Study on the impact of temperature on the warm bending of aluminium alloy sheets

A Mauduit* and A Maillard²

¹Cetim (Technological institute of mechanics) Centre Val de Loire
²Cetim Senlis

* arnold.mauduit@cetimcentrevaleloire.fr

Abstract. Warm forming of aluminum is a recent process and its developments have been mainly focused on drawing. This study takes a look at bending, a process widely used in industry. After the 2017A T4 and 6061 T6 aluminum alloys are characterized at both room and warm temperatures, bending of these materials is carried out at different temperatures. Various bending strategies are studied. The findings point to the value for these materials in heating the bend during the forming operation to avoid cracking, in some cases, and to minimize springback. An analysis of the sheet metal distortion mechanism is carried out based on micrographic sections sampled in the bend. The analysis highlights the formation of “macro-bands” indicating the location of the distortion. Asperities are observed on the outer surface. This could be the fracturing site of certain grains located in the grooves of the asperities, with possible intergranular or transgranular cracking. A potential follow-up to this study could be to assess the changes in the mechanical characteristics after the aluminum alloy sheets have cooled to room temperature.

1. Introduction

Weight reduction has become a priority in the development of new products for the transport sector. Many studies [1], [2], [3], [4] have been carried out on the warm forming of aluminium, especially in the automotive industry, as this process provides the potential for forming hard aluminium grades thereby making it possible to replace heavier steel solutions [5] or to reduce part thickness while guaranteeing equivalent strength. The forming operations studied with this process are geared towards drawing, where the shapes of the parts to be manufactured may require complex warm forming strategies [6]. Metal sheet bending is an easier forming operation which offers the advantage of simplifying the tool, reducing costs and development time, provided that the part is designed to suit this type of operation [7]. However, this type of part is more commonly used in the aerospace industry where the series productions are smaller and the forming equipment is more similar to that used for sheet metal working with dedicated bending equipment, particularly with press brake.

The aim of the work presented here is to study the application of warm forming to bending through two materials designed for the mechanical and aerospace industries, namely the 2017A T4 and 6061 T6 aluminium alloy grades (as per standard EN 485-2). After characterising the materials using tensile tests at various temperatures, the bending tests under various forming conditions are presented. The results and analyses of the tests are outlined, particularly the micrographic examinations of the bends.
2. Characterisation of the materials
The materials studied are 2017A T4 and 6061 T6. 2017A, also known as Duralumin, is an Al-Cu-Mg alloy and can be considered as having played a predominant role in the development of aluminium in the aviation sector. 6061 alloy belongs to the family of Al-Si-Mg-(Cu) alloys and exhibits excellent formability in the annealed (O) and as quenched condition, however the products thus formed must then be heat-treated to be used in the T6 condition.

The 2017A T4 and 6061 T6 aluminium alloys were characterised via tensile tests under quasi-static conditions at different temperatures.

The tensile test conditions were as follows:
- Tensile test speed of 5 mm/min,
- Three sampling directions of the specimens: 0° - 45° - 90° with respect to the rolling direction,
- Heating up time and test time less than 12 minutes,
- Two specimens per configuration,
- Test temperatures: room temperature and 180°C.

Figure 1 shows the results of the engineering tensile tests (engineering quantities) for room temperature and 180°C. We noticed the following behaviours with the temperature increase: a lowering of the Rm and Rp0.2 values, and an increase of the ultimate elongation.

The additional quantities n and r, respectively strain-stress hardening and Lankfort Coefficient, are obtained from the true stress-strain curves and are summarised in tables 1 and 2.

We noted an influence of the specimen sampling direction for grade 2017A T4 (figure 1a), a decrease of n with the temperature that was more pronounced for grade 6061 T6 and a stability for r.

These results reveal that during the forming process, as often with the temperature, the elongation gain may be counterbalanced by the decrease in work hardening [8].

![Figure 1](image.png)

**Figure 1.** Engineering stress-strain curves at room temperature (RT) and at a temperature of 180°C (180°C) in the three directions 0° - 45° - 90° with respect to the rolling direction. One specimen per configuration. (a) 2017A T4 alloys – (b) 6061 T6 alloys
Table 1. 2017A T4 alloy (average values of the two specimens per configuration)

| State / Temperature | Direction vs the rolling direction | Rm (MPa) | Rp0.2 (MPa) | A% failure | n_average | r_average |
|---------------------|-----------------------------------|----------|-------------|------------|-----------|-----------|
| As-delivered state T4 at RT | 0 | 429 | 292 | 22.1 | 0.213 | 0.64 |
|                      | 45 | 410 | 260 | 21.1 |          |          |
|                      | 90 | 423.5 | 269.5 | 21.1 |          |          |
| At 180°C            | 0 | 323.5 | 226.5 | 25.9 |          |          |
|                      | 45 | 307 | 189.5 | 32.4 | 0.169 | 0.66 |
|                      | 90 | 310.5 | 210.5 | 29.5 |          |          |

