Warm forming of AA7075-T6: optimizing the heating time to maintain T6 condition

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Keywords: Warm Forming, AA7075-T6, Heating Time, Aging, Precipitation

Abstract. Warm forming at 200°C is an interesting way of improving the formability of AA7075-T6. The T6 condition offers the highest ultimate and yield strengths of this aluminium alloy. It is therefore important to maintain these excellent mechanical properties at the end of the forming process. With the hot forming process at temperature above 450°C, it is necessary to add a heat recovery treatment obtained during paint baking to keep this T6 state, which is costly in terms of time and energy. In warm forming process, it is possible to maintain the T6 condition by controlling the heating time to avoid precipitation changes. The objective of this study is to find these optimal heating time conditions to maintain the T6 state during warm forming multi-step process. Different heating times were reproduced using a Gleeble 3500 machine. Electrical conductivity and hardness were measured after these different conditions to make the link with the evolutions of precipitates of AA7075-T6. Tensile tests were also performed to characterize the mechanical behavior at the end of these heating cycles. A holding time of less than 10 seconds is determined to maintain the T6 state at 200◦C. Two multi-step warm forming devices (a cylindrical cup in two steps and a U-channel part) were finally tested to validate these optimal time forming conditions.

Introduction

7xxx series aluminium alloys (Al-Zn-Mg-Cu) have very good mechanical characteristics and are therefore very interesting candidates for replacing steels and thereby reducing the weight of automobile parts and therefore CO2 emissions [1]. Unfortunately, these alloys are difficult to form at room temperature and have a high springback. To overcome this difficulty, it is increasingly being considered to form them at high temperature using a multi-stage forming process to increase the depth of draw.

Regarding the possible forming processes in temperature, AA7075 sheet can be stamped either by hot forming or by warm forming [2]. After hot forming at 480°C (immediately above its solvus temperature) which needs simultaneous forming and quenching, the material requires an artificial aging cycle to reach the T6 state which gives the highest mechanical strength [3]. Because of all these steps, this makes this process costly in time and energy. To avoid this drawback, warm forming technology is a promising approach to improve the formability of peak-aged 7075 aluminium alloys (AA7075-T6) [4]. However, to avoid any paint baking operation and changes in precipitation state due to the temperature [5], it is important to control the heating time. For example, the precipitation of the η phase in η' appears at a temperature of 200 °C and leads to a reduction in the mechanical properties if the temperature holding time is too long [6]. In the literature, several authors have analysed the deterioration of mechanical properties and the microstructural evolution of 7xxx alloys during long-term exposure to high temperature [7,8]. However, these studies focus mainly on the influence of temperature on extended holding times of more than a minute or even an hour. But with the development of warm multi-stage forming operations compatible with industrial rates, we need to consider times of the order of 2 to 20 seconds for a complete heating and drawing cycle.

To know the influence of the heating cycle time, the objective of this study is to determine the evolution of the mechanical properties for very short heating cycle times to maintain the T6 state of 7075 alloy. For this purpose, different heating time were reproduced with a Gleeble 3500 machine on samples of AA7075-T6. The electrical conductivity and hardness were then measured and compared to the standard values to respect the T6 state. The optimum time values obtained were then validated by analysing the hardness and conductivity values on the final stamped parts of a warm-formed cylindrical cup [9,10] and a U-shaped channel [11,12].

Material

Aluminium alloy sheet AA7075 with a thickness of 0.8mm is considered in this work. The commercially purchased aluminium is directly received in the T6 state. The chemical composition of this alloy is presented in Table 1. The mechanical properties (Yield Strength YS, Ultimate tensile strength UTS and elongation at break E%) and the conductivity and hardness properties measured under standard conditions to meet the T6 condition and the reception conditions for the alloy are given in Table 2.

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

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 2 Mechanical and electrical properties of AA7075-T6 to comply with the standard and those obtained at reception.

Condition	YS [MPa]	UTS [MPa]	E [%]	Conductivity [MS/m]	Hardness [HV10]
Standard	≥ 460	≥ 525	≥ 6	17-21	-
Reception	500	557	14.6	18.5	188

Experimental conditions to control the T6-state

Different conditions of holding time at 200°C were reproduced using a Gleeble 3500 machine in order to reproduce the conventional conditions used in the multi-step warm forming process. With the Gleeble 3500 direct resistance heating system, a dog-bone specimen was heated by temperature with a thermocouple welded to the center of the specimen. The thermal cycles, presented in Table 3, consist of initial heating at 250 °C/s (200°C in 0.8 s), which corresponds to heating obtained by direct contact with heating tools. Four different holding times of 2, 10, 20 and 30 s were then applied, followed by cooling at 2°C/s, identical to cooling in free air.

