

Improvement of Wear Resistance of 356 Aluminum Alloy by High Energy Electron Beam Irradiation

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Abstract—This study is concerned with the microstructural analysis and improvement of wear resistance of 356 aluminum alloy by a high energy electron beam. Shock hardening on material by high energy electron beam improved wear resistance. Particularly, in the surface of material by shock hardening, the wear resistance was greatly enhanced to 29% higher than that of the 356 aluminum alloy substrate. These findings suggested that surface shock hardening using high energy electron beam irradiation was economical and useful for the development of surface shock hardening with improved wear resistance.

Keywords—Al356 alloy, HEEB, wear resistance, frictional characteristics.

I. INTRODUCTION

ALUMINUM and its alloys have been extensively used outdoors, particularly in the field of transportation, building, electrical engineering, aircraft, and aerospace [1]. 356 Aluminum alloys, having excellent specific tensile stress, have been mainly used for aircraft pump parts, automotive transmission cases, aircraft fittings and control parts, water-cooled cylinder blocks or wherever excellent cast ability and good weldability, pressure tightness, and good resistance to corrosion are required. A356.0: aircraft structures and engine controls, nuclear energy installations, and other applications where high-strength permanent mold or investment castings are required. One of the recent research efforts in surface hardening on the base of shock hardening is to use high energy electron beams [2].

Physical deposition techniques such as ion implantation [4] and plasma spray [5] coating and thermochemical surface treatments such as nitriding [6], carburization [7], and boriding [8] have been used in order to improve the surface properties of substrate. The former techniques improve the resistance but they cause deformation of the substrate material and surface damage.

In this study, a process is suggested to create shock hardening on the surface of material by high energy electron beam. Shock hardening can improve wear resistance of 356 aluminum alloy. In many aluminum structures, there are regions of lower strength than the rest of the structure [9]. The strength of these regions can be increased by a post-weld heat treatment or by mechanical working, such as rolling the weld bead and explosive shocking. However, these approaches are often either impracticable or undesirable. Recently, other methods have brought a possibility to increase the wear

resistance of aluminum alloys such as laser induced shock hardening, electromagnetic wave absorption, and shock hardening by high energy electron beams (HEEB). The use of a laser beam is attractive because the hardening can be localized to the desired region. Moreover, it is rapid and it can be easily adapted to numerical control.

There are some of the reasons for active metallurgical interests in the effects of shock hardening on the mechanical properties of aluminum alloys. The relationship between hardness and the occurrence of dislocations, stacking faults, deformation twins, or phase transformation has been extensively investigated [3]. In most of these studies the observed terminal phenomena have been related only to the peak shock stress experienced by the metal. It is obvious that pulse duration is important: for a given shock stress, a shorter duration shock pulse produces less hardening. With increasing shock stress, the terminal hardness reaches a saturation value.

The high energy electron beam induced shock hardening of metal surfaces has several advantages over the conventional surface hardening methods. In order to improve the shock hardening process, investigation into the involved physical processes is necessary. The recoil pressure developed during the surface ablation [10].

Rapid energy deposition can lead to very large temperature and pressure rises within a material. The instantaneous pressure distribution will remain constant for times on the order of the 50 ns pulse length. The pressure profile can only evolve at a rate equal to the wave speed in the material, which is on the order of 10^3 m/s. Over a 50 ns pulse length, this distance is tens of microns. The value of the instant pressure rise is given by the Grüneisen coefficient [3]:

$$\Delta P = \Gamma_0 \Delta E$$

$$\Gamma_0 = \left(\frac{\partial P}{\partial E} \right)_{r_0} \quad (1)$$

where Γ_0 is the Grüneisen coefficient. The values of this constant are well-characterized in the literature [11]. This equation may be integrated to get the pressure rise if Γ_0 is known as a function of P and E over the range of values of interest. The temperature rise can be found by assuming that the irradiated portion of material experiences adiabatic compression. This temperature distributed will also remain constant over the pulse length, because the characteristic heat conduction distance for a 50 ns pulse is several microns [3].

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Once the pressure wave is generated in the region of beam – material interaction, it propagates through the material resulting in plastic deformation. This plastic deformation can produce substantial hardening, and this is the basis of the shock hardening effect. Once the shock hits the other free surface, these will be reflections.

Shock waves propagating in materials will generate substantial new dislocation density in addition to interacting with existing microstructural features. Hardening mechanism such as formation of dense cellular networks, precipitation hardening, interactions with dispersed oxide particles, and interactions with inclusions all play a role. Twinning is important in BCC metals and alloys, and there have been some reports of shock – induced martensite formation. There have been many experiments that have used conventional shock loading techniques to characterize shock – loaded deformation microstructures [3].

