U-channel forming of an 7075-T6 in warm conditions

S Royne¹, H Laurent¹ and A Maillard²
¹ Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France
² Cetim, F-60300 Senlis, France
E-mail: sylvain.royne@univ-ubs.fr

Abstract. The use of high mechanical strength aluminum coupled with the warm forming process makes it possible to replace certain steel parts in vehicles, thus reducing its mass and consequently greenhouse gas emissions. Warm forming of aluminum alloys requires heating the part between 150°C and 250°C to increase formability and reduce springback. In this study, a 7075-T6 alloy U-channel part was warm formed at 200°C in a short enough time to maintain the T6 state of the material. The process consisted of successively performing the heating by contact and stamping steps on the same mechanical press. From a thermomechanical characterization of the alloy in the temperature range between RT and 200°C and several strain rates, numerical simulations of the forming of the U-channel part were carried out using Abaqus. The experimental springbacks reduced with temperature were in agreement with the numerical simulations. An analysis of the conductivity and hardness of the material showed also that the 7075 keeps its T6 state until 10 s of warm forming.

1. Introduction

Aluminum alloys with high mechanical strength and low density, such as the alloys of the 7xxx series, are an interesting alternative to conventional steels for reducing the mass of vehicles and therefore greenhouse gas emissions. Despite these good characteristics, these alloys have reduced formability and significant springback at room temperature (RT). Warm forming process, around 200°C, makes it possible to reduce these two defects [1, 2]. However, this process can lead to metallurgical transformations for temperature above 150°C. For example, the precipitation of the η′ in η appears at a temperature of 200°C and leads to a decrease in the mechanical characteristics if the temperature holding time is too long [3].

This paper aims to study the warm forming of the U-channel of an AA7075-T6 alloy and to analyse the influence of temperature on its springback. Forming tests are carried out at room temperature and at 200°C using a multi-step stamping press. Springback results are compared to numerical simulations performed with Abaqus.

Anymore, the influence of holding time on the metallurgical state at the end of process is rarely studied in the literature [4, 5] and determine the optimum holding time is important in order to find the best duration of the warm forming process. Thus, the other objective of this paper is to find the best holding time in temperature to maintain the T6 state of the alloy which offers the highest ultimate and yield strengths. For that, conductivity and hardness tests are carried out for different holding time conditions at 200°C in order to analyze the influence of this holding time on the metallurgical and mechanical characteristics.
2. Material and methods

2.1. Material
AA7075-T6 sheet aluminum alloy with 0.8 mm thickness is used in this work. Commercially purchased aluminum was directly received in T6 state. The chemical composition of this alloy is presented in table 1. Its mechanical, conductivity and hardness properties measured in the standard and received conditions are given in table 2.

| Zn | Mg | Cu | Si | Cr | Fe | Mn | Ti | Al |
|----|----|----|----|----|----|----|----|----|
| 5.1-6.1 | 2.1-2.9 | 1.2-2.0 | 0.4 | 0.18-0.28 | 0.5 | 0.3 | 0.2 | Balance |

Table 1. Chemical composition of AA7075-T6 sheet in %wt.

| Condition | $R_{p0.2}\%$ [MPa] | $R_m$ [MPa] | $\geq 6$ | Conductivity [MS/m] | Hardness [HV10] |
|-----------|-------------------|-------------|---------|---------------------|-----------------|
| Standard  | $\geq 460$        | $\geq 525$  | $\geq 6$ | 17-21               | -               |
| Receiving | 500               | 557         | 14.6    | 18.5                | 188             |

Table 2. Mechanical and electrical properties at RT of the AA7075-T6 measured at receiving condition and standard limit values given for the T6 temper.

2.2. Warm forming tests of a U-channel
U-channel parts are formed under warm forming condition using a multi-step device manufactured by CETIM [6]. This device is presented in figure 1-a. It consists of two blanking stages to switch from a sheet metal strip to blanks of 250 mm $\times$ 60 mm attached between them. Then, a heating stage makes it possible to reach a uniform temperature of the blank of 200 $^\circ$C in 0.8 s via clamping contact. Finally, a forming step is performed with tools heated to the target temperature with the help of heating cartridges. An industrial rate of around 30 strokes/min is used. The theoretical dimensions of U-channel part are presented in figure 1-b.

![Figure 1](image_url)

Figure 1. a) Three stages of the multi-step device in the industrial press with blank before and after cutting stages; b) Theoretical dimensions of the U-channel part in mm (width=60 mm); c) Final U-channel part at 20 $^\circ$C (RT) and at 200 $^\circ$C after springback.
The dimensions of the tools are presented in figure 2. A clamping force of 5000 N is applied to the blank-holder. Forming tests are performed at RT and at 200 °C. The parts obtained after the springback at RT and at 200 °C are shown in figure 1-c. Three tests per condition are performed to check the reproducibility. Measurements of the part profile after springback are obtained by using a FARO Quantum S 2.5m 7-Axis 3D machine with an integrated Probe-Laser scan.

