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RESEARCH ARTICLE

Stored Energy of Dislocations in Deformed 8006 AL Alloy by Positron Annihilation Lifetime Technique

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Abstract

This work describes the usage of positron annihilation lifetime technique (PALT) in determining the stored energy in 8006 Al alloy samples during plastic deformation performed by hydraulic press at room temperature (RT).The 8006 Al alloy is more and more used for manufacturing sheets and foils. Samples were homogenized at 773.0 K for 10 h then annealed to reach RT. The spectra of lifetime of positron are measured for samples with various degree of plastic deformation up to 48.30 %. It is known that at plastic deformation type of dislocation defects are generated basically. The concentration of dislocations with thickness reduction could be received and used to determine the stored energy which was found as a function of the thickness reduction. The variation of the stored energy with the thickness reduction seems to be an exponential growth from 0.59 KJ/m^3 at 1.80 % to 49.00 KJ/m^3 at 15.30 % thickness reduction related to the increasing of the dislocation density as predicted theoretically.

INTRODUCTION

PALT has already been successfully used to study the structure of lattice defects in metals and alloys [1, 2]. In single crystals the deformation is simple and produces dislocations but in polycrystalline samples the deformation becomes complex due to the various interactions between dislocations and the grain boundaries [3]. Since 1960 evidence has shown that positrons can become trapped at imperfections in solids. Several groups [4-6] have proposed a phenomenological trapping model for positrons in metals and alloys. The main assumption of the simple trapping model is that positrons annihilate in a solid in a free or trapped state.

A part of the applied external work (E_{ext}) used for deforming a metal is expended in increasing the energy stored (S) in the metal; the rest of it is converted into heat (H). According to the first law of thermodynamics,

$$E_{ext} = S + H \tag{1}$$

where E_{ext} is the mechanical (external) work; S is that part of the external work which is stored in the metal; and H is the part which is converted into heat depending on the type of loading and on the degree of deformation [7].

When a polycrystalline material is deformed, both statistically-stored S_d and geometrically-necessary dislocations S_{gb} are required to hold the deformation [8, 9].

Because of the important significance of the stored energy during cold work, there is a large literature aimed at its experimental determination [10–18]. The present work studies the proportion of the input energy that is stored in the alloy in the form of statistically-stored dislocations only and its dependence on the thickness reduction (degree of plastic deformation) using PALT. Also the work tries to relate the stored energy with recrystallization temperature.

2. Materials and Methods:

The 8006 Al alloy specimens were prepared from commercially available alloy material. The composition (atomic %) of this alloy is:

Table 1. The chemical composition of the investigated sample

Alloy	Cu	Fe	Mg	Mn	Si	Zn	Other	Al
8006	0.3	1.2 -2.0	0.10	0.30-1.0	0.40	0.10	0.20	Remainder

8006 Al alloy specimen of dimensions 2mm x 10mm x 5mm were used in this experiment. The samples were polished, etched chemically in a solution containing phosphoric acid and nitric acid; before they were annealed to 773.0 K for 10 h in a non-vacuum furnace to avoid defects precipitation. One set of samples (13 pairs) were subjected to consecutive deformations from 1.80 % to 48.30 % at RT by using a hydraulic press which is able to determine the applied pressure. Positron annihilation lifetime measurements were performed using fast coincidence technique, described elsewhere [19, 20] to study the nature and properties of deformation induced defects.

^{22}Na is used as a radioactive source of positron.The resolution of the system is 342 ps as measured by using the coincidence as given by ^{60}Co. Each spectrum was accumulated for a period of 3 h during which about 5×10^5 coincidence counts were accumulated which give a good statistics.

3. Results and Discussion:

First, external work W was applied at RT using a hydraulic press on the samples to obtain samples with different degrees of deformations (thickness reductions). The relation between the external applied work and the thickness reduction was drawn as in Figure 1.

The external work W was determined for each deformation step by measuring the exerted pressure which can be converted directly to the work per unit volume.

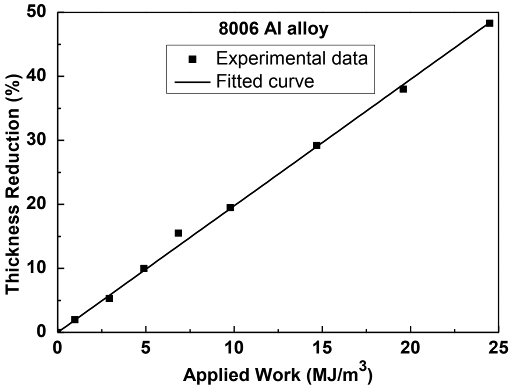

Figure 1. Thickness reduction as a function of external applied work for 8006 Al alloy.

As shown the thickness reduction increases with increasing the applied work.

