Estimation of the stored energy of dislocation for plastically deformed 6082 heat treatable Al-Alloy

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This work describes cold work effect on the positron annihilation parameters, which are used in determination of the stored dislocation energy of the investigated 6082 Al-alloy samples. The investigated samples were homogenized for 6 h at 723 K then annealed at room temperature and finally plastically deformed up to 23 % degree of deformation. The annihilation parameters of the alloys under investigation were determined using the trapping model after fitting with the experimental measured data of the positron annihilation lifetime. 12% thickness reduction was found to be the start of saturation trapping region of positron in defect states at which an annihilation lifetime value of about 209±4 ps is obtained.A trapping efficiency of 6×10^{-7} cm^3s^{-1} gives the best fit of the experimental measurements with the theoretical mean lifetime values obtained using the trapping model. The stored dislocation energy can be determined from the data of the positron annihilation lifetime due its ability to determine the density dislocation during plastic deformation. An increase in the strain (degree of deformation) creates comparable increase in both defect and dislocation densities, hence an increase in the measured stored dislocation energy. Maximum stored dislocation energy of about 29.5 KJ/m^3 was obtained at the region of saturation of dislocation.

Keywords: Dislocation; Alloys; Analysis.

1. INTRODUCTION

The Earth's crust is rich with aluminum and its alloys, which have a wide-ranging of applications due to their worthy properties such as high strength, good corrosion, oxidation, high thermal and electrical conductivities, low density, and pretty low cost. Aluminum and its alloys are nontoxic and have the face-centered cubic (fcc) structure leads to an excellent and easiest formability and recyclability to any of the structural materials. The 6xxx Al-alloy series (Al-Mg-Si) is one famous series of wrought heat treatable Al-alloys which can be precipitation hardened to improve the strength levels of alloys. Cold work (deformation below half alloys melting point) is an important method that produces dislocations mainly used in improving the mechanical properties of the Al-alloys. When a sufficient compression is applied to a metal or alloy, it causes either an elastic or plastic deformation in the material. Plastic deformation produces an irreversible shape change after removing the applied work. Plastic deformation of single crystals samples is simple and definitely produces dislocations but in polycrystalline plastic deformation becomes complex due to several interactions between the grain boundaries and dislocations [1].

The energy consumed in plastically deformed metal is mainly divided into two parts, one part is transformed into heat depending on the type of the loading and on the degree of deformation. The other part is stored inside the defects in the form of strain energy [2]; means the metal becomes battery of energy. The stored energy during cold work was experimentally determined by many authors [3–7]. Positron annihilation lifetime spectroscopy (PALS) is one method that can be used in determination of this stored energy during cold work. Positron annihilation technique is a sensitive, powerful and non- destructive nuclear method used heavily in studying defect properties in metals and alloy [8-12]. The effect of plastic deformation on positron annihilation in metals was extensively studied by many groups [13-15]. It has been suggested that positrons may be trapped in the core of dislocations which are produced during deformation. The localized variations in electron density at these dislocations in metals and alloys are able to trap positrons and thereby cause them to annihilate with a different electron distribution than in a defect free lattice. In this work the trapping model of the positron lifetime measurements was used to determine the positron annihilation parameters, which are used in determination of the dislocation energy stored in plastically deformed Al-alloy.

2. EXPERIMENTAL PROCEDURE

Samples of (Al-Mg-Si) 6082-alloy with chemical composition given in table (1) and with dimensions (12 x 12 x 3) mm^3 were cleaned, chemically etched, then annealed to room temperature after homogenized for 6 hours at 723 K in a non-vacuum furnace. These prepared samples were then deformed in the range of 0% to 23% from its original thickness at room temperatureusing a hydraulic press. A fast coincidence positron annihilation technique, described elsewhere [16, 17], was used in measuring the mean lifetime ofpositron for 12 couples of plastically deformed Al 6082 samples. The resolution of the system is 337.9 ps as measured using the coincidence by ^{60}Co. A very thin radioactive ^{22}Na was used as a positron source in this study, so that only small portion of the positrons annihilate in the source. The positron source is inserted between two similar samples [18]. The samples thickness is suitable to absorb all emitted positrons. The source-sample configuration was then wrapped in a thin aluminum foil. The lifetime value of the source contribution (kapton foil) was subtracted during the analysis. Each spectrum was accumulated for a period of 3 h during which about 5×10^5 coincidence counts were accumulated. The data of the lifetime spectra for

