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EVOLUTION OF MECHANICAL BEHAVIOR OF ALUMINUM ALLOY Al 7075 DURING MATURATION TIME

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ABSTRACT

The Aluminum 7075 (Al 7075) alloy is a precipitation hardening material instead of a strain hardening material. These mechanical properties are of a particular microstructure obtained by thermo-mechanical treatments. Among other things, this is a complicated microstructure which is responsible for the mechanical performance. The evolution of the mechanical properties of aluminum alloys is dependent on aging time parameters after heat treatment. In this study, the material has undergone a tempering heat treatment followed by a series of tensile tests. The experimental data (tensile curves in three directions during maturation time) is used to describe the evolution of the mechanical characteristics in terms of loading directions and maturation time, denoted respectively as: Ψ and t. The tensile curves are the source of data to begin the problem of identifying the behavior law of studied material using Barlat's model and Hollomon's isotropic hardening law. Thus, from the identified parameters (anisotropy coefficients and hardening coefficients), the evolution of the Lankford coefficient, deformation rate and load surfaces during the maturation time for three load directions (0°: rolling direction, 45° and 90°) are described. This study allows optimizing the response of the aluminum alloy to plastic strains, resulting from forming processes measured against the best time during maturation and the best load direction.

Keywords: Aluminum 7075 alloy Al 7075; Anisotropy; Maturation time; Tensile tests; Thermo-mechanical treatments

1. INTRODUCTION

Known as a mainstay in the aerospace industry since it was introduced, Aluminum 7075 alloy brings moderate toughness as well as an excellent strength-to-weight ratio. It is also important to note that at sub-zero temperatures Aluminum 7075 increases in strength (Yespica, 2012). Due to these outstanding benefits, Aluminum 7075 is used extensively for a number of applications, including: highly stressed structural parts, aircraft fittings and missile component.

Barralis and Maeder have shown that Aluminum 7075 alloy, with zinc as the main alloying element, is a high-strength alloy that provides good stress corrosion cracking resistance. It is available in clad form to improve corrosion resistance (Barralis & Maeder, 2002).

Knowing that the Aluminum 7075 alloy is a precipitation hardening material (age hardening), the selected authors (Lin et al., 2013a; Lin et al., 2013b; Leacock et al., 2013; Ben Mohamed et al., 2015; Znaidi et al., 2015) make the case for an interesting background to describe the evolution of hardening precipitates and their effect on the mechanical characteristics of this

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alloy until maturation and stabilization.

For several decades, previous research works have studied the mechanical behavior of aluminum alloys (Bagaryatsky, 1952; Ringer et al., 1998; Alberto & Glioli, 1962). The study by Ben Mohamed et al. (2014) was instrumental in developing a complex constitutive law that takes into account loading direction and the maturation time for two aluminum alloys in order to describe their mechanical characteristics.

The aim of this paper is to establish a series of tensile mechanical tests in various load directions Ψ (0°, 45° and 90°), respectively and in different maturation times (t). These tensile tests are intended to describe clearly the evolution of the mechanical properties of the aluminum alloy that is causing the precipitation kinetics. In order to identify the anisotropy coefficients and the hardening law coefficient an identification strategy proposed by Znaidi et al. (2016a) will be applied to Aluminum alloy sheets in the same manner as indicated in the experimental study below. Following this strategy, the mechanical behaviour, as a function of maturation time surveyed in three different loading directions, will be predicted. Additionally, the response of the aluminum alloy to plastic strains resulting from the forming processes will be optimised.

2. METHODOLOGY

2.1. Experimental Study

The prismatic test tensile tests were laser cut from rolled sheet provided to the state of marketed 7075-T73 materials. These specimens were heat treated by quenching. The heat treatment is performed in an electric furnace with uniform temperature. The test pieces of Al 7075 material have suffered a heating to the temperature of dissolution $460^{\pm 5}$ followed by an isothermal hold for homogenizing the structure. This thermal treatment is completed by a quenching in water at room temperature (Ben Mohamed et al., 2015; Znaidi et al., 2016b).

