WARM FORMING CHARACTERISTICS OF AA7050-T6

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Abstract. The formability of AA7050 aluminum alloy sheet is characterized under isothermal forming conditions at room temperature and 150 °C. The material was tested in the T6 condition. Nakazima limiting dome height (LDH) tests in conjunction with stereoscopic digital image correlation (DIC) strain measurements are used for the formability assessment. Four-point forming limit curves (FLCs) were developed at the two test temperatures. AA7050-T6 is shown to respond positively to elevated temperature forming with a 0.19 major true limit strain for a 76.2 mm Nakazima specimen, for example, compared to 0.13 at room temperature. The current results for AA7050-T6 are compared to the formability of AA7075-T6 alloy tested under similar conditions; a slightly higher formability was observed for the AA7075-T6 alloy at the elevated temperature.

1. Introduction

The strength-to-weight ratio of aluminum alloys has made them an appealing option for weight reduction in various industrial applications. Recently, 7000-series age-hardenable aluminum alloys, which are more commonly used in the aerospace industry, have attracted attention in the automotive industry due to their considerably higher strengths compared to 6000- and 5000-series alloys [1] [2].

Previously, it has been shown that high strength aluminum alloys exhibit limited formability characteristics at room temperature, making them incompatible for complex industrial forming processes [3] [4]. Warm forming is often used to increase the formability of aluminum alloys; however, 7000-series alloys are susceptible to over-aging at temperatures above 200 °C resulting in precipitate coarsening and loss of strength and ductility [5].

The current study looks to build upon the growing research around warm forming of 7000-series alloys by investigating the warm formability of sheet aluminum alloy AA7050. This alloy is currently a candidate for application in high strength automotive structures. In this work, the formability of the alloy is characterized under isothermal conditions at room temperature and 150 °C. Formability testing of the alloy was completed following a lab-grade T6 heat treatment schedule, details of which are included in the main body of this manuscript. Constitutive characterization of the alloy in the T6 temper was completed in the 0°, 45°, and 90° directions of the sheet metal relative to the rolling direction at room temperature. Formability was evaluated using the ISO12004:2-2008 standard [6], given its wide
understanding and application within the forming community. Finally, the formability of the AA7050-T6 alloy is compared with that of AA7075-T6 for one of the loading conditions.

2. Material
The principal material under study in the current work is AA7050 aluminum alloy sheet, with a nominal thickness of 2.0 mm and nominal composition listed in Table 1. The nominal composition of the commercial AA7075-T6 (2.0 mm) alloy used for comparison purposes in this work is also included in Table 1. The primary composition differences between the two alloys lie in the higher Zr and lower Cr content of AA7050 relative to AA7075.

| Alloy | Zn  | Mg  | Cu   | Fe  | Si   | Zr   | Cr   | Mn | Ti | Other | Al- |
|-------|-----|-----|------|-----|------|------|------|----|----|-------|-----|
| 7050  | 5.7-6.7 | 1.9-2.6 | 2.0-2.6 | <0.15 | <0.12 | 0.08-0.15 | <0.04 | <0.1 | <0.06 | <0.15 Total | Bal |
| 7075  | 5.1-6.1 | 2.1-2.9 | 1.2-2.0 | <0.5  | <0.4  | -    | 0.18-0.28 | <0.3 | <0.2 | <0.15 Total | Bal |

The alloy was received in the annealed condition. Prior to formability assessment, the material was subjected to a heat-treatment cycle meant to produce a lab-grade T6 condition [8]. The basic heat-treatment cycle entailed solutionizing the alloy at approximately 470°C, water-quenching and artificially aging the alloy at 120 °C for 24 hours. This heat-treatment cycle was done on a per-specimen basis, using a convection furnace. Figure 1 provides a schematic of the heat-treatment process, with a sample thermal-history for the solutionizing treatment. The time to reach the solutionizing temperature was approximately 8 to 11 min (depending on the mass of the specimen) and the time at the solutionizing temperature was 8 min. Boulis et al. [9] examined the influence of time at solutionizing temperature and found that longer times at solutionizing temperature did not result in a change in hardness after T6 treatment (which was 189 HV with an indenter mass of 1000 grams), indicating that the minimum time period of 5 min was sufficient to solutionize the alloy.
3. Methodology

3.1. Tensile Results
Tensile testing of the AA7050-T6 alloy was completed in the 0°, 45°, and 90° directions of the sheet metal relative to the rolling direction at a nominal strain rate of 0.01/s on an MTS Criterion Model 45 Tensile Frame. Testing in the rolling direction (RD) of the AA7075-T6 sheet was also completed. All tensile specimens were full-size ASTM E8 specimens with a gauge length of 50 mm and critical section width of 12.7 mm.

All tensile testing was completed with \textit{in situ} stereoscopic digital image correlation (DIC) measurement of strain. The image acquisition and DIC analysis software used in all of the mechanical testing were Vic Snap 8 and Vic 3D 8 [10]. In all DIC assisted testing, specimens were painted with a random speckle pattern of white base and random black speckle. During tensile testing, a pair of 180 mm focal length lenses were used for image acquisition and were operated at a frame rate of 50 frames per
second, yielding approximately 400 or more images of deformation per tensile test. In DIC analysis, a step size of 3 pixels, a subset size of 29 to 35 pixels, and a strain filter size of 5 pixels were used in the Vic 3D 8 software. DiCecco et al. [4] expand on the role of these settings in localized strain measurements; however, their influence in extracting tensile strains over large gauge lengths, as in the current work, is less significant. An AMD 2990wx-equipped computer was used for DIC analysis, to use core-count to reduce DIC processing time.

