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RESEARCH ARTICLE

Evolution of Mechanical Properties of an AA 6061 T6 Aluminum alloy Processed by Cold Working (CW)

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HIGHLIGHTS

- *The study explais the importance of thermomechanical treatment*
- *The study explains the relationship between mechanical properties and microstructure*
- *Dependence of yield stress and ultimate tensile strength on grain size accords with Hall–Petch equation.*

Keywords:

- AA 6061T6
- Cold working
- Ultrafine grain
- Mechanical properties
- Sever plastic deformation

GRAPHICAL ABSTRACT

The evolution of mechanical properties, microstructure and their stability after different thermomechanical treatment of an AA6061 heat treated industrial to T6 condition alloy processed by cold working were studied by tensile tests and analyzed by optical microscope. It is shown that a ultrafine-grained structure in alloy 6061 can be formed already after two cycles of treatment by cold working. Along with grain refinement, in the process of a CW treatment there occurs in the alloy a dynamic strain aging, which results in the formation of fine particles of a strengthening. It has been established that the alloy in the UFG state demonstrates a considerably higher level of strength and better plasticity in comparison with the material after a standard strengthening treatment. Cold work by compression high pressing (CW-CHP) can be applied in several cycles depending on the hardening behavior of the material. The influence of the nonmetric size of the grains produced by the (CW-CHP) of a cylindrical rolling machine with four passes of sever plastic deformation with different reduction ratios

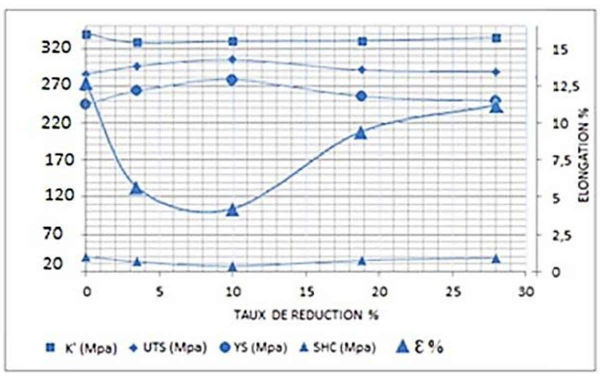

Figure A. Evolution of mechanical properties undre cold work processing

Aim of Article : *evaluation of mechanical properties of AA 6061 T6 thermo mechanically treated by cold working.*

Theory and Methodology: *Principal of cold working, tensile tests and microscopic observations were presented in the work.*

Findings and Results: *Results are summarized in Figure A of the ectended abstarct*

Conclusion : *The use of cold working as a method of sever plastic deformation, made it possible to obtain a uniform UFG structure at the first and second cycles of mechanical treatment at room temperature.*

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HIGHLIGHTS

- *The study explains the importance of thermomechanical treatment*
- *The study explains the relationship between mechanical properties and microstructure*
- *The highest strengths (about 305 MPa) and yield stress (278 MPa) are resulted at the second cycle of cold working.*
- *Dependence of yield stress and ultimate tensile strength on grain size accords with Hall–Petch equation.*

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ABSTRACT

Nano scale grain size reduction (Ultra-fine grain) is one of three suitable methods for improving the mechanical properties of 6000 series aluminum alloys, by structural precipitation, strain hardening or by cold work hardening. For the cold working, several techniques are now available such as (Equal channel angular pressing with parallel channels), (Equal Channel Angular Extrusion), (Torsion under High Pressure), (Mechanical Milling), (Accumulative Roll Bonded), (Cold Working). Cold work by compression high pressing (CW-CHP) can be applied in several cycles depending on the hardening behavior of the material. The influence of the nonmetric size of the grains produced by the (Cold working-compression haute pressing) of a cylindrical rolling machine with four passes of Sever plastic deformation with reduction ratios of (3.5, 10,18.8 and 28%), on the mechanical behavior of the alloy 6061 T6, was analyzed by determining the ultimate tensile strength (Rm), yield strength (Rp0.2, the strain hardening capacity SHC (Rm-Rp0.2), the work hardening coefficient n', the modulus of 'work hardening K' . The increase in the rate of work hardening by the reduction of the sample sections and consequently the reduction of the grain size at the first and the second pass, improves the mechanical properties of the alloy to the maximum values, and then the presence of crack initiation participates to the moderate decrease of the mechanical properties.