![Figure 2. Dimensions of the forming tools in mm](image)

2.3. Numerical simulations of the warm forming process and springback

Isothermal numerical simulations of the forming process and springback are conducted in using Abaqus/Standard. A 2D plane stress model is used with tools modeled as rigid surfaces. A section of the blank is meshed with 2D quadratic quadrilateral elements CPS8. A fine mesh size of approximately 0.15 mm is used in the radius zone of the die whereas the size is increased to approximately 1.5 mm at sections away from this zone. Moreover, 13 elements are used through the thickness. The blank is assumed to have elastic-plastic behaviour described with a Swift law (1) identified through tensile tests at RT and 200 °C performed at a strain rate of $2 \times 10^{-2}$ s$^{-1}$.

$$\bar{\sigma} = K.(\varepsilon_0 + \bar{\varepsilon})^n$$  \hspace{1cm} (1)

$K$, $\varepsilon_0$, $n$ are material parameters and $\bar{\varepsilon}$ is the equivalent plastic strain.

The parameters of the hardening law at RT and 200 °C are summarized in table 3.

| Temperature | $K$ [MPa] | $\varepsilon_0$ | $n$  |
|-------------|-----------|-----------------|-----|
| 20°C        | 851.8     | 0.0518          | 0.15|
| 200°C       | 485.7     | 0.026           | 0.195|

**Table 3.** Swift’s law parameters at RT and 200 °C identified through tensile tests performed at $2 \times 10^{-2}$ s$^{-1}$.

During the springback simulation, tools movements are simulated as during the experimental process. The purpose of the numerical simulations is to analyze the influence of the friction coefficient on the prediction of the springback.
3. Results and discussion

3.1. Experimental and numerical springbacks
The experimental springback results at RT and 200 °C are presented in figure 3. They are compared to the numerical results. The outer surface of the experimental and numerical profile is taken. The influence of friction coefficient is crucial in the numerical prediction of the forming and springback. After several numerical trials, a friction coefficient making it possible to get as close as possible to the experimental results is fixed at 0.2 between the blank and the die and the blank-holder, whereas a friction coefficient of 0.15 is applied between the punch and the blank. These parameters allow a good agreement between the experimental and numerical in the springback results. As expected, the increase in temperature strongly reduces the springback. Nevertheless, the comparison between the theoretical and numerical/experimental profiles indicates that despite this increase in temperature, the springback remains significant on this type of part with significant free strands.

Finally, it is important to notice that at the die radius, there is a change of curvature in the profile of the blank which could be due to a phenomenon of attachment of the material during the opening of the tools. Other numerical simulations by modifying the friction coefficient only in the zone of the die radius are still in progress to verify this hypothesis.

![Figure 3](image-url)

3.2. Verification of the T6 state at the end of the process
Measurements of mechanical characteristics, electrical conductivity and hardness after different temperature holding times are easy methods to determine the metallurgical changes of alloys occurring during thermal cycles [7, 8]. These measurements make it possible to define the optimum time for the warm forming process to guarantee the T6 condition after forming.

Experimental thermal cycling tests were performed on a Gleeble 3500 machine to reproduce the warm forming process by varying the holding time at 200 °C. During these tests, Joule heating of a dog-bone specimen was controlled by a thermocouple welded in the center of the
specimen. Two thermocouples placed at ±5 mm from the central thermocouple verified also the homogeneity of the temperature over the length of the sample. The thermal cycle used is presented in Figure 4. Its corresponds first to heating with a rate of 250 °C/s (200 °C in 0.8 s) similar to the heating rate used in the experimental warm forming process. Then, after different holding time of 2, 10 and 30 s at 200 °C, a cooling rate of about 2 °C/s which corresponds to cooling in the open air with cooled jaws was imposed on the specimen. After this thermal cycle, tensile tests at RT were performed on an Instron 5969 tensile machine using a DIC system to measure the deformation in the center of the sample. Finally, at this stage, conductivity and hardness tests were carried out in the homogeneous temperature zone (rectangle of 3 mm × 6 mm in the center of the sample).

![Figure 4. Experimental thermal cycle performed on a Gleeble 3500 machine with the different cycle parameters. Conductivity and hardness tests are carried out after the thermal cycle at RT. Tensile tests are performed on a Instron 5969 tensile machine.](image)

Table 4 presents the results of the electrical conductivity, hardness and mechanical characteristic obtained after different holding times at 200 °C. Results obtained in receiving state T6 are also given in this table. In the case of a holding time of 2 and 10 s, the electrical conductivity remains stable with respect to the receiving condition, whereas after 30 s of holding time, the conductivity increases slightly indicating the occurrence of metallurgical changes.

| Conductivity [MS/m] | Receiving condition | 2s  | 10s  | 30s  |
|---------------------|---------------------|-----|-----|-----|
| Hardness [HV10]     | 188                 | 180 | 175 | 172 |
| Rp0.2% [MPa]        | 500                 | 495 | 460 | 410 |
| Rm [MPa]            | 557                 | 565 | 553 | 539 |
| A%                  | 14.6                | 12.8| 11.6| 10.9|

Table 4. Mechanical, hardness and electrical characteristics according to the different holding times at 200 °C. The conductivity, hardness and tensile tests were carried out at RT.