The frequency of achieving the tensile mechanical testing for each direction and for each material is as follows:

- Fresh Quenching (Q fresh)
- After 1-hour of quenching (Af 1h)
- After 2 hours of quenching (Af 2h)
- After 1 day of quenching (Af 1d)
- After 7 days of quenching (Af 7d)

We pushed tensile mechanical tests for different directions to 7 days after tempering and it is the time required to reach the stage of maturation of the aluminum alloy.

2.2. Modelling-identification

Data from mechanical traction tests were used in the identification of the behavior of the material with the most suitable models; namely, Barlat's model for isotropic hardening and Hollomon's hardening law.

Al 7075 is face-centered cubic, for this, we used the Barlat yield criterion (Barlat et al., 1991), as shown in Equation 1:

$$\sigma_e^m = |q_1 - q_2|^m + |q_2 - q_3|^m + |q_1 - q_3|^m \tag{1}$$

q_1, $q_2$and q_3 are the principal values of the tensor **q** defined as follows in Equation 2:

$$\boldsymbol{q} = \boldsymbol{A} : \boldsymbol{\sigma}^D \tag{2}$$

A is the fourth order orthotropy tensor defined by the anisotropy coefficients (*f*, *g*, *h* and *n*), $\boldsymbol{\sigma}^D$ is the deviator tensor of the Cauchy stress tensor, and *m* is the form factor. The anisotropic behaviour is modeled using a non-quadratic Barlat criterion and the Hollomon hardening law. The anisotropy is represented by 6 parameters in the form of fourth order symmetric tensor of the yield surface and two parameters of hardening law. Introducing the angle θ that defines the orientation of $\boldsymbol{\sigma}^D$ (Znaidi et al., 2016a; Daghfas et al., 2015), the deviatoric space is written as shown in Equation 3:

$$\bar{X}_1 = |\boldsymbol{\sigma}^D| \cos \xi,\ \bar{X}_2 = |\boldsymbol{\sigma}^D| \cos \theta \cos 2\Psi \ \text{and}\ \bar{X}_3 = |\boldsymbol{\sigma}^D| \cos \theta \sin 2\Psi \tag{3}$$

The different values of θ for various tests are defined as follows: simple tensile (S.T) for θ = π/3, simple shear (S.S) for θ = π/2, plane tensile (P.T for θ = π/6) in the deviatory plan (Znaidi et al., 2015). The behavior model is represented by the Hollomon Hardening Law shown in Equation 4:

$$\sigma = K\,\varepsilon^n \tag{4}$$

Generally, the plastic behavior with different directions is assessed by the anisotropy coefficient or Lankford coefficient (Lankford ratios). The Lankford coefficient is defined by Equation 5:

$$r(\Psi) = \frac{\dot{\varepsilon}_{11}}{\dot{\varepsilon}_{33}} \tag{5}$$

where $\dot{\varepsilon}_{11}$ and $\dot{\varepsilon}_{33}$ are the strain rates in the width and thickness directions respectively. Additionally, the width and thickness strain rates are identical for isotropic materials.

3. RESULTS AND DISCUSSION

3.1. Experimental Tensile Curves for Al 7075

In this part, we will represent the stress-strain curves in different directions (the rolling direction 0°, 45° and 90° direction) and dice the fresh quenching until maturation (state T4) (Znaidi et al., 2016b).

The experimental tensile curves for three directions and for different times of quenching are presented in Figures 1, 2, and 3.

