Retrogression forming and reaging of AA7075-T6 Alclad to produce stampings with peak strength

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Abstract

A retrogression heat treatment was combined with simultaneous warm forming to produce cross-shaped stampings from AA7075-T6 Alclad sheet. This process is termed retrogression forming. A maximum-allowed-retrogression-forming-time, which includes sheet heat up, transfer, and stamping, was predicted by calculation to achieve peak-aged strength through a single reaging heat treatment after forming. Sheets of 1.6-mm-thick AA7075-T6 Alclad were stamped at 200 °C to a depth of 45 mm within 2 seconds without splitting. The formed geometry exhibits a complexity appropriate to automotive structural components. These stampings were then subjected to one of two reaging heat treatments. A full reaging heat treatment of 120 °C for 24 hours produced strength levels in excess of the original, peak-aged T6 alloy sheet. A simulated paint bake heat treatment at 185 °C for 25 minutes recovered 95 % of the strength lost during warm forming. Successful retrogression forming and reaging of AA7075-T6 provides new possibilities for stamping high-strength aluminum alloys into complex geometries without sacrificing strength.

I. Introduction

High strength aluminum alloys (HSAAs), such as AA7075, are of interest to the automotive industry as a potential replacement for ultra-high strength steels (UHSSs) in automotive structural applications [1-6]. While HSAAs have only a quarter of the strength of UHSSs, they are also only one-third as dense [7-8]. This combination suggests that for some applications, particularly those involving anti-intrusion and bending, components made of HSAA can produce a crash performance comparable to components made of UHSS while reducing total mass. For example, Nieuwerburgh predicted that an automotive B-pillar made of an unspecified high-strength AA7xxx-series aluminum alloy will provide crash performance equivalent to components made of boron steel, but with a 40 % mass reduction [9].

Unfortunately, HSAAs have low room-temperature ductility [7], which limits the geometry of components that can be formed at room temperature. Thus, the conventional stamping processes currently used to form steel components cannot be used to form HSAA components. Deforming at elevated temperatures (200 to 500 °C) was demonstrated to improve the ductility of AA7075 [1-6,10-13]. However, exposure to these temperatures can significantly reduce the subsequent strength of AA7075-T6 [10-13]. To increase the post-formed strength back to the equivalent of the T6 condition the component may require a series of heat treatments [7] that that may induce warping.

Ivanoff *et al.* [12] first proposed a possible solution to this predicament: retrogression forming and reaging (RFRA). This new forming process combines warm forming with retrogression and subsequent reaging after forming [12-13]. In the first step, a retrogression heat treatment [14-15] is applied simultaneously during warm forming of a sheet material originally in the T6, or peak-aged, condition [12-13]. The material is heated to a temperature that is suitable for warm forming, is formed at that temperature, and is then cooled back to room temperature. This first step is carefully designed to ensure that the total time at elevated temperature does not exceed the maximum allowed time for an effective retrogression heat treatment [12-13]. The fully-formed component is subsequently reaged to recover the original, peak-aged strength of the alloy [12-13]. An example of a component produced through RFRA is shown in Figure 1.

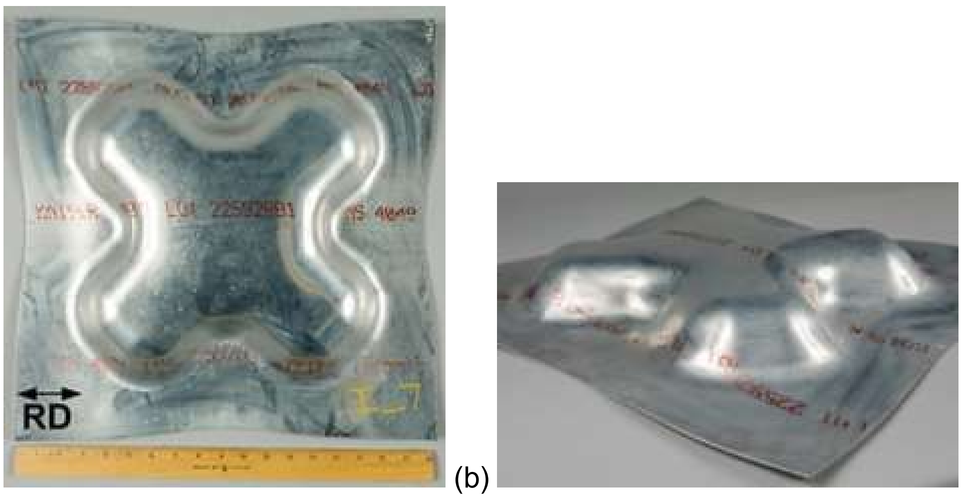
(a) (b)


