum alloys [11, 12].

In the present study, tensile experiments were performed in a universal testing machine over a wide range of strain rates from 0.001-2/s and temperatures from 180-480°C on AA7075 specimens in the W temper condition using an induction heating system, to investigate the plasticity behavior during hot forming. Based on the obtained experimental results, a candidate plasticity model with an empirical mixed Swift-Voce hardening law and a Johnson-Cook type strain rate and temperature dependence is calibrated [13].

2. Experimental protocol

2.1. Materials and specimens
The material used for the study was AA7075 in the as-fabricated F temper condition with a thickness of 2.08 mm. The material was provided in the form of rolled sheets of dimensions 500 x 500 mm. The processing window for AA7075 for hot stamping applications can be inferred from the time-temperature-peak strength curve [14]. In the range of temperatures from 280-400°C, only up to ten seconds are available for the entire hot stamping process before precipitates start to form within the alloy microstructure. In the present study, the applicable loading rates for each target temperature considered
were selected based on the maximum allowable processing time before precipitation hardening. Uniaxial tension (UT) specimens with a 10 mm wide and 40 mm long gage section were extracted from these sheets using CNC water-jet cutting to characterize the elasto-plastic material response (Fig. 1a).

The specimens were extracted at 90° with respect to the sheet rolling direction. The effect of anisotropy was not considered in the present study. In all the experiments, the specimen displacements were obtained using a 9 mm virtual extensometer of the planar digital image correlation (DIC) software VIC2D (Correlated Solutions). A random white speckle pattern of about 10µm diameter was applied to the specimens prior to testing.

2.2. Experimental procedure

The experimental program was designed to cover a wide range of temperatures (180-480°C) and strain rates in the range of 0.001-2/s. Based on the processing window for AA7075, UT tests at a nominal strain rate of 0.001/s were performed only for test temperatures of 180°C and 480°C. For higher nominal strain rates of 0.1/s and 2/s, fracture experiments were performed over the full range of temperatures from 180-480°C in intervals of 60°C for all five specimen types. At least two repeat tests were performed for each experiment, i.e. a total of 28 experiments.

All experiments were performed on an Instron 8801 hydraulic universal testing machine equipped with a 10 kN load cell. High pressure water-cooled clamps were used to grip the specimen and ensure its alignment with respect to the loading frame. The low strain rate UT experiments were performed under displacement control at an actuator speed of 2.4 mm/min, corresponding to a nominal strain rate of 0.001/s. Intermediate strain rate tests were conducted at loading rates of 240 and 4800 mm/min, corresponding to nominal strain rates of 0.1/s and 2/s, respectively. For experiments at a strain rate of 0.001/s, the software VicSnap (Correlated Solutions) was used to observe the displacement field, by acquiring images at a frame rate of 2 Hz taken by a 5MP digital camera (AVT Pike F-505B/C). For higher values of strain rates, a high speed camera (Vision Research, Phantom v7.3), triggered by the rise in the force signal measured by the load cell, was used to record images at a resolution of 1024 × 1024 pixels at a frame rate of 2000 Hz.

For the fracture experiments across the range of strain rates considered, the temperature field in the specimen gage section was monitored using a high speed infrared camera (FLIR X6900sc SLS LWIR). Infrared images were recorded at a resolution of 256 x 256 pixels and a frame rate of 4 Hz for low strain rate tests (0.001/s), while a higher frame rate of 500 Hz was prescribed for intermediate strain rate tests (0.1/s and 2/s). A custom-made induction heating system with pyrometer based temperature control was used in the experiments. The emissivity of the graphite base coating was measured for the temperature range from room temperature up to 500°C using a K-type thermocouple attached to the center of the specimen gage section, and was used to calibrate the pyrometer and infrared camera prior to the experiments. All the experiments were subsequently performed with pyrometer based temperature control, i.e. by setting the target temperature equal to the calibrated pyrometer set temperature at the center of the specimen gage section.

The temperature profile for elevated temperature tests on the different specimen types is shown in Fig. 1b. Initially, the AA7075 specimens in the as-fabricated F temper were heated to a target temperature of 510°C, above the solution heat treatment temperature of 480°C, and soaked for 600s to ensure adequate dissolution of pre-existing precipitates in the microstructure, resulting in the formation of a W temper region at the center of the gage section. The length of the W temper region, measured using infrared images was observed to be 15 mm. The minimum time taken to guarantee the formation of the W temper condition above 480°C is determined to be 480s, according to a recent study by Omer et al. [8].