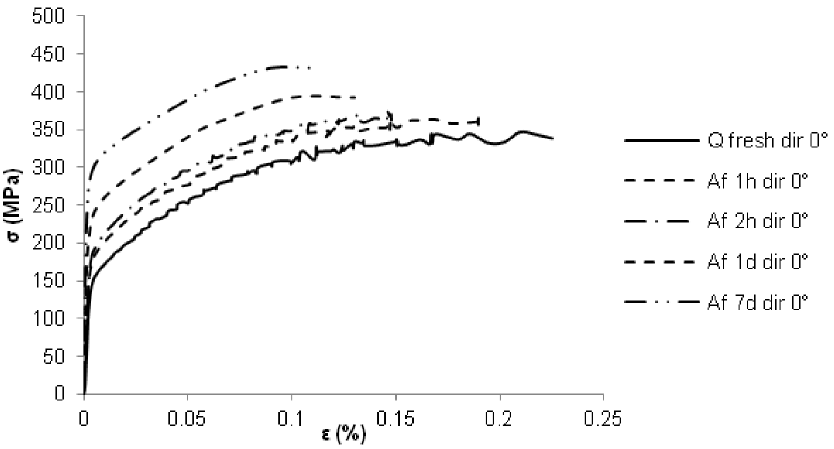


Figure 1 Experimental curves of tensile tests for the direction 0°

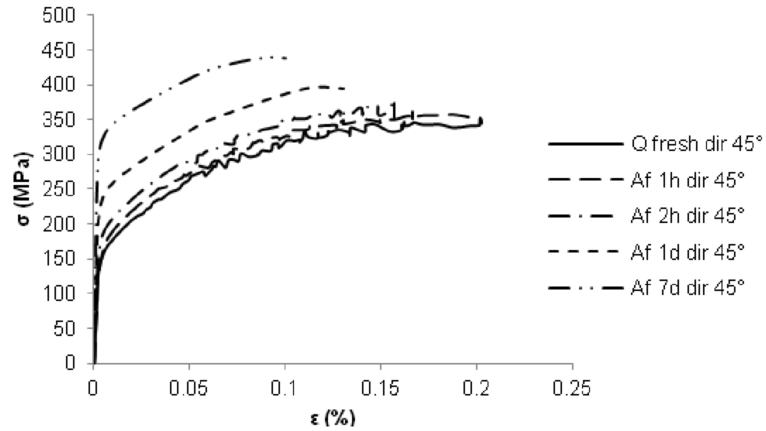


Figure 2 Experimental curves of tensile tests for the direction 45°

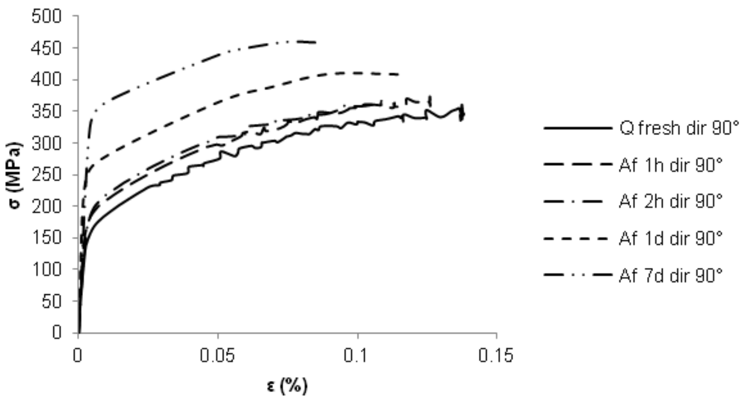


Figure 3 Experimental curves of tensile tests for the direction 90°

The realization of mechanical tensile tests with a variation of time after quenching and during maturation as the stabilization of the materials is of a remarkable influence. The variation of loading direction for experimental tensile tests and microstructural evolution in the maturation time shows a remarkable influence in the mechanical characteristics (Figures 1, 2, and 3).

Indeed, the fresh quenching considerably weakened the values of the mechanical characteristics. This is explained by the dispersion of the main addition elements (especially Zn) within the mass of the material of the aluminum alloy to form coherent atoms with the substitution of alloy matrix. During hardening and tempering from fresh up to 7 days of maturation, the atoms of alloying elements are agglomerated to form incoherent precipitates with the matrix. These precipitates are originally cured in the microstructural evolution by generating increasingly studied mechanical properties. It can be said that the response of aluminum alloys depends firstly on the loading direction of the specimens and secondly on the curing time parameters and maturation time.

Therefore, the 7075 aluminum alloy in state T4 is more efficient to plastic forming and deep drawing between the seven day and fresh quenching stages. During the maturation time, the material requires less effort to achieve deformation with a fairly high elongation. The mechanical characteristics have been changed, especially in the plastic field.

