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Work hardening characteristics of gamma-ray irradiated Al-5356 alloy

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ABSTRACT

Effects of γ-irradiation and deformation temperatures on the hardening behavior of Al-5356 alloy have been investigated by means of stress–strain measurements. Wire samples irradiated with different doses (ranging from 500 to 2000 kGy) were strained at different deformation temperatures T_w (ranging from 303 to 523 K) and a constant strain rate of $1.5\times10^{-3}\ s^{-1}$. The effect of γ-irradiation on the work-hardening parameters (WHP): yield stress σ_y, fracture stress σ_f, total strain ε_T and work-hardening coefficient χ_p of the given alloy was studied at the applied deformation temperature range. The obtained results showed that γ-irradiation exhibited an increase in the WHP of the given alloy while the increase in its deformation temperature showed a reverse effect. The mean activation energy of the deformation process was calculated using an Arrhenius-type relation, and was found to be ~80 kJ/mole, which is close to that of grain boundary diffusion in aluminum alloys.

1. Introduction

In the last decade, aluminum alloys were increasingly utilized as structural components in automobiles and high-speed ships because of their enhanced formability and high specific strength. During service, these components can be subjected to dynamic loading, such as during impact or collision with foreign objects. Therefore, the material properties and failure behavior of these alloys at low and high rates of deformation need to be well understood. Alloy composition, strain rate, service temperature and microstructure may have an effect on the mechanical properties and failure mechanisms of aluminum alloys [1–6].

Alloying elements are usually added to aluminum to increase its strength. Magnesium, for example, forms a solid solution in Al and it can be dissolved up to 10 wt% at high temperatures. Moreover, this alloying element is known to enhance the recovery process and may therefore enhance superplastic response of this alloy [7]. So, Al–Mg alloys exhibit medium durability and very good corrosion resistance. These factors make this combination of elements widely used as construction materials, especially for the marine structures subjected to moderate loads. Plastic deformation of the aluminum alloys during tensile tests occurs according to a dislocation mechanism. Point defects (Mg atoms in the solid solution α or vacancies) cause an anchoring of dislocations. A detachment of dislocations requires instantaneous increase in stress σ in order to liberate the dislocations from the defects. This is followed by a decrease in stress up to the moment of distortion of the dislocations movement occurring at subsequent defects. A single effect described above is repeated periodically up to the moment of necking of the stressed sample [8]. This process, known as serrations or the Portevin–Le Chatelier (PLC) phenomenon, is observed only under certain conditions at a specific regime of temperature, strain and strain rate [9–12].

In many industrial applications, the mechanical properties of Al–Mg alloys are required to be further improved. Irradiation is one of the methods used to improve the mechanical properties of Al–Mg alloys.

The effects of irradiation on the mechanical (and metallurgical) properties include changes to strength and ductility. Mechanical properties are directly related to microstructural characteristics of a given material. In general, nuclear irradiation tends to destroy the well-defined lattice structure of crystalline materials. These imperfections ultimately alter the basic material properties such as hardness, ductility, etc. The irradiation damage is primarily due to point defects being created in the crystalline structure. Metals represent an appropriate material for which to examine the mechanical effects of radiation. The changes produced by radiation are comparatively small in metals. The radiation effects are similar to those produced by cold working; specifically, the hardness and the creep rate are increased, and the electrical and thermal conductivities are decreased. In addition, ordered alloys become disordered [13].

The main effect of radiation damage in metals is the displacement of atoms and electrons [14]. The radiation damage is actually composed of several distinct processes [15]. These processes and their orders of occurrence are as follows:

(i) Interaction of energetic incident γ-irradiation with the lattice atom.

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(ii) Transfer of kinetic energy to the lattice atom gives birth to a primary knock-on atom (PKA).
(iii) Displacement of the atom from its lattice site.
(iv) The passage of the displaced atom through the lattice and the accompanying creation of additional knock-on atoms.
(v) Production of a displacement cascade (collection of point defects created by the PKA).

The radiation damage is concluded when the PKA comes to rest in the lattice as an interstitial. The result of a radiation damage event is the creation of a collection of point defects (vacancies and interstitials) and clusters of these defects in the crystal lattice. Several investigations were carried out to interpret the effect of γ-irradiation on the mechanical and electrical properties of metals and alloys [16–18]. The results mostly showed that γ-irradiation effect causes an increase of the strengthening parameters and electrical resistivity of the irradiated materials. This was attributed to the irradiation-induced point defects created in the irradiated materials.

One of the most essential phenomena in deformed irradiated metals or alloys is the work-hardening effect. The effect of deformation temperature on the work-hardening characteristics of the irradiated Al-based alloys was found to return back to the initial values of the strengthening parameters [16]. This was attributed to the annihilation of the irradiated defects at their sinks at temperatures where the defects become appreciably mobile [19].