Then the solution heat treated specimens were rapidly cooled to the test temperature (180-480°C) by adjusting the target temperature of the induction system and using a quenching air nozzle. The applied rate of cooling was >50°C/s. Finally, the test specimens were isothermally deformed up to failure to obtain the force-displacement response. The maximum time required to quench the specimens to the
target temperature and initiate the test was 6s (for 180°C). The load control option on the Instron machine ensured that there was no residual stress within the specimen due to thermal effects prior to initiation of the test.

Figure 1. (a) Uniaxial tension (UT) specimen geometry, with central W temper region highlighted in yellow; (b) Temperature profile for UT tests at elevated temperatures. Note that the soaking temperature is 510°C to ensure a 15 mm W temper region at the centre of the UT specimen.

3. Plasticity model
The empirical model used in the present study is a modified form of the Johnson-Cook plasticity model, with the isotropic hardening of the material described through the Swift-Voce law [13]. An isotropic von Mises yield surface with an associated flow rule was assumed for AA7075-W. The yield function is given by:

\[ f = \bar{\sigma}[\sigma] - k[\bar{e}_p, \bar{e}_p, T] = 0 \] (1)

where, \( k \) is the deformation resistance, which depends on the equivalent plastic strain \( \bar{e}_p \), equivalent plastic strain rate \( \dot{\bar{e}}_p \) and temperature \( T \). \( \bar{\sigma} \) is the von Mises equivalent stress, given by:

\[ \bar{\sigma} = \sqrt{3J_2} = \sqrt{\frac{3}{2} \mathbf{s} : \mathbf{s}} \] (2)

where, \( J_2 \) is the second deviatoric stress invariant and \( \mathbf{s} \) denotes the deviatoric stress tensor.

The true strain hardening is given by a linear combination of the Swift and Voce laws, with a Johnson-Cook type strain rate and temperature dependence:

\[ k = \left( \alpha A(\bar{e}_p + \dot{\bar{e}}_0)^n + (1 - \alpha)(k_0 + Q(1 - e^{-\beta \dot{\bar{e}}_p})) \right) \left( 1 + C\ln \left( \frac{\dot{\bar{e}}_p}{\dot{\bar{e}}_0} \right) \right) \left( 1 - \left( \frac{T - T_{c}^r}{T_{m} - T_{c}^r} \right)^m \right) \] (3)

where, \( A, \dot{\bar{e}}_0 \) and \( n \) are Swift parameters and \( k_0, Q \) and \( \beta \) are Voce parameters. Here, \( 0 \leq \alpha \leq 1 \) is a weighting parameter governing the shape of the hardening curve. The parameters \( C \) and \( \dot{\bar{e}}_0 \) determine the strain rate effect, while the parameters \( T_{c}^r, T_{m} \) and \( m \) describe the effect of temperature.

4. Results and discussion

4.1. Experimental results
The axial true stress-strain curve is calculated from the force-displacement curves (up to the force maximum) obtained from experiments on the UT specimens across the entire range of strain rates and
temperatures. It is observed that for test temperatures of $180^\circ$C and $240^\circ$C, strain localization and failure takes place outside the W temper region (i.e. outside the $15$ mm zone at the center of the gage section) for all strain rates considered. For temperatures in the range of $300$-$480^\circ$C, onset of necking and subsequent fracture takes place within the W temper region. The force-displacement curves for test temperatures from $300^\circ$C to $480^\circ$C show considerable post-necking softening behavior before final fracture. Therefore, for the sake of clarity, axial true stress-strain curves are presented for different strain rates for test temperatures of $180^\circ$C and $240^\circ$C (Figs. 2a and 2b, respectively), while axial nominal stress-strain curves are presented for test temperatures in the range $300$-$480^\circ$C (Figs. 3a and 3b, respectively).

From Fig. 2a, it is observed that for test temperature of $180^\circ$C, mild strain rate softening occurs when the strain rate is increased from $0.001$/s to $2$/s. However, repeat tests indicate that this apparent observed strain rate softening is within the bounds of experimental scatter. While the value of true strain at force maximum decreases from $0.048$ at a strain rate of $0.001$/s to $0.022$ at a strain rate of $2$/s, the shape of the hardening curve remains fairly constant with respect to strain rate. For test temperatures from $240$-$480^\circ$C (Figs. 2b, 3a and 3b), strain rate dependent hardening is observed. Furthermore, a decrease in the value of true strain at maximum force from $0.067$ to $0.037$ corresponding to an increase in strain rate from $0.1$/s to $2$/s is also observed for tests at $240^\circ$C, accompanied by a change in the shape of the hardening curve.