Hardness, dislocation density, stored deformation energy, yield stress, and ultimate tensile strength increase with increasing shock pressure, and then reach a maximum cellular dislocation structure. Very similar to copper: at pressures above 1000 kbar, no cellular structure observed, but dislocation density is very high. When shocks travel in [001] direction, twinning will form. First experimental observation about twinning was performed for an FCC metal [12]. No dislocation cell structure formed up to pressures of 150 kbar although one may expect. The observed structure was composed of randomly distributed, heavily jogged dislocations, high point defect concentration, and many dislocation loops [13]. As stacking fault energy goes down due to alloying additions, cellular structure gives way to planar dislocation arrays, stacking faults, and twinning [14].

The high power levels and shock generation capabilities of HEEBs can be used in heat treatment in several ways. Firstly, the beam may be defocused to cover large areas and heat them uniformly. The uniform temperature profile in the workpiece may be controlled by varying the rep rate of the beam and its spot size. Uniformity of temperature profiles especially during cooling will insure the uniformity of composition in the heat treated component. However, if the beam is narrowly focused, shocks are possible. These shocks may be used to directly harden the material or they may serve to create nucleation sites for the subsequent phase transformations. This latter possibility is the basis for the third way in which HEEBs may be used for heat treatment, which is a combined mechanical / thermal treatment. This process has two steps. The beam is first narrowly focused to introduce shocked regions in the material. After this mechanical hardening, the beam is defocused to cover large areas. Shock does not form any longer, and the material is uniformly heated to promote the diffusional phase transformations. The transformed material will preferentially form at the sites which have been subjected to shock treatment. This technique of introducing nucleation sites and then transforming the material can also be applied to the recrystallization heat treatments. This would allow greater control over the size of the recrystallized grains, since the grain nucleation sites and their spacing can be chosen.

A HEEB offers a unique heat source which may be used for a wide variety of materials processing applications. The unique physical characterizations that make HEEB based processing so attractive in depth energy penetration, are very high average power levels, shock generation capabilities and potential for atmospheric or inert gas environmental operations. High energy electrons penetrate several millimeters into most materials allowing subsurface heat treatment. Rapid energy deposition produces moderate-to-strong shocks in many materials, and many potential applications exist which exploit this phenomenon [3].

Recently, the high-energy beam treatments have emerged as the powerful surface modification of the metallic materials techniques. The simplicity and reliability of this technique renders the particular advantages over the laser and ion beam treatments in the potential industrial applications. High Energy Electron Beams (HEEBs) offer a unique and volumetric heat source capable of high deposition rate, which can potentially deposit material with the tempo of 250 kg/h. During this process, the transient heating and cooling occurs on the treated material surface and have many interesting phenomena subject to the thermal and stress fields [1].

II. EXPERIMENTAL METHODS

The material studied in the present paper is Al 356 alloy having the following composition: Al 90.5 wt.%, Si 7.3 wt.%, Fe 0.52 wt.%, Mn 0.34 wt.%, Mg 0.3 wt.%, Zn 0.29 wt.%, Cu 0.2 wt.%.

HEEB treatment was carried out using an electron beam source named 'Rudotron'. Energy of electron beam was 10 MeV. The sample was irradiated under dose of 70 KGY.

Prior to the HEEB treatment, the sample was cut into a disc with dimension of 30 mm × 30 mm × 5 mm and the surface was mechanically grounded and polished.

Microstructure formed in the near-surface layer of untreated and treated specimens were examined with scanning electron microscopy (SEM) from the surface of the samples. X-ray diffraction (XRD) measurements were carried out to detect the phase changes in the surface layers.

The tribological tests were made utilizing a pin-on-disc wear device. The Al disc is fixed by a clamping device and then pressed on a rotating surface with a constant force. The disc specimen which is made up of AL 356 alloy to be investigated has a square contact area of 9 cm². The rotating 52100 steel disc was grinded to a desired surface roughness. The applied force was 20 N with a sliding velocity of 0.4 m/s. The test results are based on the coefficient of friction which is monitored as a function of Slip distance.

III. RESULTS

A. XRD

XRD analysis of Al356 alloy was carried out before and after radiation and it is shown in Figs. 1 and 2. For both initial and irradiated state, six peaks correspond to Al and three peaks correspond to Si. High intensity of the peaks reveals the crystalline formation of the samples.

It is also interesting to note here that the diffraction peaks do not shift toward either higher or lower angles after the radiation process which shows that residual stress produced after shock hardening, was not enough to change the formations of atoms in crystal.

The comparison between these two states shows that the radiation process does not produce any significant composition.

