Determining a Retrogression Heat Treatment to Apply During Warm Forming of a High Strength Aluminum AA7075 Sheet Material

Katherine Rader, Thomas Ivanoff, Hyunwook Shin, Jon Carter, Louis Hector, and Eric Taleff

Abstract

Combining retrogression heat treatment with simultaneous warm forming provides an opportunity to significantly increase the formability of high-strength aluminum alloy AA7075-T6 sheet material while subsequently regaining nearly peak-aged strength through a single reaging treatment. This new technological approach to forming high-strength aluminum alloy sheet is termed retrogression forming. Times and temperatures suitable to the retrogression forming of AA7075-T6 sheet material are examined. Differential scanning calorimetry is used to determine the activation energy associated with precipitate dissolution during retrogression. Heat treating experiments determine the changes in hardness during retrogression as a function of temperature and time. The concept of temperature-compensated time is used to construct a master curve that predicts appropriate retrogression forming conditions.

Keywords

Aluminum • Retrogression • Forming • AA7075

K. Rader (✉) · T. Ivanoff · H. Shin · E. Taleff
The University of Texas at Austin, Mechanical Engineering, Austin, TX 78712, USA
e-mail: kate.rader@utexas.edu

T. Ivanoff
e-mail: ivanoff.t@gmail.com

H. Shin
e-mail: paulhwshin@utexas.edu

E. Taleff
e-mail: taleff@utexas.edu

J. Carter · L. Hector
General Motors, Research and Development, MC 480-106-RL1, 30470 Harley Earl Blvd., Warren, MI 48092-2031, USA
e-mail: jon.t.carter@gm.com

L. Hector
e-mail: louis.hector@gm.com

Introduction

Current forming technologies used by the automotive industry are unable to form high-strength aluminum alloys into the complex shapes desired for many automotive structural components without either sacrificing the strength of the alloy or using additional energy-and-time-intensive heat treatments. The objective of this research is to combine the retrogression-reaging (RRA) process with warm forming to explore a new forming technology, "retrogression forming." This approach is expected to improve the formability of high-strength aluminum alloys through warm forming while allowing nearly peak-aged strength to be easily recovered after forming through a simple reaging step.

Retrogression refers to a heat treatment developed in the 1970s to improve the stress-corrosion cracking (SCC) resistance of peak-aged 7000-series aluminum alloys, such as AA7075 [1]. An example of a typical retrogression heat treatment for AA7075-T6 is 240 °C for 30 s [1, 2]. This process has been regularly used in the aerospace industry since then [3]. The benefits of RRA treatment to stress-corrosion cracking resistance arise from changes to precipitate structures at grain boundaries, which are compatible with achieving peak-aged strength [2–5].

Retrogression occurs when a specimen is heated to a temperature between the aging and solutionizing temperatures of the alloy [1]. In addition to improving SCC resistance, retrogression changes the hardness of 7000-series aluminum alloys. As Fig. 1 demonstrates, there is an initial decrease in hardness, which is attributed to the slow dissolution of fine precipitates, as described by Park and Ardell et al. [2, 4, 5]. A slight recovery in hardness then occurs as the specimen is held at temperature. This is likely a result of changes in the η′ precipitates [2, 4, 5]. These changes lead to a local hardness maximum that is followed by an unrecoverable drop in hardness with further time at temperature. If a specimen is retrogressed for a time prior to this local hardness maximum, then the original hardness can be recovered

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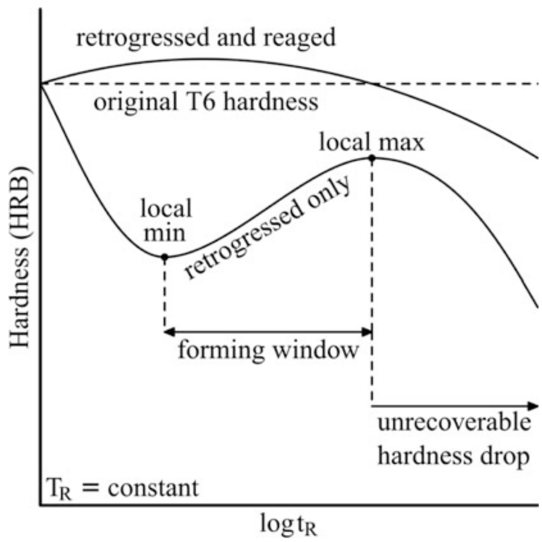