Figure 1. (a) A plan view of a part of Alclad AA7075-T6 formed by stamping at 200 °C to a depth of 45 mm is shown. (b) The same part as in (a) is shown in an isometric view

The maximum-allowed-retrogression-time is defined in Figure 2 as t_R^{max}. Figure 2 schematically describes the retrogression and reaging (RRA) behavior of AA7075-T6 with no plastic deformation [14-20]. RRA with no plastic deformation was previously investigated by Park and Ardell in terms of precipitate structure change [16, 17]. The lower curve in Figure 2 shows the room-temperature strength of AA7075-T6 after retrogression at a constant temperature as a function of the time that it was retrogressed (i.e., the retrogression time). The initial decrease in strength as retrogression time increases up to t_R^* is dominated by the dissolution of the strengthening η’ phase precipitates [16, 17]. The slight recovery in strength from t_R^* to t_R^{max} and the subsequent decrease of strength beyond t_R^{max} are due to the precipitation and eventual coarsening of the η phase [16, 17]. The upper curve in Figure 2 shows the final strength of the alloy after retrogression and reaging with the recommended reaging heat treatment, 120 °C for 24 hours [14-15]. For material that was retrogressed for a time less than t_R^{max}, the reaging heat treatment grows and re-precipitates the η’ phase, thus recovering all of the strength lost during retrogression [16, 17]. For material that was retrogressed for a time longer than t_R^{max}, the reaging heat treatment cannot recover all of the strength lost during retrogression. This is because the solute elements were consumed by coarse precipitates during retrogression, preventing the formation of fine η’ and η precipitates during reaging [17]. During retrogression forming, the material being formed cannot be at elevated temperature for a time exceeding t_R^{max} if full peak-aged strength is to be recovered by reaging.

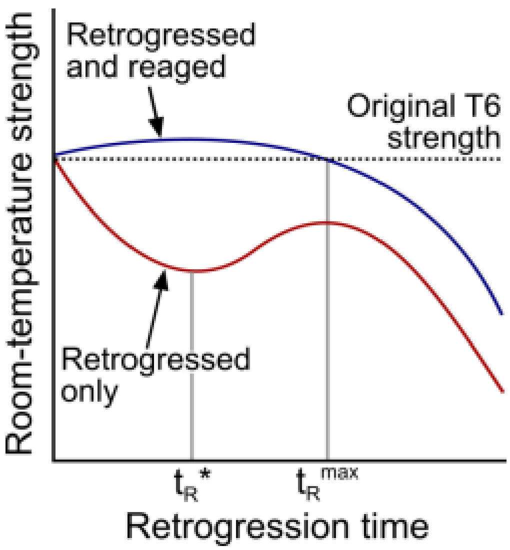


Figure 2. Room-temperature strength of AA7075-T6 after a retrogression heat treatment (red line) and then a subsequent reaging heat treatment (blue line) is plotted schematically as a function of retrogression time.

The concept of reduced time is used to predict t_R^{max}, noting that the maximum-allowed-retrogression-time, t_R^{max}, decreases as the retrogression temperature increases. Reduced time for retrogression was proposed by Ivanoff *et al.* [12] to simultaneously account for both retrogression time and temperature. Reduced time is calculated using the simple Arrhenius relationship of Equation 1:

