Review of Retrogression Forming and Reaging for AA7075-T6 Sheet

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Abstract

Retrogression forming and reaging (RFRA) is a new warm-forming process designed to produce automotive structural components from high-strength aluminum alloys. A scientific approach is described to determine appropriate RFRA conditions for AA7075-T6 and is applied to laboratory-scale forming experiments. The concept of reduced time is used with the activation energy of retrogression measured for AA7075-T6 to predict appropriate times and temperatures for retrogression forming. Conditions recommended for AA7075-T6 are retrogression at 200 °C for 3 to 12 min while forming at strain rates of up to 10^{-1} s^{-1}. The recommended reaging heat treatment to fully restore strength to the T6 condition after retrogression forming is 120 °C for 24 h. These RFRA conditions were successfully applied in laboratory-scale experiments to form AA7075-T6 Alclad sheet and produce a final strength equivalent to the T6 condition. Data from tensile tests provide flow stresses and tensile ductilities across the range of conditions appropriate for RFRA.

Keywords: Retrogression; Warm-forming; AA7075; Aluminum

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Introduction

High strength aluminum alloys (HSAAs), such as the precipitation strengthened AA7xxx-series aluminum alloys, are of interest to the automotive industry for their unique combination of high strength and low density. This makes them potential replacements for heavier ferrous alloys used in automotive structural applications, such as door beams and B-pillars [1-6]. AA7075-T6, in particular, is attractive because of its high yield strength, 500 MPa, and low density compared to steel (2.8 g/cm^3 and 7.7 g/cm^3, respectively) [7-8]. One of the barriers to implementation of these alloys is their poor formability [1-6]. Conventional cold stamping is not possible because HSAAs have low room-temperature ductility in the peak-aged T6 temper. For example, the typical room-temperature tensile elongation of AA7075-T6 is 11 % [7]. Superplastic forming (SPF) and quick-plastic forming (QPF) are two elevated-temperature forming processes that can achieve substantial tensile elongation in aluminum alloys [6, 9-10]. However, these forming processes can only be applied to a limited number of alloys that do not include AA7075 [6, 11]. Hot forming at temperatures at or near 500 °C can produce large elongations in AA7075 and achieve complex components with high strength, after subsequent heat treatments [3, 12]. However, hot forming presents difficulties with material handling, quench sensitivity, and required heat treatments [6].

Retrogression forming and reaging (RFRA) is a new forming technique that addresses the challenges to forming AA7075 sheet. RFRA is specifically designed to produce automotive structural components from HSAAs by combining retrogression and reaging (RRA) with simultaneous warm forming [13-16]. During the first step, retrogression forming, a sheet that is already in the peak-aged T6 temper is warm formed to increase ductility and induce retrogression. Previous work demonstrated that a warm temperature of 200 °C can sufficiently increase tensile ductility to produce automotive structural components [1, 11, 17]. After retrogression forming, a single reaging heat treatment is applied to the fully-formed component to restore strength to that of the T6 temper.