Figs. 3a and 3b indicate temperature dependent strain rate hardening behavior of AA7075 in the W temper state. The amount of strain rate dependent hardening increases gradually from $300^\circ$C ($2\%$ increase in the force maximum) to $480^\circ$C ($64\%$ increase in the force maximum), as the strain rate is increased from $0.1$/s to $2$/s. There is a no significant change in shape of the hardening curve (up to maximum force) with strain rate, for all temperatures except $300^\circ$C. Onset of necking and subsequent fracture is observed outside the W temper region at $180^\circ$C, while necking and failure occurs near the center of the specimen gage section at $300^\circ$C.

The uniformity of the temperature field in the specimen gage section was verified using temperature profile data obtained from the infrared camera. It is observed that the surface temperature averaged across the width of the specimen drops by up to $13^\circ$C and $16^\circ$C from the center of the gage section to the boundary of the W temper region ($15$ mm) for test temperatures of $180^\circ$C and $300^\circ$C, respectively. Further, temperature profiles of the W temper region at different values of strain indicate a reasonably uniform distribution of temperature within the UT specimen gage section.

The effect of temperature on the axial true stress-strain curves up to maximum force is shown in Figs. 4a and 4b (left panel) for nominal strain rates of $0.1$/s and $2$/s, respectively. A monotonic decrease in the hardening behavior of AA7075-W is observed with an increase in test temperature across the strain rate range considered. Further, there is an increase in the value of true strain at maximum force with an increase in strain rate from $0.1$/s to $2$/s, for test temperatures between $300^\circ$C and $480^\circ$C. This behavior is in contrast to that observed for tests at $180^\circ$C, indicating a temperature dependent response of true strain at maximum force versus strain rate.

4.2. Modelling of plastic response

4.2.1. Modified Johnson-Cook model calibration
For AA7075, the assumed material properties are $E=72$ GPa, $\nu=0.33$, density $\rho=2810$ kg/m$^3$, specific heat capacity $C_p=900$ J/(kgK) and Taylor–Quinney coefficient of $0.9$. Further, the reference strain rate $\dot{\varepsilon}_0=0.1$/s, reference temperature $T_r=180^\circ$C and melting point $T_m=635^\circ$C.
Based on the experimental UT true stress-plastic strain response of AA7075-W up to force maximum over a wide range of temperatures and strain rates, two aspects of the plasticity behavior are apparent; change in shape of the hardening curve with an increase in temperature, and a significant increase in the strain rate dependent hardening response with an increase in temperature. It is therefore necessary to consider the temperature dependence of parameters $\alpha$ and $C$ in the yield function defined in Section 3.

The first step towards calibration of the proposed plasticity model is to assume a purely Swift hardening behavior for a temperature of 180°C and a purely Voce hardening response for test temperature of 480°C, at the reference strain rate of 0.1/s. The Swift and Voce parameters thus obtained are presented in Table 1. Next the weighting parameter $\alpha$ which governs the shape of the hardening

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**Figure 2.** Experimental true stress-strain curves from tests on AA7075-W UT specimens at different strain rates; (a) test temperature = 180°C, (b) test temperature = 240°C.

**Figure 3.** Experimental nominal stress-strain curves from tests on AA7075-W UT specimens at different strain rates; (a) test temperatures in the range of 300-420°C (solid lines indicate strain rate = 0.1/s, dashed lines indicate strain rate = 2/s), (b) test temperature = 480°C.
response is adjusted for each intermediate test temperature (at the reference strain rate) until a best-fit curve is obtained based on a least squares error approximation. α gradually changes from 1 for tests at 180°C to 0 for tests at 480°C in an approximately linear fashion (Table 2). Thus, a good approximation of the shape of the plastic response for any intermediate temperature can be readily obtained based on the obtained α values.

![Graph](image1.png)

![Graph](image2.png)

Figure 4. True stress-plastic strain curves up to maximum force for AA7075-W UT specimens at different test temperatures (left panel) and 3D plots of the predicted hardening behavior of AA7075-W at different temperatures (right panel), at strain rates of; (a) 0.1/s, (b) 2/s. In the left panel, solid lines indicate experimental results and dashed lines indicate the corresponding model predictions.