Table 3 Conditions of heating rate, holding times and cooling rate.

Heating rate [◦C/s]	Holding time[s]	Cooling rate [◦C/s]
250.	2., 10., 20., 30.	2.

After these thermal cycles, tensile tests at room temperature (RT) were performed on an Instron 5969 tensile machine with a strain rate of $2.10^{-4}s^{-1}$. Strain measurement was obtained by using the GOM Aramis DIC system in the central zone of the specimen (6mmx10mm rectangle), which corresponds to the homogenous temperature of the sample. The tests were repeated 3 times for each condition. The YS, UTS and E values for all these tensile tests were then determined from the nominal stress-strain curves. Finally, at this stage, conductivity and hardness tests were carried out in this temperature-homogeneous zone of specimens.

Results after tensile tests

Table 4 shows the results for electrical conductivity, hardness and mechanical properties obtained after various holding times at 200°C. These results must be compared with the values obtained at reception and with the standard values for maintaining the T6 state presented in Table 2.

Table 4 Mechanical and electrical properties of the AA7075-T6 alloy after various holding times.

Holding time [s]	YS [MPa]	UTS [MPa]	E [%]	Conductivity [MS/m]	Hardness [HV10]
2.	488±7.78	551±0.71	12.22±0.31	18.48±0.094	180±1.56
10.	459±8.49	538±2.69	11.58±0.08	18.55±0.090	175±1.42
20.	448±8.08	533±3.21	11.27±0.08	18.66±0.067	174±1.68
30.	442±1.41	526±0.67	12.04±1.77	18.71±0.079	172±1.07

The overall trend in conductivity and hardness presented in Table 4 shows an increase in conductivity and a decrease in hardness. However, the conductivity did not change between 2 and 10s compared with the values measured in reception condition. For longer holding times, an increase in conductivity of 18.66 and 18.71 MS/m was observed at 20 and 30s respectively, indicating an evolution of the metallurgical after a holding time of more than 10s. In the case of hardness, a continuous decrease was noted from 188 HV10 in reception condition to 172 HV10 after 30s of holding time. This decrease also indicates metallurgical changes which is in contradiction with the results of conductivity between 2 and 10s, i.e. decrease in hardness while conductivity does not change. This decrease in hardness can be associated with the phenomenon of coalescence of precipitates and can therefore imply a reduction in the mechanical characteristics.

Concerning these mechanical properties, there was no evolution from the reception condition after 2s of holding time. After 10s, YS and UTS decrease respectively of 29MPa and 13MPa and of 46MPa and 25MPa, respectively between 2 and 30s.

In comparison with the values required to comply the condition T6 (Table 2), for the YS, hardness and conductivity values, 10s appears to be the limit value for the holding time. Concerning the UTS, after 30s, its value is close to the standard value of 525MPa. It is also important to note that all the values of the total elongation are higher than the limit given by the standard (≥ 6%). However, this elongation condition is very difficult to control due to the thermocouple welded to the specimen to control temperature, which can lead to a premature rupture, and it is therefore not relevant to analyse this parameter. Finally, it appears that 10s seems an optimum time to keep the material in a T6 state.

To verify this optimum time, two warm forming process are tested in the following with different heating and forming times. Conductivity and hardness measurements are compared to control the validity of this time.

Warm forming of a cylindrical cup in two steps

The first process involves warm forming of a cylindrical cup in two successively drawing steps on a 200 KN press. Fig. 1 presents the device developed by the CETIM including a heating step and two forming steps [9,10]. Fig. 2 shows the theoretical dimensions and the actual cup after each forming step, obtained from an initial diameter of the blank of 157 mm.