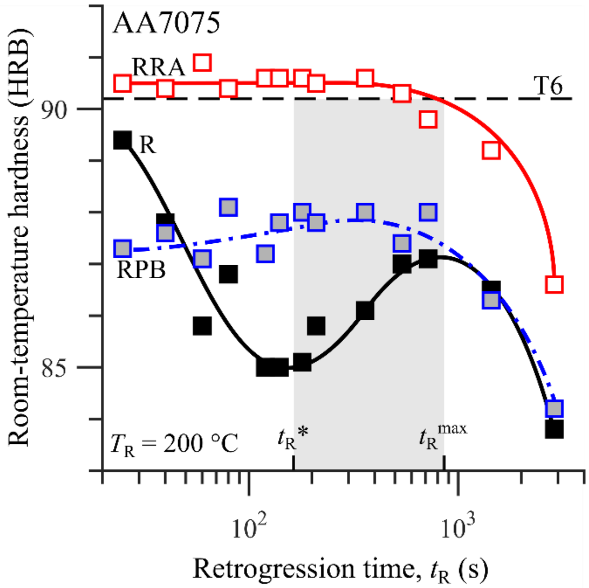

Figure 1. Room-temperature hardness data of AA7075-T6 after retrogression at 200 °C are plotted against retrogression time, t_R, on a logarithmic scale and are labelled R. The original T6 hardness is indicated by the horizontal dashed line labelled T6. The first and second critical retrogression times, t_R* and t_R^{max}, are identified. Room-temperature hardness data after retrogression and then reaging with a simulated paint-bake are labelled RPB. Room-temperature hardness data after retrogression and then reaging with the recommended reaging heat treatment are labelled RRA.

RRA is a two-step heat treatment process originally developed to improve the stress-corrosion-cracking resistance of AA7075-T6 [18-19]. During the first step, retrogression, material in the T6 temper is soaked at a temperature between the aging and solutionization temperatures of the alloy. One example of a retrogression heat treatment for AA7075-T6 is 240 °C for 12 s [18-19]. Figure 1 presents the room-temperature hardness of AA7075-T6 after retrogression at 200 °C as a function of retrogression time, t_R, on a logarithmic scale [14]. These data are labelled R in Figure 1. Hardness was measured as a surrogate for strength. As the alloy is retrogressed for increasingly longer times, there is an initial decrease in room-temperature hardness followed by a slight increase in room-temperature hardness. This produces a local minimum in hardness at the first critical retrogression time, t_R*. As retrogression time continues to increase, there is a second decrease in room-temperature hardness. This produces a local maximum in hardness at the second critical retrogression time, t_R^{max}. After the alloy is retrogressed, it is reaged to restore strength equal to or greater than that of the T6 temper. A typical reaging heat treatment for AA7075 is 120 °C for 24 h [13-16, 20]. The data labelled RRA in Figure 1 are for the room-temperature hardness of AA7075 after retrogression at 200 °C and reaging at 120 °C for 24 h as a function of retrogression time. If the alloy is retrogressed for a time shorter than t_R^{max}, then this reaging heat treatment restores or exceeds the T6 hardness. If the alloy is retrogressed for a time longer than t_R^{max}, then there is an unrecoverable loss of hardness during retrogression that cannot be fully restored by reaging.

Retrogression forming is unique in that it is a controlled warm forming process. The retrogression forming processing window spans from t_R^* to t_R^{max}. The first critical retrogression time, t_R^*, is a target time for retrogression forming. However, processing times shorter than t_R^* are acceptable. The second critical retrogression time, t_R^{max}, is the absolute time limit for retrogression forming. Processing times longer than t_R^{max} are not recommended as they will result in an unrecoverable loss of strength. By controlling how long the retrogression forming process lasts, we ensure that a single reaging heat treatment can restore strength in the fully-formed component to that of the T6 temper.

This review of RFRA presents the scientific approach used to determine appropriate RFRA conditions for AA7075-T6 [14-15]. The concept of reduced time is used with the activation energy of retrogression measured for AA7075-T6 to predict appropriate times and temperatures for retrogression forming. The plastic flow behavior of AA7075-T6 at these temperatures is evaluated to determine recommended RFRA conditions. These conditions were applied to produce demonstration parts of Alclad AA7075 with peak strength [16]. These demonstration parts were produced using sheet stamping with a cross-shaped die, which generated deformation modes and strains typical of automotive stamping processes.

Method to determine appropriate RFRA conditions

Differential scanning calorimetry was used to measure an activation energy of retrogression in AA7075-T6 [14]. Round discs of AA7075-T6 were heated at a constant heating rate from 25 to 300 °C. The heating rates studied include 5, 10, 15, 20, and 25 °C/min. An example of the experimental heat flow and specimen temperature data collected during DSC experiments is shown in Figure 2. The data are plotted so that peaks correspond to endothermic reactions. The endothermic peak identified in Figure 2 corresponds with the dissolution of η′ precipitates, which is one of the first reactions to occur during retrogression [21-22]. The temperature at which peak heat flow occurred, *i.e.* peak temperature, T_P, was measured from a third-degree polynomial fit to the data, shown in Figure 2 as a dashed line. In Figure 2, peak temperature is indicated by the vertical gray bar, and the width of the gray bar represents the uncertainty of the measurement.