Table 2. 6061 T6 alloy (average values of the two specimens per configuration)

| State / Temperature | Direction vs the rolling direction | Rm (MPa) | Rp0.2 (MPa) | A% failure | n_average | r_average |
|---------------------|-----------------------------------|----------|-------------|------------|-----------|-----------|
| As-delivered state T4 at RT | 0 | 334.5 | 311 | 14.1 | 0.079 | 0.60 |
|                      | 45 | 334.5 | 298.5 | 12.9 |          |          |
|                      | 90 | 335.5 | 296.5 | 13.8 |          |          |
| At 180°C            | 0 | 261.5 | 257.5 | 20.5 |          |          |
|                      | 45 | 262.5 | 237.5 | 15.8 | 0.024 | 0.59 |
|                      | 90 | 261 | 249.5 | 21.8 |          |          |

3. Bending tests

During the tests, we carried out V bottom air bending and coining (figure 2). The latter process is used to reduce the springback by stamping of the inner bend radius [9].

![Figure 2](image_url)

**Figure 2.** (a) V bottom air bending – (b) Coining.

Where e: thickness of the sheet metal - α₀: bending angle (V angle) – Ri: inner bend radius.

3.1. Test conditions and equipment

The specimens were cut parallel (0°) and perpendicular (90°) to the rolling direction. The dimensions of the specimens are: 160x50x1.2 mm. The equipment used for all the tests consists of a 120 ton bending press, a heating enclosure to heat the specimens, heating resistors and a temperature controller. The tool is made up of a V die (12 mm wide, 88° angle, 415 mm long) and a punch (88° angle, tool radius 0.2 mm, length 100 mm). The die and the punch are individually heated by heating resistors. Figure 3 shows the bending operation.
In the case of a test at high temperature, three configurations are studied and described below:

- Configuration No. 1: Bending with only the specimens heated to the set temperature (the tools are at room temperature). V bottom air bending.

- Configuration No. 2: Bending with all the specimens and tools heated to the set temperature. Setting adjusted to the “zero penetration position of the punch to avoid coining” under these conditions (consideration of expansion). V bottom air bending.

- Configuration No. 3: Bending under the same conditions as previously, without taking into account expansion. Setting of the “zero” position at room temperature. This configuration leads to coining.

The test temperatures are set at 100°C, 180°C and 260°C. The specimens are preheated in a heating enclosure and the holding time is set at 7 minutes 30 seconds for all configurations. The tools are heated and kept at the temperature with heating resistors and the temperature controller. The temperature on the surface of the tools is controlled with a contact thermometer.

3.2. Results and analyses

The results relate to the absence or not of bending cracks, springback and the micrographic examinations.

3.2.1. Cracking and springback

The materials studied exhibit characteristics limited to bending. European standard EN 485-2 specifies that, for the 2017A T4 alloy, the minimum bending radius is 3.6 mm and, for the 6061 T6 alloy, this radius is 3 mm. The radius of the punch used is 0.2 mm which is deliberately low (refer to paragraph 3.1) and thus may lead to fractures on the outside of the bend.

After each test, the bends are examined and the absence or not of cracking on the outside of the bend is noted. The springback $\Delta \alpha$ as measured is presented in figure 4.
Figure 4. Springback upon bending.

The springback is characterised by coefficient K defined by the equation (1).

\[ K = \frac{(180-\alpha)}{(180-\alpha_0)} \]  

Therefore, when K is equal to 1 the springback is zero (\( \alpha = \alpha_0 \)).

3.2.2. Influence of temperature on springback and the risk of cracking

Figure 5 shows the results obtained regarding the condition of the bends (cracking or not) and the springback for the two materials and the different temperatures.

As for the risk of cracking, only the 2017A T4 grade shows a risk of cracking if the temperature is less than 180°C. The 6061 T6 grade does not pose this risk, in consistency with the lower minimum bending radius for this material. By way of contrast, the relationship with the ultimate elongation is not established as the 2017A T4 grade exhibits a higher elongation than that of the 6061 T6 grade at room temperature or warm temperature.

