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Study of texture, mechanical and electrical properties of cold drawn AGS alloy wire

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Abstract. An investigation has been done to study the evolution of the microstructure, mechanical and electrical properties of AlMgSi alloy destined for the transport of electric energy, in function of the deformation caused by the cold drawing process. We identified that drawing of aluminum wire causes development of a fibrous texture of type <111> and <100>. We notice also that the electrical resistivity and mechanical resistance increases with the increasing of the deformation level. Characterization methods used in this work is: The Electron Back Scattered Diffraction EBSD, X-Ray diffraction, Vickers microhardness, Tensile test, Measuring electrical resistivity, the Scanning Electron Microscope (SEM) and Energy Diffraction Spectrum (EDS).

Keywords: aluminum alloy; microstructure; texture; electrical resistivity; mechanical resistance; deformation by drawing wire

1. Introduction

Al-Mg-Si alloys are mostly used in modern era due to their adequate age hardening characteristics, reasonable weldability, good corrosion resistance and comparatively low cost (Amancio-Filho *et al.* 2008, Miao and Laughlin 1999) The precipitation sequence in AlMgSi alloys is reported to be the; SSSS atomic clusters GP zones β'' β' β (Mg_2Si) (Honyek *et al.* 1981, Westengen *et al.* 1979). The mechanical properties of these alloys mainly depend upon the nano-sized precipitates which are the precursor phases to the equilibrium Mg_2Si phase (Livak 1982). Cold or hot working of Al–Mg–Si alloy changes the physical as well as mechanical properties because it affects the microstructural morphology of the strengthening phases.

The aluminum electrical cables intended for the transportation of electrical power require a balance of mechanical characteristics and electrical resistivity. Aluminum occupies an important place in the transport of electrical energy because of its good electrical and thermal conductivity

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(Zidani *et al*. 2014, Serradj *et al*. 2010). The drawing is a necessary operation for the production of small diameter electrical wires. During this process, the reshaping of the material is performed by a plastic deformation mechanism. After the deformation, shifts along the sliding plan extend grains in the direction of the applied forces. The greater number of grains has a preferred orientation (texture) when the alloy is more deformed (Farh *et al.* 2010).

A study conducted by (Adeosun *et al*. 2011) has shown the effect of cold working on 6063 aluminium alloy and pointed to the fact that significant effects on mechanical and electrical properties are in great numbers. More precisely, considerable improvement on toughness, strength, and hardness is observed, while low resistance to current flow was reported possible at a thickness reduction of about 5%, and impairment of conductivity is considered under severe plastic deformation; however, no attempt was made to carry out such deformation.

As it is manifested, the current elements made of commercial Al-Mg-Si alloys in the form of a wire of various diameters have produced strength of 275-330 MPa and electrical conductivity of 57.5%-52.0% IACS (International Annealed Copper Standard), (Davies 1988). These properties are achieved through conventional thermo-mechanical processing T81, including quenching, cold drawing, and artificial aging in a sequential order (Cervantes *et al*. 2010).

We have recently suggested a new approach for enhancing the properties of commercial aluminium alloys of the Al-Mg-Si system with the aim to allow in increase both strength and electrical conductivity of the materials. If this is to be achieved, there is a need to combine the UFG structure formation and solid solution decomposition accompanied by the formation of strengthening Mg_2Si phase precipitates of both metastable and stable modifications using severe plastic deformation (SPD) (Bobruk *et al*. 2012, Sabirov *et al*. 2013, Valiev *et al*. 2014, Murashkin *et al*. 2013, Sauvage *et al*. 2015). It has been proven that the strengthening up to 365 MPa can be the achieved with a grain refinement during SPD, as well as through precipitation hardening induced by following dynamic aging. Studies (Bobruk *et al*. 2012, Sabirov *et al*. 2013, Valiev *et al*. 2014, Murashkin *et al*. 2013, Sauvage *et al*. 2015, Sha *et al*. 2014) have also shown that SPD substantially accelerates the decomposition of a supersaturated solid solution in parallel with the formation of UFG structure, and contributes to a significant reduction of the content of alloying element atoms in the aluminium matrix of Al-Mg-Si alloys as compared to conventional processing techniques. In accordance with the Matthiessen's rule for dilute alloys (Rositter, 2003), this is leading to the increase in electrical conductivity of UFG alloys up to more than 58% IACS (Bobruk *et al*. 2012, Sabirov *et al*. 2013, Valiev *et al*. 2014).

