Influence of temperature, strain-rate and aging on the mechanical behaviour of an Al-Mg-Si alloy

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Résumé:

Ce travail vise à analyser l'influence de la température, de la vitesse de déformation et de la durée de vieillissement sur le comportement mécanique de l'alliage EN AW 6016-T4, vieilli naturellement. Cet alliage a été sélectionné car il est couramment utilisé dans l'industrie automobile. Les essais mécaniques de traction ont été réalisés pour une gamme de température comprise entre la température ambiante et 300°C, pour différentes vitesses de déformation et à des temps différents après leur production. Les résultats constituent une nouvelle base de données expérimentale qui permettra d'évaluer les applications potentielles de la mise en forme à chaud de cet alliage.

Abstract:

This work aims to analyse the influence of temperature, strain-rate and aging time in the mechanical behaviour of an EN AW 6016-T4 alloy, naturally aged. This Aluminium Alloy was select since it is commonly used in the automotive industry. Uniaxial tensile tests were performed within a temperature range between room temperature and 300ºC, for different strain rates and at different times after its production. The results collected constitute an experimental database for evaluating the potential application of warm forming processes to this alloy

Mots clefs: Al-Mg-Si Alloys; Mechanical Characterization; Temperature; Strain rate; Aging

1 Introduction

The new milestones of societies comprise the reduction of pollution and Greenhouse gas, namely CO_2. Herein the transport sector plays a crucial role, for which the use of recyclable and lighter materials can contribute to the energy cost reductions and, consequently, the ecological footprint. In this context, the Aluminium Alloys (AA) present a great benefit since they are light and highly recyclable materials, namely when compared with conventional steels [1-2]. However, they also present lower formability and higher springback when compared with conventional mild steels. Thus, a key challenge is the

improvement of AA formability in order to extend their applications. Herein the warm forming is a potential solution [3].
Numerous studies show the importance of temperature as a key parameter to improve formability and reduce springback. Toros et al. [4] presented a literature review on warm forming of Aluminum–Magnesium alloys highlighting the use of a temperature range from 200°C to 300°C, to achieve improved formability and better surface quality of the final product. Further on 5xxx series, with AA5754, Laurent et al. [5] also showed that warm forming condition reduce flow stress and springback. Moreover, and also in AA5754, the warm forming can avoid the problems of dynamic strain aging (DSA) known as Portevin–Le Chatelier (PLC) effect present in 5xxx series at room temperature [6-7]. Concerning 6xxx series, although does not present the higher strength, it is commonly used too. Bolt et al. [8] and, Ghosh et al. [9] studied the warm forming of AA6016, concluding that warm forming offers a good possibility for drawing complex parts, which cannot be made at room temperature without extra forming operations. In the stretch-drawing of a rectangular conical shape, Bolt et al. [8] observed the best increase of the critical deep drawing ratio for a temperature of 175°C, within a range from room temperature to 250°C. In deep drawing of a cylindrical cup, Ghosh et al. [9] observed that, with the increase of temperature, the amplitude of earing decreases while the number of ears remains the same, indicating that the in-plane trend of the mechanical properties does not changes with temperature but becomes slightly more isotropic. Concerning the warm forming of AA5052 and AA6061 sheet alloys, Mahabunphachai and Koç [10] concluded that the change of grain size due to the effects of elevated temperatures and strain rates were not significant. Therefore, they concluded that the decrease in the flow stress at high temperature levels was mainly due to the thermally activated dislocation lines. In brief, warm forming conditions may reduce the flow stress and rate of work hardening, improving the material ductility and toughness.

The Aluminium Alloy EN AW 6016-T4 is used in this study. This alloy is commonly used in the automotive industry. It is known as a Si excess alloy since Mg/Si ratio in mass fraction percentage [wt.%] is less than one. The EN AW 6016-T4 sheets were made and supplied by Constellium with a Mg/Si ratio equal to 0.19 [wt.%], and; were cold rolled up to 1mm thickness, annealed, quenched and natural aged (T4). The material received was solution treated on March 25th, 2014. The mechanical properties evaluated by uniaxial tensile tests performed with four days of maturations are presented in Table 1.

Table 1 – Mechanical properties of EN AW 6016-T4 (supplier results). 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. n_{4-6} strain hardening coefficient between 4 and 6 % of plastic elongation. n_{10-15} strain hardening coefficient between 10 and 15 % of plastic elongation (terms and definitions according with the European Standard EN 10002-1).