3.2. Identification of Model Coefficients

The experimental results from different traction curves were fitted, taking into account the variation of t and Ψ and these have led to the determination of k and n. Figure 4 below presents a good fit between experimental data and the theoretical expression (Equation 4) used in the identification of parameters *K* and *n*.

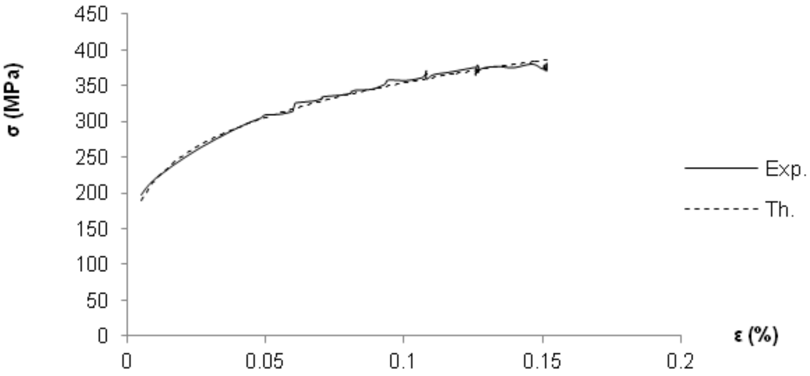


Figure 4 Identification of the hardening curve of the Al 7075 after 2 hours for Ψ = 90°

The values of the parameters *k* and *n*, determined from curve fitting of the theoretical expression to the experimental data, are presented in Table 1 at each maturation time and during the three testing directions. Different values of *K* and *n* found for the different curves are listed in Table 1 for each point of maturation time and for the three directions.

Table 1 Different values of *K* and *n* for each point of maturation time and for the three directions

Time	$K_{0°}$	$K_{45°}$	$K_{90°}$	$n_{0°}$	$n_{45°}$	$n_{90°}$
Fresh Quenching	530.39	526.29	567.86	0.2431	0.2321	0.2405
After 1h	529.89	532.05	587.14	0.2090	0.2206	0.2241
After 2h	555.49	547.71	591.87	0.2084	0.2088	0.2191
After 1-day	565.20	562.20	596.50	0.1680	0.1682	0.1635
After 7days	582.94	568.84	611.78	0.1305	0.1084	0.1117

As shown in Table 1, the factors *K* and *n* are dependent on time and loading direction. The strain hardening coefficient *n* decreases with maturation time to reach a value of n=0.1 at the end of 7 days. Indeed, it is interesting and compelling to identify the behavior of the study material during the ripening time *t* and *Ψ* depending on the loading direction.

In this part of the identification process the anisotropy coefficients (*f*, *g*, *h* and *n*) and the form factor *m* are determined through the use of Barlat's criteria (Equation 1). The obtained results are presented in Table 2 below.

Table 2 Anisotropy coefficients and form factor

Time	*f*	*g*	*h*	*n*	*m*
Fresh Quenching	0.31	0.36	0.24	0.95	8.2
After 1h	0.24	0.33	0.28	0.93	8.56
After 2h	0.35	0.34	0.25	0.99	7.16
After 1-day	0.33	0.36	0.24	1.02	7.59
After 7days	0.26	0.36	0.23	1.01	7.96

Thus, Barlat's model is used to study the effect of maturation time on deformation anisotropy (Lankford coefficient), the deformation rate, and loading surfaces of different tests. The evolution of plastic behavior characteristics of Al 7075 aluminum alloy in state T4 is presented in Figures 5, 6, and 7.

3.3. Evolution of the Lankford Coefficient

The anisotropy coefficients identified for different maturation times of the material are used to represent the evolution of the Lankford coefficient.

