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TENSILE AND ELECTRICAL PROPERTIES OF Al-Si ALLOYS UNDER COMBINED TORSION-TENSION DEFORMATION

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The relation between tensile strain $\Delta L/L_0$ and the relative change in resistance $\Delta R/R_0$ caused by torsion-tension deformation for Al-Si samples pre-annealed at different temperatures (room temperature up to 773 K) was studied. The empirical relation $\Delta L/L_0 = k\Delta R/R_0$ was found, where k is a constant depending on the silicon content and its distribution in the matrix.

1. Introduction

The aim of the present work has been to investigate the mechanical and electrical properties of aluminium-silicon alloys. The addition of silicon to aluminium causes basic changes in the macroscopic properties of the aluminium alloys which are of special technological interest.

The study of change of resistivity of metals as a function of plastic strain has been recognized as a very efficient tool for investigating the concentration and nature of cold-work induced defects [1,2].

Most of the above quoted investigations have been performed in tensile tests and have an experimental limitation, namely the small deformation fracture. That way one can not reach a thorough insight on the production of defects during cold work.

Large amounts of strain can be reached by deforming the material by torsion [3-6], provided the sample is submitted at the same time to a small tensile stress.

Keeping in mind these considerations, we have undertaken a study of the dependence of both the relative change of resistance ($\Delta R/R_0$) and of the flow stress ($\Delta L/L_0$) on strain of polycrystalline (Al-Si) alloys at room temperature. The material was tested by torsion till fracture. These measurements are expected to yield more information on mechanical and electrical properties of Al-Si alloys, related to the interaction of silicon atoms with vacancies and dislocations in the aluminium matrix. It is hoped to provide deeper insight on the role of silicon atoms on the mechanical and electrical properties, aggregated or dispersed, of the alloys.

2. *Experimental results*

2.1. *Material preparation*

Wires of the test were made of Al, alloyed with 0.60, 0.83, or 1.85 wt % Si, and were prepared as described previously [7]. The wires were subjected to uniform twisting using the twisting machine [8]. The degree of torsional deformation was measured by the dimensionless quantity (ND/L_0), N being the number of turns of the twist, D the wire diameter (0.5 mm) and L_0 the original wire length (50 mm).

The samples of each alloy were investigated either untreated (as they were received) or pre-annealed for one hour at temperatures of 373, 573, 673 and 773 K. The aim was to study the various phases of the contaminated silicon either aggregated or dispersed through the matrix.

2.2. *Tensile strain behaviour*

During plastic twisting the pre-annealed wire was axially loaded by the tensile stress of 6.11 MPa. The tensile elongation ΔL, associated with the combined torsion-tension deformation, was successively measured till fracture. The experiments were repeated (on new samples) using axial tensile stresses of 10.2, 12, 14.5 and 17.1 MPa. These stresses were within the elastic range of the tested wires. Figure 1 shows room temperature variations of tensile strain ($\Delta L/L_0$) with torsional deformation (ND/L_0), for the samples of the three alloys, pre-annealed at the different temperatures and strained under the different axial tensile stresses. The results show that:

a. The relation between torsional deformation (ND/L_0) and accompanying tensile strain ($\Delta L/L_0$) is nearly linear.

b. Negative values of tensile strain ($-\Delta L/L_0$) occur in untreated samples and those pre-annealed at lower temperatures (below 573 K). Absolute value of the gradient decreases by increasing both pre-annealing temperature and axial tensile stress or by decreasing Si content.

c. Positive values of tensile strain ($+\Delta L/L_0$) occur in samples pre-annealed at higher temperatures (> 573 K). The gradient increases with increasing pre-annealing temperature, axial tensile stress and decreasing silicon content.