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the investigated 6082 Al-alloys samples was analyzed using the PATFIT computer program [19].

Table 1 The chemical composition of 6082 Al-alloy.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Wt %	0.7-1.3	0.0-0.5	0.0-0.1	0.4-1.0	0.6-1.2	0.0-0.25	0.0-0.2	Remi nder

3. RESULTS AND DISCUSSION

3.1. Estimation of the positron parameters (mean lifetime, trapping rate, trapping efficiency, defect density and dislocation density)

The relation betweenexperimentally measured mean lifetime (τ) values (data points) and the degree of deformation (thickness reduction) is shown in figure (1). The positron mean lifetime value of the undeformed (annealed) sample is 183$\pm$5.8 ps after which, an increase in the values of the positron mean lifetime was observed with increasing the thickness reduction until 12% is reached. Above 12% thickness reduction, the obtained results of τ is approximately kept constant in the region for saturation trapping of positron in defect states. A positron annihilation lifetime value of about 209$\pm$4 ps is obtained for saturated dislocation samples.

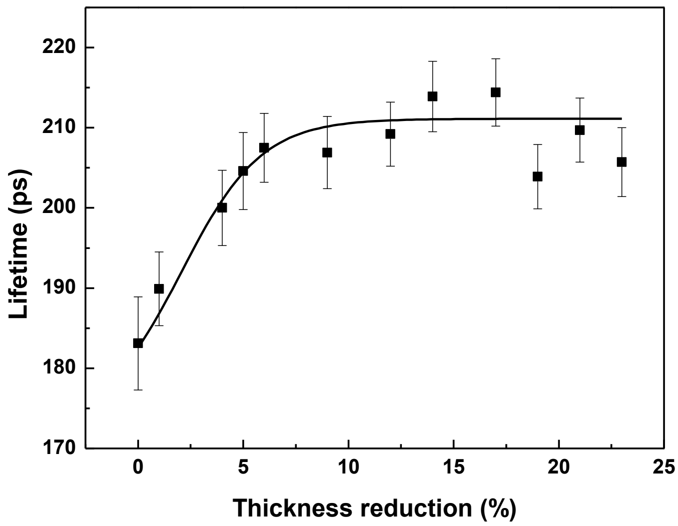

Figure 1 Experimental results (data points) and the theoretical fitted curve (solid line) of the mean lifetime as a function of thickness reduction of 6082 Al-alloy.

The trapping model described in equation (1) [20] was used to analyze the obtained positron lifetime results in order to determine the fitted mean life time curve shown in figure (1). This trapping model presumes that the positron can exist either in the Bloch (free) state or in the defect (trapped) state of the material.

$$\tau = \tau_f \frac{1+\kappa_d\tau_t}{1+\kappa_d\tau_f} \quad (1)$$

where τ_f is the mean lifetime for the annealed sample (defect free), τ_t is the mean lifetime of dislocation saturated sample and κ_d is the trapping probability per second (trapping rate). The missing positron trapping rate κ_d values of equation (1) must be determined using equation (2):

$$\kappa_d = 1.248\, x10^{-3}[\log(1-\mathrm{R})]^2 \frac{\nu}{b^3} \quad (2)$$

where R is the fractional thickness reduction and b is the Burger vector of Al = 2.86 Å and ν is the trapping efficiency.

