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Structural, electrical, and mechanical characteristics of proton beam irradiated Al5086 alloy

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ABSTRACT

Al5086 alloy specimens were irradiated in a vacuum $\sim 10^{-6}$ mbar with 2 MeV proton beam (200 nA) for different exposure times in the range 10–50 min (dose range: 0.35×10^{15}–1.75×10^{15} p/cm^2). Surface hardness was found to increases on irradiation for 10 min, and later on it decreases with the increase in exposure time. The electrical resistivity of the specimens measured by four-point probe technique was also found to follow the same pattern. The observed behavior has been explained in terms of relative contribution of two processes, namely defects formation and heat generation due to proton–material interaction. Structural characterization of the specimens was done by X-ray diffraction technique. Both surface hardness as well as electrical resistivity of un-irradiated and irradiated specimens is found to decrease with the increase in X-ray crystallite size. Moreover, the surface hardness follows the Hall–Petch relation, which indicates that crystallite boundaries progressively impede the motion of dislocations as the crystallite size gets smaller.

1. Introduction

The bombardment of energetic ions beam on the materials results in the modification of their mechanical properties (e.g., [1–5]) as well as can cause phase transformation [1,6] and amorphization [7] of the materials. For instance, Afzal et al. [1] studied the structural and mechanical characteristics of Ni–49.5% Ti alloy (nitinol) irradiated at 298 K with 2 MeV proton beam using Pelletron accelerator for various exposure times in the range 15–60 min under vacuum to a fluence of 10^{15} p/cm^2. They found that proton beam irradiation of nitinol suppresses the direct austenite to martensite phase transformation by introducing an intermediate rhombohedral R-phase between austenite and martensite phases. Stresses necessary to initiate R-phase (σ_{RS}) and martensite phase (σ_{MS}) decrease with increase in exposure time from 15 to 60 min. However, the hardness of nitinol increases as exposure time increases. They attributed the generation of R-phase and decrease of σ_{RS} and σ_{MS} to the lattice disorder and stress fields associated with the defects produced during irradiation.

Similarly, Mitsuda et al. [2] observed that Vickers hardness of Al–Cu–Mg alloy specimens increased remarkably on irradiation with 10 MeV iodine ions (I^{3+}) at room temperature using a tandem accelerator. The abrupt increase in hardness was attributed mainly to the irradiation induced precipitates of 2.9 nm diameter. Recent investigations by Mitsuda et al. [3] further elucidated that hardness of Al–Cu–Mg alloy specimens simply thermally aged at 423 K was much lower than that of the ones pre-irradiated with I^{3+} ions and subsequently aged at 423 K. Similar results were also obtained by Mitsuda et al. [3] when this alloy was irradiated with 5 MeV aluminum ions (Al^{2+}) at room temperature instead of 10 MeV iodine ions (I^{3+}).

On the other hand, Al5086 is a typical aluminum alloy of $5 \times \times \times$ series, having 3.5–4.5 wt% Mg as its main constituent. This alloy is non-heat treatable, and therefore cannot be strengthened by heat treatment or thermal ageing. Hardening mechanisms in such alloys are solid-solution hardening, randomly dispersed second-phase particles, and strain hardening. Khaleeq-ur-Rahman et al. [8] investigated KrF Excimer laser irradiation effects on the hardness of Al5086 alloy for 100 to 500 shots in air and in vacuum. The surface hardness followed an increasing trend till 200 shots and afterward it decreased in both the cases. Similar trend was observed in the dependence of dislocation line density derived from the XRD patterns on the number of laser shots. The surface

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hardness of Al5086 alloy specimens, whether irradiated in air or vacuum, was found to depend linearly on the dislocation line density. A comparison of XRD patterns for both virgin and laser-treated specimens also revealed that laser irradiation did not influence the basic crystal structure (face-centered cubic) and chemical nature (Mg_2Si phase) of the alloy.

The main purpose of the present research work was to investigate the proton irradiation effects on the structure, electrical resistivity, and surface hardness of Al5086 alloy by using 2 MeV proton beam for different exposure times or proton doses. Another purpose was to compare the surface hardness results of Al5086 alloy after proton irradiation with the ones reported by Khaleeq-ur-Rahman et al. [8] for Al5086 alloy shined with KrF Excimer laser.

2. Experimental work

Five specimens of Al 5086 alloy were cut out from a rectangular bar of thickness 5.5 mm. They were machined to the dimension of $14 \times 8.5 \times 5.5$ mm^3. All the specimens were annealed simultaneously under the same conditions at 500 °C for 120 min in an electric muffle furnace (Model: Lab Tech. LEF-105S) and air cooled. Chemical composition of the alloy was determined by the Optical Emission Spectrometer (Model: J75/80, Italy) in wt% as: Mg (4.172), Fe (1.342), Mn (0.575), Si (0.239), Cr (0.105), Cu (0.051), Zn (0.028) and Al (balance).The specimens were wet ground and polished by using 250, 400, 600, 1000 and 1200 silicon carbide papers stepwise. The polished specimens were then cleaned and washed out in an ultra sonic bath.