3.1 Estimation of dislocation densities during cold work in 8006 Al alloy by PALT:

The mean lifetime (τ) is a reflection of the characteristics of the defect formation as a function of a degree of thickness reduction. The data for the lifetime spectra was analyzed using the PALSfit program [21]. The value of the source contribution (kapton foil) of lifetime and its intensity was subtracted during the analysis. The result of the positron annihilation experiment on 8006 Al alloy containing defects that trap positrons were analyzed in terms of Baram and Rosen method.

Figure 2 (points) shows the mean lifetime (τ) as a function of the thickness reduction. It is obvious that the lifetime increases with increasing the degree of thickness reduction which means an increase in the dislocation density and thus the dislocation stored energy and that above 15.30 % thickness reduction, the value of (τ) is approximately constant. This constant value represents saturation of trapping of positron in defects. Variation of (τ) as shown from Figure 2 is from τ_f =(178.4±6.3) ps for the annealed sample to τ_t = (234.0±7.0) ps for saturated dislocation samples.

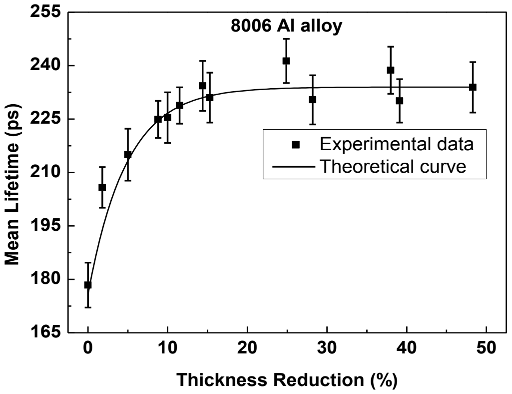

Figure 2.The mean lifetime as a function of thickness reduction of 8006 Al alloy.

The solid line in Figure 2 must be fitted to the trapping model described in equation (2) [22],

$$\tau = \tau_f \frac{1+\kappa_d \tau_t}{1+\kappa_d \tau_f} \tag{2}$$

where τ_f (free lifetime) is the mean lifetime for the annealed sample, τ_t (trapped lifetime) is the mean lifetime of dislocation saturated sample and κ_d is the trapping rate.

Now, τ is being calculated using equation (2) to obtain the best fit for the experimental results. For doing so, values of κ_d must be obtained firstly, equation (3) can be used for such a determination,

$$\kappa_d = (1.248) \times 10^{-3} [\log (1-R)]^2 \frac{\nu}{b^3} \tag{3}$$

where ν is the trapping efficiency ($cm^3\ s^{-1}$), R is the fractional thickness reduction and b is Burger vector of Al. The best fit of expression (3) to the experimental data is represented in Figure 2. The value of ν which give such a best fit is 4×10^{-7} $cm^3 s^{-1}$.

Figure 3 shows that the trapping rate (κ_d) increases exponentially as a function of thickness reduction at constant value $\nu = 4\times10^{-7}$ $cm^3 s^{-1}$ as predicted from equation (3).

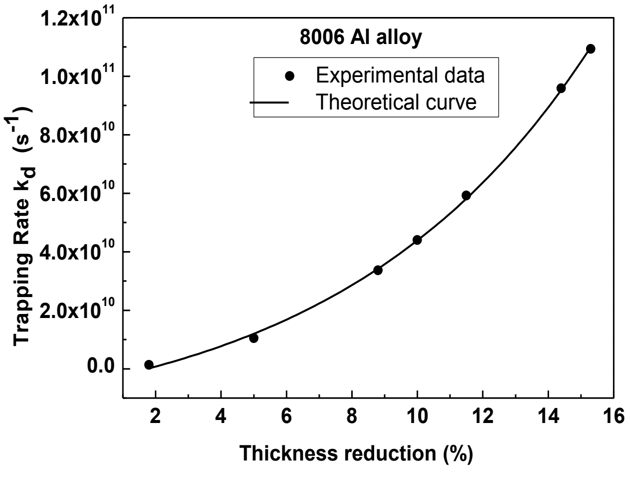

Figure 3.The trapping rate as a function of thickness reduction of 8006 Al alloys.

The results were interpreted in the way of Baram and Rosen [22], the dislocation density can be calculated from the equation.

$$\rho(cm^{-2}) = \frac{b.k_d}{\upsilon} \tag{4}$$

where b is the Burgers vector for Aluminum = 2.86 Å, ρ (cm^{-2}) is the dislocation density, k_d is trapping rate which is calculated from equation (3), and υ is the trapping efficiency ($cm^3\ s^{-1}$) as predicted from equation (3) to be 4×10^{-7} cm^3s^{-1}.