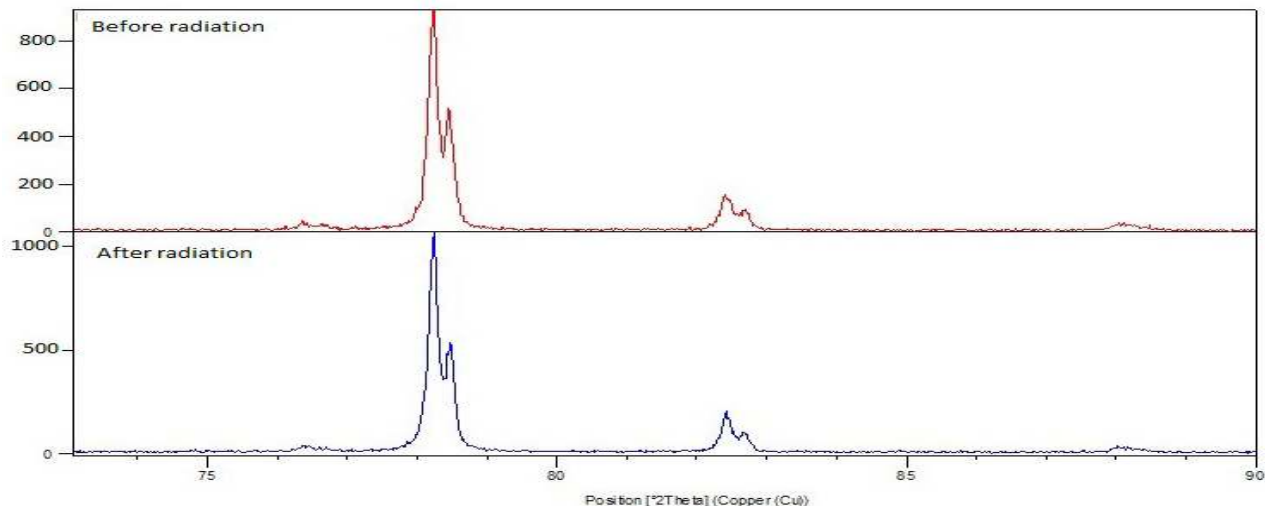


Fig. 1 XRD patterns of Al356 alloy samples before radiation

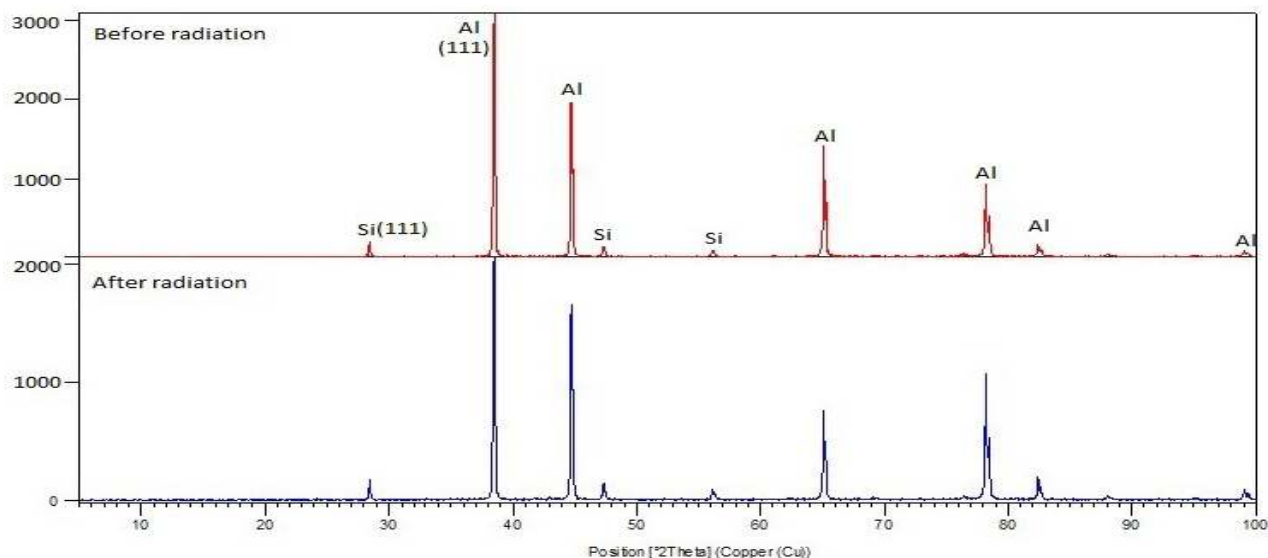


Fig. 2 XRD patterns of Al356 alloy samples after radiation

B. SEM

Fig. 3 is SEM images for irradiated and non-irradiated samples in 5000x magnification. A comparison between irradiated and non-irradiated samples reveals that the high density electrons of short durations induce dynamic field in the surface layers giving rise to superfast shock and possible moving dislocations. This is evident due to the cracks and crater-like morphology on the surface of the irradiated sample. The crater-like morphology, which is typical phenomenon of

metallic materials after HEEB treatment, is observed on the irradiated surface.

Craters are the result of the eruptions occurred in the subsurface layer of a target material when treated by the high energy electron beam.

