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Influence of Plastic Deformation on the Properties of 6066 Heat Treatable Aluminum Alloys

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Abstract

The aims of this work are to (1) study the influence of plastic deformation on the properties of 6066 aluminum alloy; (2) study the effect of deformation on the age hardening of these alloys; (3) study the recovery of these defects from the samples. These effects were investigated in terms of microstructure using positron annihilation spectroscopy (PAS) analysis and mechanical properties by hardness measurements. Dislocations facilitate nucleation of precipitates. At first sight, deformed specimens had lower hardness as compared to non-deformed ones, and as the deformation increase, the hardness decreases. Another output of the mechanical test was the increase in hardness in the specimens after artificial aging with an increase in percent deformation.

Keywords: Plastic deformation, age hardening, aluminum alloys, HV values, positron annihilation lifetime spectroscopy

Introduction

Defects in solids

The perfect crystals are assumed to have all their atoms at sites, which lie on a perfect periodic lattice. But this condition does not hold for real crystals because all real crystals contain a variety of tiny inhomogeneities (imperfections) [1]. Real materials have a number of imperfections or defects in their crystal structure. These include both impurity atoms and irregularities in the alignment of atoms. The behavior of these defects is the key to our understanding of material properties. Defects contribute to the mechanical properties of metals.

Positrons in solids

The positrons are injected into a sample from a radioactive source (e.g., ^{22}Na) which emits positrons with a mean energy of a few hundred keV. The injected positrons slow down to thermal energies by ionization and excitation of the atoms of the solid. During thermalization, the positrons penetrate the solid to an average depth of about 20-100 pm). Hence, the positrons probe bulk material in such measurements.

The rate at which the positrons annihilate the electrons in the medium is proportional to the density of electrons at the site of the positron. Therefore, the mean lifetime of positrons is a measure of the electron density at the positions of the positrons [2-6], in such a way that a lower electron density is reflected in a longer positron lifetime.

Structural defects with missing, or a reduced density of, ions will provide attractive potentials for positrons [7]. Trapped in such a defect, the positron will experience a lower electron density than in the bulk material and its lifetime will therefore increase. The annihilation characteristics depend on the type of defect in which the positron is trapped.

Aluminum alloys

Aluminum and its alloys offer an extremely wide range of capability and applicability, with a unique combination of advantages that make it the material of choice for numerous products and markets [8]. The 6xxx alloys are heat treatable, and have moderately high strength coupled with excellent corrosion resistance. 6xxx can be used in a variety of applications, including aircraft fuselage skins and automobile body panels and bumpers, after appropriate heat treatments, instead of the more expensive 2xxx and 7xxx alloys [9]. Hence, microstructural characterization of the alloy and processing procedure is important for that approach. This heat treatment process is known as age hardening which can be used to strengthen the 6xxx alloys. This process to increase the strength of aluminum alloys has a three-step process:

1. Solution heat treatment: dissolution of soluble phases
2. Quenching: development of super saturation
3. Age hardening: precipitation of solute atoms either at room temperature (natural aging) or elevated temperature (artificial aging or precipitation heat treatment).

The precipitate particles act as obstacles to dislocation movement and thereby strengthen the heat-treated alloys. Another study on 6xxx carried out by Matsuda *et al.* (2002) showed that the addition of copper to Al-Mg-Si alloys not only changes the precipitation sequence but also enhances hardness [10]. Another output of the mechanical test in the aging process was an increase in strength with an increase in percent deformation [11,12].

Experimental procedure

This research was conducted using wrought 6xxx series aluminum rods (6066 Aluminum alloy), as-received materials with the chemical composition stated in **Table 1**. Firstly, specimens from a rod of each alloy with the required dimensions (1.5×1.5×0.2 cm^3) were cut by using a precision cut off machine (Minitom) running at low speed.

Table 1 Chemical composition of the alloys (wt. %).

Alloy	Mg	Si	Cu	Fe	Mn	Cr	Al
6066	0.8	0.9	0.7	0.5	0.6	0.4	Bal.