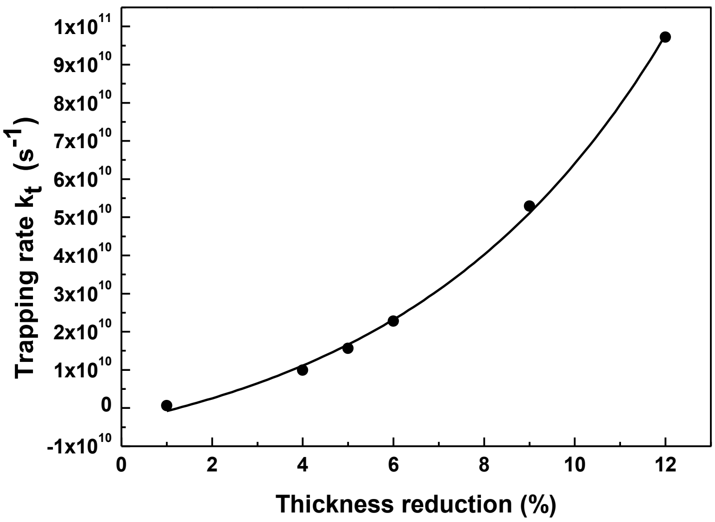

Figure 2 The trapping rate versus thickness reduction of6082 Al-alloys.

The predicted value of the positron trapping efficiency (ν) which gives the best fit of the experimental positron lifetime data points of figure (1) after substituting in the positron trapping rate equation (2) was determined to be 6×10^{-7} cm^3s^{-1}. The theoretical (fitted) mean lifetime values obtained using the trapping model equations (1 and 2) is shown in the solid line of figure (1). The trapping rate values obtained using the trapping model of equation (2) using the predicted fixed value of the trapping efficiency versus thickness reduction is presented in figure (2). An exponential increase in the trapping rate values of positron was observed. A slow increase at lower thickness reduction up to 6% degree of deformation is obtained. This increase in the trapping rate of positron is followed by a bit faster increase with increasing of thickness reduction. Positron trapping rate value of about $9.6x10^{10}s^{-1}$ was obtained at 12 % thickness reduction.

The positron trapping rate, κ_d, is proportional to the defect density (defect concentration), $\bar{\rho}$, which is the trapping sites number per unit volume as:

$$\kappa_d = \nu\bar{\rho} \quad (3)$$

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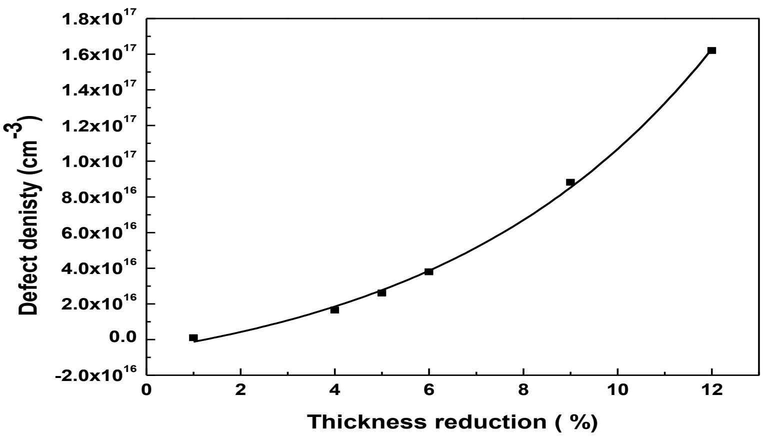

Figure 3 The defect density of 6082 Al-alloy as a function of thickness reduction.

