Experimental and numerical study on mechanical properties of aluminum alloy under uniaxial tensile test

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ABSTRACT. The main objective is to model the behavior of 7075 aluminum alloy and built an experimental database to identify the model parameters. The first part of the paper presents an experimental database on 7075 aluminum alloy. Thus, uniaxial tensile tests are carried in three loading directions relative to the rolling direction, knowing that the fatigue of aircraft structures is traditionally managed based on the assumption of uniaxial loads. From experimental database, the mechanical properties are extracted, particularly the various fractures owing to pronounced anisotropy relating to material. In second part, plastic anisotropy is then modeled using the identification strategy which depends on yield criteria, hardening law and evolution law. In third part, a comparison with experimental data shows that behavior model can successfully describe the anisotropy of the Lankford coefficient.

KEYWORDS. Aluminum alloy; Experimental tensile test; Identification; Lankford coefficient; Mechanical properties.

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INTRODUCTION

The study of the behavior of metallic materials during the forming process is an important subject. The nature of the used materials and solicitations require a formulation taking into account elastoplastic behavior, finite deformation and the anisotropy of the material, in particular for thin sheet metal forming [1].

Despite the importance of the work in this field, aluminum alloys continue to be the center of interests of several researches in materials science. Their use in the automotive and aviation industry depends largely on their mechanical and thermal characteristics. The addition of zinc in aluminum does not alter the mechanical properties. Therefore metallurgists have turned to ternary aluminum-zinc-magnesium alloys (with or without copper) of the 7000 series that have been widely used as structural materials due to their attractive comprehensive properties, such as low density, high strength, ductility, toughness and resistance to fatigue [2, 3].

The 7075 aluminum alloy (a typical Al–Zn–Mg–Cu alloy) is one of the most important engineering alloys. It is mainly used in the automotive industry, in transport and aeronautics due to its excellent strength/weight ratio [4]. These alloys have very good mechanical properties; it is the high-strength aluminum alloys with a low resistance to corrosion. The mechanical strength of these alloys is increased by structural hardening phenomenon [5]. This type of alloy is mainly used in the automotive industry, in transport and aeronautics especially in the design of the fuselage of the airbus [6].

Metal sheets, that have undergone extensive plastic deformation by rolling or extrusion, exhibit a significant anisotropy of mechanical properties. Thus, they have a particular texture, characterized by a preferred orientation of the grains constituting the material [7]. This texture gives the sheet a special plastic behavior. For modeling the plastic behavior, two aspects of the anisotropy are taken into account: the initial anisotropy due to the initial texture of the metal sheets and the anisotropy induced by cold working [8], mainly due to the development of dislocation structures in the material [9; 10].

Recently, researches on aluminum alloy are focused on mechanical properties, texture and anisotropic behavior that give rise from processing of aluminum alloy sheet [6-7, 10-11]. There has been little research on formability and anisotropic behavior of commercialized 7075 aluminum alloy. However, the influences of loading orientations on aluminum alloy plate are still an open question.

The purpose of the present study is to describe and characterize the mechanical properties, anisotropic behavior of high-strength aluminum alloy loaded at 0°, 45°and 90° to the rolling direction of the 3 mm thick plate, and provide direction for obtaining the optimized parameters for 7075 aluminum alloy in metal forming. As the initial anisotropy is taken into account through a yield criterion [9], the Yld91 anisotropic yield function proposed by Barlat et al. [12] is chosen to model the elastoplastic behavior of the 7075-T7 aluminum alloy. The plastic parameters were determined using an experimental database from uniaxial tensile tests. Numerical simulations of the experimental tensile tests were performed using the anisotropic elastoplastic model. Predicted stress-strain curves were in very good agreement with the experimental curves for three loading directions. The results of simple tensile test were used subsequently to show the evolution of plastic anisotropy called Lankford coefficient and load surface for several tests.

EXPERIMENTAL PROCEDURE

Material

The 7075 aluminum alloy with structural hardening is used. This alloy is a thin rolled sheet with a thickness of 3.5 mm.

The material used in this investigation is a commercially produced 7075 aluminum alloy with the following chemical compositions: Al- Zn (6.1%)-Mg (2.1%)-Cu (1.2%) and balance Al (all in mass pct) [13].

The heat treatment process for this material is T7351. T7 temper is achieved by solution-treatment at 465°C (±5°C), quenching in water (<40°C), maturation at room temperature during 4 days and tempering (135°C ±5°C 12h) and then 2% pre-stretching to release residual stress [13].