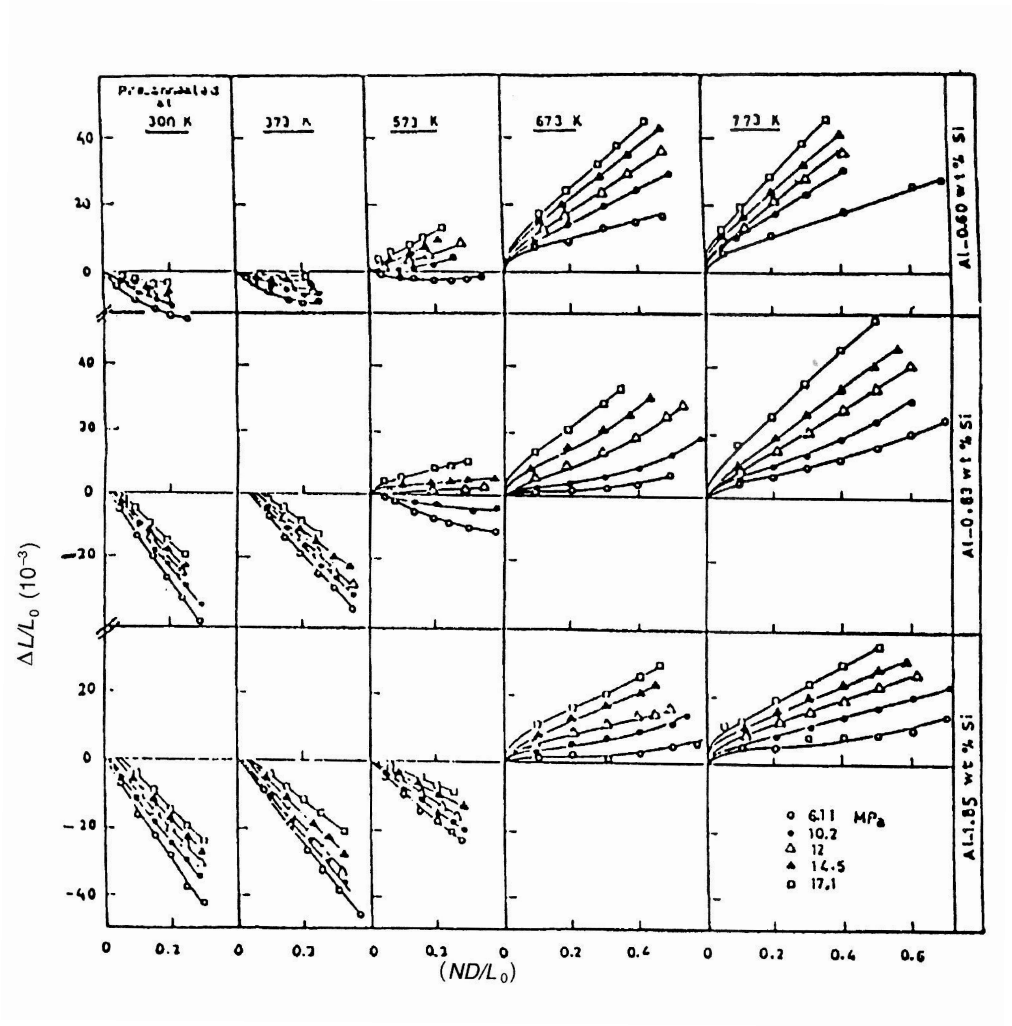

*Fig. 1. Room temperature variation of tensile strain $\Delta L/L_0$, due to torsional deformation ND/L_0 for samples of the three (*Al-Si*) alloys, untreated (300 K) and pre-annealed at temperature of 373, 573, 673 and 773* K, *and strained by axial tensile stresses of 6.11, 10.2, 12, 14.5 and 17.1* MPa.

2.3. *Electrical behaviour*

The electrical resistance of the samples was measured at room temperature using a Kelvin double bridge sensitive to 10^{-7} Ω.

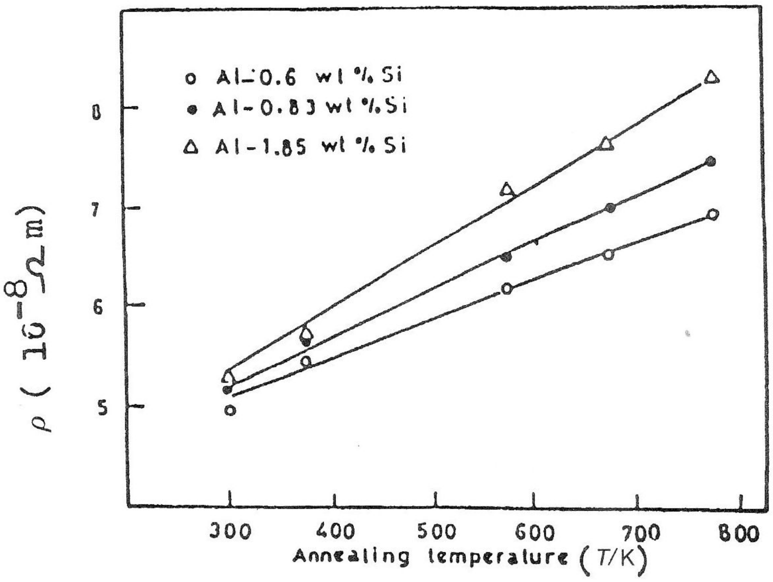

Fig. 2. Dependence of resistivity of samples on pre-annealing temperature for the three alloys.