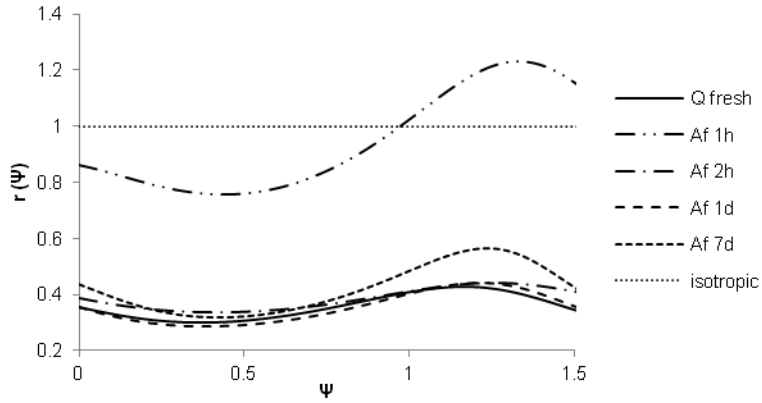


Figure 5 Evolution of the Lankford coefficient

Figure 5 represents the variation of Lankford ratio in terms of *Ψ*. The material is considered isotropic for *r* (Ψ) = 1. After 1-hour of quenching (Af 1h), according to Figure 5, the material behavior is near to the isotropic material. However, for the other tempering (Af 1d and Af 7d) the variation of the Lankford ratio was far removed from value 1, so that the anisotropy became very important especially for the 45° direction (See Figure 6) and for a test done after 1-day (Af 1d). It is shown that this material has the best performance for plastic forming for the 45° direction from the rolling direction and tempering during 1-day.

3.4. Evolution of Deformation Rate

Figure 6 presents the evolution of deformation rate denoted by V_1 along rolling direction using the Green Lagrange reference frame (Znaidi, 2004; Daghfas et al., 2015).

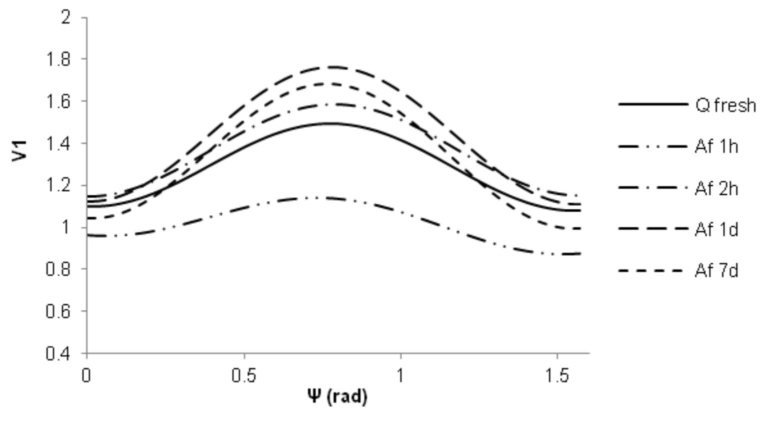
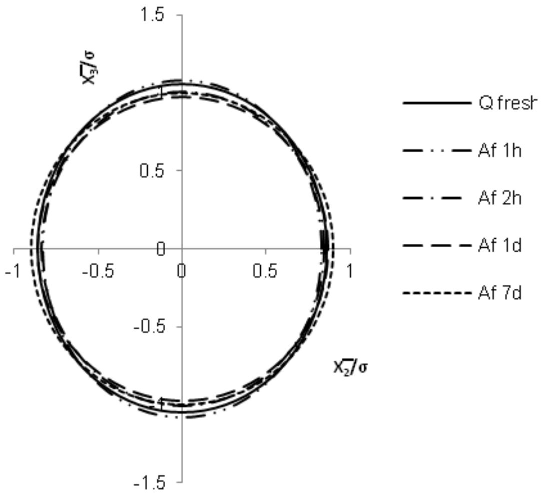