Dimensions and form of the test specimens

The uniaxial test is ensured by a specific geometry defined by the standard NF A 03-151 [14]. Schematic tensile specimen used for this study is shown in Fig. 1. The current dimensions of useful part are L0=50mm and b0=12.5mm.

The specimens are cut in three directions relative to the rolling direction (RD) in the plane of the sheet (see Fig. 2 (a)). In the following, the rolling direction is referred to as RD, the transverse direction as TD and the direction (45° from the RD) as DD. The angle between the loading direction and the rolling direction will be noted subsequently ψ .

Three samples were prepared for each loading direction to verify repeatability. Each specimen was machined in different directions of the plate to enlighten the anisotropy of the material.

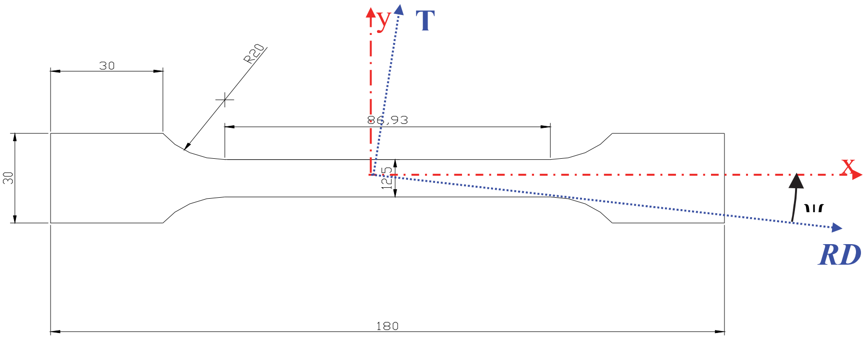
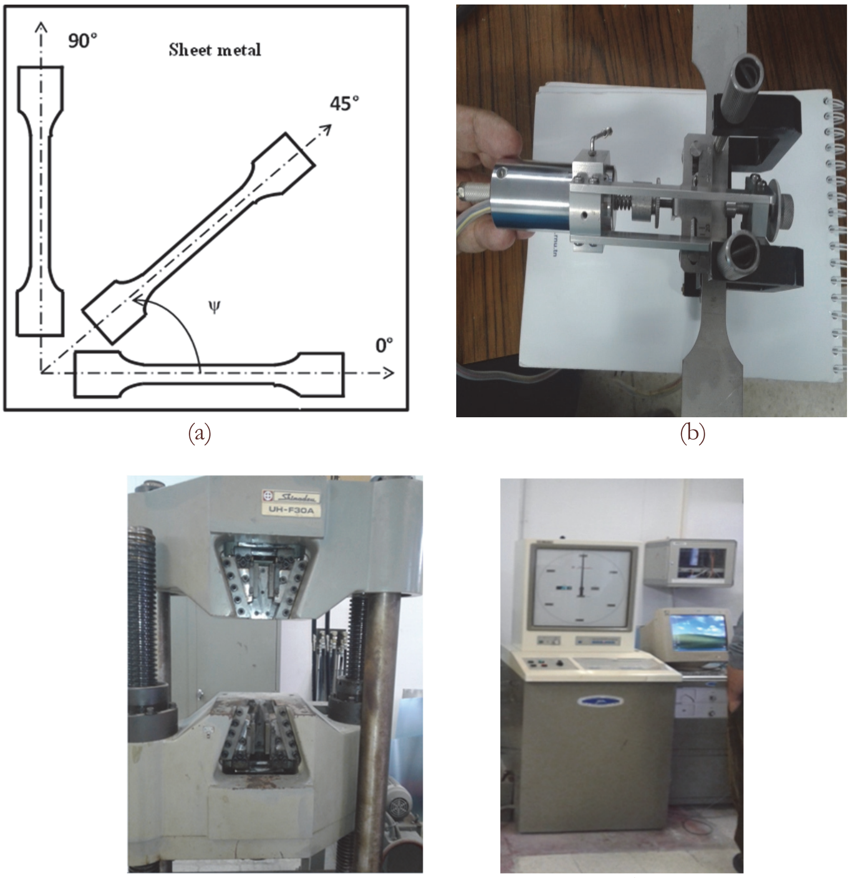


Figure 1: Tensile specimen used in the present study, the useful area (L0=50mm, b0 = 12.5mm).