$$\tau = t_R \cdot e^{\left(-Q/_{R \cdot T_R}\right)} \qquad (1)$$

where τ is reduced time, t_R is the retrogression time in seconds, Q is the activation energy of retrogression (Q = 94.8 kJ/mol·K for AA7075-T6 [13, 20]), R is the universal gas constant, and T_R is the retrogression temperature in Kelvin. Reduced time was used to predict the maximum-allowed-retrogression-times for AA7075-T6 across a range of retrogression temperatures [13, 20]. However, Equation 1 assumes that the retrogression temperature is constant. This assumption is not valid for large components that can only be heated and cooled slowly. To account for temperature changes during component heating and cooling, Equation 1 was used to define an accumulated reduced time. Accumulated reduced time is calculated using the integral shown in Equation 2:

$$\tau_{acc} = \int_0^{t_R} e^{\left(-Q/_{R \cdot T_R(t)}\right)} dt \qquad (2)$$

where τ_{acc} is accumulated reduced time, t_R is the retrogression time in seconds, Q is the activation energy of retrogression in J/mol·K, and R is the the universal gas constant. Here, however, the constant T_R is replaced with $T_R(t)$, which is the time-dependent retrogression temperature in Kelvin. The thermal history, i.e. $T_R(t)$, during blank heating, holding, transfer, stamping, and cooling can be measured experimentally or predicted through experimentally validated simulations.

II. Experimental procedure

A. Material

Sheets of 1.6-mm thick AA7075-T6 Alclad were selected for RFRA experiments. Because the aluminum cladding is quite thin, it does not affect the retrogression and reaging behaviors of the bulk material. Table 1 lists the alloy limits of both the bulk and cladding materials, as provided by the manufacturer, Kaiser Aluminum™, for lot number 225928B1. Sheets of AA7075-T6 Alclad were sheared into blanks measuring 470×470×1.6 mm. Each blank was assigned a unique identification (ID) code. The corners of each blank were engraved with the ID code and a mark indicated the rolling direction to ensure that all blanks were oriented in the same way for stamping. Both sides of each blank were lubricated with Forge Ease™ AL 278 (Fuchs Lubricants Co., Harvey, IL), which was allowed to air dry prior to stamping.

Table 1. Alloy limits (in wt %) of Alclad AA7075, according to the manufacturer's report produced by Kaiser Aluminum™ for lot number 225928B1

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Al
Bulk (7075)	0.0 to 0.4	0.0 to 0.5	1.2 to 2.0	0.0 to 0.3	2.1 to 2.9	0.2 to 0.3	5.1 to 6.1	0.0 to 0.2	0.0 to 0.05	0.0 to 0.05	87.2 to 91.4
Cladding (7072)	0.0 to 0.3	0.0 to 0.4	0.0 to 0.1	0.0 to 0.1	0.0 to 0.1	0.0 to 0.05	0.8 to 1.3	0.0 to 0.05	0.0 to 0.05	0.0 to 0.05	97.5 to 99.2

B. Cross-shaped warm stamping experiments

The warm stamping experiments were performed at EWI in Columbus, OH, using the experimental facilities first used and described by Kim *et al.* [21-22]. Blanks were heated in an infrared (IR) furnace, shown in Figure 3a. An automatic linear transfer system transferred each blank from furnace to die in approximately 15 seconds. The blanks were stamped in the 160-ton Minster™ press, shown in Figure 3b. After each heated blank was placed on the punch, the upper die was lowered to stamp the blank. After stamping, the thicknesses of the formed parts were measured at several locations using a Krautkramer CL3™ ultrasonic thickness measurement device.

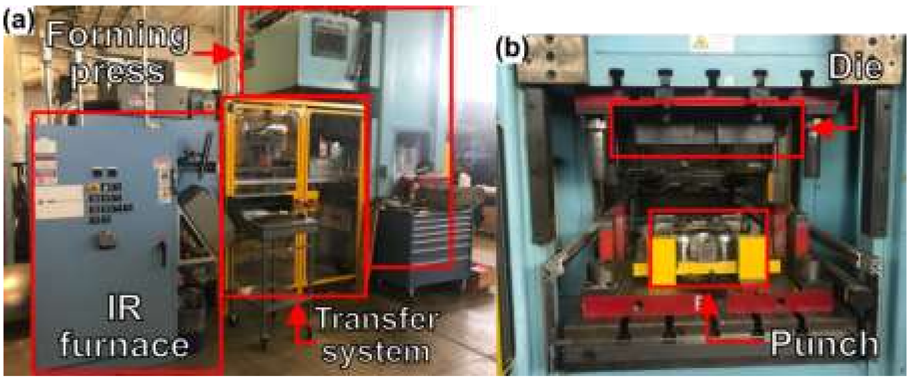


Figure 3. (a) The experimental facilities at EWI for warm stamping experiments are shown. (b) The press and die set used for stamping operations are shown from the open side used for part extraction.

