The influence of warm forming conditions on the natural aging and springback of a 6016-T4 aluminum alloy

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Abstract. Heat treatable aluminum alloys are very attractive materials to replace traditional steels in automotive body-in-white construction. However, their reduced formability and high springback limits their application in sheet metal forming operations. Moreover, these alloys are prone to natural aging that causes variability in forming operations and increases the amount of scrap. Warm forming can be a very interesting solution to improve formability and reduce springback. However, depending on the processing time, precipitation hardening may occur during the warm forming of these heat treatable alloys. Thus, punch speed has a major influence on the success of sheet metal forming operations. The present study addresses the influence of natural aging and punch speed in the warm forming of an Al-Mg-Si alloy: EN AW 6016-T4. The thermo-mechanical behavior was studied in function of temperature (from 22 to 300 °C), punch speed (from 0.1 to 10 mm·s⁻¹) and storage time (from 1 to 18 months), using uniaxial tensile tests, cylindrical cup tests, and split ring (springback) tests. Warm temperatures between 200 and 250 °C reduce the flow stress, minimizing the effects of natural aging on the variability of the mechanical properties. A high punch speed is advantageous since it minimizes the occurrence of precipitation hardening which contributes to increase the springback. Thus, warm conditions at high punch speed can be used as an effective solution to minimize the variability caused by the natural aging in forming operations of heat treatable aluminum alloys.

1 Introduction

Lightweight vehicles are crucial to reduce energy wastage in the transports sector. Thus, it is essential to reduce vehicles body-in-white weight, while safety demands require increasing structural strength. Since aluminum alloys present a good strength-to-weight ratio and crash energy absorption, its demand in the automotive sector is rising [1,2]. However, when compared with traditional mild steels, the aluminum alloys present lower formability and higher springback. In non-heat treatable aluminum alloys, warm forming has been highly studied in order to improve formability [3] and reduce the springback [4,5]. Large improvements in formability can be achieved using a temperature gradient in the blank [6], which can be achieved by decreasing the punch temperature relative to the one of the die/blanks-holder in deep drawing operations [6,7]. However, the material strain rate sensitivity increases as the temperature increases, since the rate of dislocation annihilation is controlled by diffusion, which is a thermally activated mechanism dictated by the time. That is why diffusion is often negligible at RT and becomes relevant for temperatures greater than approximately one third of the absolute melting temperature [8]. Usually, aluminum alloys present positive strain rate sensitivity at warm temperatures,
thus an increase of punch speed is often disadvantageous since it leads to the decrease of formability [9] and the increase of springback [5,10]. In brief, concerning the non-heat treatable aluminum alloys, the improvement of formability and springback is achieved when performing the forming operation at higher temperatures but at lower punch speed. Anyway, in case of non-isothermal warm forming, a higher punch speed contributes to minimize the heat transfer, keeping the temperature gradient in the blank, which is advantageous [5].

Recently, the heat treatable aluminum alloys stimulated the interest of automotive industry due to the advantage of switching from high ductility (in-forming) to high strength (in-service) [2,11]. Additionally, formability improvement due to warm forming is also observed [3,11,12]. Nevertheless, for the heat treatable aluminum alloys, the warm forming above 200 °C can be counterproductive for the post forming properties, since it can lead to the decrease of the strength required for in-service behavior [11,13]. Moreover, a sufficiently low punch speed can lead the initial soft (ductile) material to gradually become harder and approach the high strength condition [12,14]. In fact, as warm forming and heat treatment temperatures are within the same range, a change in the heat treatment can occur due to long exposure time to high forming temperatures. Besides, heat treatable alloys are prone to natural aging that causes variability in forming operations and increases the amount of scrap [15,16]. Natural aging results from precipitation hardening at room temperature (RT), which leads to the increase of the yield stress and the work hardening [17,18]. Face to the difficulties exposed, the present study aims to improve knowledge about the influence of the natural aging, temperature, and punch speed on the springback behavior and formability of heat treatable aluminum alloys during warm forming processes.