(a) (b)

(c) (d)

Figure 2: (a) Loading Direction of cutting (b) Electronic extensometer (c) Tensile test machine and (d) acquisition chain.

Experimental set

The test is carried out on a hydraulic press (SHIMADZU) that has a maximum load capacity of 30 kN (Fig. 2 (c)), class 0.5 BS EN ISO-1 [15]. A chain acquisition (see Fig. 2 (d)) allows recording the strain as a function of stress. The loading speed is 4MPa.s-1. Two electronic extensometers are used to measure the strain rate according to the width and the thickness along the tensile test (Fig. 2(b)).

Experimental results

Experimental database contains three tensile curves and their experimental Lankford coefficients ($r_{0°}$, $r_{45°}$ and $r_{90°}$ presented in Tab. 1).

Experimental tensile curves of 7075-T7 in three directions 0°(RD), 45° (DD) and 90°(TD) from the rolling direction are presented in Fig. 3.

Uniaxial tensile tests taken for three orientations to the rolling direction reveal the nature of anisotropy in this material where strengths and ductility vary with orientation in the plane of the sheet.

Fig. 3 shows similar yield strength and plastic deformation characteristics in the rolled RD and DD directions until 11.5% in strain. The TD direction has a similar yield strength but different hardening characteristics and lower elongation (8%). This result exhibit a marked tensile anisotropy.

Fig. 3 indicate that the 7075 in temper T7 is defined by maximum percentage elongation along the rolling direction and minimum value along the transverse direction.

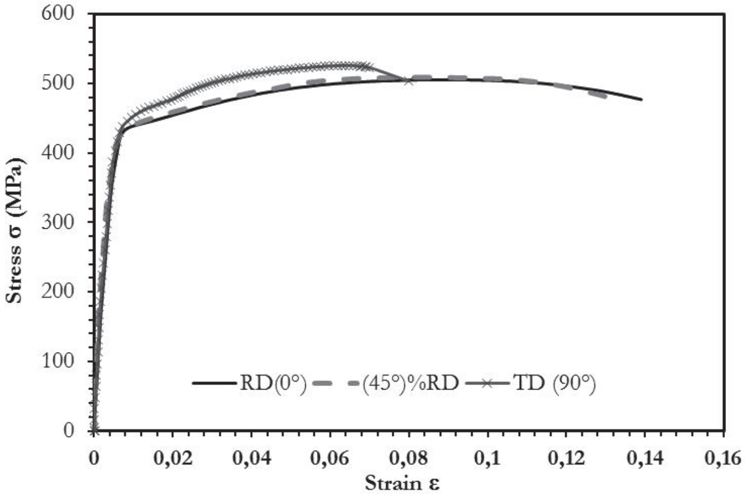


Figure 3: Experimental tensile curves obtained at RD, DD and TD from the RD.

The 7075-T7 aluminum alloy has high mechanical properties both in terms of strength and ductility compared to pure aluminum A5 [16].

Maximum yield R_e and tensile R_m strengths are observed especially in the transverse direction but a significant decrease in percentage elongation A%. This is explained by the structural hardening.

The commercialized aluminum alloy in T7 temper is much stronger than pure Aluminum (around 40 MPa against 430 MPa for the yield strength), but it has a failure elongation (maximum plastic deformation of 0.13 against 0.27 for pure aluminum).

According to the experimental results we are seeing the influence of the anisotropy on the specimen fracture especially after transverse loading (90°).

We present in Tab.1 the experimental Lankford coefficients relating to three loading directions.

ψ	r(ψ)
00°	0.069
45°	0.138
90°	0.099

Table1: Experimental Lankford coefficient for different loading directions.

The anisotropy coefficient illustrates the deformation mode of the metal sheet. A small Lankford Coefficients indicated by 7075-T7 led to a significant reduction in thickness.

The tensile test is the simplest and most widely used because it allows obtaining a lot of information (elastic modulus, yield strength, maximum load, elongation at break ...) and maintaining a homogeneous strain in the useful part.

ANISOTROPIC ELASTO-PLASTIC MODEL

This work is limited to plastic orthotropic behavior. The materials are treated as incompressible with negligible elastic deformations. Models are formulated for standard generalized materials with an isotropic hardening described by an internal hardening variable, a law of evolution and an equivalent deformation. The material is initially orthotropic and remains orthotropic; isotropic hardening is assumed to be captured by a single scalar internal hardening variable denoted by ε^p .

