

Plastic flow of AA6013-T6 at elevated temperatures and subsequent reaging to regain full strength

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Abstract

Combining a retrogression heat treatment with simultaneous warm forming can increase the formability of peak-aged, high-strength aluminum alloys while allowing peak-aged strength to be recovered through a single reaging heat treatment after forming. This process is termed retrogression-forming-and-reaging (RFRA). This study investigates the applicability of RFRA to AA6013-T6 sheet material. Elevated-temperature tensile tests were performed at temperatures from 230 to 250 °C and strain rates from 3.2×10^{-3} to 10^{-1} s^{-1} . Tensile tests were followed by reaging with a simulated paint-bake heat treatment. Flow stress at a true strain of 0.10 ranges from 230 MPa (250 °C and $3.2 \times 10^{-3} \text{ s}^{-1}$) to 290 MPa (230 °C and 10^{-1} s^{-1}), significantly lower than the room-temperature yield strength of 360 MPa in the T6 condition. The average elongation to rupture and reduction in area from elevated-temperature tests are 22 % and 56 %, respectively, which are similar to the room-temperature values for the T4 condition. Elevated-temperature testing reduced material hardness compared to the original T6 condition. Subsequent reaging with a simulated paint-bake raised hardness to 96 % of the T6 condition in un-deformed material, but slightly decreased the hardness of the deformed material. Recommendations for implementing RFRA of AA6013-T6 are presented.

Keywords: Retrogression, Forming, High-strength, Aluminum, AA6013

I. Introduction

High-strength aluminum alloys have a potential to reduce the overall mass of vehicles without compromising safety performance [1-9]. This results from a unique combination of high strength and low density [7-9]. Current automotive body structures typically use 5xxx and 6xxx-series aluminum alloys because of their low cost and high stress-corrosion cracking resistance [10]. Examples applications include outer body panels for the Ford F150 [11] and the Cadillac CTS-V [12]. The 6xxx series aluminum alloy AA6013 is unique because it contains a copper alloying addition, which provides the alloy with a high strength among 6xxx-series materials [13]. AA6013 is typically produced and formed in the T4 temper, which is more ductile than the T6 condition but has a lower yield strength, 210 versus 360 MPa [13]. Table 1 reports the room-temperature tensile properties of AA6013 measured in this study for the T4 and T6 tempers. The typical values reported by the supplier are provided in Table 1 within parentheses.

Table 1. The room-temperature tensile properties measured for AA6013 in the T4 and T6 tempers are reported with typical values reported by the supplier in parentheses [13]

Temper	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation to rupture (%)	Reduction in area (%)	Hardness (HRB)
T4	210 (185 typ.)	380 (325 typ.)	21 (24 typ.)	39	68.0
T6	360 (370 typ.)	420 (405 typ.)	14 (9 typ.)	37	48.6

Retrogression forming and reaging (RFRA), first proposed by Ivanoff *et al.* for AA7075 [14], might be a possible means of producing AA6013 components that have the strength of the T6 temper but the formability of the T4 temper. Retrogression forming [14-15] combines a retrogression heat treatment [16-17] with simultaneous warm forming. A subsequent reaging step can recover the strength lost during forming [14-15]. Previous work demonstrated the

feasibility of RFRA for the high-strength aluminum alloy AA7075-T6 [14-15]. However, an alloy such as AA6013-T6 may offer some advantages over AA7075-T6 for automotive applications because of its improved stress-corrosion cracking resistance and lower cost [13]. Despite having a very different precipitate structure than AA7075-T6, AA6013-T6 exhibits retrogression-reaging behavior [18], as shown by the hardness data in Figure 1. Whereas retrogression of AA7075-T6 is characterized by reactions such as the dissolution of η' precipitates [19], retrogression of AA6013-T6 may be associated with the dissolution of β'' phase precipitates [18, 20]. The retrogression heat treatment is bound by the maximum time that the material may be at elevated temperature before the hardness or strength loss during retrogression is greater than what can be recovered through subsequent reaging. This maximum retrogression time decreases as retrogression temperature increases [17-19]. The maximum time that AA6013-T6 can be allowed to retrogress at 240 °C is approximately 10 minutes [18]. A subsequent reaging heat treatment of 190 °C for 1 hour was previously determined to fully recover hardness loss from retrogression under those conditions [18]. This study expands on that prior work by adding simultaneous deformation during retrogression to investigate the potential to apply RFRA to AA6013-T6 sheet. The elevated-temperature tensile behavior of AA6013-T6 is compared to the room-temperature tensile behavior of AA6013-T4 to determine if the recommended retrogression temperature, 240 °C, provides sufficient ductility for forming. The potential for a single reaging heat treatment to recover the strength lost during retrogression with simultaneous plastic deformation, as experienced in retrogression forming, is then investigated.

