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Determination of the Positron Parameters and the Stored Dislocation Energy of Plastically Deformed Wrought 3004 Al-Alloy

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Abstract: Aluminum and its alloys are widely used in aircraft automotive and in construction industries because of their desirable physical properties. Positron annihilation lifetime technique (PALT) is non-intrusive method, which is used extensively in materials science. The positron annihilation lifetime spectra were measured for plastically deformed Al-3004 samples at different degrees of deformation up to 25% using hydraulic press at room temperature.Plastic deformation basically produces dislocation defects. Saturation trapping of positron in defect states starts at 6% thickness reduction at which the positron annihilation lifetime of about 215±5ps was obtained. The two-state trapping model of positrons after fitting with the experimental measured positron lifetime data was used to calculate the concentration of dislocations which are used in determination of the stored dislocation energy at different degree of deformation. The variation of the stored dislocation energy with thickness reduction seems to be an exponential growth, reaches its maximum value of 6.8 KJ/m^3 at 6% thickness reduction according to the increasing of the dislocation density as predicted theoretically.

Keywords: Stored energy, Positron annihilation lifetime technique, 3004 Al-alloy, Dislocation density, Plastic formation.

1 Introduction

There are several types of crystalline defects that can cause a significant improving in the properties of the materials, including interstitial point defects and vacancy in addition to dislocation line defects [1]. Aluminum-manganese series (3*xxx*) as FCC materials is one of non-heat-treatable wrought Al-alloys whichcan't be strengthened by precipitation hardening; these alloys are primarily hardened by cold work (plastic deformation due to compression). Plastic deformation is a permanent shape change that is irreversible even after removing the applied load. It occurs in metals and alloys when they are subjected to loads exceed the energy required to bring dislocations movement. A "dislocation" as a strengthening deformation effect can be visualized as a line defect formed when in the interior crystalline solid; an incompletely formed plane of atoms is terminated [6]. Selection of structural materials involves compromise among ductility and strength since high ductility materials normally have low strength, and vice versa [2]. Commonly, BCC metals offer higher strength while FCC metals offer higher ductility. A highly desirable feature for structural materials is to become stronger when deformed by cold work up to a certain degree of deformation. The energy expended in plastic deformation of a metal is mainly divided into two parts, one part is converted into heat depending on the type of the loading and on the degree of deformation and the other part is stored inside the defects in the form of a strain energy [3]; means the metal becomes battery of energy. The stored energy during cold work was experimentally determined by many authors [4–8].

Positron annihilation lifetime technique (PALT) is a method that is used recently in determination of the stored energy during cold work. PALT is a powerful sensitive non-destructive nuclear technique used in material science to investigate defect properties in metals and alloys [9-13].

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The main advantage of PALT lies in its ability to detect and distinguish between different types of defects [14] such as voids, grain boundaries, dislocations, vacancies and vacancy clusters, etc. It covers the range of vacancies with concentration from 0.1 to 500.0 ppm [15]. The effect of plastic deformation (cold work) on positron annihilation in metals and alloys was experimentally studied [16-18]. It has been suggested that local variations in electron density at dislocations which are produced by plastic deformation in metals and alloys, are able to trap positrons. These trapped positrons annihilate with a different distribution of electrons than in a defect free lattice. In this work the trapping model of the positron annihilation lifetime measurements was used to determine the positron annihilation parameters, which are used in determination of the stored dislocation energy of plastically deformed 3004 Al-alloys.

2 Experimental Procedure

Al-alloy 3004 with dimensions (12 x 12 x 3) mm^3 and chemical composition given in table (1) were cleaned, chemically etched, homogenized for 6 hours at 723 K in a non-vacuum furnace, then annealed to room temperature. These prepared samples were deformed at room temperature up to 25% of their original thickness using a hydraulic press. A fast coincidence positron annihilation technique [19, 20], was used in measuring the positron mean lifetime values of the plastically deformed samples under investigation. The system resolution is 337.9 ps using the coincidence by ^{60}Co. A very thin radioactive ^{22}Na, which is sandwiched between two identical samples was used as a positron source in this study [21]. The thickness of the samples is suitable to absorb all emitted positrons. The source-sample arrangement 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 3 h during which about 5×10^5 counts were collected. The data of the lifetime spectra for the investigated 3004 Al-alloys samples was analyzed using PATFIT computer program [22].

Table (1). The chemical composition of 3004 Al-alloy.

Element	Si	Fe	Cu	Mn	Mg	Zn	others	Al
Wt %	0.3	0.7	0.25	1.0-1.5	0.8-1.3	0.25	0.15	Reminder

3 Results and Discussion

3.1 Estimation of The Positron Parameters (Mean Lifetime, Trapping Rate, Trapping Efficiency, Defect Density And Dislocation Density)

The positron mean lifetime values of the undeformed and deformed 3004 Al-alloys with different degree of deformation were measured. The relation between the experimentally measured mean lifetime (τ) values (data points) and the degree of deformation is shown in figure (1). The positron mean lifetime value of the undeformed (annealed) sample is 173±4.8ps after which, an increase in the mean lifetime values was observed with increasing the thickness reduction until 6% degree of deformation is reached. Above 6% 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 215±5ps was measured for saturated dislocation samples.