The behavior model is defined by:

Yield function

In particular, we will assume that the elastic range evolves homothetically, the yield criterion is then written as follows:

$$f\left(\mathbf{q},\varepsilon^{p}\right)=\sigma_{c}\left(\mathbf{q}\right)-\sigma_{s}\left(\varepsilon^{p}\right)\leq 0 \tag{1}$$

σ_c : Equivalent stress is given by the Barlat criterion 91[12]:

$$\sigma_{c}\left(\mathbf{q}\right)=\left(\left|q_1-q_2\right|^{m}+\left|q_2-q_3\right|^{m}+\left|q_1-q_3\right|^{m}\right)^{1/m} \tag{2}$$

where $q_{k=1,2,3}$ are the eigenvalues of a modified stress deviator tensor $\mathbf{q}$ defined as follows:

$$\mathbf{q}=\mathbf{A}:\boldsymbol{\sigma}^{\mathrm{D}} \tag{3}$$

$\boldsymbol{\sigma}^{\mathrm{D}}$ is the deviator of the Cauchy stress tensor (incompressible plasticity).

The fourth order tensor **A** carries the anisotropy by 6 coefficients c1, c2, c3, c4, c5, c6.

$\sigma_s\left(\varepsilon^{p}\right)$: Isotropic hardening function; where ε^{p} is the equivalent plastic strain.

Hardening law

Using as a hardening function respectively a Hollomon and Voce laws [17]:
Hollomon law

$$\sigma_{s}\left(\varepsilon^{p}\right)=K\left(\varepsilon^{p}\right)^{n} \tag{4}$$

K and n: the Hollomon parameters to be identified
Voce law

$$\sigma_{s}\left(\varepsilon^{p}\right)=\sigma_{s}+\left(1-\alpha\exp\left(\beta\boldsymbol{\varepsilon}^{p}\right)\right) \tag{5}$$

This law introduces a hardening saturation σ_s, α and β describe the non-linear part of the curve during the onset of plasticity where 0< α <1 and β <0)

Evolution law

The direction of the plastic strain rate $\dot{\varepsilon}^{p}$ is perpendicular to the yield surface and is given by:

$$\dot{\boldsymbol{\varepsilon}}^{p}=\dot{\lambda}\frac{\partial f}{\partial\boldsymbol{\sigma}^{D}} \tag{6}$$

With λ plastic multiplier that can be determined from the consistency condition $\dot{f}=0$

Lankford coefficient

In the characterization of thin sheets, the plastic anisotropy with different directions is frequently measured by the Lankford coefficient r_ψ that is given by the following expression:

$$r_\psi = \dot{\varepsilon}_{yy} / \dot{\varepsilon}_{zz} \tag{7}$$

where $\dot{\varepsilon}_{yy}$ and $\dot{\varepsilon}_{zz}$ are the plastic strain rates in-plane and through the thickness, respectively.

The subscript specifies the angle between the axis of the specimen and the rolling direction (Fig 2 a).

In the case of orthotropy r_ψ varies depending on the off axis angle ψ .This scalar quantity is used extensively as an indicator of the formability.

IDENTIFICATION PROCEDURES

In this section we focus on the phenomenology of plastic behavior; especially modeling plasticity and hardening based on experimental data represented as families of hardening curves, and Lankford coefficient data. In order to simplify our identification process, the following assumptions are adopted:

Identification through "small perturbations" process, the tests used are treated as homogeneous tests, we neglect the elastic deformation; the behavior is considered rigid plastic incompressible, the plasticity surface evolves homothetically (isotropic hardening) and all tests are performed in the plane of the sheet resulting in a plane stress condition.

The identification of this constitutive law requires the identification of the hardening function, the anisotropy coefficients c_1, c_2, c_3, c_4, c_5, c_6 of the Barlat criterion (Eq. 2), the shape factor m and the Lankford coefficients $r(\psi)$.

The Barlat criterion or Yield 91 is proposed by Barlat et al [12] as a non quadratic criterion for anisotropic materials. Respecting to plane stress condition, the anisotropy coefficients are reduced to 4 (c_1, c_2, c_3, c_4).

First identification step

By smoothing the experimental tensile curves the Hollomon and the Voce parameters are determined for three loading directions. Tab. 2, Tab. 3 and Tab. 4 illustrate respectively the identified parameters of Hollomon and Voce laws.