The scope of this work is to study the structural behavior and monitoring of mechanical and electrical properties of AlMgSi alloy designed for the manufacture of electrical wire. This work is in collaboration with engineers working in international business ENICAB (Biskra - Algeria).

2. Experimental methods

The Al–Mg–Si alloy was provided by the company MIDAL CABLES (BAHRAIN), in the form of wire coils from initial diameter of 9.5 mm with three different level of deformation (ε_1 = 21.26%, ε_2 = 68.99% and ε_3 = 86.81%). The chemical composition of the investigated alloy is given in Table 1. The mechanical and electrical characteristics of the aluminum alloy in the initial state (as-received) are shown in Table 2 (Hadid 2012). Characterization methods used to study the evolution of microstructure, texture deformation and to measure the mechanical and electrical properties are: the Electron Back Scattered Diffraction (EBSD), the Scanning Electron Microscope

(SEM), the X-Ray diffraction (pole figures), microhardness, tensile test and the measurement of the electrical resistivity.

Table 1 The chemical composition of studied material (aluminum alloy (6101 series) determined by the Laboratory-ENICAB company, Biskra-Algeria (weight %)

(Al)	(Mg)	(Si)	(Fe)	(Cu)
98.46	0.687	0.589	0.211	0.020

Table 2 The mechanical and electrical properties of studied material (aluminum alloy (6101 series) determined by the Laboratory-ENICAB company, Biskra-Algeria

Mechanical properties			Electrical properties
Breaking resistance *Rm* [N/mm^2]	Microhardness [HV]	Elongation *A* [%]	Electrical resistivity ρ [Ω×mm^2/m]
235.35	70.37	15	0.03362

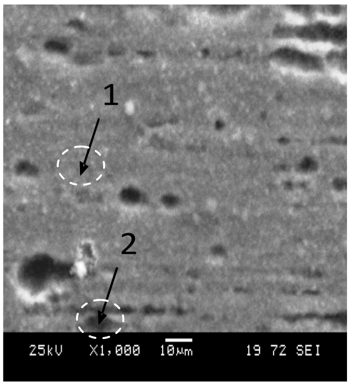


Fig. 1 SEM micrographs of the aluminum alloy (as received wire)

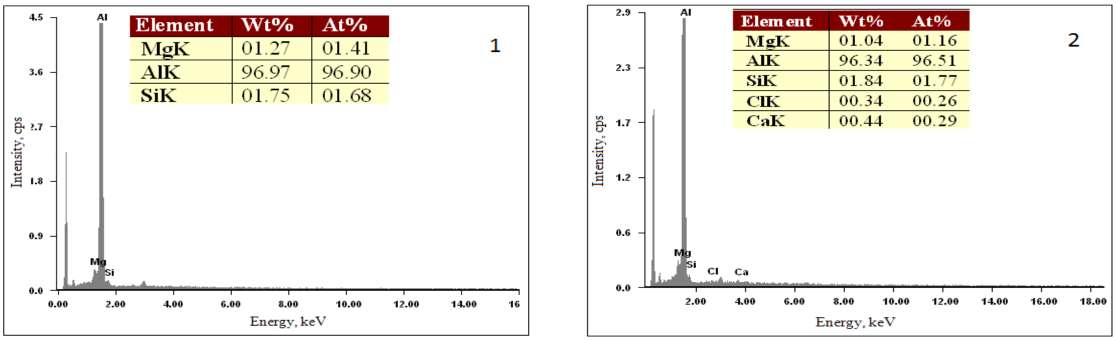
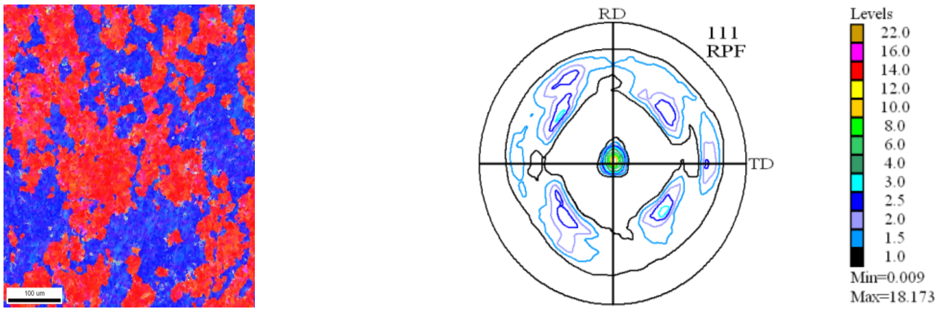