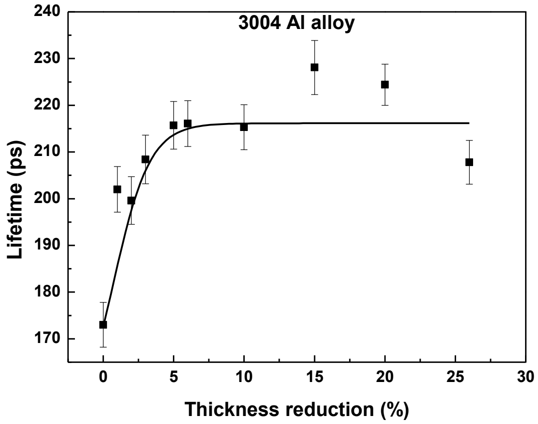

Fig. 1: Experimental results (data points) and the theoretical curve (solid line) of the positron mean lifetime as a function of thickness reduction of 3004 Al-alloy.

The obtained results of the positron lifetime measurements were analyzed using the positron trapping model described in equation (1) [23] to determine the theoretical mean life time curve shown in figure (1). The trapping model assumes that the positron can exist either in the free or in the defect state of the material.

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

whereτ_f and τ_t are the mean lifetime of the defect free (annealed) and the dislocation saturated samples respectively, and κ_d is the trapping rate (trapping probability per second).

The positron trapping rate κ_d values of equation (1) was determined using equation (2):

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

where R is the fractional degree of deformation and b is the Burger vector of Al = 2.86 Å and ν is the positron trapping efficiency.

The positron trapping efficiency (ν) value, which gives the best fit of the experimental measured data point of the positron lifetime of figure (2) after substituting in the positron trapping rate equation (2) was determined to be 2×10^{-6} cm^3s^{-1}.The theoretical mean lifetime values obtained using the positron trapping model as a function of thickness reduction is shown in the solid line of figure (1). The trapping rate values obtained using the trapping model of equation (2) using the predicted value of the positron trapping efficiency versus thickness reduction is shown in figure (2). An exponential increase in the positron trapping rate values was observed with slow increase at lower thickness reduction up to 6% degree of deformation. This increase is followed by faster increase with increasing of the thickness reduction. Positron trapping rate value of about $7.7\times10^{10}s^{-1}$ was obtained at saturation dislocation region of 6 % thickness reduction.

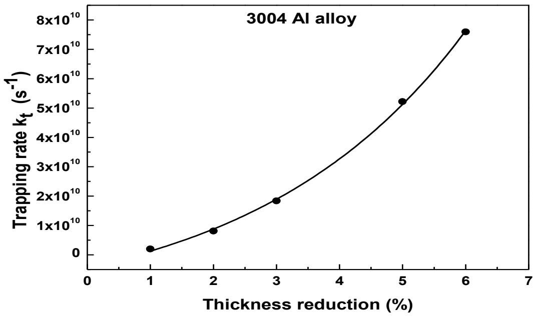

Fig. 2: The trapping rate as a function of thickness reduction of 3004 Al-alloy.

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

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

The defect density $\bar{\rho}$ (cm^{-3}) is related to the dislocation density ρ (cm^{-2}) as interpreted in the way of Baram and Rosen [23] according to:

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

The variations of the defect density and the dislocation density with thickness reduction are shown in figures (3 and 4) respectively.

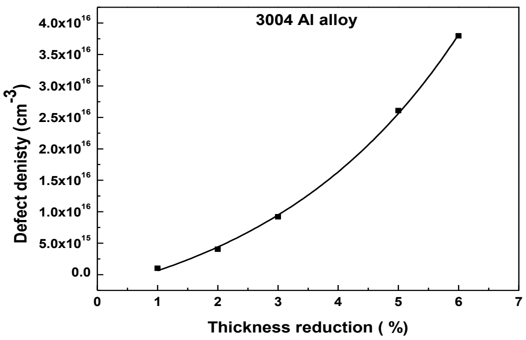

Fig. 3: The defect density of 3004 Al-alloy as a function of thickness reduction.

Both defect and dislocation densities values were estimated from the trapping rate values as in equations (3 and 4).The defect density and the dislocation density reveal the same behavior as the calculating trapping rate shown in figure (2) as a function of thickness reduction. Maximum values of defect and dislocation densities of about $3.6\times10^{16}cm^{-3}$ and $1.1\times10^{9}cm^{-2}$ respectively obtained at 6% degree of deformation.