Knowing that the coefficient n is the same for all tests [18-19], by convention we choose n for traction in direction ψ = 00° as reference. For n=0.0718, we present different values of k (see Tab. 3).

The different values of Voce parameters are illustrated in Tab. 4.

ψ	k	n
00°	606.8441	0.0718
45°	622.0848	0.0766
90°	671.2648	0.0853

Table 2: Identification of the constants of Hollomon law for different loading directions.

ψ	k
00°	606.8441
45°	613.0297
90°	640.4611

Table 3: Identification of the constant hardening law for fixed n.

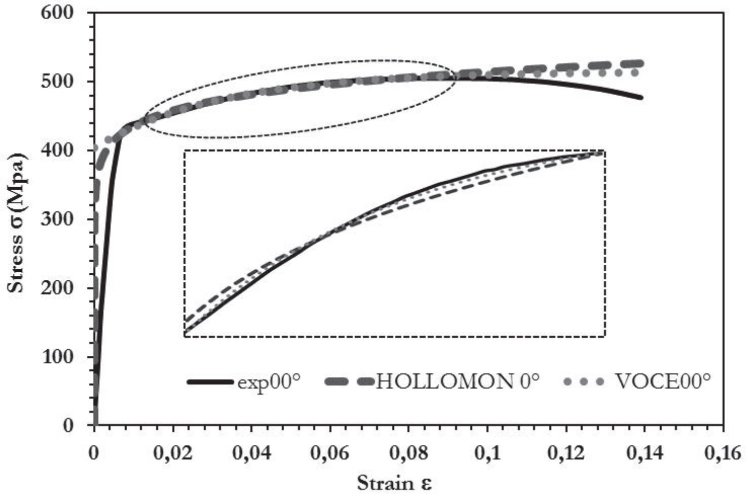
ψ	σ_s	α	β
00°	508.0623	0.2111	-36.8421
45°	511.1316	0.2161	-39.3294
90°	531.9995	0.2613	-49.5677

Table 4: Identified parameters of Voce law.

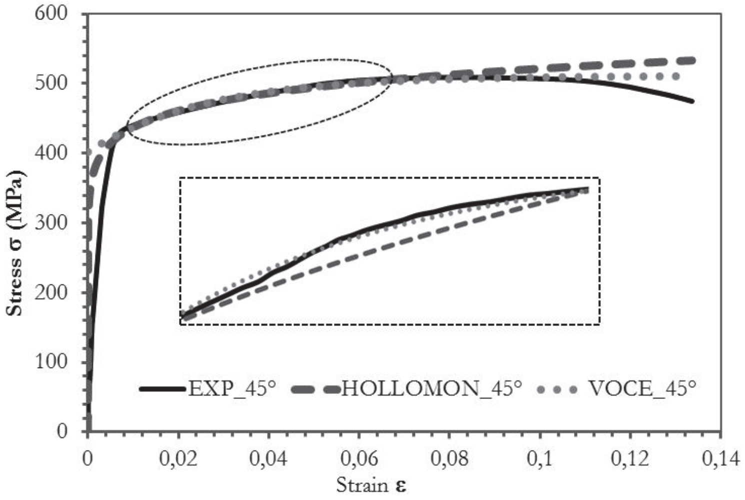
The identified curves by Hollomon and Voce laws compared to the experimental hardening curves obtained in the two directions relative to the rolling direction (00° and 45°) are presented in Fig. 4a and Fig.4 b respectively. Then a comparison is made in order to show the most suitable law for the identification of hardening curves. A significant difference in result between the two laws is visible by zooming the curves.

It is seen that in the homogeneous part of the plastic deformation the voce law describes the specimen fracture better than the Hollomon law for two loading directions from the rolling direction.

By convention, the voce hardening law is selected subsequently to identify anisotropy behavior relating to this alloy.



(a) ψ = 00°



(b) ψ = 45°

Figure 4: Identification of the hardening curve: (a) ψ = 00° (b) ψ = 45°.

Second identification step

Using the simplex algorithm and using the non-quadratic Barlat criterion (2) and respecting the assumptions, the second step of identification strategy is equivalent to choosing the coefficients of anisotropy (c_1, c_2, c_3, c_4) and the shape coefficient m (Tab. 5) while minimizing the squared difference between the theoretical and experimental results.

c_1	c_2	c_3	c_4	m
0.3612	0.3431	0.113	1.0539	6.2486

Table 5: Identification of anisotropic coefficients and a shape coefficient m.