The dependence of resistivity of the samples on pre-annealing temperature is shown in Fig. 2. One can see that the resistivity for each alloy increased rather linearly with pre-annealing temperature. The rate of increase of resistivity with pre-annealing temperature $\partial\rho/\partial T$ was calculated, and its dependence on Si content is given in Fig. 3. It shows that the rate increased linearly with Si content.

The relative change in electrical resistance $(\Delta R/R_0)$, as well as the relative change in tensile strain $(\Delta L/L_0)$ with torsion deformation (ND/L_0), for the three alloy samples, untreated or pre-annealed at temperature of 373, 573, 673 and 773 K, stressed by 6.11 MPa, is shown in Fig. 4. The figure shows that:

a. The relative change in electrical resistance $(\Delta R/R_0)$ decreases by torsional deformation for the untreated samples and those pre-annealed at 373 K, while it increases for samples pre-annealed at higher temperatures. Generally, the observed change whether negative or positive, increased with increasing torsion deformation, pre-annealing temperature and/or increasing Si content.

b. By comparing the results in Fig. 4a and Fig. 4b one can see that there is a correspondence between the variation of tensile strain $(\Delta L/L_0)$ and of electrical resistance $(\Delta R/R_0)$ as caused by the same torsion-tension deformation (ND/L_0).

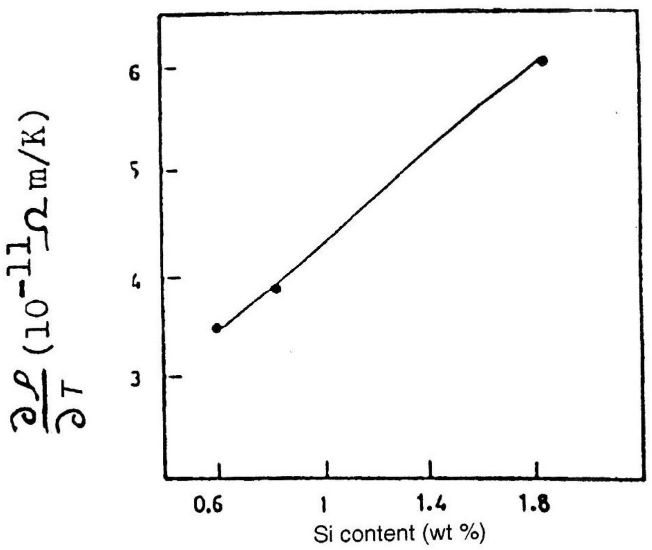

Fig. 3. Dependence of $(\partial\rho/\partial T)$ on silicon content.

3. *Discussion*

The untreated samples were full of vacancies, dislocations and Si impurities due to alloy preparation and subsequent plastic deformation by cold swaging. In the course of annealing, motion of vacancies reduces the internal energy by forming vacancy-silicon pairs [9]. These pairs migrate to dislocations or grain boundaries, thus forming complex Si aggregates by vacancy cluster mechanism.

When polycrystalline Al-Si wires were subjected to increased torsional stress, an intercrystalline slip seemed to start in some grains. These grains were the most favourably oriented relative to the stress axis. It is also known that twisting of a polycrystalline metal wire causes the slip planes in the various grains to rotate. Thus under combined tensile-torsional deformation stress, and before the slip occurred, slip planes could rotate in such a way as to be more favourably oriented to the tensile axis. The probability of plane misorientation in the various grains increased as the number of grains per unit volume in the wire increased.

The grains of the untreated samples were found to be elongated and of fibrous structure. In these elongated stressed grains, and during twisting, Luder's bands were formed at grain boundaries, giving rise to crack nucleation followed by crack propagation. Along these cracks the fibrous grains seemed to move with respect to each other during the twisting. The orginally straight fibers twist into a helical shape, resulting in shortening of the sample's length. Therefore, a negative tensile strain $(-\Delta L/L_0)$ was observed.