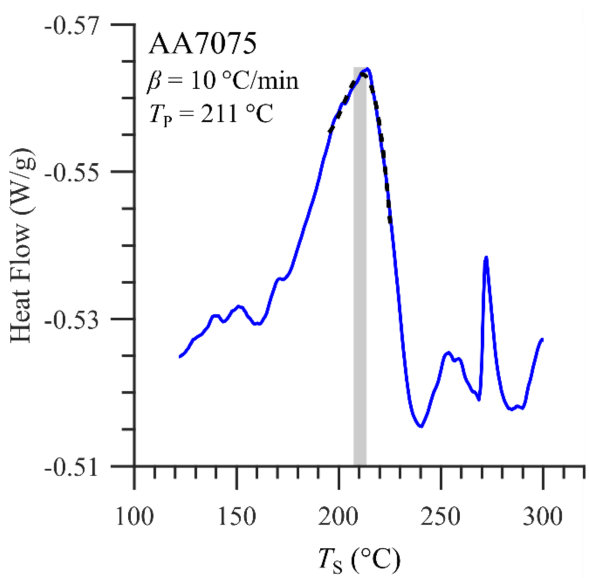

Figure 2. An example of DSC data acquired from a specimen of AA7075-T6 heated at a constant heating rate of 10 °C/min is shown as heat flow normalized by specimen mass as a function of specimen temperature. The temperature at which peak heat flow occurs, termed peak temperature, is identified.

For a given DSC experiment conducted at a constant heating rate, as the heating rate increases, the temperature of the endothermic peak, T_P, also increases [14, 22-23]. Using Equation 1, which was developed by Barczy and Tranta, an activation energy for retrogression is measured from these data, as follows,

$$\ln\left(\frac{T_P - T_0}{\beta}\right) - \frac{Q_R}{R}\frac{1}{T_P} = B \quad , \qquad (1)$$

where T_P is the peak temperature in Kelvin, T_0 is room-temperature, β is the heating rate, Q_R is the activation energy of retrogression, R is the universal gas constant, and B is a material constant [14, 23]. In Figure 3, $\ln\left({(T_P - T_0)}/{\beta}\right)$ is plotted as a function of $1/T_P$ so that the slope of the data equals $-Q_R/R$. From these data, the activation energy of retrogression in AA7075-T6 is measured to be 97 kJ/mol. This activation energy provides a scientific basis for understanding precipitate dissolution during retrogression. It is consistent with the activation energy for precipitate dissolution in Al-Mg-Zn alloys measured by Baldarach *et al.* [24]. According to Park and Ardell, the precipitates relevant to retrogression in AA7075-T6 are η' and η, both of which have the chemical composition Mg_2Zn [21]. The diffusion of a single species, thought to be Zn, is hypothesized to control the complex precipitate reactions that occur during retrogression of AA7075-T6 [13]. By this hypothesis, a single activation energy is sufficient to reasonably characterize the kinetics of the retrogression process.