Figure 6 Evolution of deformation rate V1 along the axis x_1

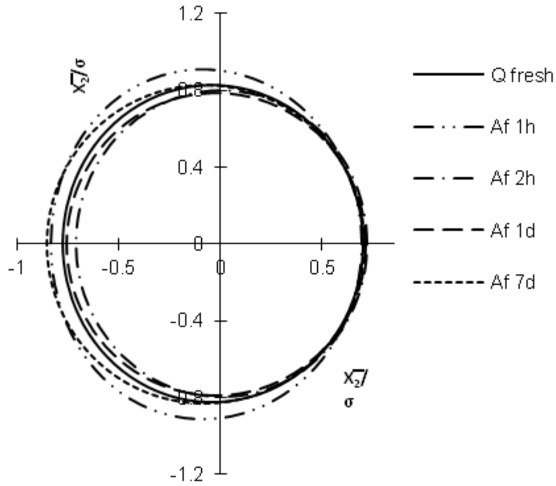
The loading direction *Ψ* and the maturation time *t* reveals a significant effect on the deformation rate of Al 7075.

According to Figure 6, there is no important variation of deformation rate in the rolling direction. In contrast, the variation is significant in the 45° direction, especially during the 1-day and 7-day maturation time periods. These two specific points of the maturation time (1-day, 7-day) correspond to values of n for the direction of 45° (0.1682 and 0.1084) respectively, as shown in Table 1. For the 1-day quenching, the value of n is important with a high deformation rate. The augmentation of the strain hardening coefficient n results in a best behavior of the materials against thinning and generates a delay in the appearance at the point of striction during deformation. Al 7075 has a good attitude for a plastic deformation at 1-day maturation time to $\psi = 45$ °.

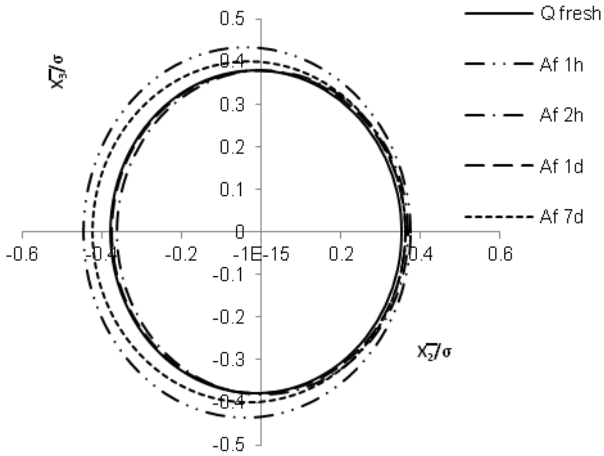
The evolution of the loading surfaces for different tests in a deviatoric base is shown in Figures 7a, 7b, and 7c.



(a) Simple Shear (S.S)



(b) Simple Tensile (S.T)



(c) Plane Tensile (P.T)

Figure 7 Different tests in deviatoric base

The effect of heat treatment and maturation time is not very pronounced on the loading surfaces, especially in the Simple Shear test. The evolution for elastic domains for different maturation time is almost symmetric and remains uninfluenced with a slight shift in the deviatoric plane for 1-hour, 1-day and 7 days for maturation. This behavior of the loading surfaces is explained by the fact that the hardening is considered isotropic. Therefore, the effect of kinematic hardening to the current state of the material is not to be neglected.

4. CONCLUSION

In this paper, the behavior of Al 7075 aluminum alloy subjected to tensile tests in different directions is studied. The change in the loading directions of the specimens and the evolution of maturation time showed their effect on the mechanical characteristics of this alloy.

The maturation time and the heat treatment applied to the material have a minor effect on the loading surfaces. The area affected by plastic deformation is quite large in planar traction and axial traction during the 1-hour maturation time. The effect is almost non-existent for shear tests.

The influence of heat treatment on strain anisotropy is most prominent after 1-hour and 1-day of maturation time. After one day of maturation time, the Lankford coefficient is relatively important allowing the material a good resistance to thinning. Results obtained show a good performance of the material after a 1-hour maturation time. The most prominent effect is after 1-day of maturation time, in this case, the risk for reaching critical strain and thinning is minimal. It can be concluded that Al 7075 after 1 day of maturation from quenching and loading at an off-axis angle of 45° yields the best performance for plastic forming and deep drawing, which are the main manufacturing procedures.

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