Fig. 1 For a 7000-series aluminum alloy, this schematic, after references [1–3, 5–8], demonstrates the change in (room temperature) hardness throughout a typical retrogression treatment at constant temperature T_R and the corresponding hardness after subsequent reaging

through a simple reaging treatment. This has been shown in experiments, some of which produced hardnesses after retrogression and reaging that were even higher than the original peak-aged (T6) hardness [1, 6–8]. These retrogression and reaging steps together make up the RRA process.

Warm forming at a temperature appropriate for retrogression can significantly improve ductility compared to deformation at room temperature. Ivanoff et al. demonstrated that the tensile ductility of AA7075-T6 increases from approximately 10% elongation at room temperature to 21% elongation at 200 °C [8]. Retrogression of AA7075-T6 at 200 °C for times less than the local hardness maximum, as shown in Fig. 1, produced material that can be readily reaged to the original T6 hardness [1, 6–8]. Thus, by warm forming AA7075-T6 at 200 °C, for a time less than the local hardness maximum, approximately 10 min at this temperature, a doubling of tensile ductility may be achieved while allowing rapid recovery of the original T6 strength through a simple reaging treatment. This is the retrogression forming concept, which may be applied to other temperatures appropriate to both retrogression and warm forming.

An important goal for exploring the retrogression-forming concept is to develop a means of predicting temperatures and times appropriate for retrogression forming. For example, the maximum time at temperature allowed during forming, the time beyond which retrogression causes unrecoverable strength loss, is of critical importance to predict. The retrogression process is controlled by the kinetics of precipitate dissolution, while strength recovery during reaging is controlled by the kinetics of precipitate reformation [2, 4, 5]. In this study, the kinetics of precipitate dissolution during retrogression are investigated by using differential scanning calorimetry (DSC) to determine the activation energy associated with dissolution of the strengthening precipitates in AA7075-T6. The changes in strength during retrogression are investigated through changes in hardness, a reasonable surrogate for tensile strength, across a range of retrogression temperatures and times. These data are used to design a forming window, a range of times during which the material is allowed to be at a specific temperature during retrogression forming. The end of the forming window is defined by the local hardness maximum, beyond which the material will experience unrecoverable strength loss. The local hardness minimum of Fig. 1 serves as a convenient reference for the start of the forming window. Although forming at shorter times without sacrificing reaged strength might be possible, such short times are unlikely to be of practical use. These definitions are used to develop a methodology for predicting temperature and times of forming windows that are suitable to retrogression forming.

Experimental Procedure

Material

The material investigated for this study is AA7075-T6 sheet with an as-received thickness of 2 mm. This material was received in the peak-aged (T6) condition. The nominal composition requirements of the AA7075 alloy designation are provided in Table 1 [9].

Differential Scanning Calorimetry

Cylindrical specimens measuring 4 mm in diameter were punched from the 2-mm-thick sheet material using a bench-mounted punch. These specimens were solutionized at 480 °C for 1 h and then water quenched. The specimens were then aged at 120 °C for 24 h to the T6 condition in accordance with the recommendations in the ASM

Table 1 The nominal chemical composition of AA7075-T6 in weight percent (wt%)

Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	Al
5.1–6.1	2.1–2.9	1.2–2.0	0.18–0.28	<0.5	<0.4	<0.3	<0.2	Bal.