Five specimens were selected for proton irradiation and one was left un-irradiated for comparison. These five specimens were mounted on a metal strip by a polymeric fixer. This strip was then mounted on a target holder of the accelerator (Pelletron Accelerator, Model: 6-SDH2), where beam of protons falls on the specimens such that irradiated surfaces of specimens and beam axis are normally oriented. A beam of diameter 16.5 mm irradiated the specimen surface uniformly so that proton flux remains uniform over the whole of the surface. Each specimen was irradiated for different time duration under vacuum but with same energy (2 MeV) and current (200 nA). The five specimens were irradiated one by one for 10, 20, 30, 40, and 50 min, respectively. Structural, electrical, and mechanical characteristics of un-irradiated and irradiated specimens were then investigated by using three diagnostic techniques, i.e. X-ray diffraction (XRD), electrical resistivity by four-point probe technique, and Vickers hardness testing.

Structural characterization of irradiated and un-irradiated Al5086 alloy specimens was done at room temperature using X-ray Diffractometer (D8 Discover, Bruker, Germany). This helped to determine some microstructural parameters, e.g. lattice spacing, crystallite size, micro-strain, and dislocation line density, etc.

To measure the electrical resistivity of Al5086 specimens, we used an assembly of four equally spaced collinear probes of spacing 2.8 mm placed at the center of the exposed face, parallel to the specimen length (14 mm) and exactly at the center of the specimen width (8.5 mm). Electric current (I) was forced to flow through the outer two probes (6220 DC Current Source: Range: 2 nA to 105 mA) and corresponding potential difference (V) was measured across the inner two probes (2182A Nano-voltmeter (Kiethly: Range: 1 nV to 120 V). One hundred V–I measurements were taken for each specimen.

Hardness tests of all six specimens were carried out by Vickers hardness tester (SUN-TEC, CLARK, Model: CV-700AT, SER#CV 70546, Japan). Hardness measurements were made by applying 0.3 kgf load for 10 s on the surface of the un-irradiated specimen as well as on the exposed face of the irradiated specimens. Four measurements were made for hardness of each specimen.

3. Results and discussion

3.1. XRD analysis

3.1.1. X-ray diffraction patterns

The X-ray diffraction patterns of both un-irradiated and irradiated Al5086 specimens are shown in Fig. 1. One can see that diffraction patterns are the same as far as basic crystal structure and precipitate phase chemistry is concerned. No new phase formation occurred due to proton bombardment of the alloy for different exposure times. The sharp intensity peaks reveal good crystalline nature of the alloy. The different intensity peaks at angle $2\theta = 38.4°$, 44.6°, 64.9°, 77.9° and 82.0° correspond to planes (1 1 1), (2 0 0), (2 2 0), (3 1 1) and (2 2 2) respectively, and are confirmed by JCPDS X-ray file data showing that this profile is of face-centered cubic aluminum. A low intensity peak at an angle $2\theta = 40.3°$ corresponding to plane (2 2 0) is of Mg_2Si (Magnesium Silicide). Highest intensity corresponding to (2 0 0) plane in all specimens shows that preferential crystal orientation is along this direction. There was neither any shift in peaks nor significant broadening of peaks, as is evident from the profiles of the irradiated specimens. Hence it shows that proton irradiation of Al5086 alloy for a given proton dose in the range employed does not significantly change the structural parameters of the alloy.

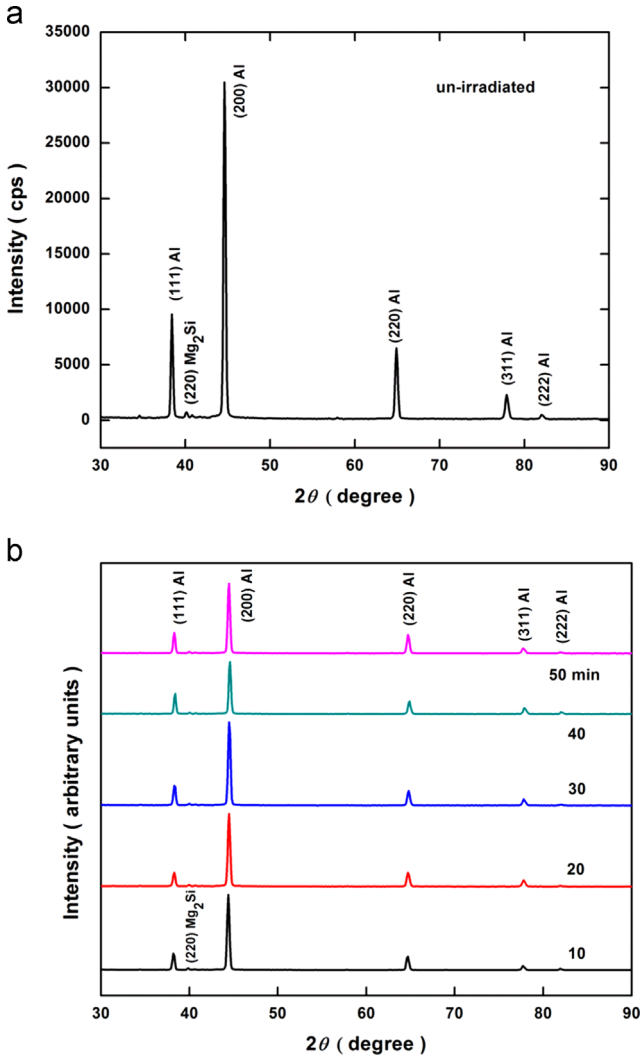

Fig. 1. XRD patterns of (a) un-irradiated Al5086 and (b) Al5086 irradiated with 2MeV proton beam for 10–50 min.