Fig. 2 The EDS-Spectra corresponding to the as received wire microstructure indicated by the area 1 and 2



(a) (b)

Fig. 3 (a) EBSD microstructure; and (b) {111} pole figures obtained by X-Ray diffraction of as-received wire

3. Characterization of the microstructure and texture of initial state (as-received wire)

The SEM microstructure of the alloy in the initial state (received wire) is shown in (Fig. 1). This microstructure shows the existence of certain phases of contrast different from the aluminum grain such as (Mg2Si) and (CuMgSiAl) (Figs. 1 and 2). Analysis of mapping by EBSD shows a fairly regular structure (Fig. 3(a)), which leads us to say that the crystallites may be substantially isotropic (Zidani *et al*. 2014). Moreover, this is proved by the pole figures obtained by the X-Ray diffraction of the as- received wire (Fig. 3(b)).

4. Characterization of the microstructure and texture of deformed state

Fig. 4 show EBSD micrograph of the deformed wires structure. The eutectic phase of coarse particles is observed lying along grain boundaries. The drawing process provokes grains deformation, which is explained by their elongation parallel to the axe of wire. The deformed alloys by biaxial compression and uniaxial tension were attributed to the germination of cavity in the surfaces of intersection of grain boundary sliding.

A cavity located at the grain boundary, whether pre-existing or nucleate, can develop during the deformation processes of diffusion and/or plastic deformation of the surrounding matrix. Relationships have been developed, and that describe the change of the radius of the cavity and the change of volume of the cavity with the strain for growth of different mechanisms (Hadid 2012).

Mapping reconstituted by EBSD shows the grains orientation of the different fibers in peripheral area of the strongly deformed wire (ε_3 = 86.81%) (Fig. 5(a)). The Fig. 5(b) shows the direct poles of the {111} texture obtained by the X-ray diffraction. We observed an increase in the {111} texture following the increase of the deformation level. This reflects that the wire drawing causes a textural effect in the microstructure. In our case, the fiber <111> // ND (ND/ / drawing axis) was major and fiber <100> // ND was a minor throughout the peripheral section of the strongly deformed wire (Total fraction: 52.4% <111> and 18% of <100> with a dispersion of 15°) (Fig. 5(a)). However (Hargue *et al*. 1995), observed in a drawn aluminum wire, a texture of mixture <001> (minority) and <111> (majority) at the center of the wire, whatever the deformation level. by contrast in peripheral area, for section reduction of 50.5% and 71.8%, the texture varies