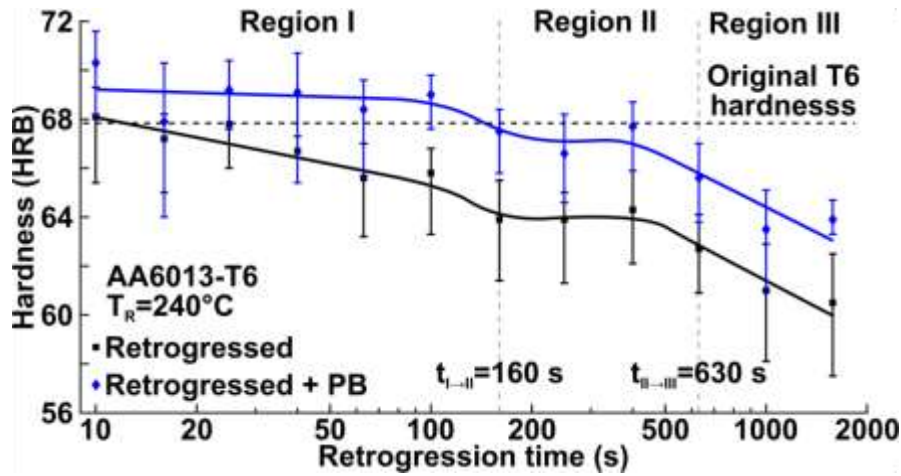


Figure 1. Room-temperature hardness of AA6013, originally in the T6 condition, is plotted as a function of retrogression time at 240 °C. The increase in hardness after a subsequent reaging heat treatment (PB indicates a simulated paint-bake reaging treatment) demonstrates that AA6013-T6 exhibits retrogression-reaging behavior.

II. Experimental procedure

A. Material

Sheets of 2-mm thick AA6013 aluminum alloy produced by Alcoa™ in the T4 condition were studied. The alloy limits of the material according to the manufacturer, in wt %, are listed in Table 2. The sheets were sheared to produce 300×300×2 mm blanks for heat treating. These blanks were solutionized in a box furnace at 570 °C for 1 hour and immediately water quenched [13]. The blanks were lightly rolled in the W temper to reduce warping and were then aged at 190 °C for 4 hours to the T6 temper [13]. Each sheet was aged within one day of being solutionized. Tensile specimens with a modified ASTM E2448 geometry [21] were machined by water-jet from the AA6013-T6 blanks.

Table 2. The alloy limits of AA6013 aluminum, in wt %, according to the manufacturer

Mg	Cu	Si	Mn	Fe	Zn	Cr	Ti	Al
0.8 to 1.2	0.6 to 1.1	0.6 to 1.0	0.2 to 0.8	≤ 0.5	≤ 0.25	≤ 0.1	≤ 0.1	Balance

B. Tensile tests

Elevated-temperature tensile tests were performed at three different temperatures: 230, 240, and 250 °C. These tests used a computer-controlled, servohydraulic test frame controlled to provide constant true-strain rates. Prior to testing, each specimen was placed in pre-heated Alloy 600 grips inside of a convection furnace, shown in Figure 2. The temperature of each specimen was monitored using two independent K-type thermocouples, one at each grip. Once a specimen reached the desired test temperature, it was held at that temperature for a designated hold time prior to starting the tensile test. The hold time for each test was chosen so that the total reduced time [14-15, 18] experienced by each specimen was identical at $\tau = 6 \times 10^{-15}$ s. Reduced time is calculated from a simple Arrhenius relationship that accounts for retrogression time and temperature:

$$\tau = t_R \times e^{(-Q/RT_R)} \quad (1)$$

where τ is reduced time, in seconds; t_R is retrogression time, in seconds; Q is the activation energy of retrogression in AA6013-T6 (160 kJ/mol [18]); R is the universal gas constant, in kJ/mol·K; and T_R is retrogression temperature (i.e. the testing temperature), in Kelvin [14-15, 18]. The reduced time specified for the design of tensile tests was sufficiently short to ensure full hardness recovery with subsequent reaging [18]. The range of true-strain rates studied is

3.2×10^{-3} to 10^{-1} s^{-1} . Each specimen was loaded in uniaxial tension until rupture and was then immediately removed and water-quenched.

Room-temperature tensile tests were conducted in a screw-driven, computer-controlled universal testing machine at a constant cross-head rate. Strain was measured using a clip-on extensometer. The results from room-temperature tensile tests are reported in Table 1.



Figure 2. Specimens were pulled at elevated temperatures in uniaxial tension until rupture using the test frame shown here. Specimens were loaded in the grips and heated within the convection furnace.

C. Reaging study

The Rockwell B hardness of each specimen was measured both before and after elevated-temperature tensile tests using an Instron™ Wilson Rockwell Series 2000 hardness tester. Prior to testing, hardness was measured at least three times in both grip sections of each

tensile specimens. After testing, hardness was measured three times in both grip sections of every ruptured tensile specimen and four times in the gauge region, taking care to avoid any necked regions. Within one day of testing, one half of each ruptured tensile specimen was reaged with a simulated paint-bake heat treatment of 185 °C for 25 minutes. The Rockwell B hardness was then measured after the simulated paint-bake heat treatment. Hardness was measured three times in the grip region and two times in the gauge region, taking care to avoid any necked region. The hardness of the original T6 condition was measured as 68.0 HRB, and the hardness of the T4 condition was measured as 48.6 HRB.

III. Results and discussion

A. Elevated-temperature tensile tests

Figure 3 shows flow stress measured at a true strain of 0.10 as a function of true strain rate for the three temperatures studied: 230, 240, and 250 °C. As temperature increases, the flow stress measured decreases. All the flow stresses measured are less than the room-temperature yield strength measured for AA6013-T6, 360 MPa, but are greater than the room-temperature yield strength measured for AA6013-T4, 210 MPa. Forming AA6013-T6 at elevated temperatures will thus reduce the force required to stamp components compared to forming at room-temperature. The low flow stress of AA6013-T6 material at 230 to 250 °C, approximately one-third less than that at room temperature, results from a combination of thermally activated recovery processes that reduce strain hardening and the partial dissolution of strengthening precipitates as retrogression proceeds. The smallest flow stress measured is 230 MPa, which occurred at 250 °C and a true strain rate of $3.2 \times 10^{-3} \text{ s}^{-1}$. This flow stress is only 10 % greater than the room-temperature yield strength measured for AA6013-T4 but is 40 % less than the tensile strength measured for AA6013-T4 at room temperature. Compared to room-temperature

forming in the T4 condition, elevated-temperature forming in the T6 condition will require approximately equal or less force. The strain rate sensitivity, m , was measured at each elevated temperature in Figure 3. Its values, reported in Figure 3, are small but positive. This is another indication of thermally activated recovery, which increases m sufficiently to be measurable but is yet insufficient to transition flow into classical creep mechanisms, which typically have m values of 0.2 and higher [22-24]. Because the strain rate sensitivities measured are too low to slow flow localization significantly, the increase in tensile ductility is likely from a change in rupture from shear fracture at room temperature to a more ductile fracture at elevated temperatures. This hypothesis is supported by visual comparison of the tensile specimens pulled at elevated temperature versus room temperature.