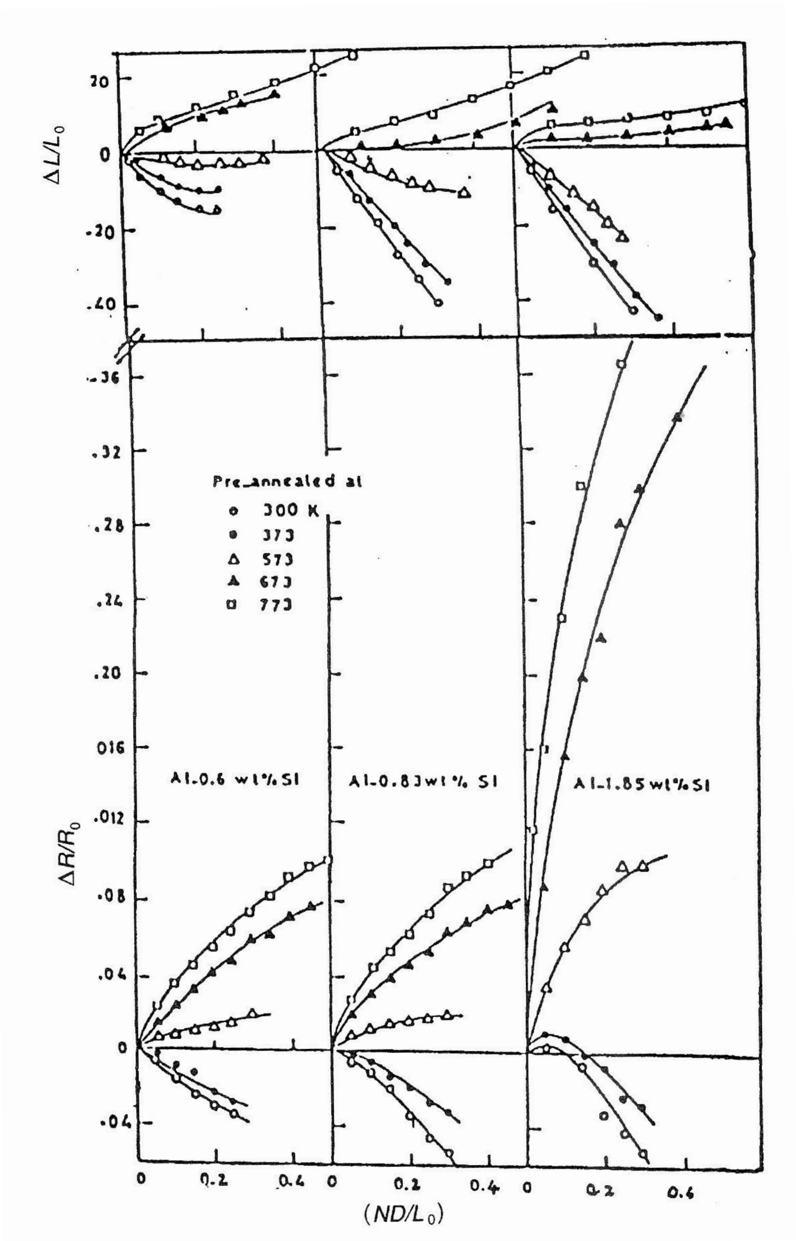

Fig. 4. The effect of torsional deformation (ND/L_0) *on the tensile strain* $(\Delta L/L_0)$ *and on the relative change in electrical resistance* $(\Delta R/R_0)$ *for the three alloys, untreated (300* K*) or pre-annealed at different temperatures and stressed longitudinally by 6.11* MPa.

To account for the relative decreases of resistance with torsional deformation in the untreated samples or those pre-annealed at 373 K, it was found that an intercrystalline slip starts in particular grains whose edges are full of Si aggregates when the samples were subjected to increasing torsional stress. Slip planes in various grains rotate in the direction of tensile axis [10] leading to increased volume of Si aggregates, in agreement with the work of Solberg and Thon [11]. They found that cold work on Al alloys increases the aggregate size and causes misorientation of the grains accompanied by increasing volume of Si aggregates and decreasing its number leading to decreasing in the overall resistance. This is in agreement with the work of Osono et al. [12] and Gaber et al. [13], also on Al alloys.

Higher pre-annealing temperature relaxes the internal structure of the specimens. Also, the grain boundaries become more matched with matrix and become equiaxed. Therefore, they orient themselves easier to the tensile axis, and by twisting give positive tensile strain (elongation). This effect was enhanced by increasing the tensile stress or pre-annealing temperature [9].

Higher pre-annealing temperature caused dissociation of existing Si aggregates [14] and their diffusion in to the matrix. The number of electron scatterers increased, giving rise to the observed increase of resistance of samples.