2 Material and Experimental procedure

2.1 Materials
In the present study, the heat treatable EN AW 6016-T4 was selected, since it is highly demanded by the automotive industry for skin applications. It belongs to the 6xxx series (Al-Mg-Si alloy), which have Mg and Si as the main alloying elements, see the chemical composition in Table 1. The designation T4 indicates solution heat treated, rapid quenching, and naturally aged to a substantially stable condition. Nevertheless, the T4 heat treatment is a metastable equilibrium and, consequently, natural aging may occur. Thus, in the present work, the evolution of the mechanical properties with the storage time was analyzed. The storage time considered varies from 1 to 18 months. In the T4 heat treatment, the aluminum alloys present good formability, while, after forming, their in-service strength can more than double by artificial aging to peak hardening. In the automotive industry, the paint bake cycle induces the artificial aging, since it is commonly performed for temperatures from 120-180 °C, during a period from 30 to 45 min [2]. The mechanical properties at RT after 4 days of maturation are presented in Table 2. The terms and definitions used are according to ISO 6892-1:2009 (i.e. $R_m$ tensile strength; $R_{p0.2}$ proof strength at 0.2% of the extensometer gauge length; $A_g$ percentage of non-proportional elongation at maximum force) and the ISO 10275:2007 (i.e. the strain hardening exponent ($n$), which in this case was evaluated between 4 and 6 % of plastic deformation, $n_{4-6}$, and 10 and 15 %, $n_{10-15}$).

| Si  | Mg  | Cu  | Fe  | Mn  |
|-----|-----|-----|-----|-----|
| 0.91| 0.41| 0.10| 0.255| 0.17|

Table 1. Chemical composition, in percent composition by mass (wt.%), supplier results.

| $R_{p0.2}$ | $R_m$ | $A_g$ | $n_{4-6}$ | $n_{10-15}$ | Thickness |
|------------|-------|-------|-----------|-------------|-----------|
| 88 MPa     | 198 MPa| 24.6 %| 0.32      | 0.27        | 1.05 mm*  |

*The thickness presented corresponds to the average value obtained with fifty measurements.
2.2 Experimental procedure
The thermo-mechanical behavior was evaluated performing uniaxial tensile tests, cylindrical cup forming tests, and split ring springback tests. The tensile tests were performed in a Gleeble machine, at RT (~22), 100, 150, 200 and 300 °C, considering an imposed initial strain rate of \( \approx 2 \times 10^{-3} \text{s}^{-1} \). At RT and 200 °C, additional tests were performed at strain rates of \( 2 \times 10^{-4} \) and \( 2 \times 10^{-2} \text{s}^{-1} \). All the tensile specimens were aligned with the rolling direction (RD). Cylindrical cup forming tests were performed in a temperature range from 22 to 250 °C, and a punch speed from 0.1 to 10 mm s\(^{-1}\). These tests were performed in a Zwick BUP200 machine with a clamping force of 6 kN, using a high-temperature aerosol grease 95cSt Jelt Grease 5411, as previously described by [7,19]. The blank is circular with a diameter of 60 mm, while the die has an inner diameter of 35.30 mm and the punch an outer diameter of 33 mm, i.e. the clearance is 1.15 mm, as shown in Figure 1 a). In warm forming a temperature differential was imposed to the tools. The die and the blank-holder were pre-heated to the test temperature using resistance heating, while the punch was water cooled to keep its temperature close to RT. Finally, the heating time was always lower or equal to 1 minute. In both tensile and cylindrical cup tests, the temperature was acquired using type K thermocouples welded on the blank surface.