Tensile strains along the length and width of each tensile specimen were obtained using virtual extensometers within the Vic 3D 8 software. The lengths of the length- and width-wise extensometers were approximately 50 mm and 10 mm, respectively. The 10 mm width-wise extensometer is the total useable width afforded by DIC analysis, which is slightly less than the total width of the tensile specimen due to the limitations of the DIC analysis around the specimen edges related to the physical test setup and speckle pattern used for testing.

3.2. Formability Characterization
The formability of the AA7050-T6 alloy was evaluated at room temperature and 150 °C under isothermal conditions. At each temperature, four different geometries were used to capture strain states corresponding to uniaxial tension, plane strain, and biaxial loading conditions. These test geometries are included in Figure 2. All AA7050-T6 specimens were tested with the rolling direction parallel to the length of the test specimens. The uniaxial and plane strain specimen geometries correspond to the ISO12004-2:2008 specifications [6] and are referred to herein as dog-bone type specimens.

![Figure 2. Formability specimen geometries](image-url)
Formability testing was completed with a 100 mm diameter hemispherical, Nakazima-type, punch. At 150 °C, the punch was operated at 1.0 mm/s and a flat Nakazima die-set was used for clamping the specimens in place. A clamping load of 300 kN was used during testing and no apparent draw-in was observed for any specimens. During room temperature testing, a flat Nakazima die-set was utilized for clamping, however, a larger clamping load of 640 kN was used to ensure draw-in was prevented as lower formability was expected. For friction reduction purposes, polytetrafluoroethene sheets with layered petroleum-jelly were used at room temperature, whereas only polytetrafluoroethene sheets were used at 150 °C. A schematic of the warm forming press and a photo of the DIC image acquisition setup is included in Figure 3.

All dome specimens were speckled using a white base and random black speckle for DIC analysis purposes. A pair of 17 mm focal length cameras were used for image acquisition and were operated at a frame rate of approximately 20 frames per second. The DIC analysis parameters used for the formability tests were identical to those used in tensile testing. The camera and limiting dome height (LDH) setup used in this work resulted in a pixel density of approximately 11 pixels/mm.

The ISO12004-2:2008 standard was used for limit strain computation and forming limit diagram (FLD) development. Although the ISO approach was not developed for elevated temperature limit strain determination, it was selected for this work due to its simplicity and extensive use within the forming community; thus, allowing for a better comparison with historical forming limit results.

A limited number of dome tests were completed with the AA7075-T6 alloy under identical conditions to those used during testing of the AA7050-T6 alloy for comparison purposes. The AA7075-T6 samples were only tested using the 76.2 mm dog-bone specimen. For the AA7075-T6 specimens, the rolling direction of the sheet metal was perpendicular to the length of the specimens.

4. Results and Discussion

4.1. Tensile Properties

Representative engineering stress-strain curves for the AA7050-T6 and AA7075-T6 alloys along the rolling direction (RD) are shown in Figure 4 (the testing to-date has considered only room temperature constitutive characterization – elevated temperature testing will be performed in the near future). The two alloys have almost identical stress-strain curves, with the AA7075-T6 alloy having an ultimate tensile strength of approximately 573 MPa and the AA7050 alloy 574 MPa. Furthermore, the yield stress (obtained using the 0.2% offset method) and uniform elongation of AA7050-T6 and AA7075-T6 (from a representative sample) alloys were found to be 519 MPa and 0.123, and 515 MPa and 0.114, respectively.
Limited anisotropy characterization was completed for the AA7050-T6 alloy, with Lankford coefficients (R-values) and stress-ratios computed for the three tested directions. In this work, Lankford coefficients were calculated over a range of 0.02 to 0.06 tensile plastic strain (logarithmic). Stress-ratios are defined as the stress in each direction normalized by the stress in the rolling direction at a pre-defined plastic work level (50 MJ/m$^3$) near that of the ultimate tensile strength in the rolling direction. A summary of the Lankford values and stress-ratios is included in Figure 5. Note that the material exhibits significant plastic strain anisotropy along the 45° direction.

Figure 6 displays the major and minor strain paths leading to failure for each loading condition for the AA7050-T6 alloy corresponding to each testing temperature. The AA7050-T6 material shows a significant increase in formability with the increase in forming temperature: (i) 37% for uniaxial conditions; (ii) 53% intermediate tensile; (iii) 48% for plane strain; and (iii) 69% for biaxial loading conditions.

The two alloys are compared in Figure 7, from which it can be seen that the AA7075-T6 alloy exhibits a slightly higher forming limit strain of 0.21 versus 0.19 for AA7075-T6 (an increase of 8%) at elevated temperature. It is noted that the AA7050-T6 alloy was tested in the rolling direction, following the ISO12004-2:2008 recommendations, while the AA7075-T6 was tested in the transverse (90°) direction. The AA7075-T6 test orientation was determined based on earlier testing in which it was determined that the TD direction corresponds to the lower ductility condition. Future work will address test orientation effects for the AA7050-T6 sheet.
It is noted that visible surface roughening, known as orange-peeling, was observed on the as-tested AA7050-T6 specimens, as shown in Figure 8. This effect may be due to a larger grain size and will be further examined in future work.

![Figure 8. The orange-peeling effect on the punch side of the as-formed AA7050-T6 specimens](image)

5. Conclusion
The formability of AA7050-T6 has been experimentally characterized at two temperatures, RT and 150°C. It was shown that elevated temperature forming results in a noticeable improvement in the formability of the AA7050-T6 specimens (37%–69% increase in formability). This study was done at temperatures lower than 200°C, above which similar alloys have shown noticeable precipitate coarsening due to over-aging. The current AA7050-T6 specimens exhibited similar strength and elongation, but somewhat lower (8%) formability relative to AA7075-T6.

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