The second step after cutting is grinding. During grinding, minimization of mechanical surface damage could be performed by subsequent polishing. The surface of the specimens was ground with silica carbide grinding papers of sizes 220, 500, 800, 1000 and 1200 grit. After that the samples were annealed to 450 °C to remove internal stresses. The samples were then deformed at room temperature. The experimental setup for deformation at room temperature requires a hydraulic press. On the base of the hydraulic press is a cylindrical metallic tank. In the tank, steel support is placed upon a steel ring of a known and exact. The samples were placed within this steel ring, and were compressed until they reached the dimension of this ring. Rods were machined with many different diameters such that approximately 1 %, up to 40 % deformation (reduction in area) could be established. The next step after deformation was to study the influence of deformation on age hardening. This was performed by using two samples of 6066, deformed at 10 and 20 %, and quenching them at 530 °C in water at room temperature. Then, the samples were artificially aged at 175 °C for 2, 4, 6, 8, and 10 h. As a final step, the effects of annealing on the deformed alloys were studied, the samples having been annealed at different annealing temperatures. The influence of aging on the samples was measured using the positron annihilation lifetime technique. Positron annihilation spectroscopy (PAS) was considered as a method for studying the electronic structure, and the changes in the mechanical properties were measured using the Vickers hardness test.

Positron annihilation lifetime spectroscopy

The positron source in this experiment was a radioactive isotope, ^{22}Na, which was evaporated from an aqueous solution of free carrier $^{22}NaCl$ with 1 mCi activity and deposited on a thin kapton foil of 7.5 μm in thickness. The ^{22}Na decays with the emission of a β+ with 511 KeV followed by a 1274 Kev γ-ray.

A sandwich configuration was used for Al alloy sample measurements. The present studies were performed using sets of two identical samples of the material under investigation.

The schematic diagram for the fast coincidence system which was used in PAL measurements is shown in **Figure 1**, with time resolution of 290 ps [13,14]. The equipment consists of a pair of rigidly mounted scintillates and photomultipliers (PMTs). A positive high voltage power supply provides power to the PMTs via a voltage divider which allows one to vary the potential applied to the two tubes. The 1274 keV γ-ray was taken as a start signal for the time to pulse height converter (TPHC), while one of the 511 keV annihilation quanta, resulting from the 2γ-rays annihilation in the material, was chosen as the stop signal.

The signal from the TPHC was fed to the multi-channel analyzer (MCA) for storage. The 1274 keV signal indicates the birth of the positron and the 511 keV indicates the positron death. Thus, the time interval between the above 2γ-rays was the lifetime of the positron or Ps in the material. The thickness of the samples is adequate to absorb emitted positrons. For most of the measurements, account periods of at least 3 h were required to obtain sufficient statistics. The technique of positron annihilation (lifetime technique) is described in more detail and shown in **Figure 1** [13,14].

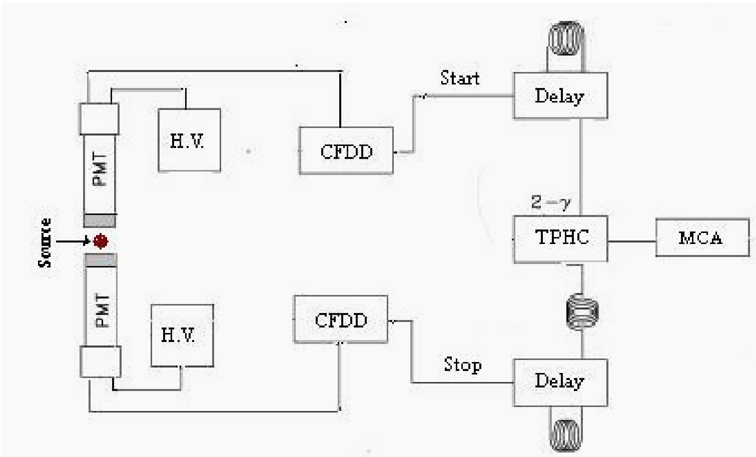

Figure 1 Schematic diagram for the detection of the 2-γ positron annihilation.

The lifetime spectra were analyzed as 2 lifetime components, τ_1 and τ_1, with corresponding intensities I_1 and I_2, with the help of the computer program PATFIT-88 [15]. The positron source was sandwiched between two identical samples. The source-sample configuration was then wrapped in a thin aluminum foil. Each sample was measured for 10800 seconds, during which about 3.17×10^5 coincidence events were accumulated.