The variations of the dislocation density as a function of the thickness reduction are shown in Figure 4. It is obvious that the dislocation density increases exponentially with increasing thickness reduction.

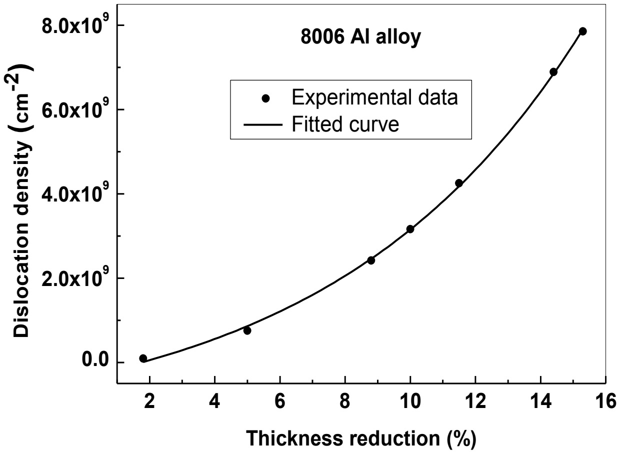

Figure 4.The dislocation density of 8006 Al alloy as a function of thickness reduction.

3.2 Determination of the stored energy in a deformed 8006Al alloy by PALT:

When the material is plastically deformed, the stored energy is due to the generation of crystalline defects such as point defects and dislocations. Based on the dislocation theory, the dislocation density ρ_d is related to the dislocation stored energy (E) such that [8]:

$$S_d = \alpha \rho_d G b^2 \tag{5}$$

where α is a constant which is the interaction between dislocations , G is the shear modulus and b is the magnitude of the Burgers vector of the dislocations.

The utilization of PALT provides an indirect approach to determine the stored energy due to dislocations by calculatingthe dislocation density from equation (4), and by substitution into equation (5) by the values of $\alpha = 0.5$, G =25.4 GPa [24], and b = 0.286 nm [24].

Figure 5 shows the change in the stored energy as a function ofthickness reduction. In Figure 5 the value of the stored energy at 1.80 % thickness reduction is 0.59 KJ/ m^3 and it varies to reach its maximum value, 48.99 KJ/ m^3, at 15.30 % deformation. Also it can be said that the variation of the stored energy is slow at small deformation and the variation becomes faster for large deformation.

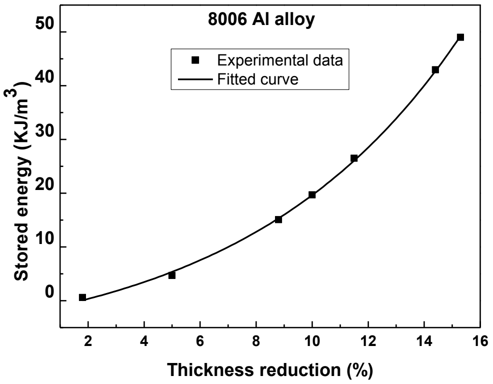

Figure 5.The dislocation stored energy as a function of the thickness reduction of a deformed 8006 Al alloy.

3.3 Relating stored energy in a deformed 8006 Al alloy by the recrystallization temperature:

The relation between stored energy and the recrystallization temperature was studied before [25]. In order to relate between the stored energy and the recrystallization temperature, the positron annihilation lifetime technique was used to study the isochronal annealing of a high deformed sample of 8006 Al alloy.

One well-annealed pair of 8006 Al alloy was subjected to plastic deformation of nearly 39.00 % and then subjected to isochronal annealing (annealing with subsequent temperatures) for a given time period (1h) for each temperature. The variation of the positron annihilation mean lifetime, with annealing temperature of 8006 Al alloy is exhibited in Figure 6.

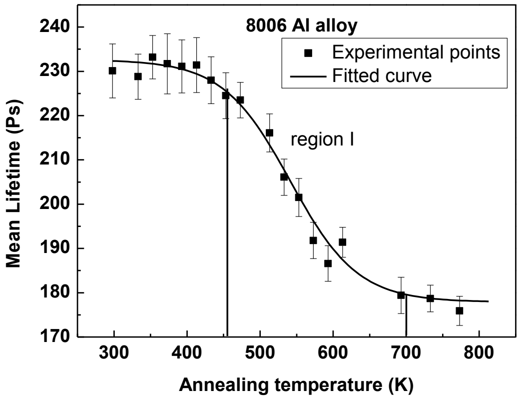

Figure 6.The positron lifetime as a function of the annealing temperature of a high deformed pair of 8006 Al alloy.

From Figure 6, region (I) represents the recovery stage of dislocations. This stage is observed from 455.0 to 700.0 K. In this stage, a certain decrease in (τ) is detected, which can be attributed to the annealing of dislocations introduced during deformation. The stage due to point defects (vacancies) is seen not to be formed for 8006 Al alloy.