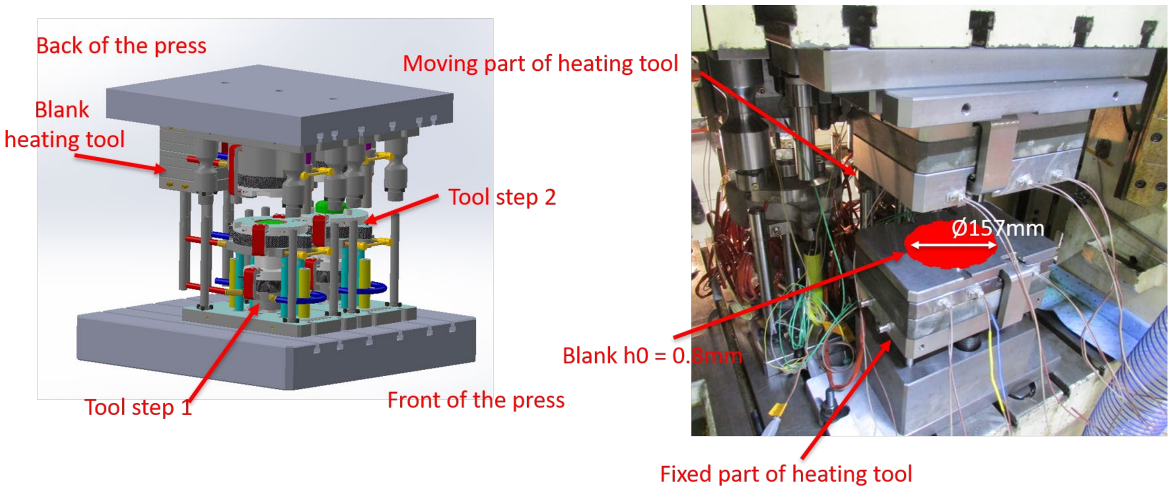

Fig. 1 Principle of press configuration with the heating step and the two forming cylindrical cup stages steps.

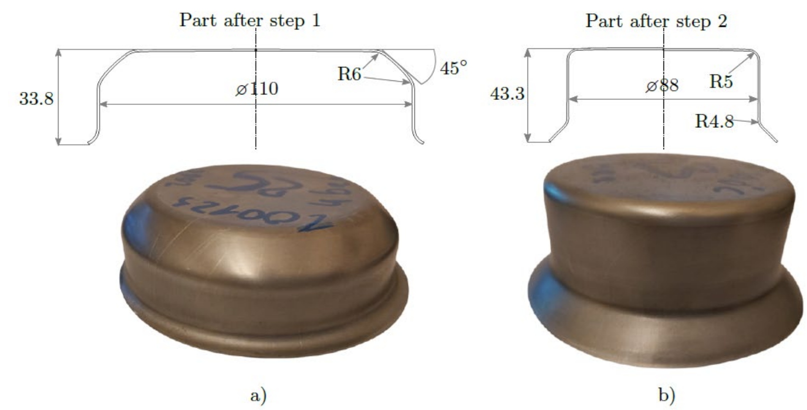

Fig. 2 a) Dimensions (in mm) of the part after step 1 and b) after step 2 [9].

The heating stage is obtained by contact clamping of the sheet to achieve a uniform temperature of 200°C in 0.45s. The blank is then manually transferred to the first and second forming stations. These two forming stations are placed next to each other to limit the transfer time, but the total time to perform the total cycle time (heating and the two forming stages) is around 20s. Heating cartridges are used to heat all the tools and K-type thermocouples control their temperature. During the first forming, a clamping force of 66kN is applied while no force is used in the second stage. A force sensor measures the reaction force under the punch during both stamping processes. A pyrometer, placed 20 mm from the blank, measures the temperature of the blank during these 2 stages. A JELT 5411 lubricant is applied to the sheet before the tests.

The tests are carried out at RT and at 200°C. At RT, the sheet metal breaks during the first stage. This is not the case at 200°C where the drawing part does not show any breakage. Four tests are performed at 200°C to check the reproducibility. At the end of the test, conductivity and hardness are measured at the bottom of the cup.

The data obtained are presented in Table 5. It is difficult to assess the T6 condition uniquely with the conductivity and the hardness measurements alone. However, by comparing hardness results with the values of UTS and YS presented in Table 4, it is possible to make the link with the conservation of the T6 condition. Here, the conductivity of 18.42MS/m remains of the same order of magnitude compared to the reception state (Table 2). The hardness of 177HV10 is reduced compared to the reception state but it is still close to that of the standard values of YS and UTS to respect the T6 material (Table 4). The total cycle time of warm forming of 20s is therefore an ultimate time to maintain the T6-state in this case of warm forming.