Vickers hardness test

This is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces. The surface is subjected to a standard pressure for a standard time interval by means of a pyramid-shaped diamond. The diagonal of the resulting indention is measured under a microscope.

Results and discussions

The first step was the study of the influence of the deformation on the samples; **Figure 2** shows the relation between positron lifetime and Vickers hardness with the thickness reduction. For 6066 alloy, it is clear that the lifetime increased at first and then reached a constant value at a deformation of approximately 5 %, whereas the Vickers hardness showed the reverse, with the lifetime decreasing to a deformation of 10 % and reaching a constant value. The explanation for this behavior is that plastic deformation introduces in the material a large density of dislocations, which has a low electron density, so that when the positron is trapping in the defects, its lifetime is increasing, and at the same time as the density of defects increases, the hardness of the alloy is decreasing. The only reason for that would be the larger grain sizes in the deformed samples as compared to the original non-deformed ones.

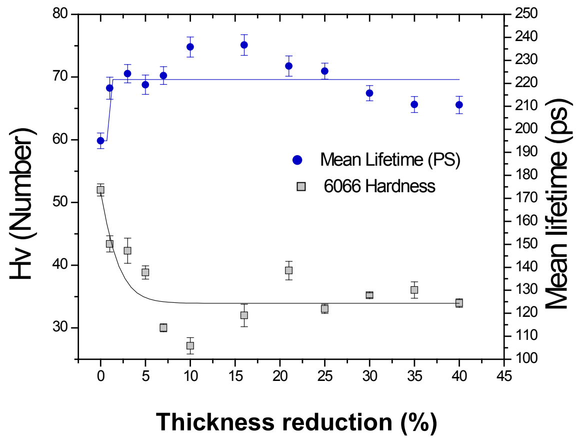

Figure 2 Hv & lifetime as a function of thickness of deformation.

The second step was the study of the influence of age hardening on the 6066 alloy; samples deformed at (10, 20 %) were used. **Figures 3** and **4** represent this influence; it is clear that the lifetime slightly increases, and after that tends to reach an approximately constant value, where the Hv values increases up to it to reach a maximum value. The maximum value to the sample which deformed at 10 % is (108) at an aging time of 8 h, but the maximum value to the sample which deformed at 20 % is (113) at an aging time of 6 h. It is clear that the maximum value at 20 % is larger than that at 10 %. At a deformation of 20 %, as the aging time increases, the maximum peak reaches an over-aged average. The presence of manganese, chromium or copper leads to the formation of, (Fe, Mn, Cu) $_3SiAl_{12}$. The other phase, Mg_2Si, was the main ingredient of 6xxx, which would readily dissolve during solutionizing and contribute to the precipitation hardening for the period of artificial aging.

Another output of the mechanical test was the increase in strength with an increase in percent deformation. Deformation leads to energy storage for the period of lattice defect creation, i.e. dislocations. During solutionizing at temperatures of 530 °C, the cold-deformed specimens led to recrystallization. Hence, after solutionizing the 10 % deformed sample has lower peak hardness than the 20 % deformed sample. It is clear from **Figure 4** the positron lifetime can be schematically divided in three stages: (i) initial drop up in the first hours of ageing; (ii) progressive increase (correlated with the hardening of the alloy up to the peak-ageing condition and (iii) weak reduction in correspondence with over-ageing (a stage of decreasing hardness).

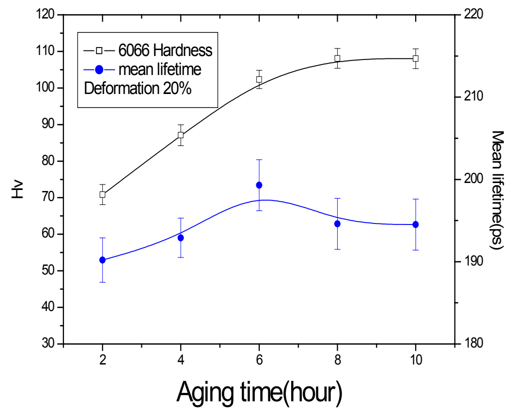

Figure 3 Hv & mean lifetime vs aging time for 6066 alloy deformed at 20 %.