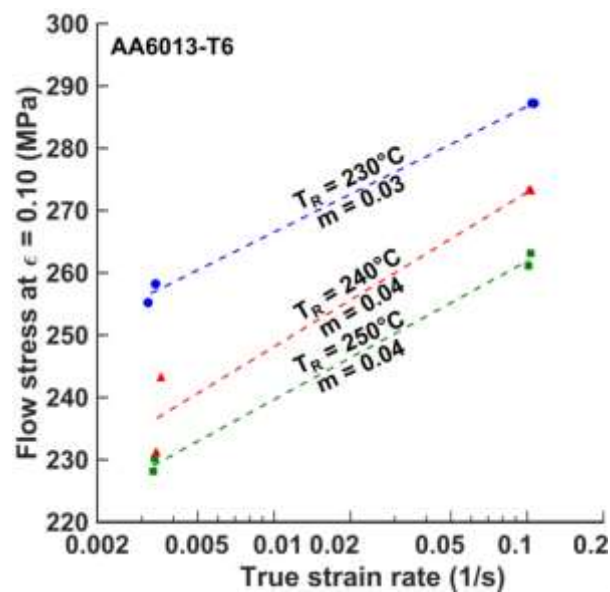


Figure 3. Flow stress measured at a true strain of $\epsilon = 0.10$ is plotted as a function of true strain rate at three different temperatures. The strain rate sensitivity, m , measured at each temperature is reported.

Figure 4 reports elongations to rupture measured at 230, 240, and 250 °C as a function of true-strain rate. The elongation to rupture of AA6013-T6 increases from 14 % at room temperature to 21 % at elevated temperature, on average. This ductility is approximately the

same as the room-temperature elongation to rupture measured for AA6013-T4, also 21 % (see Table 1). Elongation-to-rupture does not appear to correlate with either strain rate or temperature across the test conditions studied. The scatter of data for elongation-to-rupture is from 18.6 % to 26.3 %.

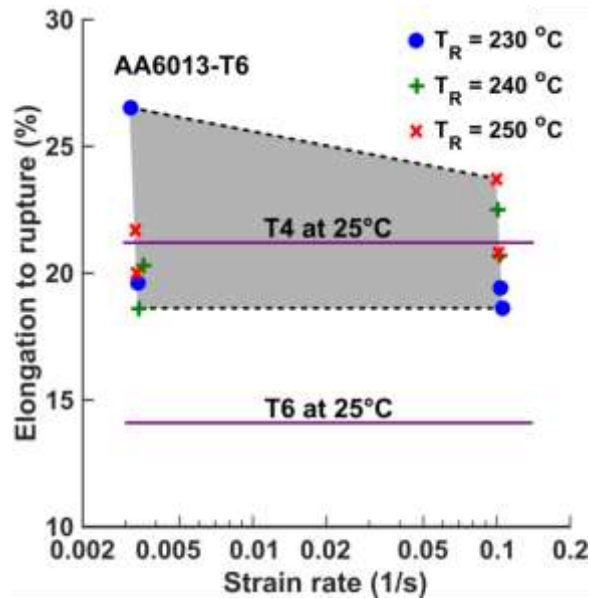


Figure 4. Elongation to rupture is plotted as a function of true-strain rate for four different temperatures. Elongation to rupture measured for AA6013-T6 at 230, 240, and 250 °C is indicated by the markers and is bounded by the dashed lines. The grey area indicates the scatter in these data. Elongations to rupture measured for AA6013-T6 and AA6013-T4 at room temperature, 25 °C, are indicated by the solid lines.

Figure 5 reports another measure of ductility, reduction in area, which was measured from specimens tested at 230, 240, and 250 °C. Reduction in area is plotted as a function of true-strain rate. It does not present any clear trend with temperature across the range of elevated-temperature test conditions studied, but it appears to generally decrease with increasing strain rate. Reduction in area ranges from 52.9 to 62.2 %, with an average of 56.4 % across the elevated-temperature test conditions. This is significantly greater than the room-temperature reduction in areas measured for AA6013-T4, 39 %, and AA6013-T6, 37 % (see

Table 1). This result supports the idea that elevated temperature increases the tensile ductility of AA6013-T6 by transitioning rupture from a more brittle to a less brittle mode.