Table 5 Results of hardness and conductivity obtained at the end of cylindrical cup forming in two steps

Total cycle time [s]	Conductivity [MS/m]	Hardness [HV10]
20	18.42±0.075	177±2.50

Warm forming of a U-channel part

The second test corresponds to the multi-step warm forming of a U-Channel part whose dimensions of the final part are presented in Fig. 2.a-b [11,12]. After two blanking steps (depicted in blue), the blank is heated by clamping contact (in red) to obtain a uniform temperature of 200°C in 0.8s. The U-channel is then formed with tools heated by heating cartridges with an industrial rate of around 30 strokes/min. Based on the technique of the progressive die, between each of these steps, the part is transferred automatically without any manual handling. The part remains at the target temperature for approximately 2.6s which includes the part transfer and the forming operation. During the transfer from the heating step to the forming step, the heat loss is around 5°C and is therefore considered negligible.

The forming process is performed three times at RT and at 200°C to check the reproducibility. Springback is greatly reduced at 200°C compared to the part obtained at RT but it is still present (see Fig. 3-c).

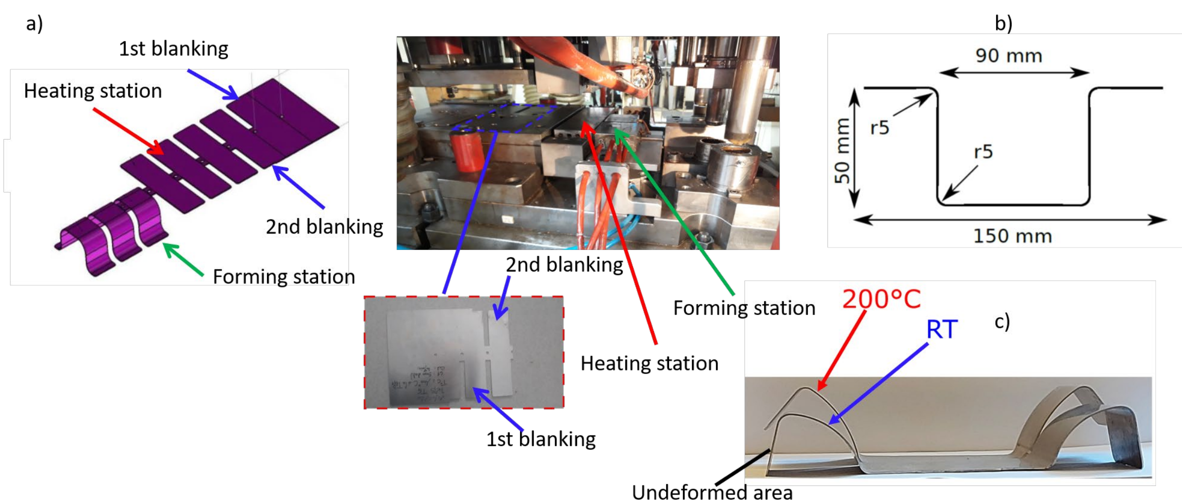

Fig. 3 a) Three stages of the multi-step device in the industrial press with blank before and after cutting stages; b) Theoretical dimensions of the U-channel part in mm (width=60 mm); c) Final U-channel part at RT and at 200°C after springback.

To control the metallurgical condition after the two steps of forming, hardness and conductivity are measured three times in the undeformed areas indicated in Fig. 3.c. Table 6 present the hardness and conductivity results obtained at RT and 200°C.

Table 6 Hardness and conductivity results obtained at RT and 200°C on the U-channel part

Temperature [°C]	Conductivity [MS/m]	Hardness [HV10]
20	18.99±0.14	188±2.22
200	18.94±0.13	182±2.55

Hardness is similar to the value obtained for the RT (Table 2) and with value measured after the Gleeble test with a holding time of 2s (Table 4) which is consistent with the total forming process time of 2.6s of this test. This is not the case for the conductivity, but this conductivity doesn't really evolve at 200°C in comparison with the values measured at RT, in the same condition after forming. Globally, there is no evolution of hardness and at this value of 182HV10, the YS and UTS are in the T6 state (see Table 2). This seems to confirm that the T6 state is preserved with this warm forming time in this case. To avoid any risk, all of these data indicate that the maximum temperature holding time at 200°C can be estimated at less 10s in order to preserve the mechanical characteristics of the T6 temper.

Conclusion

After reproducing different heating cycles using a Gleeble machine, electrical conductivity, hardness and tensile tests made it possible to determine the temperature holding time at 200°C to maintain the T6 state during warm forming. A total time of less 10s must be used to be sure to respect the T6 state. Two warm forming tests have confirmed this cycle time to respect. However, this value constitutes a safety limit to avoid any evolution due for example to the composition of the alloy considered and in the case of any plastic deformation are applied on the part.

Acknowledgements

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

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