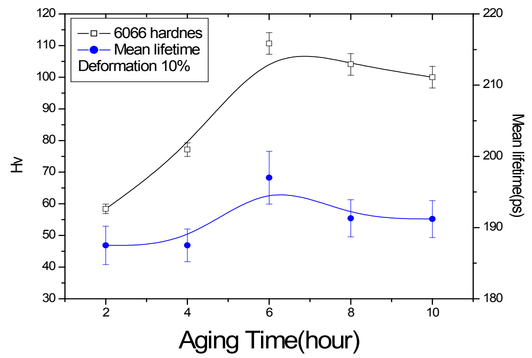

Figure 4 Hv & mean lifetime vs aging time for 6066 alloy deformed at 10 %.

It is also clear that dislocation-precipitate interaction mechanisms in the domain of small deformations are needed to access the observed hardening. In aluminum alloys, improvement of the mechanical properties is classically obtained by the nanoscale precipitation produced by the decomposition of the supersaturated solid solution during ageing. The hardening effects result from dislocation interaction with the nano-sized precipitates acting as obstacles to the dislocation motion.

The second step was the study of the influence of age hardening on the deformed 6066 alloys. Samples deformed at 10 and 20 % were chosen for study. **Figures 3** and **4** represent this effect. It is clearly shown that the lifetime increases slightly, and thereafter has a tendency to saturate. The Hv value increase until it reaches a maximum value. The maximum value of Hv for the sample deformed at 10 % is (108) at an aging time of 8 h but the Hv maximum value for the sample deformed at 20 % is (113) at a 6 h aging time; the Hv maximum value at 20 % is larger than that at 10 %. At a deformation of 20 %, as the aging time increases, the maximum peak reaches the over-aged average.

The presence of manganese, chromium or copper leads to the formation of (Fe, Mn, Cu) $_3SiAl_{12}$. The other phase, Mg_2Si, is the main ingredient of 6xxx, which readily dissolves during solutionizing and contributes to the precipitation hardening for the period of artificial aging. Another outcome of the mechanical test was the increase in strength with increasing thickness reduction. Deformation leads to energy storage for the period of lattice defect creation, i.e., dislocations. During solutionizing at temperatures of 530 °C, the cold-deformed specimens are recrystallized. Hence, after solutionizing the 10 % deformed sample has lower peak hardness than the 20 % deformed sample. It is also clear that dislocation-precipitate interaction mechanisms in the domain of small deformations are needed to access the observed hardening. In aluminum alloys, improvement of the mechanical properties is classically obtained by the nanoscale precipitation produced by the decomposition of the supersaturated solid solution during ageing. The hardening effects result from dislocation interaction, with the nano-sized precipitates acting as obstacles to the dislocation motion.

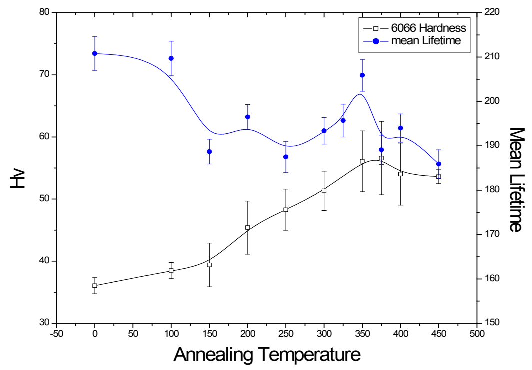

Figure 5 Hv & mean lifetime vs annealing temperature for 6066 Alloy.

The last step in this research was to study the influence of annealing on the deformation of the samples (**Figure 5**). The sample was treated with a constant heating rate and the annealing temperature was changed (isochronal annealing). It is clear that the lifetime and the Hv have an opposite behavior to each other; the lifetime decreases until it reaches a constant value, where Hv increases to reach a constant value equal (52) which is the value of the un-deformed 60660 alloy. Hence, this process removes the defects from the crystal.

Conclusion

In this study, the effect of deformation on mechanical properties of a 6xxx series aluminum alloy was investigated. Following the determination of the ideal conditions for solutionizing and aging processes, specimens were mechanically deformed by swaging at 2 different deformations and then heat treated. The primary conclusions obtained from this study can be summarized as follows:

- As deformation amount increased, the strength and hardness reduced.
- Another output of the mechanical test was the increase in strength after artificial aging with an increase in percent deformation.
- The annealing process removed defects from the alloys.

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