Keywords: *AA 6061T6, Cold working, Ultrafine grain, Mechanical properties, Sever plastic deformations*

I. INTRODUCTION

Aluminum alloys are widely used for the manufacture of high-strength structures with minimum weight as the aeronautical, automotive and marine fields. The 6000 alloy of the Al-Mg-Si system is characterized by a very good formability and a medium resistance but it is suitable for thermal and thermochemical treatments [1]. The purpose of the heat treatment is to increase the mechanical performance by applying a solution cycle at 520°C followed by isothermal hold in order to dissolve the intermetallic particles then a water quench to freeze the SSSS state, this primary cycle must be followed by a second cycle of artificial maturation at 180°C for 8

hours to activate the precipitation phenomenon when arriving at the stable Mg_2Si state according to the sequence: [2-4]

$$\alpha(SSS) \rightarrow GPZones \rightarrow \beta''\text{needle shaped} \rightarrow \beta'\text{rodlike} \rightarrow \beta\text{plates } (Mg_2Si)\ .$$

SSS denotes “supersaturated solid solution”, GP denotes “Guinier-Preston”, metastable β″

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precipitates with needle shaped forms, metastable β′ precipitates with rodlike forms and stable β phase.

The improvement of the mechanical properties of the AA 6061 alloy already treated to T6 condition, by the reduction of the grain size to the Nano metric scale (Ultra-fine grain "UFG") has attracted the attention of several studies.

Several techniques are used to generate the UFG structures, such as Equal channel angular pressing with parallel channels (ECAP-PC) [5,6], Equal Channel Angular Extrusion (ECAE) [7], Accumulative Roll Bonded (ARB)[8, 9], Mechanical Milling (MM) and Cold working-compression high pressing (CW-CHP)[10], all these techniques use the same phenomenon of hardening which is an important parameter for expressing the élastoplastique behavior of materials, particularly for their shaping by plastic deformation (PD). It participates in the evolution of the crystallographic texture of the material and the accumulation of dislocation energy during deformation. Work hardening generally results in a hardening of metals. The hardening laws are presented as well as the evolution of the microstructure by recrystallization. They used several models to describe strain hardening such as Hall Peach's relationship (1) and Hollomon's equation (2):

$$R_{P0,2}= \sigma_0+k/d^{1/2} \qquad (1) \quad [11]$$

Where d is the average grain size.

$$R_{P0,2}= K.\mathcal{E}^n \qquad (2) \quad [12]$$

Cold working by high radial pressure is a successful severe plastic deformation (SPD) technic to produce ultrafine grained (UFG) metals and alloys, without any limitations that restrict its application under conditions of industrial production for obtaining UFG aluminum semi-finished products.

Haneen M. Saud and Mohammed A. Abdulrazzaq [13] investigated the influence of cold working by peening and burnishing process on AA2024 T4 ,different times of peening were used to analysis the effect of time on mechanical properties .the result showed that the fatigue strength, the hardness and the roughness improved with increase the time of peening until certain value of time.

Marta Harniˇcárová et al. [14] confirmed that the refinement of the microstructure after processing by the ECAP method on an aluminum alloyAlMgSi0.5 is the reason for the changes in mechanical properties.

Abdulrahaman Shuaibu Ahmad et al. [15] investigated the effect of residual stress generated by manufacturing process and they confirmed that the cold working compression reduces the residual stresses significantly and efficiently based on the compression ratio used for an aluminum alloy 2219 sample. The 2 % compression ratio is observed to have the highest percentage of residual stress reduction.

The aim of this work is to present a technique that combines the two treatments, thermal and mechanical, in order to improve the mechanical properties of the AA 60661 T6 alloy as much as possible.

II. MATERIALS AND METHOD

The material used in this investigation is an industrial 6061 Aluminum- Magnesium-Silicon alloy. The Chemical composition as determined by EDS is shown in Table I. The material was supplied in the form of a bar with 16 mm as diameter in a T6 condition. This condition is achieved by the following combination of operations: solution treatment at a temperature of 520 ◦C for 8 h, followed by quenching in water (20 ◦C) and aging treatment at a temperature of 180 ◦C for 8 h.

Table I. Example Chemical composition of the base material AA 6061 aluminium alloy (wt. %).

Al	Mg	Si	Cu	Mn	Fe	Cr
Balance	0.82	0.47	0.17	0.06	0.19	0.03

In order to study the influence of various sequences of cold working on mechanical properties of AA6061 T6, different series of mechanical treatments were utilized, at room temperature, as illustrated in Figure 1.

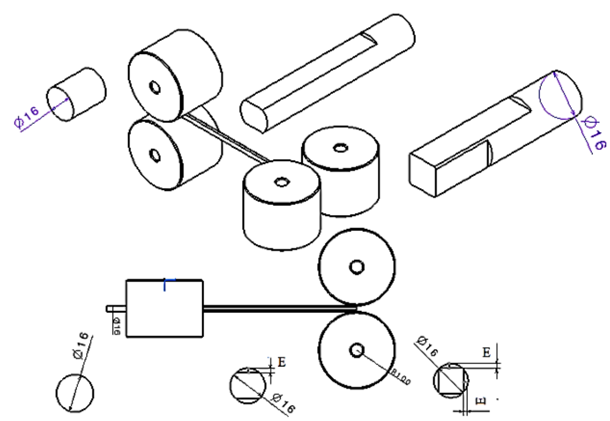

Figure. 1. Scheme of the CW treatment.