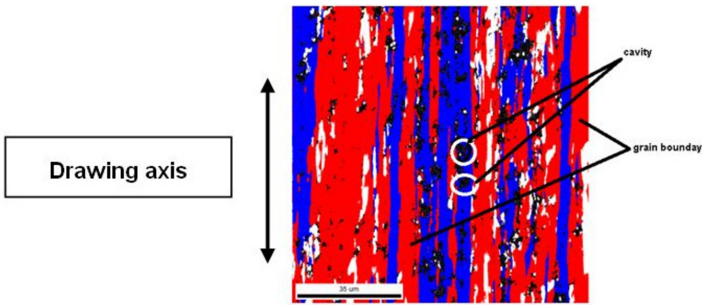
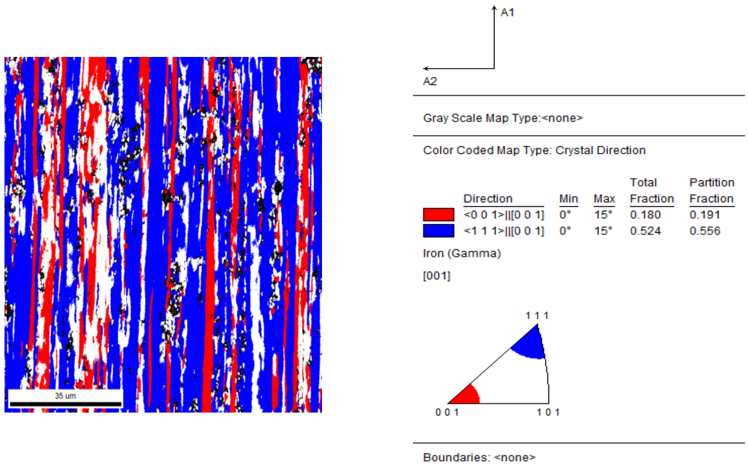
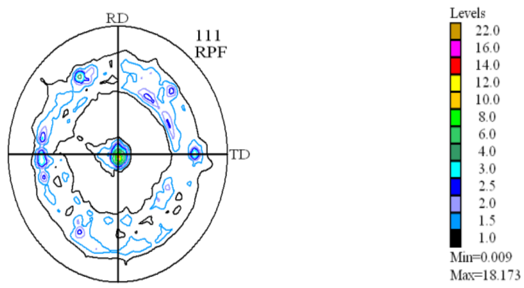


Fig. 4 EBSD microstructure of drawn wire at ε_3 = 86.81%



(a)



(b)

Fig. 5 (a) EBSD microstructure; and (b) {111} pole figures obtained by X-Ray diffraction after reduction by wire drawing (ε_3 = 86.81%)

between the two components <111> and <112> and for the strong deformation level (> 93.0%) there is a complete development of the fiber <111> (Jakani 2004).

According to these authors (Adeosun *et al*. 2011, Bobruk *et al*. 2012), this phenomenon is due to the heterogeneity of deformation in the section of the wire during drawing.

5. Evolution of mechanical and electrical properties

The results of mechanical and electrical properties are illustrated in Table 3. The measurements of the breaking resistance have showed an increase of this latter as a function of the deformation caused by the structural hardening. Its value achieves 362.61 N/mm^2 at the deformation of 86.81% after being 235.35 N/mm^2 at the non-deformed state. Hardening of a metal or alloy is to increase its hardness and mechanical resistance (resistance at the limit elasticity), but in the other hand decreasing its plasticity, (Figs. 6 and 7). The cold plastic deformation leads to the hardening of the material. This hardening depends on the chemical composition of the material, the applied strain rate and deformation conditions (temperature, rate and mode of deformation). Indeed, cold deformation causes a substantial increase of the dislocation density (i.e., stored elastic energy) in the material. It follows a heterogeneous microstructure and crystallographic texture in grain.

We also deduced an increase of electrical resistivity with the deformation level (Zidani *et al.* 2014, Hadid 2012) (Fig. 8). It is well known that at ambient temperature the resistivity of polycrystalline alloys can be written in the following form: $\rho = \rho_T + \rho_I + \rho_R$. The three terms in this expression represent the three classes of scattering mechanisms, which are respectively: phonons (ρ_T), chemical impurities (ρ_I), and defects related to the microstructure (grain boundary, surfaces and interfaces, ρ_R). In our case, the alloy has undergone a strong cold deformation, so it is affected by the effect of hardening, which deeply disturbs the order of the crystal lattice and influences the electrical resistivity, which explains its gradual increase after each wire drawing pass (Zidani *et al.* 2014).