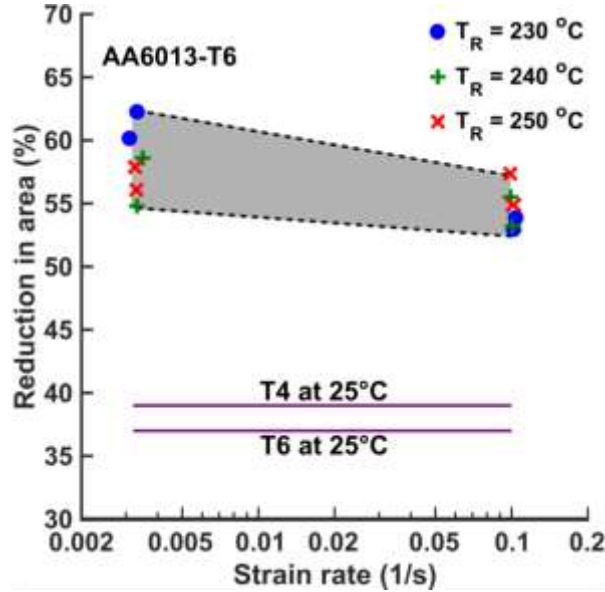


Figure 5. Reduction in area is plotted as a function of true strain rate for four different temperatures. Reduction in area measured from tensile specimens of AA6013-T6 tested at 230, 240, and 250 °C is indicated by markers and bound by dashed lines. The grey area indicates the scatter in these data. Reductions in area measured at room temperature, 25 °C, for AA6013-T6 and AA6013-T4 are indicated by the solid lines.

B. Reaging study

After testing, the average hardness values in the un-deformed grip regions and deformed gauge regions were 64.3 and 62.4 HRB, respectively. Although the hold time at temperature prior to tensile straining was controlled to keep reduced time constant for all elevated-temperature tensile tests, the average as-tested hardness of the ruptured specimens in the un-deformed grip region decreased slightly with increasing temperature, from 65.4 HRB at 230 °C to 63.2 HRB at 250 °C. The simulated paint-bake heat treatment of 185 °C for 25 minutes increased the average hardness of the ruptured specimens in the un-deformed grip region to 66.0 HRB, which is 3 % less than the original T6 hardness, 68.0 HRB. However, the

same simulated paint-bake decreased the average hardness of the ruptured specimens in the deformed gauge region to 61.0 HRB, which is 10 % less than the original T6 hardness. This suggests that simultaneous plastic deformation during a retrogression heat treatment negatively affects the ability of a subsequent reaging heat treatment to recover strength. Regardless, the hardness values throughout the ruptured specimens after the simulated paint-bake heat treatment are significantly greater than the room-temperature hardness of AA6013-T4, 48.6 HRB.

IV. Conclusions

Specimens of high-strength aluminum alloy AA6013-T6 were tested in uniaxial tension until rupture at temperatures from 230 to 250 °C and strain rates from 3.2×10^{-3} to 10^{-1} s^{-1} , which are conditions of interest for retrogression forming. After tensile testing, specimens were reaged with a simulated paint-bake heat treatment of 185 °C for 25 minutes. The data produced lead to the following conclusions:

1. The flow stresses measured at a true strain of 0.10 range from 230 MPa at 250 °C and $3.2 \times 10^{-3} \text{ s}^{-1}$ to 290 MPa at 230 °C and 10^{-1} s^{-1} . These stresses are considerably less than the yield strength of AA6013-T6 measured at room temperature, 360 MPa.
2. The average elongation to rupture at elevated temperature is 21 % and did not vary significantly from 230 to 250 °C or with strain rate. The elongation to rupture of AA6013-T6 at elevated temperature is significantly greater than at room temperature, 14 %, and is comparable to the room-temperature elongation of AA6013-T4, 21 %. The average reduction in area measured is 56.4 %, which is significantly greater than the room-temperature reduction in area for both AA6013-T4 and AA6013-T6, 39 % and 37 %, respectively.

3. After a simulated paint-bake heat treatment of 185 °C for 25 minutes, the average hardness of the un-deformed grip regions in specimens tested in tension at elevated temperature increased to within 4 % of the original T6 hardness. The same simulated paint-bake heat treatment was not effective for recovering the hardness in the deformed specimen gauge region.

V. Acknowledgements

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