A mechanical treatment by radial pressure parallel to the axis of extrusion of the samples is applied by a rolling mill with a diameter of 200 mm in order to generate cold radial pre-deformations (CW), and also to reduce the size of the grains superficially as indicated in Figure 2, according to the principle cold working. Four compression passes are applied which allows us to make a passage from diameter 16 to diameter 12 x 12 mm^2, with a surface reduction rate presented in table II.

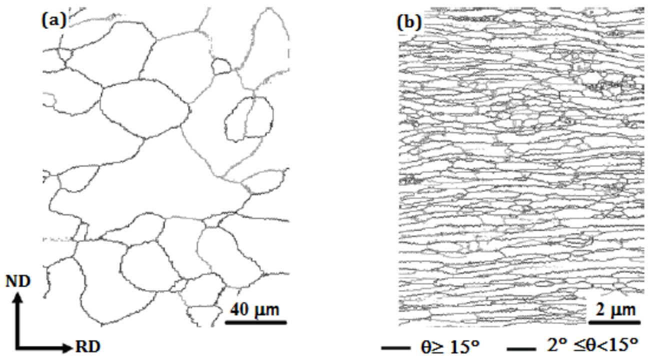

Figure. 2. Ultrafine grain generation by cold working.

Table II. Area reduction rate.

Round bar (16 mm od diameter)				
Height of arc (reduction) mm	0.5	1	1.5	2
Area reduction rate %	3.5	10	18.8	28

Some strips were cut from cold worked bars AA6061T6 in rolling direction. Tensile test specimens were then prepared from all the strips according to ASTM E-8 specifications (Figure 3) in rolling direction. The gauge length of specimens was 90 mm. Tensile tests were performed, at room temperature, with a deformation rate of ($d\varepsilon/dt=10^{-3}\ s^{-1}$) and crosshead speed of 2 $mm.min^{-1}$, with loading direction parallel to the working direction by using hydraulic testing machine. Nominal stress- strain curves and data were analyzed and yield strength, tensile strength and elongation of different thermal-mechanical samples were compared.

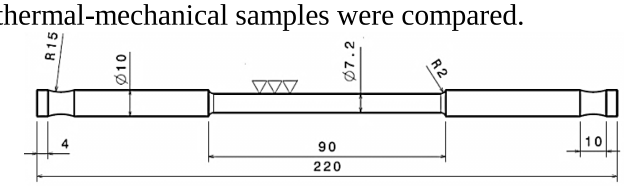

Figure. 3. Tensile test specimen "all dimensions in mm".

III. Results and Discussion

Data and representative tensile engineering stress-strain curves of the AA 6061 T6 (reference for comparison) and cold worked, from one to four cycles, samples can be seen in Figure 4 and Table III. The results show that with increasing number of cold working cycles, a proportional successive improvement of the yield stress and ultimate tensile strength accompanied with the decrease in elongation and remarkable changes in its microstructures.

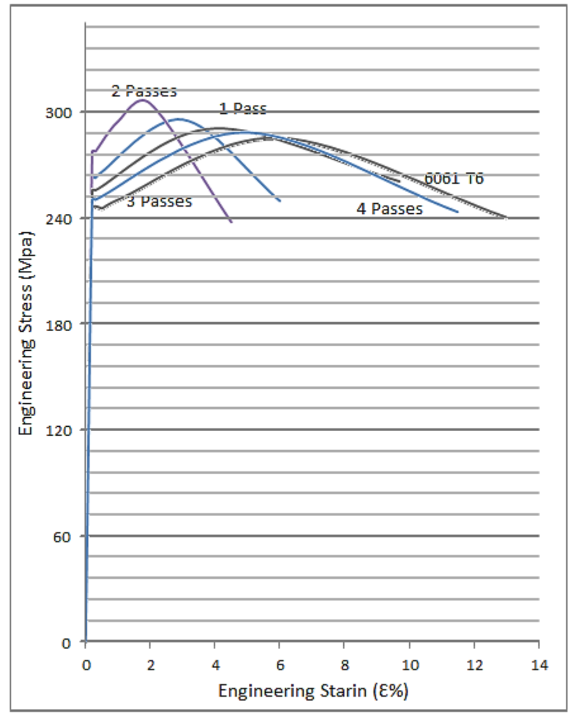

Figure. 4. The Engineering stress-strain curves of 6061 alloy after CW-CHP processing and conventional heat-treatment to T6 condition.

After the first and second cold working cycles, there was formed a substructure (Figure 5), which contains an increased dislocation density; this structure ensures a considerable increase in the strength characteristics of the material in comparison with the initial T6 condition.