Table 3 Results of mechanical and electrical properties before and after drawing

ε (%)	*Rm* [N/mm^2]	*HV*	*A* (%)	ρ [Ω×mm^2/m]
0	235.35	70.37	15.0	0.03362
21.26	310.04	92.12	6.5	0.03408
68.99	324.85	100.9	6.0	0.03494
86.81	362.61	118.6	5.1	0.03568

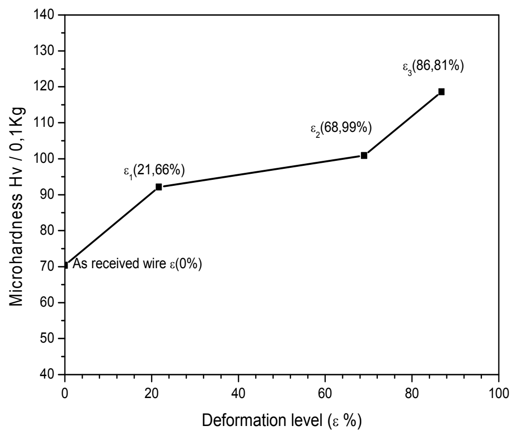


Fig. 6 Evolution of the mean value of microhardness according to deformation level

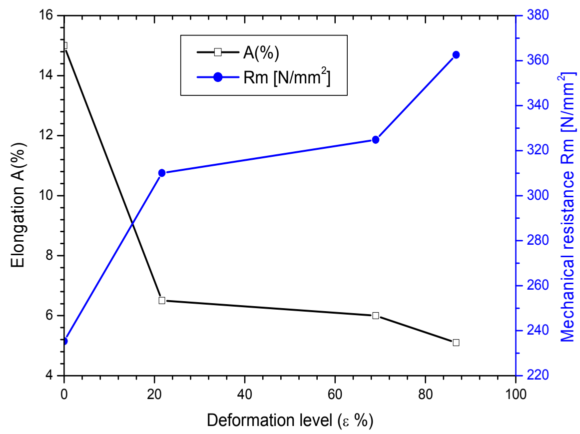


Fig. 7 Evolution of mechanical properties according to deformation level

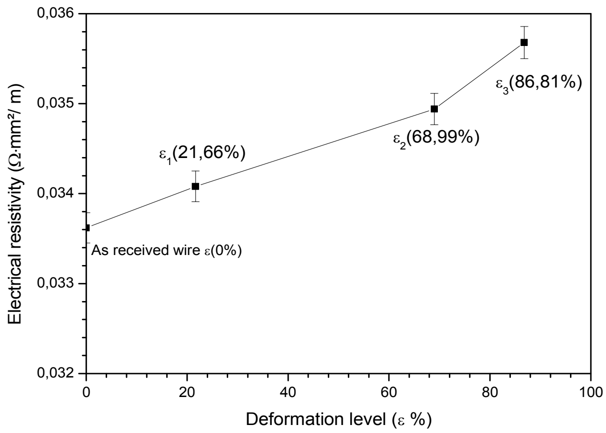


Fig. 8 Evolution of electrical properties according to deformation level

6. Conclusions

Based on the analysis of experimental test results presented in this paper, it can be concluded that:

Wires drawing of aluminum provoke a development of a fibrous texture. The developed deformation texture in peripheral area, for section reduction of 86.81% is essentially formed by fiber <111> // ND (majority) and fiber <100> // ND (minority) (ND/ /drawing axis). Thus, an increase in mechanical properties (microhardness and mechanical resistance) is a function of deformation level. The cold plastic deformation leads to strain hardening of the material, and hardening causes a substantial increase of the dislocation density (i.e., stored elastic energy) in the material. However, elongation will drop depending on the deformation .The electrical resistivity also increases with the deformation level, which can be explained by the disruption of the crystal lattice by curing, which reflects the increase in resistivity.

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