Springback was analyzed using the split ring test, which according to ASTM E2492-07 [20] consist of: i) cut one ring from the cup wall (trimming); ii) open the ring along the RD, split ring; and iii) measure the ring opening. However, in the present work, three rings were extracted from the vertical wall, each one with 3 mm height, as shown in Figure 1 b). This procedure allows a more detailed analysis of the springback behavior since it was previously shown that the magnitude of the ring opening is influenced by its vertical position along the cup wall [21,22]. Electrical discharge machining (EDM) was used to open and cut the rings, as also suggested in [20]. The variation of the ring diameter, before and after splitting, gives an indirect measure of the springback phenomenon and of the amount of the circumferential residual stresses present in the formed cup [4]. The ring opening was measured using a microscope to assure high measurement accuracy, and the EDM cut thickness (0.3 mm) was taken into account in the measured value.

Figure 1. a) Dimensions of the tools used in the cylindrical cup test. b) Dimensions of the rings.

3 Results
3.1 Tensile test
The uniaxial tensile tests were performed in a Gleeble 3500 machine that uses a high-speed heating method by direct resistance (Joule heating), which enabled a heating time of 20 seconds (s). This heating method leads to a temperature gradient along the specimen length, with higher temperature and symmetry at the specimen center, as shown in Figure 2 a). Nonetheless, at 200 °C, the temperature difference between the specimen center and a point located 1.5 mm from it does not exceed 0.4 °C [23].
However, this temperature gradient promotes heterogeneous mechanical properties along the specimen length direction, leading to a higher deformation at the specimen center. Accordingly, only a rectangular gauge measurement area of 6 mm width and 3 mm length at the specimen center is used to compute the strain, see Figure 2 b) (also detailed in [23]). The strain field was acquired by digital image correlation with the system Aramis-4M (GOM mbH).

![Figure 2](image_url)

**Figure 2.** Tensile tests performed at a strain rate of $2 \times 10^{-3}$ s$^{-1}$ at 100, 150 and 200°C: a) temperature gradient along the specimen length direction, measured with four thermocouples located at the mid-width (black circles); b) strain gradient along the specimen length direction for four strain instants: at $\varepsilon = 0.04$, at $\varepsilon = 0.10$, at $R_m$ and just before rupture.

The engineering stress – strain curves are presented in Figure 3 a) and b), regarding the influence of temperature and strain rate, respectively. The tests performed at RT show a noteworthy variation of the mechanical properties due to the storage time in the period from 1 to 7 months, stabilizing from 7 to 18 months (see Figure 3 a)). However, this influence of the natural aging decreases with the temperature increase. Additionally, the increase of temperature contributes to the decrease of the flow stress, resulting in lower yield stress and tensile strength values. On the other hand, the strain-rate sensitivity, that is negligible at RT, becomes very significant at 200 °C. In fact, at 200 °C, the strain-rate sensitivity is initially positive but changes to negative for higher strain values, see Figure 3 b).

![Figure 3](image_url)

**Figure 3.** The engineering stress – strain curves: a) the temperature influence at $2 \times 10^{-3}$ s$^{-1}$; b) the strain rate influence at 1 month of natural aging. The times presented correspond to the test duration until attaining the $R_m$ instant.

### 3.2 Punch Force

The punch force-displacement curves obtained during the cylindrical cup forming are shown in Figure 4 a) and b), regarding the influence of temperature and punch speed, respectively. Two different phases
are distinguished: (i) the drawing and (ii) the ironing. The drawing phase occurs until a punch displacement of \(\approx 21\) mm. During this phase, first, the punch force increases rapidly until a displacement of \(\approx 11\) mm, which corresponds to the instant that the die and the punch shoulder radii are completely formed in the part. Afterward, it decreases until it reaches a local minimum at \(\approx 19\) mm of punch displacement, which is related to the fact that the tool presents no blank-holder stopper. This minimum occurs just before the loss of contact between the blank and the blank-holder, since at this stage the blank-holder promotes the movement of the sheet into the die cavity and, consequently, reduces the punch force. Then, the ironing of the cup wall occurs since the gap between the punch and the die (1.15 mm) is not sufficiently large to allow the thicker material to flow. In fact, the circumferential compression stress state induced in the flange leads to a thickening to approximately 1.25 mm [24], which corresponds to a reduction ratio of approximately 9%. This ironing phase can be associated with the increase of the punch force until attaining a local maximum (\(\approx 23\) mm of punch displacement), followed by a decrease until the end of the process.