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

2 Experimental setup and procedure

Uniaxial tensile tests were performed at temperatures ranging from room temperature up to 300°C and at strain rates ranging from $2x10^{-4}s^{-1}$ up to $2x10^{-2}s^{-1}$. The anisotropy was studied using specimens cut along three different directions in the sheet plane: 0°, 45° and 90° with the rolling direction. Tensile tests were performed with a 6 month time lag, to evaluate the influence of static strain aging. In this context, the first series of tensile tests were performed approximately 1 month after heat treatment and

the second series 7 months after. All tests were performed in a Gleeble 3500 electromechanical testing machine, which involves a closed loop system using direct resistance Joule heating, via a 50 Hz AC current. The strain fields were locally measured, in the specimens' middle zone with 6mm width, by Digital Image Correlation (DIC) technique using ARAMIS 5M 3D optical system.
A minimum of two tensile tests were performed for every condition under analysis (temperature, strain-rate, anisotropy and aging time). The results were always reproducible, with an average scatter of true stress less than ±1MPa for the same value of true strain. Thus, in the following section only the result of one of the tests is presented.

3 Results and Discussion

Figure 1 presents the results of the uniaxial tensile tests performed for five different temperatures: 20°C (room temperature), 100°C, 150°C, 200°C and 300°C. The increase in temperature leads to a decrease of the yield stress and the ultimate stress. Although not shown here, the uniaxial tensile tests performed at different orientations to the rolling direction show that the material presents a negligible anisotropic behaviour of the yield stresses that does not change with temperature.
Concerning natural aging, due to material storage, the 6016-T4 alloy reveals a variation of the mechanical properties with time. As shown in the same figure, the aging leads to an increase of the yield and ultimate stresses; the total elongation is reduced due to the aging effect.

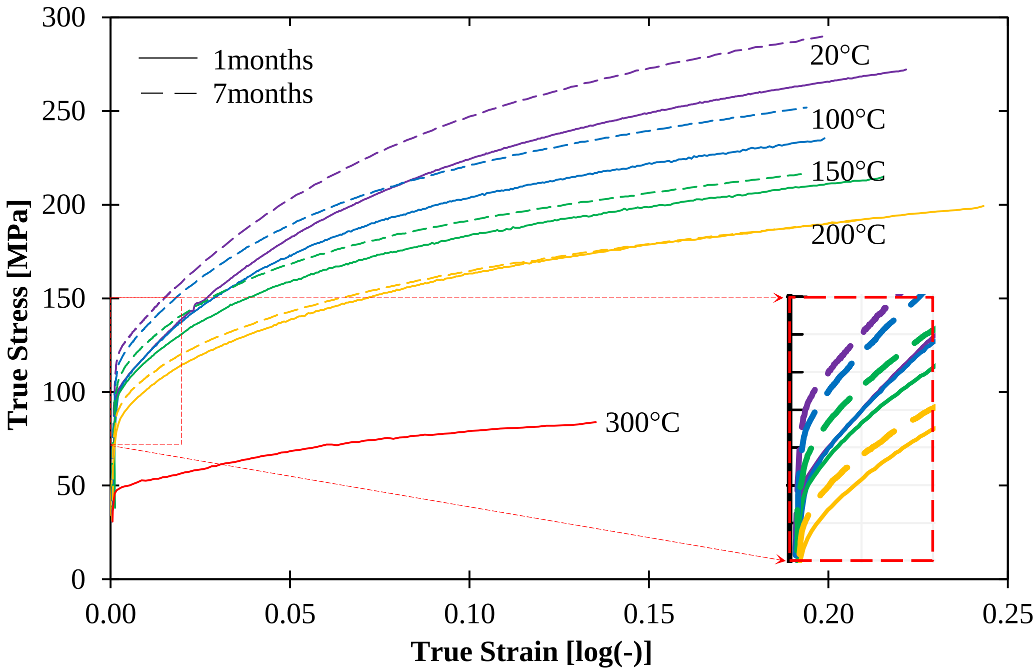

Figure 1 – Influence of aging on stress-strain curves obtained from uniaxial tensile tests performed at different temperatures, for specimens oriented along the rolling direction.

A summary of the mechanical properties obtained from the nominal tensile test curve is presented in Table 2. The results correspond to the ones obtained at 1 month's maturation. Regarding the percentage of total elongation at maximum force (A_{gt} [%]), no significant variation is noticeable between 20°C and 200°C, with a decrease at 300°C. The percentage of total elongation (A_t) shows a constants increase with increasing temperature between 20°C and 300°C, with the highest change occurring between 20°C and 100°C. The tensile strength (R_m) presents a constant decrease with the increase of temperature. The tensile test results are in agreement with the ones reported by Kurukuri [11]. The flow stress reduction and the increase of total elongation indicate that under non-isothermal conditions the limit drawing height of deep drawn components can be improved as reported by Bolt et al. [8] and Ghosh et al. [9].