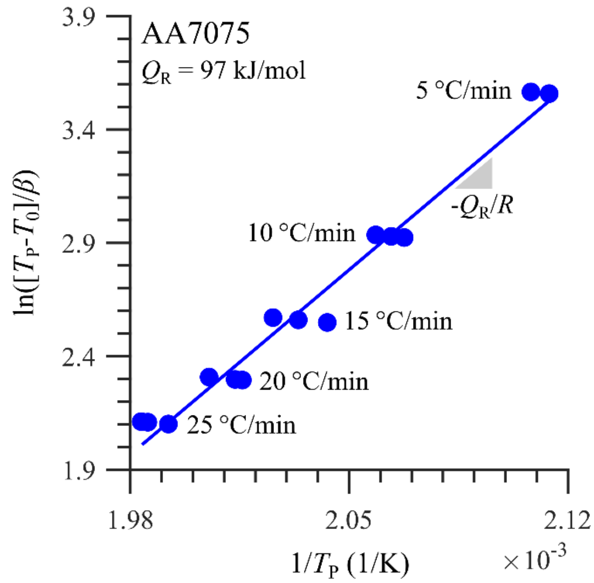

Figure 3. The natural logarithm of $\left({(T_P - T_0)}/{\beta} \right)$ is plotted as a function of the inverse of peak temperature so that the slope of the data equals -Q_R/R, according to the relationship developed by Barczy and Tranta [23]. From these data, the activation energy of retrogression in AA7075-T6 is measured to be 97 kJ/mol.

For retrogression forming of AA7075-T6, the recommended processing window ranges from t_R* to t_R^{max}. While times shorter than t_R* are allowed, times longer than t_R^{max} are not recommended because they will result in an unrecoverable loss of strength during forming. Critical retrogression times, t_R* and t_R^{max}, were measured for AA7075-T6 at several retrogression temperatures using hardness as a surrogate for strength [14]. Square specimens of AA7075-T6 measuring 25×25×2 mm were retrogressed in molten salt at 192, 200, 210, and 220 °C. Specimens were then reaged with either a simulated paint-bake heat treatment of 185 °C for 25 min or the recommended reaging heat treatment of 120 °C for 24 h [13-16, 20, 24-26]. Rockwell B hardness measurements were performed before retrogression, after retrogression, and after reaging to monitor the change in room-temperature hardness [27]. An example of the hardness data collected is shown in Figure 1 [14]. For retrogression times less than t_R^{max}, the recommended reaging heat treatment (120 °C, 24 h) restores hardness to the level of the T6 temper. For retrogression times from t_R*

through t_R^{max}, reaging with a simulated paint-bake heat treatment (185 °C, 25 min) improves hardness but is not as effective as the recommended reaging heat treatment (120 °C, 24 h).

The concept of reduced retrogression time, first proposed by Ivanoff *et al.*, is used to predict combinations of forming temperatures and processing times that are suitable for RFRA [13-14]. Reduced retrogression time is calculated using Equation 2, which uses the activation energy of retrogression to account for retrogression time and retrogression temperature. Equation 2 is as follows,

$$\tau_R = t_R \times \exp\left(-\frac{Q_R}{RT_R}\right) , \qquad (2)$$

where τ_R is reduced retrogression time, t_R is retrogression time, Q_R is the activation energy for retrogression, R is the universal gas constant, and T_R is retrogression temperature [13-14]. When retrogressed hardness is plotted as a function of reduced retrogression time, as shown in Figure 4, the critical retrogression times at different retrogression temperatures align to a single master curve. The critical reduced retrogression times for AA7075-T6 are $\tau_R^* = 2.9\times10^{-9}$ s and $\tau_R^{max} = 1.5\times10^{-8}$ s. From these data, retrogression processing times can be predicted for a range of retrogression temperatures. For example, at 200 °C the retrogression forming window is predicted to span from 3 to 12 min.