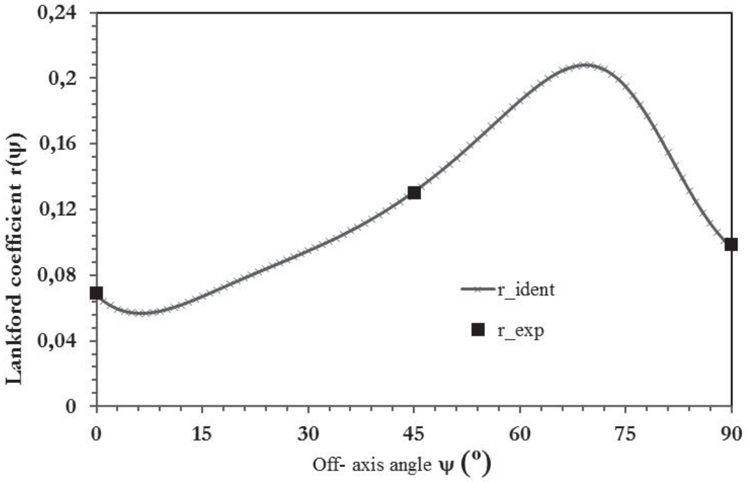
Using the identified anisotropic coefficients, the evolution of Lankford coefficient and the anisotropy based on off-axis angles are presented in Fig. 5(a) and Fig. 5(b) respectively.

Fig. 5 (a) displays the evolutions of Lankford coefficient based on off-axis angle ψ.

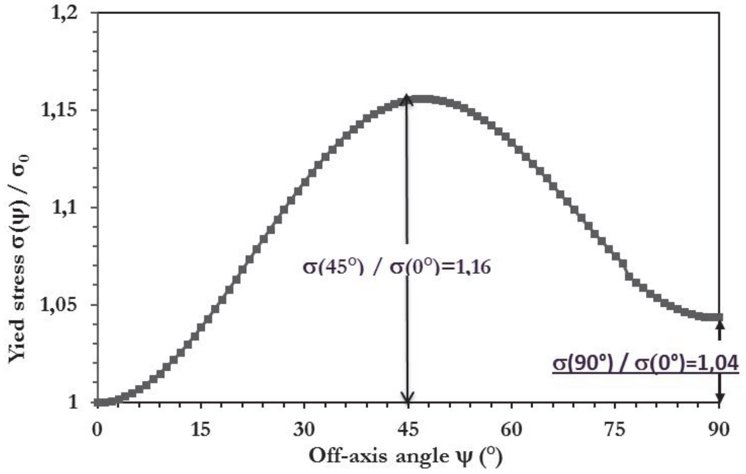
A good agreement has found between experimental and predicted Lankford coefficients with respect to the rolling direction. Thus, the behavior model describes very satisfactory the plastic behavior of this alloy because its yield function and its hardening law are suitable for aluminum alloys.

The evolution of anisotropy of 7075-T7 is more pronounced especially in 45°direction from the rolling direction (see Fig. 5(b)), therefore the 7075-T7 is more suitable for forming process for the manufacture of the aerospace parts.

It is shown that this material has the best performance for plastic forming for the 45° direction from the rolling direction.



(a)



(b)

Figure 5: (a) Evolution of Lankford coefficient (b) Evolution of the yield stress anisotropy based an off axis ψ .

Third identification step: validation

In order to validate the behavior model, the experimental tensile curve in transverse direction and the identified anisotropic parameters of behavior model are used.

Fig. 6 shows a good agreement between the theoretical results of behavior model and the experimental data for transverse direction.

Evolution of the yield surface in deviatory plane $\left(\overline{x_2},\overline{x_3}\right)$ *and the yield stress anisotropy*

After having identified and validate the behavior model, we will study the evolution of load surfaces for several tests and the stress anisotropy of material.

Using the identified anisotropic coefficients (Tab. 2), the behavior model allows to represent the load surfaces on each test (simple tensile ST for $\theta = \pi/3$, simple shear SS for $\theta = \pi/2$, wide tensile WT for $\theta = \pi/6$) in the deviatory plan [16, 19], where

$$\begin{cases} \overline{x_2} = \left|\sigma^D\right| \sin\theta \cos 2\psi \\ \overline{x_3} = \left|\sigma^D\right| \sin\theta \sin 2\psi \end{cases} \tag{8}$$

Fig. 7 shows the comparison between the yield surfaces calculated by behavior model on different tests.