Next, the temperature exponent m is calibrated based on the thermal softening observed in the plastic behavior at 180°C and 480°C at the reference strain rate (Table 1). Finally, the temperature dependence of the strain rate hardening parameter C is calibrated by considering the increase in the yield strength with respect to strain rate, for each test temperature considered (Table 2). The temperature dependence of C is approximated using a second order polynomial fit to the obtained experimental data.

4.2.2. Model validation
Figs. 4a and 4b (left panel) present a comparison between the experimental results and model predictions for different temperatures and strain rates considered. Recall that all true stress-strain curves at the
reference strain rate of 0.1/s have been used to calibrate the change in shape of the plasticity response. Similarly, a pair of true stress-strain curves at two different strain rates (0.1/s and 2/s) for each temperature are used to calibrate the model. Therefore the shape of the hardening behavior for different temperatures at a strain rate of 2/s, and the temperature dependent softening response can be considered to be validation cases for the proposed model. A good overall match between the experimental and predicted true stress-strain curves up to maximum force is obtained. The plasticity model considered is capable of accurately predicting the change in shape of the hardening response with temperature, at a strain rate of 2/s. 3D plots of the hardening behavior of AA7075-W for different test temperatures and strain rates of 0.1 and 2/s are presented in Figs. 4a and 4b (right panel), respectively. These plots clearly illustrate a transition from Swift hardening at 180°C to Voce hardening at 480°C for both strain rates considered.

Table 1. Mixed Swift-Voce hardening and Johnson-Cook model parameters for AA7075-W

| A [MPa] | $\epsilon_0$ [-] | n [-] | $k_0$ [MPa] | Q [MPa] | $\beta$ [-] | $\dot{\epsilon}_0$ [1/s] | $T_r$ [°C] | $T_m$ [°C] | m [-] |
|---------|-----------------|------|-------------|---------|-------------|-----------------|-----------|--------|-------|
| 527.2   | 0.006           | 0.2235 | 89.7       | 83.7     | 1337.2      | 0.1             | 180       | 635    | 0.93  |

Table 2. Values of parameters $\alpha$ and $C$ for different test temperatures.

| 180°C | 240°C | 300°C | 360°C | 420°C | 480°C |
|-------|-------|-------|-------|-------|-------|
| $\alpha$ | 1     | 0.926 | 0.834 | 0.355 | 0.227 | 0     |
| $C$    | 0     | 0.016 | 0.017 | 0.082 | 0.107 | 0.157 |

4.3. Discussion

From Fig. 4a, it is observed that the proposed plasticity model does not correctly predict the hardening response for a test temperature of 360°C at the reference strain rate. However, the model provides a good estimate of the thermal softening experienced by the UT specimen for all other test temperatures, as well as for a higher value of strain rate.

Further, from Fig. 4b, there is a mismatch between the experimental and predicted true stress-strain curves at larger values of true strain for a test temperature of 300°C and strain rate of 2/s. This is because the weighting parameter $\alpha$ is considered to be independent of the strain rate. A possible way to improve the prediction would be to calibrate $\alpha$ for different temperatures at the higher value of strain rate considered in the present study (2/s) and obtain $\alpha$ across the range of strain rates considered.

Lastly, the plasticity model used in the present study is not used to predict the post-necking response of the material. It should be noted that for test temperatures ≥300°C, the material undergoes considerable post-necking deformation before final fracture. Capturing this behavior is therefore essential will be the subject of further work. The present study serves as a basis to investigate further the plasticity and fracture response of AA7075 in the W temper condition for hot stamping applications.

5. Conclusions

The objective of the present investigation is to study the strain rate and temperature dependent plasticity of AA7075 for hot forming applications. The main conclusions are:

- Reliable experimental stress-strain data is obtained to characterize the plastic behavior of AA7075 in the W temper condition over a range of strain rates from 0.001/s to 2/s and test temperatures in the range of 180-480°C.
- An empirical mixed Swift-Voce hardening law with Johnson-Cook type strain rate and temperature dependence captures the plastic response up to onset of necking with good accuracy.
- It is necessary to introduced the temperature dependence of the weighting parameter $\alpha$ and strain rate dependent hardening parameter $C$ of the Johnson-Cook model to obtain reasonable agreement with the experimental results.

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