Handbook on Aluminum and Aluminum Alloys [10]. These heat treatments removed the cold work from the punching operation and reestablished the T6 condition throughout each specimen. A Mettler Thermographic Analyzer™, Model TGA/DSC 1, was used to perform the DSC experiments. Specimens were heated to 300 °C at a constant specified heating rate. The heating rates used in this study are 5, 10, 15, 20, and 25 °C/min. Multiple experiments were conducted for each heating rate using separate specimens. Heating rate was controlled from 100 °C for heating rates of 10 °C/min and slower and from 80 °C for heating rates faster than 10 °C/min. The specimen temperature, heat flow out of the heating element, and time were recorded during each experiment.

Retrogressed Hardness

Specimens were prepared from the 2-mm-thick AA7075-T6 sheet material by shearing it into 25-mm-square tabs that were then ground flat using SiC paper to a final grit size of 400 or finer. Each specimen was retrogressed from the as-received T6 condition in a salt pot at a set temperature for a prescribed time and then immediately water quenched. Specimens were retrogressed for up to 100 min at retrogression temperatures from 200 to 220 °C to determine the variation of hardness as a function of retrogression time for each retrogression temperature. The hardnesses of the specimens were measured on the Rockwell B scale using an Instron Wilson Rockwell Series 2000™ hardness tester.

Results

Differential Scanning Calorimetry

An example of data from a DSC experiment conducted at a heating rate of 10 °C/min is shown in Fig. 2. These data are plotted so that the endotherms associated with precipitate dissolution are upward peaks and exotherms are downward. Two endothermic peaks are identified in Fig. 2. The first endothermic peak, at 208.4 °C, is associated with the dissolution of strengthening η and/or η′ precipitates during retrogression [2, 4, 5, 11–15]. The temperature of this peak shifts as heating rate is changed. The MATLAB™ polyfit function was used to determine the temperature at which this endothermic peak occurred, referred to as the peak temperature, T_p, by calculating the maximum of a cubic polynomial fit to the isolated curve [16]. The peak temperature was measured from DSC data for each heating rate in this manner.

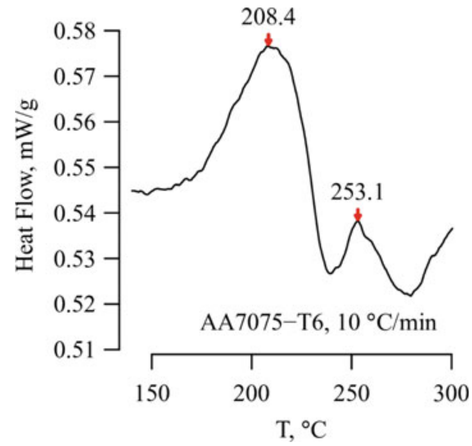


Fig. 2 An example of DSC data acquired from the AA7075-T6 material at a heating rate of 10 °C/min is shown. Data are plotted so that endotherms are upward

The activation energy associated with the dissolution of the strengthening precipitate(s) in AA7075-T6 was determined according to the model developed by Bárczy and Tranta [11]. The relationship between the peak temperature measured over various heating rates and the activation energy associated with the dissolution of the strengthening precipitate(s) in the material can be described by the following equation:

$$\ln\left(\frac{T_p - T_0}{\beta}\right) - \frac{Q}{RT_p} = B \tag{1}$$

where T_p is the peak temperature calculated in Kelvin for the heating rate, β, measured in Kelvin per minute; T_0 is the initial temperature in Kelvin, taken as room temperature for the context of this study; Q is the activation energy in J/mol associated with the endothermic peak; R is the universal gas constant; and B is a unitless material constant. When $\ln\left(\frac{T_p-T_0}{\beta}\right)$ is plotted against $1/T_p$, the slope of the data is Q/R, and the y-intercept is B.

Figure 3 presents DSC data from five different heating rates. These data are used to measure the activation energy associated with the first endothermic peak. This peak corresponds to the dissolution of the strengthening precipitate(s) in the material. The activation energy was measured using a linear fit to the data, from which the slope of the data was determined. The uncertainty in the value measured was estimated using the 95% confidence interval on the value fitted for the slope. Based on these results, the activation energy associated with the dissolution of the strengthening precipitate(s) in AA7075-T6 was determined to be 96.8 ± 6.7 kJ/mol.