Regarding the springback, the analysis based on the changes in the coefficient K, reveals that configuration No. 1 (heating of the specimens alone, with the tool at room temperature) does not improve the springback and even deteriorates it for the 2017A T4 grade. The low thermal inertia of the sheet metal is probably the reason for this result. Configuration No. 2 (tool and sheet metal heated without coining) reduces the springback. In this configuration, for the 6061 T6 grade, the temperature significantly reduces the springback. Configuration No. 3 (sheet metal and tool heated and bend coining) exhibits the best results with almost complete elimination of the springback for the 2017A T4 grade and a springback value that is especially low the higher the temperature for the 6061 T6 grade. Therefore the coining operation, used in the press tools to correct the geometric defects, seems well suited to warm bending.
3.2.3. Micrographic examinations

Figure 6 shows a bending operation at room temperature (configuration No.2) for the 2017A T4 alloy. In the panel (bottom left-hand corner), we note the surface bending on the outer side and the presence of cracks as well as the formation of surface asperities. The micrographic section shows the presence of a crack directed approximately $45^\circ$ with respect to the tensile stress on the outside of the bend. There is also significant surface roughness in which the recessed portions give rise to the formation of bands indicating the location of the distortion which are also directed at approximately $45^\circ$ with respect to the stress. These distortion location bands seem to be the crack initiation site. We can also note a grain structure that is directed along the plane parallel to the rolling direction.

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**Figure 6.** 2017A T4 alloy – Micrographic sections of the bend – Room temperature. (configuration No.2)
Figure 7 shows a micrographic section of the bend performed at 180°C (configuration No. 2) with the 2017A T4 alloy. In this case, there is no cracking (see the panel showing the surface bending on the outer side). As with room temperature, there is a significant roughness on the outer skin of the bend and there are also bands indicating the location of the distortion directed approximately 45° with respect to the stress direction.

![Micrographic section of the bend](image)

Figure 7. 2017A T4 alloy – Micrographic sections of the bend – Temperature of 180°C (configuration No. 2).

The same examinations are carried out for the 6061 T6 alloy. Therefore, the distortion mechanism noted [10] seems to take place regardless of the bending configuration studied, as follows:
- Formation of “macro-bands”, indicating the location of the distortion directed at approximately 45° with respect to the direction of the stress (tensile stress). These bands indicating the location of the distortions stem from the combination of the distortion (shear) and the rotation of some grains in the alloy along their crystallographic directions.
- Development of roughness on the outer skin of the bend due to the location of the distortion.
- For the 2017A T4 alloy, reduction of area and fracturing of certain grains located in the grooves of the asperities on the outer skin, then inter or transgranular cracking in certain bands indicating the location of the distortion.

4. Conclusion
The use of warm bending for two aluminium alloys revealed that heating helped to reduce the risk of cracking and that the full tool and metal sheet heating conditions were more favourable to reducing springback. The coining process at the end of bending further helps to control springback and, along with heating, may be a good method for reducing springback.

The 6061 T6 alloy is more suited to warm bending with a response that is improved the higher the forming temperature. The 2017A T4 alloy is more susceptible to cracking and a minimum forming temperature must be achieved. For this alloy, warm coining seems especially efficient to reduce springback.

The metallurgical analysis highlights a strain mode based on localised shear bands which may result in crack formation.

This study will next focus on the impact of temperature on the final mechanical characteristics of the two alloys after a return to room temperature.
References

[1] Shehata F, Painter M J, Pearce R 1978 Warm forming of aluminium/magnesium alloy sheet Journal of Mechanical Working Technology, vol. 2, pp. 279–291

[2] Kim H 2018 Comparison of Drawability between Warm Forming and Cold Forming of Aluminum 6xxx Alloys IDDRG June 5-7 (Kitchener)

[3] Bolt P J, Lamboo N 2001 Feasibility of warm forming of aluminum products Journal of Materials processing technology, 115, 118

[4] Maillard A, Piat C 2014 Study of a progressive die for warm forming of aluminum IDDRG June 1-4 (Paris)

[5] Ota E, Yogo Y, and Iwata N 2019 Improvement of formability for hot stamping of aluminum alloy sheets by press motion control IDDRG 5-7 (Enschede)

[6] Schlosser J, Schneider R, Rimkus W, Kelsch R, Gerstner F, Harrison D K & Grant R J 2017 Materials and simulation modelling of a crash-beam performance – a comparison study showing the potential for weight saving using warm-formed ultra-high strength aluminium alloys IDDRG June 3-5 (Munich)

[7] Gasser C, Kolleck R 2013 Air bent safety components for the carbody IDDRG 2-5 (Zurich)

[8] Hui W, Luo, Y B, Friedman P, Chen M H & Lin G 2012 Warm forming behavior of high strength aluminum alloy AA7075. Transactions of Nonferrous Metals Society of China, 22(1), 1-7.

[9] Cinar Z, Asmael M, Zeeshan Q, & Safaei B 2021 Effect of springback on A6061 sheet metal bending: a review. Jurnal Kejuruteraan, 33(1), 13-26.

[10] Mattei L 2011 Pliabilité des tôles en alliages d’aluminium pour la carrosserie automobile analyse des mécanismes d’endommagement, Thèse de l’École Nationale Supérieure des Mines de Saint-Étienne.