As a result, higher Si content leads to an increase in the number of aggregated Si atoms and of their volume, leading to an increase of $(-\Delta L/L_0)$ as well as the observed decrease of electrical resistance. Also, higher Si content leads to an increase in the number of dissociated, randomly distributed Si atoms and, consequently, to an increase of the resistance of samples.

To consider the relation between the measured $(\Delta L/L_0)$ and $(\Delta R/R_0)$, caused by the torsional deformation for untreated samples and those pre-annealed at 673 K, we show the data in Fig. 5. A linear relation between $(\Delta L/L_0)$ and $(\Delta R/R_0)$ has been obtained. The observed linear behaviour can be expressed by the relation

$$\frac{\Delta L}{L_0} = k\frac{\Delta R}{R_0}.$$

The slope of the straight line, k, is constant but depends on the Si content and the pre-annealing temperature. The factor k was derived from the data and is given in Table 1. It is clear that in case of untreated samples, k increases with Si content. This might be because the Si aggregates decrease the tensile strain more than they decreases relative change in resistance. In case of recrystallized samples, k decreases with increasing Si content, showing that diffused Si atoms have a tendency act as electron scatterers more than to facilitate slipping action.

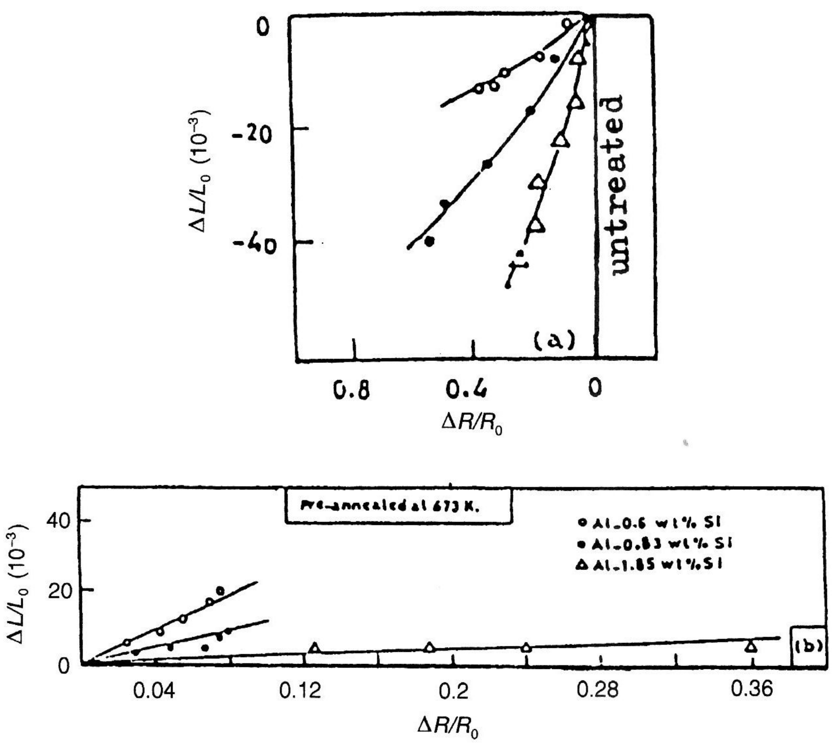

Fig. 5. Correspondence between tensile strain ($\Delta L/L_0$) and relative change in electrical resistance ($\Delta R/R_0$) for the three alloys, stressed longitudinally by 6.11 MPa*: (a) untreated (b) pre-annealed at 673 K.*

TABLE 1.
The experimental values of the factor k for untreated samples (300 K*) and for recrystallized samples (673* K*).*

Pre-annealing temperature	*Alloy*		
	Al-0.60 wt % Si	*Al-0.83 wt % Si*	*Al-1.85 wt % Si*
300 K (Recovery stage)	*0.357* ± 0.02	*1.000* ± 0.01	*2.000* ± 0.01
673 K (Recrystallization stage)	*0.260* ± 0.002	*0.133* ± 0.002	*0.022* ± 0.002

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RASTEZLJIVOST I ELEKTRIČNA SVOJSTVA LEGURA Al–Si U OVISNOSTI O TORZIJI I NAPETOSTI

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Razmotren je odnos rastezljivosti $\Delta L/L_0$ i relativne promjene električne otpornosti $\Delta R/R_0$ koja nastaje zbog torzije i napetosti u uzorcima Al–Si prethodno otpuštanim na različitim temperaturama (293 do 773 K). Postavljen je empirički izraz $\Delta L/L_0 = k\Delta R/R_0$, gdje konstanta k ovisi o količini i raspodjeli silicija u matrici legure.