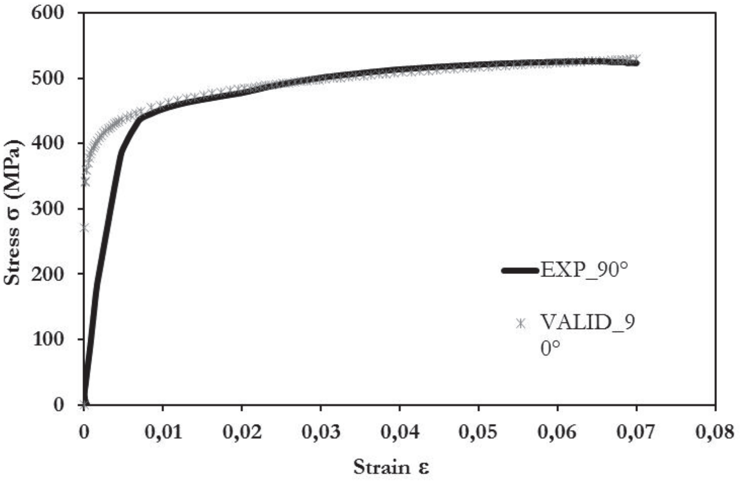


Figure 6: Validation of hardening tensile curve at $\psi = 90^\circ$.

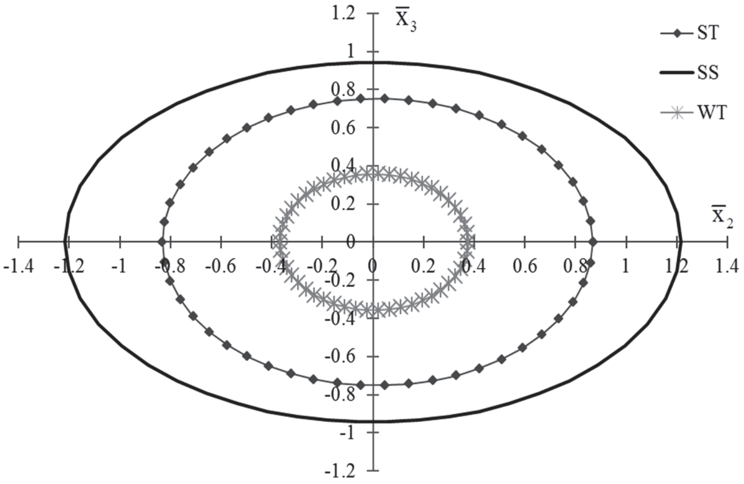


Figure 7: Evolution of the load surface in the deviatory plan $(\overline{x}_2, \overline{x}_3)$.

It appears also that this material is resistant to simple shear much more than simple tensile and wide tensile. Furthermore, for simple tensile and simple shear tests the 7075-T7 alloy is plasticized quickly along the 45° direction from the rolling direction. It is deduced that the best shaping in the design of the fuselage is realized using the 7075 alloy in the 45° direction. In contrast, in wide tensile, it is achieved at the same time at three loading directions.

CONCLUSION

Since the commercial 7075 aluminum alloys are essentially aeronautics alloys, off - axis tensile tests are carried on 7075aluminum alloy through three loading directions from the rolling direction. These experimental results have allowed to investigate the mechanical properties and to identify the plastic behavior model using a proposed identification strategy. In this study, Barlat yield criterion with isotropic hardening is used. By comparing both experimentally measured and calculated data based on this criterion, it is demonstrated that this criterion leads to a good description of the phenomena. However, the Barlat criterion with isotropic hardening may be sufficient to correctly identify the behavior of the aluminum alloy in uniaxial test.

The influence of the off-axis angle on anisotropy is studied. The results of simple tensile test were used subsequently to show the evolution of load surface for several tests.

It is deduced that the best shaping in the design of the fuselage and the RADOM is realized using the 7075 alloy in the 45° direction. This direction allows us to have a good formatting with minimal fracture comparing with directions 0° and 90°.

In Mechanical construction the shaping of materials requires good mechanical characteristic. It is seen that this type of alloy has the important mechanical strengths but low percentage elongation. In order to remedy tis disadvantage a succession of thermo-mechanical treatments will be applied to this commercial aluminum alloy. This latter point presents the topic of the next work.

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