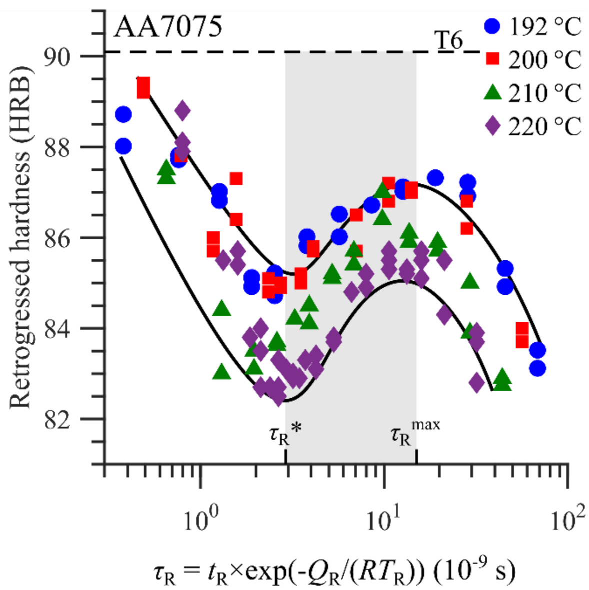

Figure 4. Room-temperature hardness of AA7075-T6 after retrogression is plotted against the logarithm of reduced retrogression time to produce a master curve. The shape and color of the data correspond to retrogression temperature. The original T6 hardness is indicated with the horizontal dashed line labelled T6. The critical reduced retrogression times, τ_R* and τ_R^{max}, are identified.

Elevated-temperature tensile tests were performed to determine the plastic flow behavior of AA7075-T6 at temperatures of interest for retrogression forming [15]. Example engineering stress-strain curves for AA7075-T6 at room-temperature and at 200 °C are shown in Figure 5 [15]. Specimens tested at room-temperature were loaded in uniaxial tension until rupture at a constant engineering strain rate using a screw-driven test machine. Specimens tested at elevated-temperature were loaded in uniaxial tension until rupture at a constant true strain rate using a computer-controlled, servo-hydraulic test machine with a convection furnace mounted to the test frame. The elevated-temperatures studied are 180, 200, and 220 °C. The true-strain rates range from 3.2×10^{-3} to 10^{-1} s^{-1}. In general, flow stress decreases as temperature increases and strain rate decreases. From 25 to 200 °C, tensile strength is reduced by approximately a third. This indicates that forming AA7075-T6 at temperatures around 200 °C will require less force than forming at room-temperature and may result in less spring-back. AA7075-T6 is strain-rate sensitive at the elevated-temperatures studied. However, the average strain-rate-sensitivity measured, m = 0.04, is an order of magnitude smaller than for superplastic materials, which typically have a strain-rate sensitivity of approximately 0.5 or greater [11, 28]. At the fastest true-strain rate studied, two measures of ductility, tensile elongation and reduction in area, approximately double from room-temperature to elevated-temperature. Within 180 to 220 °C, there is no strong correlation between temperature and either measure of ductility. Both measures of ductility increase as true strain-rate decreases.

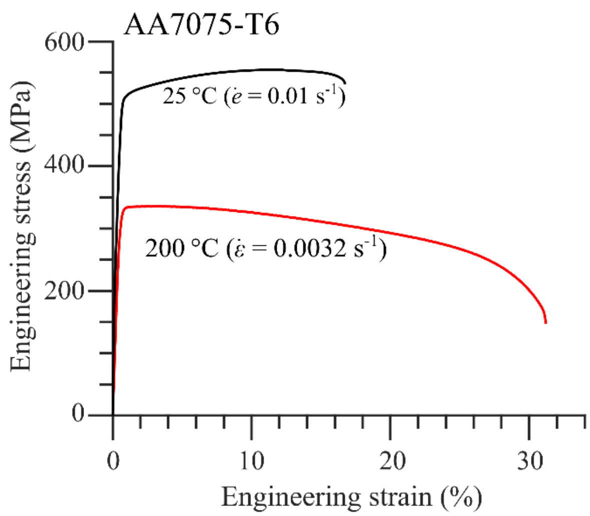

Figure 5. Example engineering stress-strain curves for AA7075-T6 at room-temperature and at 200 °C are shown. Note that from room-temperature to 200 °C, tensile strength nearly halves and tensile elongation nearly doubles.

From these data, retrogression forming of AA7075-T6 at 200 °C and strain rates up to 10^{-1} s^{-1} is recommended. At these conditions, there is sufficient ductility to form automotive structural components of moderate geometric complexity. The retrogression forming processing window at this temperature ranges from 3 to 12 min. While shorter times are acceptable, the retrogression forming process must be completed in less than 12 min to ensure that T6 strength can be restored with a single reaging heat treatment. The recommended reaging heat treatment is 120 °C for 24 h. While the paint-bake may improve strength after retrogression forming, is it not as effective as the recommended reaging heat treatment for AA7075.