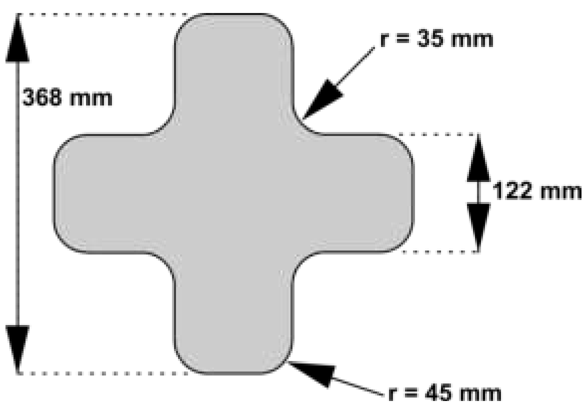


Figure 4. The cross-shaped die used to stamp the blanks is shown by a schematic drawing.

Prior to the warm stamping experiments, temperature was measured as a function of time and position on an instrumented blank during heating in the IR furnace and air-cooling after blank removal from the furnace. Thermocouples were bolted to three different positions on the instrumented blank. Once inserted into the IR furnace, which was preheated to 235 °C, the instrumented blank reached 215 °C in approximately 8.5 minutes. The instrumented blank then cooled approximately 15 °C in 15 seconds once removed from the furnace. During the warm forming experiments, the temperature of each blank was monitored in the IR furnace using a thermocouple in contact with the blank. Each blank was removed from the IR furnace immediately upon reaching 215 °C and then air-cooled to approximately 200 °C during blank transfer into the stamping die, when stamping could begin. The die was lowered at a constant speed of 22.5 mm/sec during stamping. Each blank was formed to a depth of 45 mm. Taking into account the time to open the die after stamping, the average time that each blank was in the press during the stamping cycle was 20 sec.

C. Reaging heat treatments and tensile tests

Two independent reaging heat treatments were studied. One applied a simulated paint bake heat treatment of 185 °C for 25 min [23]. The paint-bake process is an existing set of heat treatments used in the vehicle assembly process. The other reaging heat treatment applied a “full” reaging heat treatment of 120 °C for 24 hr. This is the reaging heat treatment that is recommended for AA7075-T6 after retrogression [14-15]. Tensile specimens in accordance with the ASTM E8 subsize tensile geometry [24] were extracted from the top of formed parts before and after reaging by one of the two reaging heat treatments. Table 2 describes the conditions of formed parts from which tensile specimens were extracted. The tensile specimens were loaded in uniaxial tension until rupture at a constant pulling speed of 0.33 mm/sec at room temperature.

Table 2. The conditions of specimens used in tensile tests

Acronym	Description
T6	As-received T6 condition (specimens were not strained or heat treated prior to testing)
RF	Retrogression formed
RF+PB	Retrogression formed and then reaged at 185°C for 25 minutes
RF+RA	Retrogression formed and then reaged at 120°C for 24 hours

III. Results and discussion

A. Cross-shaped stamping trials

Blanks measuring 470×470×1.6 mm were successfully stamped to a depth of 45 mm in a cross-form die without any splitting or visible defects; see Figure 1. Previous work with the same cross-form die observes that AA7075-T6 “shattered” for a draw depth of less than 25 mm when stamped at room temperature [22]. The cross-form die used during stamping demonstrates a complex geometry with deformation modes that are common in automotive stampings [25]. The largest thickness strains were measured in the corners and outer sidewalls of the stampings. The inner corner experienced thickness strains of up to 12 % reduction, while the thickness strains at the outer corner and outer sidewall ranged from 6 % to 1 % reduction, respectively. The severity of thickness strain at the inner corner is likely related to the nearly plane strain condition at that location.