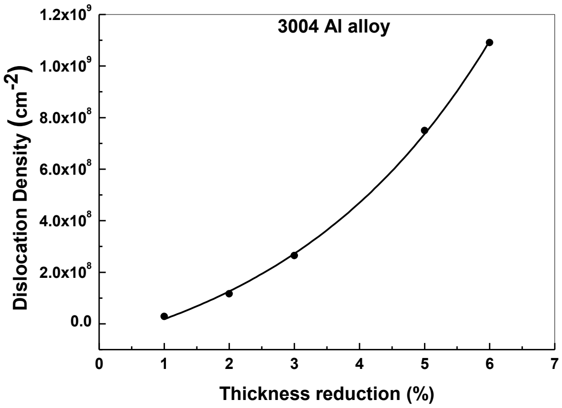

Fig. 4: The dislocation density of 3004 Al-alloy as a function of thickness reduction.

The trapping coefficient (μ) can be calculated by substituting equation (3) into equation (4):

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

A linear relationship for the dislocation density (ρ) as a function of the positron trapping rate (k_d) is depicted in figure (5). The positron trapping coefficient which is the ratio between the positron trapping efficiency and the Burgers vector of the Al-alloy can be determined from the figure as 68.58 cm^2/s.

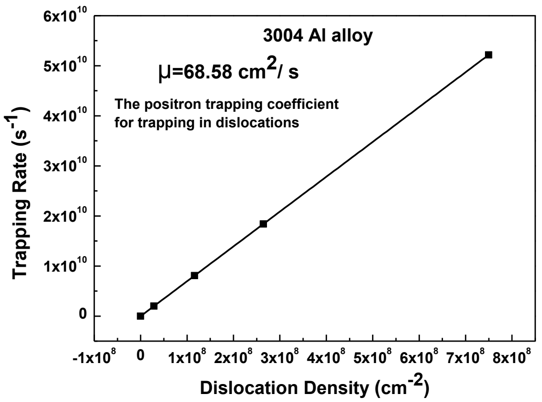

Fig. 5: The positron trapping rate of 3004 Al-alloy as a function of dislocation density.

3.2 Estimation of the Stored Dislocation Energy

Stored energy is related to the amount of cold work (plastic deformation) acquired by the material [24]. A plastically deformed metal or alloy contains normally large stored dislocation energy and with annealing at higher temperatures and during recovery and recrystallization, it will typically return to a lower energy state by structural growth [25].The stored dislocation energy (E) due to the generation of crystalline defects can be determined on the basis of the dislocation theory. The dislocation density (ρ) is related to the dislocation stored energy (E) as [25]:

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

whereαis 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) [26, 27].

PALT provides an indirect approach in determination of the stored dislocation energy as a result of cold work effect (plastic deformation). Substituting the values of the dislocation density calculated from the trapping model into equation (6), the stored dislocation energy can be determined.

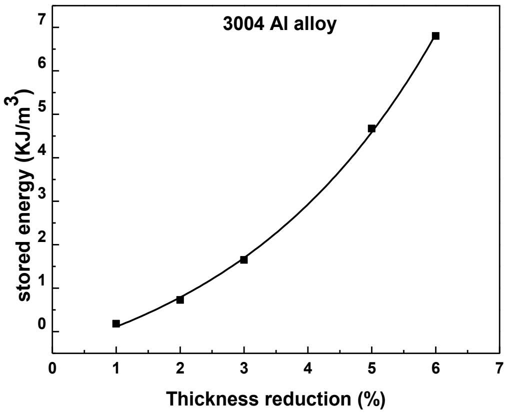

Fig. 6: The stored dislocation energy as a function of thickness reduction of 3004 Al-alloy.

Figure (6) reveals the changes of the stored dislocation energy as a function of thickness reduction. From the figure, a small stored dislocation energy value of about 0.15 KJ/m^3 is obtained at 1 % degree of deformation. This value is followed by a slow increase in the stored dislocation energy at lower thickness reduction. The probability of producing dislocations is small at lower degree of deformation. This probability increases with increasing of the degree of deformation, lead to an increase in the calculated stored dislocation energy, described by a faster increase of E at higher thickness reduction.Maximum stored dislocation energy of about 6.8 KJ/m^3 is reached at 6 % degree of deformation.

4 Conclusions

PALT was used in determination of the positron annihilation parameters (mean lifetime, trapping efficiency, trapping rate, defect and dislocation density) in wrought 3004 Al-alloy, these parameters was used to determine the stored dislocation energy of the alloy under investigation.

Saturation trapping of positron in defect states starts at 6% degree of deformation at which a positron annihilation lifetime and trapping rate values of about 215±5psand 7.7x10^{10}s^{-1} was respectively calculated.

A trapping efficiency of 2×10^{-6}cm^{3}s^{-1} gives the best fit of the experimental measurements with the theoretical mean lifetime values obtained using the positron trapping model.

An increase in the degree of deformation creates comparable increase in both defect and dislocation densities lead to an increase in the calculated stored dislocation energy.

At the region of saturation of dislocation, maximum stored dislocation energy of about 6.8 KJ/m^3 was calculated.

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