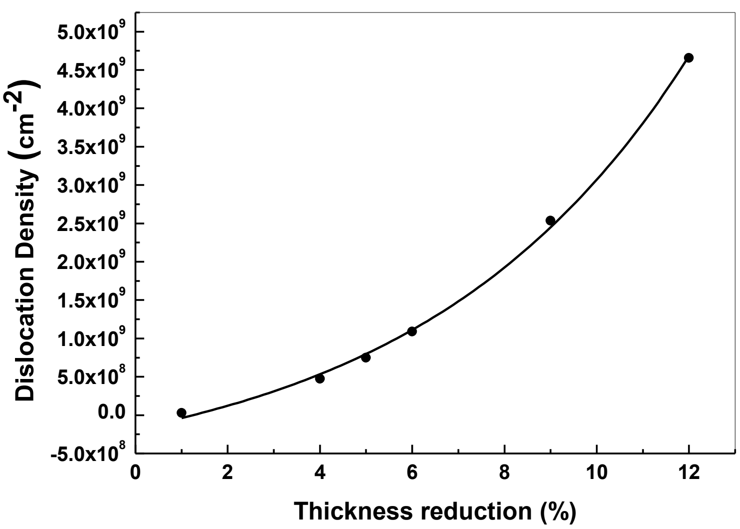

Figure 4 The dislocation density of 6082 Al-alloy as a function of thickness reduction.

The dislocation as a result of plastic deformation is considered to be a chain of spherical scattering centers as interpreted in the way of Baram and Rosen [20], means that the defect density $\bar{\rho}$ (cm^{-3}) is connected to the dislocation density ρ (cm^{-2}) according to:

$$\bar{\rho}(cm^{-3}) = \frac{\rho\ (cm^{-2})}{b} \qquad (4)$$

The variations of both the defect and the dislocation density as functions of thickness reduction are depicted in figures (3 and 4) respectively, where both values of the defect density and the dislocation density was estimated from the trapping rate values as in equations (4 and 5). The defect density and the dislocation density reveal the same behavior as the calculating trapping rate shown in figure (2) as a function of the degree of deformation.

Maximum values of defect and dislocation densities of about 1.65x10^{17}cm^{-3} and 4.75x10^{9}cm^{-2} respectively obtained at 12% thickness reduction.
The positron trapping coefficient (μ) can be calculated by substituting from equation (3) into equation (4) as follows:

$$K_d(s^{-1}) = \frac{\upsilon}{b}\,\rho(\mathrm{cm}^{-2}) = \mu\,\rho(\mathrm{cm}^{-2}) \quad (5)$$

A linear relationship for the dislocation density (ρ) as a function of the trapping rate (k_d) is depicted in figure (5). From this figure, the positron trapping coefficient which is the ratio between the positron trapping efficiency and the Burgers vector of the Al-alloy can be determined as 20.87 cm^2/s.

3.2. Determination of the stored energy based on the dislocation density

Stored energy, classically, is related to the amount of cold work (plastic deformation) a material receives [21]. A deformed metal or alloy has normally large energy stored at dislocation and, on annealing at higher temperatures; it will typically return to lower energy state by structural progression during recrystallization and recovery [22].The energy stored in dislocation (E) due to the generation of crystalline defects such as point defects and dislocations can be determined on the basis of the dislocation theory. The dislocation density ρ is related to the stored energy (E) as [22, 23]:

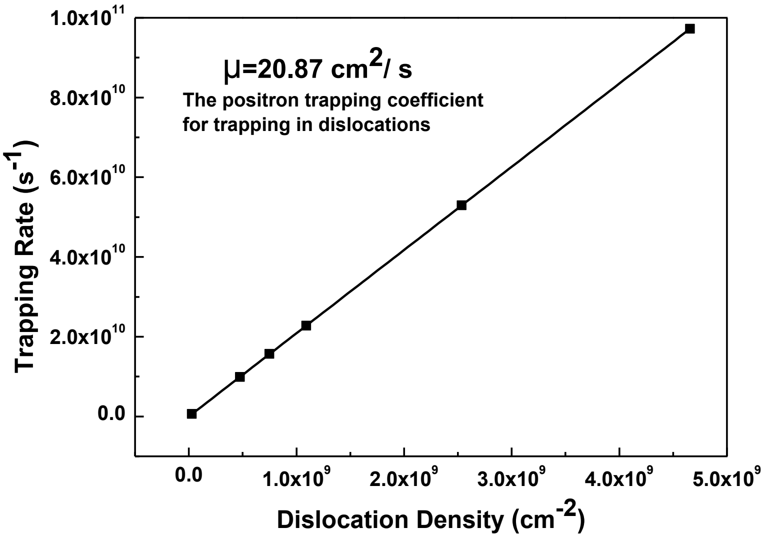

Figure 5 The trapping rate of the 6082 Al-alloy as a function of dislocation density.