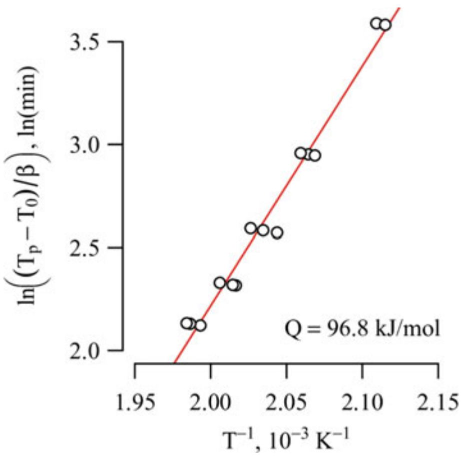


Fig. 3 Peak temperature is plotted according to the model developed by Bárczy and Tranta so that the slope of the data is equivalent to Q/R [11]

Retrogressed Hardness

Figure 4 displays HRB hardnesses of the AA7075-T6 material after retrogression at three different temperatures as a function of the logarithm of retrogression time. Hardness profiles typically associated with retrogression heat treating are observed [1–4, 6–8]. Decreasing hardness leads to a local hardness minimum followed by a small increase in hardness as retrogression time increases. This proceeds to a local hardness maximum, after which hardness decreases monotonically with increasing retrogression time. As retrogression temperature increases, the times at which the local minimum and the local maximum in hardness occur decrease. In short, as the material is retrogressed at increasingly higher temperatures, the hardness decreases more rapidly.

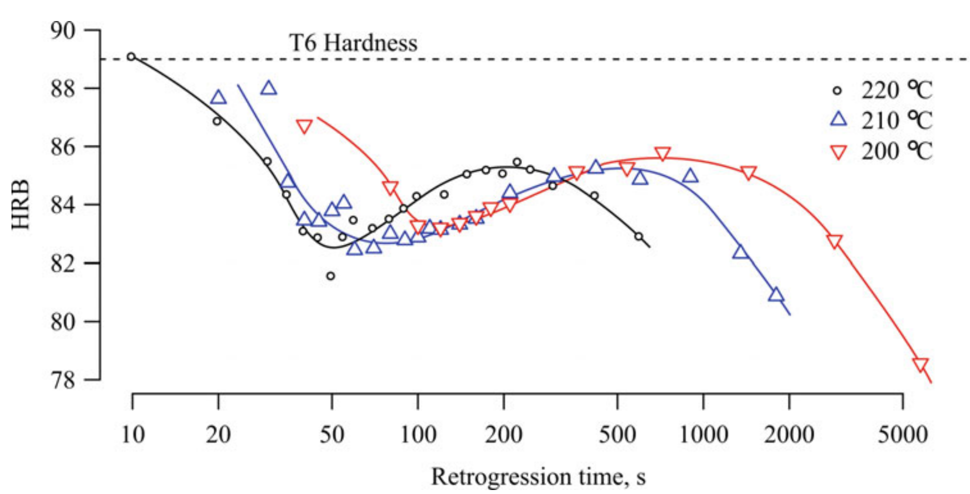
Discussion

Because the change in hardness during retrogression results from a thermally activated process, namely diffusion associated with precipitate dissolution, it might be predicted using the Arrhenius relationship [16]. This approach would allow calculation of the unique forming window of times for each possible retrogression temperature. By normalizing retrogression time to account for retrogression temperature, the retrogressed hardness data from multiple retrogression temperatures can be condensed onto a single master curve [8]. This master curve can be used to calculate the unique range of times for a forming window at any retrogression temperature. Figure 5 presents the data from Fig. 4 as a master retrogression curve produced in this manner. Hardness (HRB) is plotted against the logarithm of temperature-normalized retrogression time, i.e. reduced time, calculated as:

$$\tau = t_R \cdot e^{(-Q/RT_R)}, \tag{2}$$

where τ is the reduced time, t_R is the retrogression time, Q is the activation energy measured from DSC data, R is the universal gas constant, and T_R is the retrogression temperature. The local hardness minimum occurs at a reduced time of 2.3×10^{-9} s, and the local maximum hardness occurs at a reduced time of 1.3×10^{-8} s. Figure 5 thereby demonstrates the ability of Eq. 2 to produce a master curve that predicts a reasonable retrogression-forming window across a range of times and temperatures. The forming window defined by reduced time in Fig. 5 is used with Eq. 2 to predict appropriate times for retrogression forming across a range of temperatures in Table 2. Also listed in Table 2 are the minimum and maximum retrogression times for forming

Fig. 4 Hardness (HRB) of retrogressed AA7075-T6 is presented as a function of retrogression time (log scale) for three different retrogression temperatures



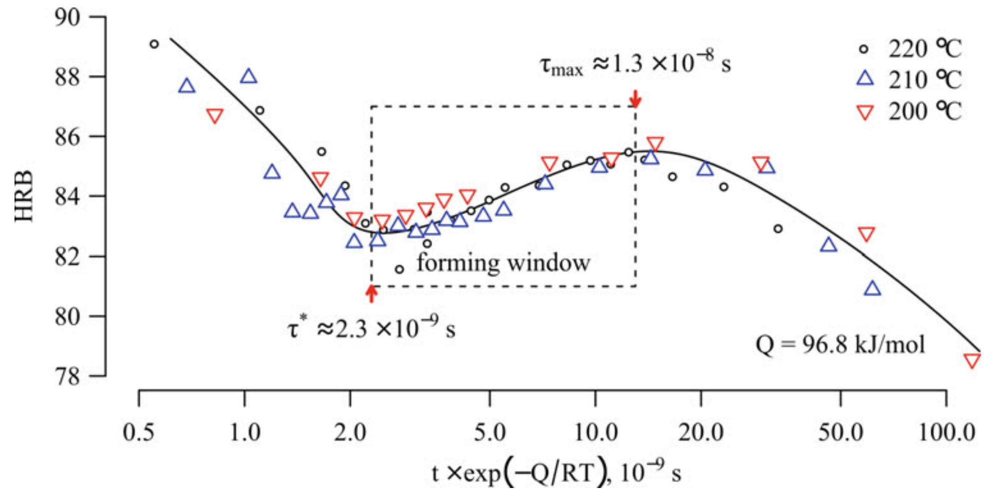


Fig. 5 A master curve for AA7075-T6 is generated by plotting retrogressed hardness against the logarithm of reduced time to collapse data from three temperatures onto approximately a single curve

Table 2 Appropriate retrogression forming windows for AA7075-T6 predicted for various retrogression temperatures are compared to values from experiments

T_R (°C)	Minimum t_R (s)		Maximum t_R (s)	
	Predicted	Experimental	Predicted	Experimental
200	110	120	630	720
210	70	60	380	420
220	40	50	230	230

windows demonstrated in the experimental data of Fig. 4. The values predicted using reduced time agree well with these.

Conclusions

- The activation energy associated with dissolution of the strengthening precipitates in AA7075-T6 was measured from DSC data to be 96.8 kJ/mol.
- An Arrhenius relationship can be used to calculate a reduced time that accounts for the effect of temperature and time together on hardness changes during retrogression.
- Plotting hardness after retrogression as a function of reduced time produces a single master curve for hardness data acquired across a range of retrogression temperatures and times. This master curve can be used to predict time-temperature windows for retrogression forming.
- For the AA7075-T6 sheet studied, the retrogression forming window extends from 110 to 630 s for a retrogression forming temperature of 200 °C. It extends from 70 to 380 s for a retrogression forming temperature of 210 °C and from 40 to 230 s for a retrogression forming temperature of 220 °C.
- Retrogression forming, followed by reaging, is expected to yield fully formed parts that have peak-aged hardness and strength.

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