Table 2 – Mechanical Properties of EN AW 6016-T4 (1 month's maturation). A_{gt} percentage of total elongation at maximum force. A_t percentage of total elongation. R_m tensile strength (terms and definitions according with the European Standard EN 10002-1).

Temperature	20°C	100°C	150°C	200°C	300°C
A_{gt} [%]	24.82	22.02	24.02	27.54	14.48
A_t [%]	40.32	49.61	51.84	53.92	57.79
R_m [MPa]	217.97	192.90	173.18	156.22	73.23

Figure 2 shows the stress-strain results of uniaxial tensile tests performed with three different values of strain rate: 2x10^{-4}, 2x10^{-3} and 2x10^{-2}s^{-1}, for two different temperatures (20ºC and 200ºC). It is shown that the strain rate sensitivity increases with the increase of temperature. In fact, at room temperature EN AW 6016-T4 alloy is not sensitive to strain rate. However, at 200ºC the results clearly show that a decrease of the strain rate leads to a decrease of the yield stress. Also at 200ºC, the work hardening is affected by the strain rate; at 2x10^{-4}s^{-1} the work hardening is initially high and saturates after a true strain of 0.05; at 2x10^{-3} and 2x10^{-2}s^{-1} the EN AW 6016-T4 presents a constant and smooth evolution of work hardening.

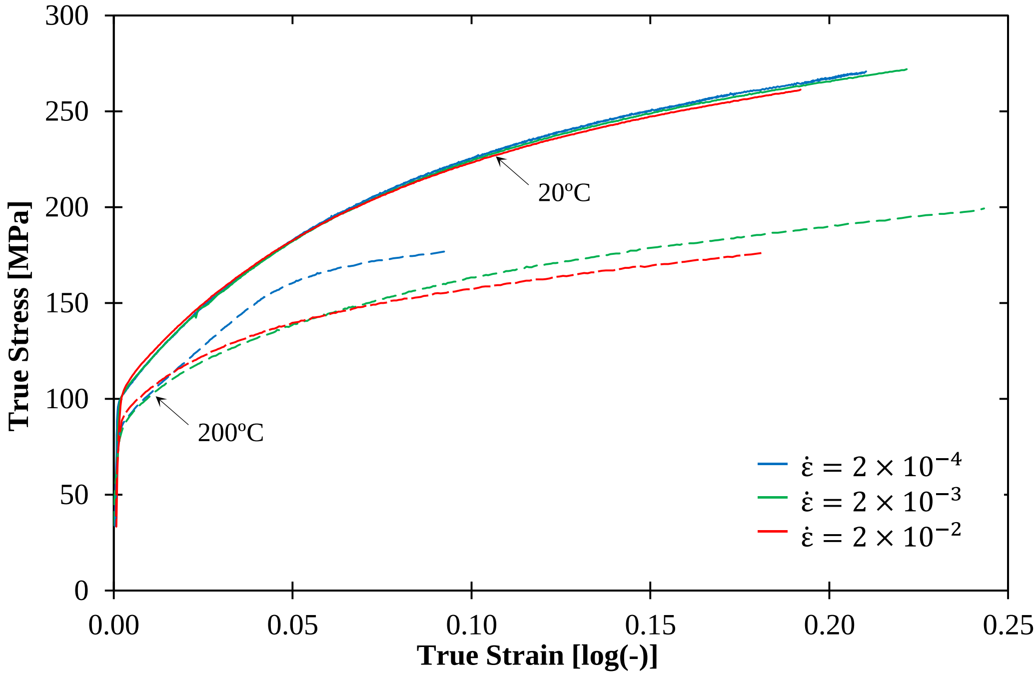

Figure 2 – Influence of strain-rate on stress-strain curves obtained from uniaxial tensile tests performed at different temperatures, for specimens oriented along the rolling direction

4 Conclusions

The main conclusions of this work are: the increase of temperature leads to a decrease of the yield and the ultimate stress; increasing natural aging time leads to an increase of the yield stress and the ultimate stress; the material presents a small orthotropic behaviour in the yield stresses that does not change with temperature; and, the strain rate sensitivity increases with the increase of temperature being null at room temperature and positive at 200°C.

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