![Figure 4](image_url)

**Figure 4.** The punch force evolution as a function of the punch displacement: a) the temperature influence for a punch speed of 1 mm\(\cdot\)s\(^{-1}\); b) the punch speed influence.

Globally, the punch force decreases with the temperature increase, see Figure 4 a). However, the influence of the punch speed on the punch force evolution cannot be neglected at warm temperatures, see Figure 4 b). As shown in this figure, at 200 °C, it is remarked a slightly higher punch force up to 9 mm of punch displacement, for a higher punch speed. However, this behavior inverts after 10 mm of punch displacement. Moreover, for the punch speed of 0.1 mm\(\cdot\)s\(^{-1}\) an unusual increase of the drawing force is observed between 10 and 15 mm of punch displacement, which will be discussed in the discussion section. Concerning the natural aging influence, at RT the results show an increase of the punch force due to the increase of the storage time, which is not affected by the punch speed. As the temperature increases, the impact of natural aging on the punch force reduces, becoming negligible at 200 °C, whatever the punch speed used.

### 3.3 Springback

The measurements of the ring opening by the split ring test are shown in Figure 5 a) and b), regarding the influence of temperature and punch speed, respectively. As presented in Figure 1 b), three rings were cut from the cup wall at various heights. It is observed that ring 3 (near the cup’s bottom) presents the highest opening value, while ring 1 (at the cup top) presents the lowest one, i.e. the ring opening shows a decreasing value as the distance to the cup bottom increases, whatever the temperature or punch speed. Moreover, ring 1 (at the cup top) presents an opening value relatively constant, whatever the temperature or punch speed. In fact, as previously studied in [24], the occurrence of the ironing stage contributes to the reduction of the through-thickness gradient of the circumferential stress component, the main component contributing for springback in the split ring test. Regarding rings 2 and 3, the springback decreases with the increase of temperature (Figure 5 a)), as a result of the reduction of the circumferential stress component.**
residual stresses in the deep drawn cups. The punch speed has a negligible effect on the ring opening at RT, while at 200 °C the ring opening value decreases linearly with the logarithmic punch speed increase, i.e. the higher ring opening occurs at the lowest punch speed of 0.1 mm∙s⁻¹, see Figure 5 b). Finally, despite the high impact of natural aging in the springback variability at RT, the variability of ring opening due to natural aging decreases as the temperature increases and is negligible at 200 °C, whatever the punch speed.

![Graph](image)

**Figure 5.** The ring opening as a function of: a) the temperature for a punch speed of 1 mm∙s⁻¹; b) the punch speed.

4 Discussion

In the present study, the thermo-mechanical behavior of the EN AW 6016-T4 was evaluated performing uniaxial tensile tests, cylindrical cup forming tests and split ring springback tests. Globally, the thermo-mechanical behavior of the material can be correlated through the three tests performed. At RT, the material storage leads to natural aging strengthening, which results in the increase of the flow stress. Consequently, the punch force and springback also increase, leading to variability in sheet metal forming operations. Natural aging strengthening occurs due to the precipitation of Mg and Si atoms in solute clusters, which restrain dislocations movement. In the Al-Mg-Si alloys, since Mg and Si are substitutional elements in the aluminum matrix, precipitation occurs by diffusion mainly assisted by “quenched-in vacancies”.