The present work is devoted to providing some additional information on the effect of γ-irradiation and the reverse effect of the deformation temperature on the work-hardening parameters of Al-5356 alloy.

2. Experimental details

2.1. Sample preparation

This study has been carried out on the commercial Al-5356 alloy supplied from the Alumisr factory, Helwan, Cairo, Egypt, in the form of rods of 3 mm in diameter. The chemical composition of the alloy under investigation is given in Table 1. The rods were cold drawn in steps into wires 0.6 mm in diameter for stress–strain measurements. A portion of the alloy was rolled into sheets of 0.3 mm in thickness and 5 mm width for microstructure investigation.

2.2. Heat treatment and irradiation techniques

Samples in the form of sheet ($5 \times 5 \times 0.3\ \mathrm{mm}^3$) and wires (50 mm in length) were annealed for 5 h at 773 K in the solid

Table 1
The chemical composition percentage of the Al-5356 solder alloy.

Al	Mg	Fe	Cu	Si	Mn	Cr	Zn	Ti	Be
93.5–94.5	4.5–5.5	0.4	0.1	0.25	0.05–0.2	0.05–0.2	0.1	0.06–0.2	0.0008

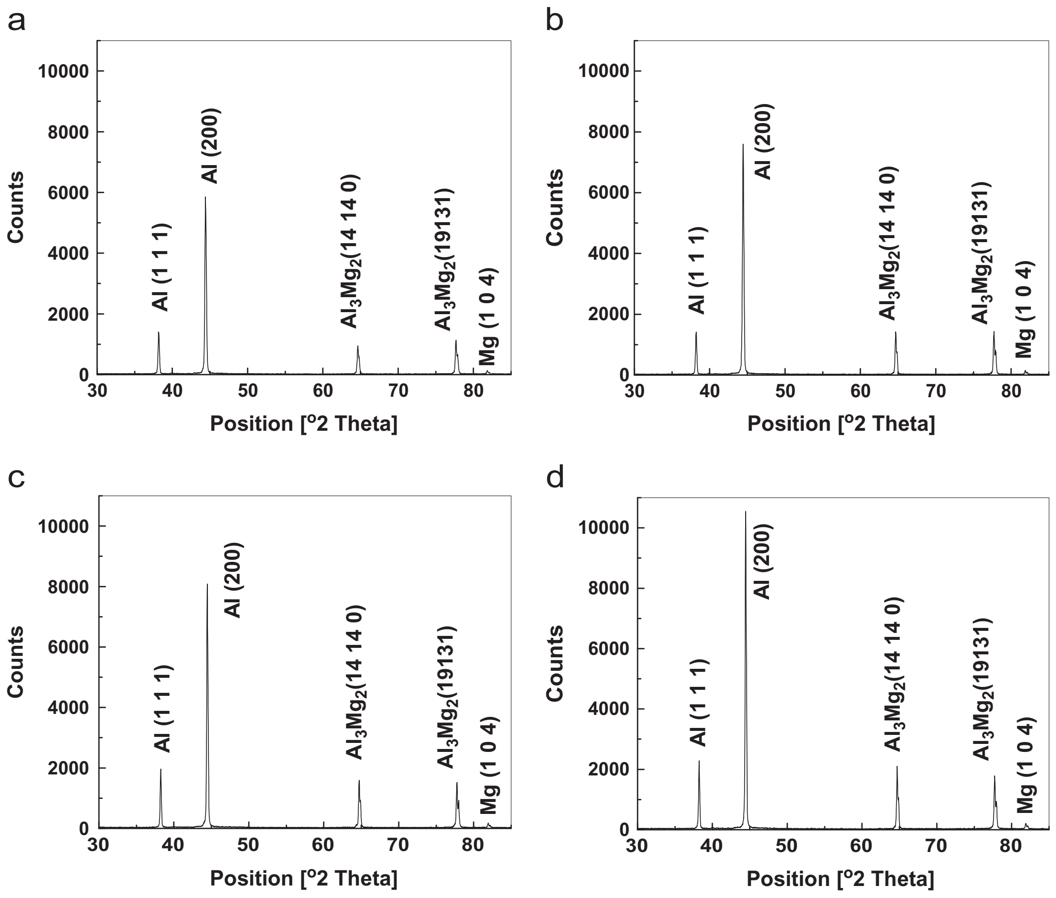

Fig. 1. X-ray diffraction patterns for unirradiated and irradiated samples of Al-5356 alloy at different doses: (a) unirradiated, (b) 500 kGy, (c) 1000 kGy, and (d) 2000 kGy.