Tensile strain and resistance variation caused by torsional deformation in dilute Al-Mg alloys

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Abstract. Pure tensile and combined torsion-tension deformation has been investigated for three Al-Mg alloys: (Al+0.50 wt% Mg), (Al+0.85 wt% Mg) and (Al+1.60 wt% Mg). Plastic instability behavior is observed in the case of combined torsion-tension deformation. The onset and disappearance of this instability is found to depend on some parameters as applied axial tensile stress, working temperature and sample grain diameters. The influence of plastic deformation on the electrical resistivity for such materials has been investigated at room temperature. Both torsion-tension deformation and electrical resistivity were found to decrease on plastic straining for samples as received, and pre-annealed from 373 till 573 K, and then it increased for samples pre-annealed at 673 K and 773 K. The results show negative tensile strain (-\(\Delta L/L_0\)) for samples annealed in the temperature range of the first annealing stage which is inferred to hardening due to internal stresses formed on clustering of Mg atoms at grain boundaries as well as the formation of Luders bands at the grain boundaries during twisting. The positive result observed for samples pre-annealed at higher temperature is attributed to dispersion of Mg precipitates inside the grains during the recrystallization process.

1. Introduction
The study of resistivity changes in metals and alloys as a function of plastic strain has been recognized as a very efficient tool for investigating nature and concentration of lattice defects induced by cold work [1,2]. It is usually found that the effect of plastic deformation is to increase the resistivity [3]. Anomalous change in electrical resistivity [4] in which the resistivity initially decreases rather than increases as a result of plastic deformation has been observed in some alloys [5]. Most of these investigations, performed in tensile tests, suffer experimental limitations, namely the low values of deformation reached before fracture and these does not enable to have enough insight on the production of lattice defects during cold-work. On the other hand recently the authors [6,7] showed that a large amounts of strain can be reached by torsion-tension deformation, provided the sample is submitted to a low tensile stress. This work is aiming to investigate the effect of various tensile stresses superimposed during twisting, as well as on the pre-annealing temperatures and/or magnesium contents in the used aluminum, on the resistivity-strain relations of Al-Mg alloys. The literature seems meager in this respect. It was interesting to consider the correspondence between measured tensile strain and the associated relative resistance simultaneously affected by torsion-tensile deformation.

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2. Experimental details

In this work three aluminum magnesium alloys were prepared from Al-Mg master alloys (Al+12wt%Mg) supplied by Helwan Company for non-ferrous metals. The master alloy was diluted using 99.99% pure Al in order to attain the required Mg concentrations in the alloys: Al+0.5wt%Mg, Al+0.85wt%Mg and Al+1.6wt%Mg. The alloys after preparation were suitably homogenized at 673K for 10 hours in an evacuated (~10^{-4} mmhg) silica tube. After homogenization the prepared alloys were shaped by cold drawing into wires of diameter 0.5 mm. The alloys were subsequently annealed in an evacuated silica tube at the selected temperatures of 300, 373, 673, and 773 K for one hour and then the furnace was cooled to room temperature.

The corresponding tensile strain ($\Delta L/L_0$), and the associated relative resistance ($\Delta R/R_0$) simultaneously affected by torsion-tensile deformation were calculated. These experimental runs were carried at room temperature, using different axial tensile stresses of 6.11 and 16.75 MPa. These stresses did not exceed one third the yield stress of the samples.

The corresponding changes in the length due to torsion were measured using traveling microscope with accuracy ± 0.01 mm. The corresponding electrical resistance of the samples was measured using Kelvin double bridge sensitive to $10^{-7}$ ohm. The relative change in resistivity due to torsion deformation calculated from the formula (after Ceresara et al.) [8]:

$$\frac{\Delta \rho}{\rho_0} = \left(\frac{\Delta R}{R_0}\right) \cdot \left(1 - \frac{2L}{L_0}\right) \cdot \frac{2\Delta L}{L_0}$$

where $\rho_0$ and $R_0$ are the resistivity and resistance of the sample of the initial length $L_0$.

The total shear strain $\gamma$ for twisting under tensile stress was calculated as

$$\gamma = \alpha N \frac{D_0}{L_0} + \beta \frac{\Delta L}{L_0}$$

where $N$ is the number of turns twist and $\Delta L$ is change in length associated with twisting of the sample of initial length $L_0$ and diameter $D_0$. The constants $\alpha$ and $\beta$ were taken as $2\pi/3$ and 3 respectively [9].

In order to reveal the grains of the studied samples, they were electrolytically polished and etched by a method described else where [10].

3. Results and Discussion

Measurements of variation in resistance $\Delta R$, and elongation $\Delta L$ during twisting at room temperature simultaneously were followed until fracture. Fig. 1 shows the measured variation of tensile strain $\Delta L/L_0$ caused by torsional deformation $ND/L_0$ with the corresponding variation in resistance $\Delta R/R_0$ for the three studied Al-Mg alloys pre-annealed at 673 K or 773 K at the two axial tensile stresses of 6.11 and 16.75 MPa. It can be observed that the torsional deformation at those temperatures caused an increase in both tensile strain, and relative resistance and this increase was higher for samples stressed with higher tensile stress (16.75 MPa).