The production of demonstration parts by RFRA

Retrogression forming trials were performed using the warm forming facilities available at EWI in Columbus, OH [16]. Sheets of AA7075-T6 Alclad measuring 470×470×1.6 mm were coated in Forge Ease AL 278 lubricant and allowed to air dry prior to forming. Sheets were preheated in an infrared furnace and transferred to a 150-ton forming press using an automated linear transfer system [17.]. Warm sheets at 200 °C were successfully stamped with a cold, cross-shaped die to a depth of 45 mm with no splitting or visible defects at die speeds of both 22.5 mm/s and 5 mm/s. Previous work with the same cross-shaped die demonstrated that AA7075-T6 sheet "shattered" when stamped at room temperature to a depth of less than 25 mm [17]. An example of a demonstration part produced via retrogression forming is shown in Figure 6. Image analysis was performed by EWI to measure local major and minor strains across the surface of the demonstration part. From these data, two locations of interest are identified on the demonstration parts. The first location is the inner sidewalls, labelled A in Figure 6. The largest magnitude strains were measured in these locations, and these far exceed those possible at room-temperature. The second location of interest is the inner corner, labelled B in Figure 6. This location experiences a near plane-strain condition during forming and is where thinning is most severe. This location is where splitting is expected to occur first if sheets were to be stamped to a deeper depth.

Figure 6. A demonstration part of AA7075-T6 Alclad sheet, originally measuring 470×470×1.6 mm, is shown. The white dots etched onto the surface of the demonstration part prior to forming were used to measure local major and minor strains and calculate through-thickness strain using image analysis techniques. Two locations of interest are the inner side-walls, located by red rectangles labelled A, and the inner corner, located by a red circle labelled B.

After retrogression forming, some of the demonstration parts were reaged to restore T6 strength [16]. Tensile specimens were extracted from the demonstration parts to measure tensile strength. During the retrogression forming process, yield strength decreased by 8 %. Reaging with the simulated paint-bake heat treatment of 185 °C for 25 min increased yield strength to 98 % that of the original T6 temper. This is significant because it demonstrates that the automotive paint-bake, which is already a part of the vehicle manufacturing process, may be an effective reaging heat treatment for retrogression formed components of AA7075-T6. Reaging with the recommended reaging heat treatment of 120 °C for 24 h fully restored the strength lost during the retrogression forming process and produced a final yield strength that exceeded that of the original T6 temper by 5 %. These data demonstrate that RFRA can be applied to successfully form AA7075-T6 and produce a final part that exceeds the original strength of the alloy in the T6 temper.

Conclusions

1. A scientific approach was used to determine appropriate retrogression forming and reaging conditions for AA7075-T6. These conditions were successfully applied to produce a demonstration part of AA7075 Alclad sheet that has a strength exceeding that of the original T6 temper.

2. The activation energy of retrogression in AA7075-T6 is Q_R = 97 kJ/mol.

3. The critical reduced retrogression times for AA7075-T6 are τ_R^* = 2.9×10^{-9} s and τ_R^{max} = 1.5×10^{-8} s. These critical reduced times are used to predict retrogression forming processing windows for AA7075-T6.

4. Retrogression forming of AA7075-T6 at 200 °C and strain rates of up to 10^{-1} s^{-1} is recommended. It is recommended that the retrogression forming process be completed in 3 to 12 min. The recommended reaging heat treatment for AA7075 is 120 °C for 24 h.

5. Sheets of AA7075-T6 Alclad measuring 1.6 mm in thickness were stamped to a depth of 45 mm at 200 °C with no splitting or visible defects. This depth is at least 20 mm greater than what can be achieved by room-temperature stamping of this part geometry.

6. RFRA was successfully applied to warm form AA7075-T6 Alclad sheet material and restore T6 strength with a single heat treatment after warm forming.

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