$$E = \alpha\rho G b^2 \quad (6)$$

where αis the dislocation interaction parameter, which is of the order of 0.5, G is the bulk modulus of Al-alloy (G = 26 GPa) and b is the burger vector (b = 2.86 Å**)** [24, 25].
PALS provide an indirect approach in determination of the stored energy due to dislocations as a result of the plastic deformation by calculating the density of dislocation from the trapping model as in figure (4). Then substituting the dislocation density values into equation (6), the stored dislocation energy can be determined.

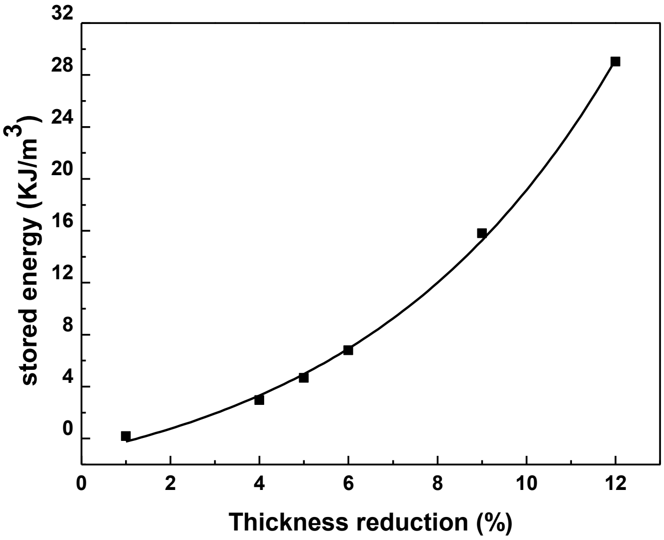

Figure 6 The stored dislocation energy versus thickness reduction (%) of 6082 Al-alloy.

Figure (6) reveals the changes of the stored dislocation energy with thickness reduction. From the figure, it is clear that a small value of stored energy is obtained at lower thickness reduction. An increase in thickness reduction creates comparable increase in the defect and the dislocation densities lead to increase in the measured stored dislocation energy. Stored energy of about 0.18 KJ/m^3 is obtained at 1 % thickness reduction. The probability of producing dislocations is small at lower degree of deformation, described by the slow increase in the stored dislocation energy at lower thickness reduction. This probability increases with degree of deformation, described by a faster increase in the stored energy of dislocation at higher thickness reduction. Maximum stored energy of about 29.5 KJ/m^3 is reached at 12 % degree of deformation.

4. CONCLUSIONS

- PALS technique can be used to determine the annihilation parameters in metals and alloys. It can be easily detecting the concentration of defects in 6082 Al-alloy under investigation.
- Saturation trapping of positron in defect states starts at 12% thickness reduction at which a positron annihilation lifetime and trapping rate values of about 209$\pm$4 ps and 9.6x10^{10}s^{-1} was respectively calculated.
- PALS technique can be used in determination of one part of the total stored energy which called the stored dislocation energy due its ability to determine the density of dislocation during plastic deformation.
- An increase in the degree of deformation creates comparable increase in both defect and dislocation densities, hence an increase in the measured stored dislocation energy.
- The probability of dislocations production is small at lower degree of deformation, this probability increases at higher deformation which leads to increasing the stored dislocation energy.
- Maximum stored dislocation energy of about 29.5 KJ/m^3 was obtained at the region of saturation of dislocation.

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