In samples annealed at these temperature ranges, it was observed a linear relation between attained torsional strain and the corresponding resistance which could be expressed mathematically by the equation:

$$\frac{\Delta L}{L_0} = K \frac{\Delta R}{R_0}$$

where $K$ is the slope of the straight lines shown in Fig. 1 and whose value increases with (i) increase of Mg content, (ii) increase of the pre-annealing temperature and (iii) increase of the axial tensile stress.
Figure 1 The correspondence of tensile strain and relative change in resistance induced by torsional deformation for the three Al-Mg alloys pre-annealed at 673 K and 773 K, stressed longitudinally at 6.11 MPa and 16.75 MPa (∆ = 1.60% Mg, O = 0.85% Mg and □ = 0.50% Mg).

Fig. 2 shows the behavior of samples as received and pre-annealed at 373 K. There it can be observed that the torsional deformation causes decrease in both tensile-strain and electrical resistance for the three tested alloys. This negativity increases with increasing Mg content, while it decreases with increasing applied axial tensile stress and/or pre-annealing temperature. The dependence of the relative change in resistivity ($\Delta \rho/\rho_o$) on total shear strain $\gamma$ for three alloy studied was calculated using equations (1, 2).

Fig. 2 The correspondence of tensile strain and relative change in resistance induced by torsional deformation for the three alloys as received and pre-annealed at 373 K and stressed longitudinally by 6.11 MPa and 16.75 MPa (∆ = 1.60% Mg, O = 0.85% Mg and □ = 0.50% Mg).

Figs 3 and 4 show the dependence of resistivity variation on shear strain for different alloys pre-annealed at different temperatures and twisted using axial tensile stress 6.11 and/or 16.75MPa. The
lines in each figure were almost parallel, with the slope (P) equal to the mean value of 0.8 and intercept (C). These two constants C and P are related to each other by the empirical formula [11]:

$$\Delta \rho = C \gamma^P$$  \hspace{1cm} (3)

where $\Delta \rho$ is change in resistivity resulting from a mean shear strain $\gamma$, while C and P are constants. The constants C was found composed from the contribution of both point defects $C_V$, and dislocations $C_d$ to the extra resistivity, i.e. $C = C_V + C_d$. From Figs. 3 and 4 one can see that the value of the relative changes in electrical resistivity $\Delta \rho/\rho_o$ at a given shear strain $\gamma$, increases with increasing pre-annealing temperatures, Mg content, and applied tensile stress.

This effect may be attributed to the decrease in dislocation density through the enhanced cross-slip mechanism during twisting. The cross slip mechanism which is stress dependent, cause annihilation of dislocations on intersecting slip planes, leading to decrease in the number of electron scatters that leads to decrease of the electrical resistance. Also the changes $\Delta \rho/\rho_o$ can be attributed to the precipitations and subsequent dissolution of meta stable and stable phases [12]. In case of recovery stage aggregates of Mg atoms with their own internal stresses, appearing at the grain boundaries, figure (5a).

In contrast, in recrystallization, when samples were pre-annealed in second annealing stage, figure (5b), the annealing process caused annihilation of lattice defects and dissociation of Mg aggregates. The dissociation of Mg aggregates increased the diffusion of Mg atoms in the matrix and in turn gave more scattering to conduction electrons leading to the observed increase in the resistance.

Peiffer and Stevenson [13], Kovas and Nagy [14] showed that the difference in values of the coefficient C obtained by various investigators is mainly due to different thermal and mechanical history of the investigated aluminum samples. The value of the exponent P (0.8) determined from the experiments (see figures 3 and 4) at room temperature at large deformation suggests [15,16] that the
most of the contribution to the extra resistivity arises from dislocations left in the alloy after annealing. The results showed that increase in magnesium content increased the resistance [17] of the sample to deformation while it decreased the sample's elongation and this might be due to the increased dissociation [18] of magnesium aggregated in the matrix that hinder slipping and decrease attained elongation.

![Fig. 5 Photomicrograph of samples in recovery stage (a) and in the recrystalization stage (b).](image)

4. Conclusion

It was found that in case of Al-Mg alloy we have two stages. A recovery annealing stage was found in as received and pre-annealed at 373 K. Recrystallization stage in pre-annealed at 673 and 773 K. A negative elongation (contraction) was observed when the Al-Mg wires were subjected to tensile torsion deformation because the aggregates hindered grain orientation during torsion (recovery stage), a decrease in resistance of the samples was found. Increasing Mg content leads to increase in the number of the aggregated Mg in the matrix, leading to decrease in elongation as well as decrease in the electrical resistivity. The second annealing stage due to the recrystallization occurred in the temperature range: 673, 773 K, it seemed to be caused by the dissociation of Mg aggregates thus increased the Mg atoms in the matrix. The electrical resistance of the samples increased because of the diffused Mg atoms increased electron scattering inside the matrix.

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