The conductivity value obtained after 10 s of holding time indicates that the 7075 alloy still remains in the T6 state since its conductivity complies with the standard for this state (see table 2). As for the hardness, it decreases directly after 2 s of holding time down to a value of 172 HV10 for 30 s. This decrease also indicates metallurgical changes which is in contradiction with the results of conductivity between 2 s and 10 s, i.e. decrease in hardness while conductivity does not change. This reduction in hardness can be associated with the phenomenon of coalescence of precipitates and can therefore imply a reduction in the mechanical characteristics.
Finally, with regard to the mechanical characteristics, in the case of 2 s of holding time, the mechanical characteristics are similar to the reception state, whereas from 10 s, they decrease. By comparing these data with the values of the standard (table 2), this indicates that after 10 s of holding time the alloy is no longer in the T6 state since the elastic limit is then equal to the limit of the standard of 460 MPa.

To validate that 10 s seems an optimum time to keep the material in a T6 state, electrical conductivity and hardness measurements are performed on the U-channel part as presented in Figure 5. Three measurements of the conductivity and hardness are taken in the undeformed area to check reproducibility. Table 5 presents the average of the three values of electrical conductivity and hardness results obtained on parts after forming at RT and 200°C.

![Figure 5. Positions (red dots) of hardness and conductivity measurements after warm forming of the U-channel part.](image)

| Temperature | 20°C | 200°C |
|-------------|------|------|
| Conductivity [MS/m] | 18.5 | 18.5 |
| Hardness [HV10] | 188 | 184 |

Table 5. Hardness and electrical conductivity of U-channel parts measured after warm forming. The measurements were made at RT

These results show that the conductivity is maintained at the receiving state (18.5 MS/m) whereas the hardness for 20°C is equal to the hardness of the receiving state (188 HV10) and for 200°C, it decreases of -4 HV10 compared to that at 20°C.

Concerning the time of the warm forming process, the holding time of the part at 200°C is estimated at 2.6 s. This time corresponds to the transfer of the blank from the heating station to the stamping station under isothermal conditions plus the time of the stamping operation. In fact, the total time of the warm forming process is less than 10 s which confirm the values of hardness and conductivity obtained with the forming parts. It is also important to note that the hardness obtained at 200°C for an estimated holding time of 2.6 s is slightly greater than that obtained for a holding time of 2 s.

All of these data indicate that the maximum temperature holding time at 200°C can be estimated at less 10 s in order to preserve the mechanical characteristics of the T6 temper. Nevertheless, the data was obtained on an AA7075-T6 alloy of a certain batch and as indicated in Table 1, the chemical composition may vary according to the batch and therefore also the mechanical characteristics. For the moment, nothing tells us that this value of 10 s is valid whatever the 7075-T6 alloy received. This value of 10 s may therefore change slightly depending on the status of the batch received.

4. Conclusion
Warm forming of a U-channel part of 7075-T6 alloy was performed at RT and 200°C with a dedicated multi-step process. Numerical springback was compared with experimental results.
As classically observed in the literature, the increase of temperature decreases the springback. Numerical simulations showed that the friction coefficient is an important parameter to obtain good correlation with experimental springback. Electrical conductivity, hardness and tensile tests have made it possible to obtain the maximum temperature holding time at 200°C to preserve the T6 state after warm forming. A total time of warm process of less 10 s allows to maintain this state. However, a modification of this time is still possible depending on the batch characteristics of the received alloy.

Acknowledgments
The authors gratefully acknowledge the financial support of the Brittany Region (France) via the program RB EMBHOTAL.

References
[1] Kumar M and Ross N G 2016 Journal of Materials Processing Technology 231 189–198
[2] Wang H, Luo Y b, Friedman P, Chen M h and Gao L 2012 Transactions of Nonferrous Metals Society of China 22 1–7
[3] Deschamps A, Texier G, Ringeval S and Delfaut-Durut L 2009 Materials Science and Engineering: A 501 133–139
[4] Lee E W, Oppenheim T, Robinson K, Aridkahari B, Neylan N, Gebreyesus D, Richardson M, Arzate M, Bove C, Iskandar M, Sanchez C, Toss E, Martinez I, Arenas D, Ogren J, Mclennan J, Clark R, Frazier W E and Es-Said O S 2007 Engineering Failure Analysis 14 1538–1549
[5] Zang J, Dai P, Yang Y, Liu S, Huang B, Ru J and Luo X 2021 Metals 11 1483
[6] Maillard A and Piat C 2014 IDDRG 2014 Conference 300–306
[7] Miyake J and Fine M E 1992 Acta Metallurgica et Materialia 40 733-741
[8] Manduit A and Gransac H 2020 Annales de Chimie - Science des Matériaux 44 141–149