The temperature increase contributes to the decrease of the flow stress, resulting in the decrease of punch force and springback. Moreover, the influence of natural aging on the punch force and springback variability becomes negligible as the temperature increases, which is in accordance with the results of the tensile tests. In fact, the temperature increase enhances the dislocation movements, minimizing the interactions between solute clusters and dislocations. Simultaneously, the solute clusters are expected to dissolve between 200 and 250 °C [25,26]. Thus, warm forming in this temperature range may contribute to reduce the influence of natural aging in the variability of the mechanical properties of the material used in the forming operation [27].

Regarding the influence of the strain rate sensitivity on the material behavior, globally the results show that at RT it has a negligible effect, while at 200 °C it cannot be overlooked. Thus, the sensitivity of the punch force evolution curves and springback to the punch speed seems to be linked to the material strain rate sensitivity. However, at 200 °C the punch speed influence on the punch force and springback does not change due to natural aging. As shown in Figure 4 b), at 200 °C, from 0 to 9 mm of punch displacement, a slight higher punch force occurs at higher punch speed, which can be linked to the initial positive strain rate sensitivity presented in Figure 3 b)). However, after 10 mm of punch displacement, a punch force increase occurs for the lower punch speed, which is similar to the one observed in the tensile tests (see Figure 4 b) at 2x10⁻³ s⁻¹). According to [12,14], a sufficiently low punch speed can lead the initial soft (ductile) material gradually to become harder and approach the high strength, as a result of dynamic precipitation. The change in the strain rate sensitivity observed between the tensile tests at
2x10^{-3} \text{s}^{-1} and 2x10^{-2} \text{s}^{-1} indicates that dynamic precipitation occurs also at 2x10^{-3} \text{s}^{-1} (see Figure 3 b). This precipitation hardening phenomenon results in an increase of the springback as the punch speed decreases, which is contrary to the results relative to non-heat treatable aluminum alloys [5,10]. In fact, precipitation occurs by diffusion, which is a thermally activated mechanism dictated by the time. Consequently, the test duration is an important parameter during warm forming of heat treatable alloys.

The exposure time range (heating and forming) of cylindrical cups for the punch speeds used matches the ones of the tensile tests for the strain rates used. Thus, the warm forming of the cylindrical cup at a punch speed of 0.1 mm s^{-1} requires a heating and forming time of approximately 60 and 300 s, respectively. Accordingly, the tensile test at the strain rate of 2x10^{-4} \text{s}^{-1} requires 20 s for heating and 450 s to attain the Rm (see Figure 3 b)). These forming times at the lower punch speed and strain rate are almost 1/3 of the time normally used for paint bake hardening (30 min). However, in warm forming the plastic deformation leads to dislocation-assisted precipitation, reducing the exposure time required for precipitation hardening, as compared to the one associated with static aging [28]. For the punch speeds of 1 and 10 mm s^{-1}, the forming time is approximately 30 and 3 s, respectively. Accordingly, the tensile tests for a strain rate of 2x10^{-1} \text{s}^{-1} and 2x10^{-2} \text{s}^{-1} require 65.5 and 5.42 s to attain the Rm, respectively. Finally, the high punch speed is advantageous to minimize dynamic precipitation, but also allows the high production rates required in industry.

5 Conclusions
The present study analyzed the influence of temperature, natural aging and punch speed on the forming behavior and springback of an EN AW 6016-T4 heat treatable aluminum alloy. In summary, warm forming contributes to reduce the forming forces, the springback, and the variability caused by the natural aging. Warm forming in a temperature range from 200 to 250 °C is recommended to achieve the above advantages. However, at warm temperatures, high processing time, due to low punch speed, is disadvantageous. In fact, dynamic precipitation occurs leading to the change of the initial microstructure, which contributes to the increase of the forming forces and of the springback. In this context, an improved analysis of the influence of strain rate and exposure time on the microstructural changes resulting from dynamic precipitation is required. From an industrial point of view, warm forming in heat treatable aluminum alloys presents several advantages, namely the reduction of variability due to natural aging. Moreover, a high punch speed, allowing high production rates, is advantageous to minimize dynamic precipitation.

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