Comparing lifetime values obtained due to deformations in Figure 2 and lifetime values obtained through the annealing process in Figure 6, it is possible to relate each deformation degree by its required recrystallization temperature and thus the stored energy with the recrystallization temperature.

A deformed metal or alloy contains a stored energy which is formed through cold work and, on annealing at elevated temperatures, will normally revert to a lower energy state by structural evolution during recovery and recrystallization [26].

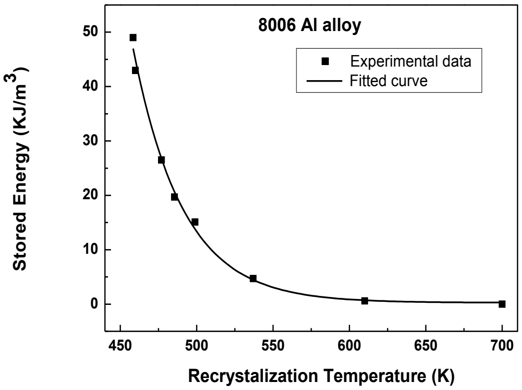

Figure 7.The stored energy as a function of recrystallization temperature of a high deformed pair of 8006 Al alloy.

It is obvious from Figure 7 that stored energy is inversely proportional to the recrystallization temperature. From this Figure increasing the annealing temperature decreases the stored energy until elimination all the stored energy at nearly 700.0 K in the highly deformed sample and finally obtains a sample free of defects (dislocations). This can be observed from the lifetime value at 700 K in Figure 6 which is the same as before deformation as in Figure 2.

Figure 8 show the dislocation stored energy and recrystallization temperature as a function of thickness reduction.

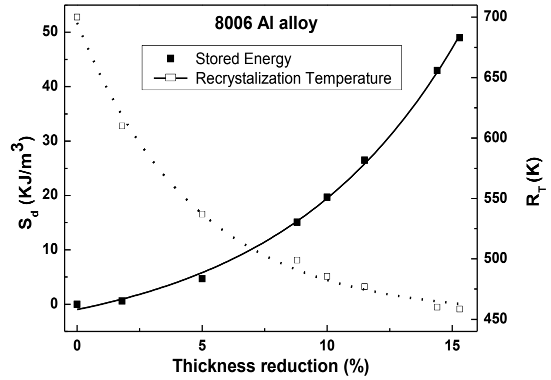

Figure 8.Stored energy and recrystallization temperature as a function of thickness reduction for 8006 Al alloy

As obvious, increasing thickness reduction will increase the amount of the dislocation stored energy in the sample. Also, it is obvious that to obtain sample free of defects, it requires higher recrystallization temperature which is about 700.0 K.

The experimental results can be summarized in the next table.

Table 2. A summary of some important experimental results

Work done in compression W (KJ/m^3)	Thickness reduction (%)	Stored energy S_d (KJ/m$^{3)}$	(S_d / W)x100 ratio (%)	Recrystallization temperature R_T (K)
Not preformed	0.0	0.00	no defined value	700.0
910.9	1.8	0.59	0.06	610.0
2530.3	5.0	4.67	0.18	537.0
4453.4	8.8	15.08	0.34	499.0
5060.7	10.0	19.70	0.40	485.5
5819.8	11.5	26.49	0.46	477.0
7287.4	14.4	42.94	0.59	460.0
7742.8	15.3	48.99	0.63	458.5

4. Conclusions:

- The PALT technique as a reliable method to detect the concentration of defects in metals can be used to determine the statistically stored dislocation energyin metals and alloys due its ability to determine the dislocation density at a certain deformation.
- It must be taken into consideration that PALT method can determine only the statistically-stored dislocation energy S_d but it is not able to determine neither the geometrically-necessary dislocation S_{gb} energy nor the total stored dislocation energy S.
- It is clear from Table 2 and Figures 1-8 on 8006 Al alloys, the following remarkable observations must be noted:
  - ✓ Increasing the external applied work means an increase in the degree of deformationand thus the stored energy.
  - ✓ The ratio (S_d/W) is a very small value which indicates that only a small amount of the applied work is stored in the form of S_d energy.
  - ✓ With increasing W, the increase in S_d becomes more rapid. The reason is that the probability of production of dislocations is small at lowdegree of deformation. This probability increases at highdegree of deformation and thus increases the probability of increasing the S value.
  - ✓ The recrystallization temperature decreases the amount of the stored energy.
  - ✓ At a certain R_T= 700 K, the investigated sample is free of defects and thus no statistically stored energy.

- ✓ S_d values above 48.99 KJ/m^3 can be eliminated at 455.0 K which is the start of the recrystallization stage.

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