Table III. Mechanical properties of the aluminum alloy 6061T after CW processing at room temperature.

Treatment condition	UTS MPa	YS MPa	ε%	SHC MPa	n'	K
AA 6061 T6	285	245	13	40	0,06	340
AA 6061 T6, 3.5 % CW	296	263	6	33	0,03	328
AA 6061 T6, 10 % CW	305	278	4,5	27	0,02	330
AA 6061 T6, 18.8 % CW	291	256	9,7	35	0,04	331
AA 6061 T6, 28 % CW	288	250	11,5	38	0,05	335

In this case, the material demonstrates very high characteristics of plasticity (stress hardening capacity SHC= 40 MPa) and Strain hardening exponent (n'= 0.06), (Table III). The formation of a mixed structure, after the first and second cycles, which contains both fragmented and ultrafine grains (Fig. 5), ensures both a further increase in the strength characteristics and a certain decrease in plasticity. These results are on total concordance with the results of [13].

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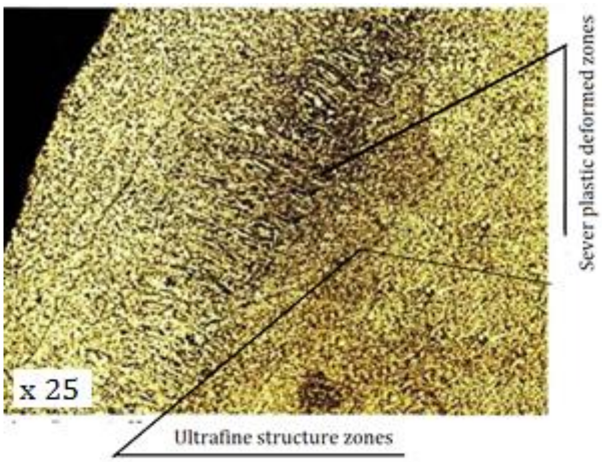

Figure. 5. Micrograph of different zones generated at the first and second cold working cycles.

The effect of the third and fourth cycles of cold working on the cross section of an AA6061 T6 specimen is presented in Figure 6, the presence of the sever plastic deformed zone always contributes to the improvement of the properties mechanical compared to the initial state, but the appearance of the initiation crack zones participate to the reduction of the mechanical properties of the alloy.

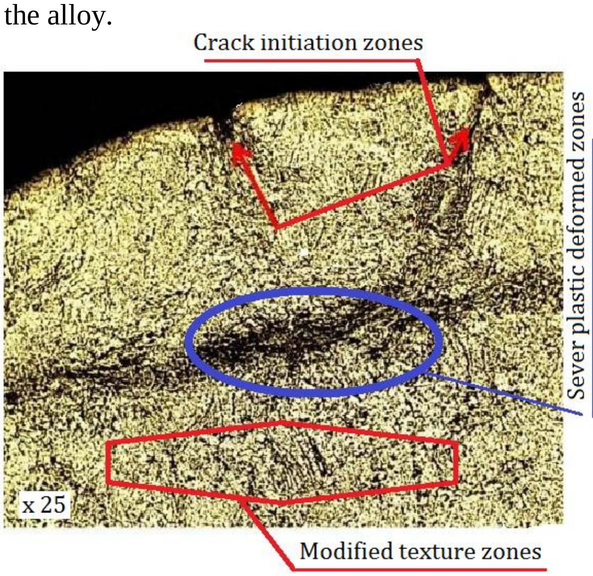

Figure. 6. Micrograph of different zones generated at the third and fourth cold working cycles.

IV. CONCLUSION

Cold working has been outlined as one of the possible ways to improve the mechanical properties of the AA 6061 T6 alloy within the studied ageing temperatures and times.

The use of cold working as a method of sever plastic deformation, made it possible to obtain a uniform UFG structure at the first and second cycles of mechanical treatment at room temperature.

The increase in the rate of work hardening by the reduction of the sample sections and consequently the reduction of the grain size at the first and the second pass, improves the mechanical properties of the alloy "increase of the mechanical resistance and the yield strength and decrease the ductility".

The 6061T6 alloy after four cycles of cold work processing exhibits a combination of further plasticity (SHC of 38 MPa) and certain increase in strength, which is very attractive for its future application.

Exaggerated increase in the work hardening rate at the third and fourth pass localizes the deformation by deterioration of the deformed bands and generates crack initiations which participate consequently in the reduction of the mechanical properties and redirects the mechanical behavior towards the initial state T6.

At the third and fourth number of cold working cycle, the elongation to failure increases from 4,5 % at the second cycle , 9,7 % at the third cycle then to 11,5 % at the fourth cycle, The mechanism of fracture is changed from brittle to ductile.

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