B. Reaging heat treatments and tensile tests

Figure 5 compares the yield strengths and ultimate tensile strengths of the warm-formed stampings before and after the two different reaging heat treatments. The original T6 strengths of the as-received sheet are indicated with horizontal dashed lines. The process of retrogression forming lost 8 % of the original T6 yield strength and 2 % of the original ultimate tensile strength. The full reaging heat treatment (120 °C for 24 hours) recovered all of the strength lost during retrogression forming and further increased the yield and ultimate tensile strengths to 5 % beyond those of the original T6 condition. This is an example of using accumulated reduced time to successfully predict retrogression forming conditions that produce a full recovery of strength with reaging. The simulated paint-bake heat treatment (185 °C for 25 minutes) increased the yield strength to within 2 % of the original T6 yield strength and fully recovered all of the ultimate tensile strength. This is significant because the paint-bake is an existing step in the vehicle assembly process. Therefore, the peak strength of RFRA automotive components can be nearly fully recovered without any heat treatments beyond that already used in current manufacturing processes. This could significantly reduce the processing cost of RFRA components compared to adding a new reaging heat treatment after retrogression forming.

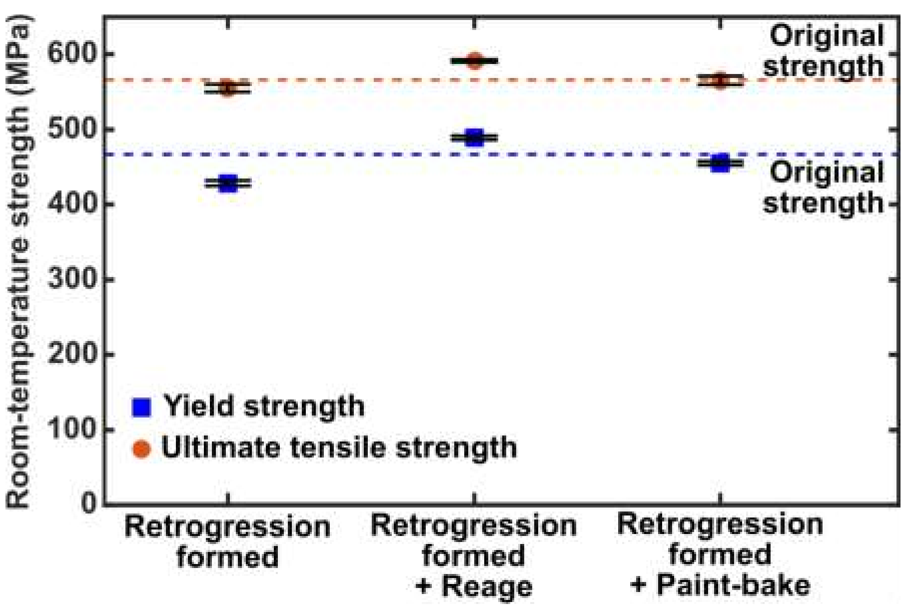


Figure 5. Room-temperature yield strength and ultimate tensile strength are shown as functions of processing condition (see Table 2).

IV. Conclusions

1. RFRA was successfully applied to aluminum alloy AA7075-T6 Alclad to regain peak-aged strength after warm forming cross-shaped stampings through complex deformation modes appropriate to automotive structural components.
2. For a maximum retrogression forming reduced time, which includes sheet heat up, transfer, and stamping, of less than $\tau = 3.3\times10^{-7}$ seconds (equivalent to 760 seconds at 200 °C), the peak-aged strength was recovered by a subsequent reaging treatment. This maximum-allowed-retrogression-forming-time was quantitatively predicted using the concept of reduced time, which relates retrogression time and temperature.
3. In the retrogression forming experiments conducted, blanks stamped to a depth of 45 mm at 200 °C exhibited no splitting or visible defects.
4. The yield and ultimate tensile strengths of RFRA stampings exceeded those of the original T6 condition by 5 % when the full reaging heat treatment of 120 °C for 24 hours was used.
5. Reaging by a simulated paint-bake heat treatment of 185 °C for 25 minutes recovered most of the peak-aged strength following retrogression forming, producing a final yield strength only 2 % lower than the original T6 condition.

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