C. Wear Result

Rapid energy deposition can lead to very large pressure rise within a material. Shock treatment has been attributed to the increase in dislocation density and grain-boundary precipitation produced due to shock deformation. Dislocations

and grain boundaries were assumed to act as precipitation sites and an increase in dislocation density.

Shock waves propagating in materials will generate substantial new dislocation density in addition to interacting with existing micro structural features. Hardening mechanisms such as formation of dense cellular networks, precipitation hardening interactions with dispersed silicon particles and interactions with inclusions play a role.

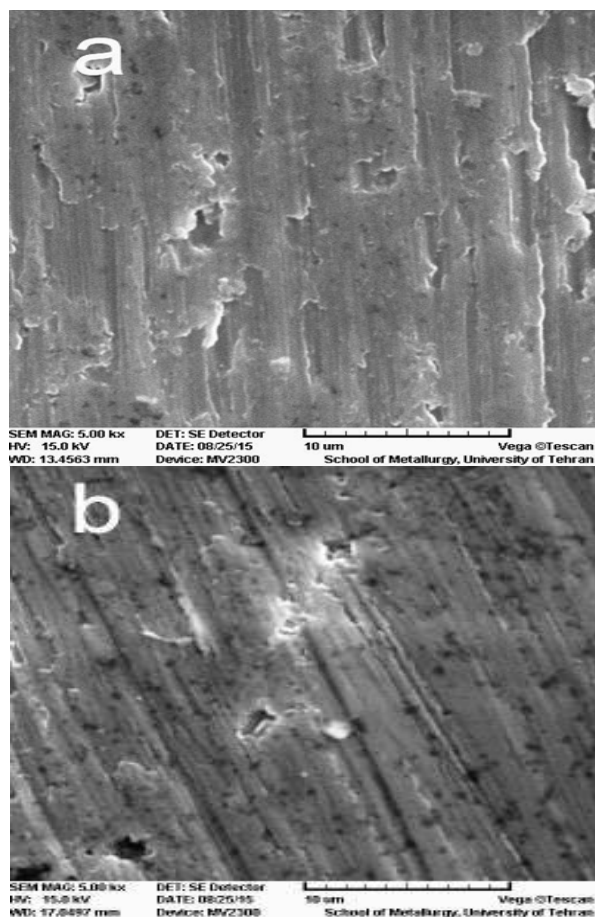


Fig. 3 SEM micrographs of the surfaces and cross-section of Al356 alloy before and after radiation, showing the different microstructure in different conditions: (a) initial sample and (b) irradiated sample for 5000X

As it can be noticed from Fig. 4, the coefficient of friction in initial sample shows more oscillations than irradiated sample and reaches higher levels at the first 300 meters. This stability of coefficient of friction for irradiated sample leads to improved wear resistance.

The comparison between mass loss of samples in 'pin on disc' test (Table I) also would give us a better aspect in usefulness of electron beam irradiation and shock hardening.

Hardness, dislocation density, stored deformation energy and wear resistance would be increased with applied shock pressure.

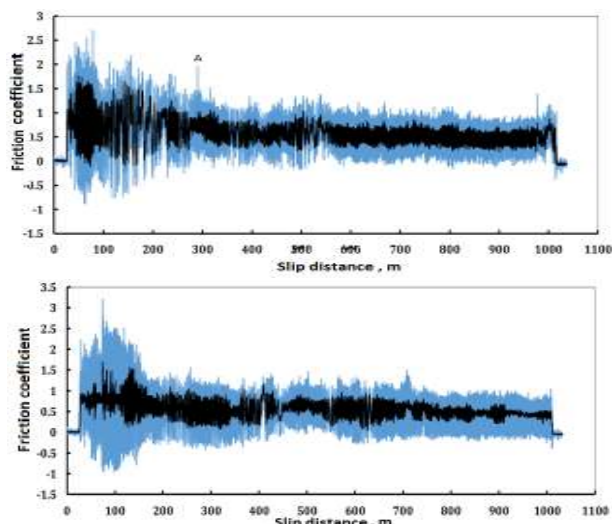


Fig. 4 Coefficient of friction of initial and irradiated Al356 alloy

TABLE I
VALUES OF MASS LOSS FOR INITIAL AND IRRADIATED AL356 ALLOY

Sample	Primary Mass	Final Mass	Mass Loss
Irradiated	12.4134	12.3601	0.0533
Initial	12.3067	12.2316	0.0751

IV. CONCLUSIONS

This research has examined the effect of HEEB treatment for modifying the surface of Al356 alloy. The major results are summarized as follows:

- 1) Electron beam irradiation under dose of 70 kGy does not change the formation of crystal and does not produce any significant composition.
- 2) HEEB treatment causes cracks and crater-like morphology on the surface of the irradiated sample due to superfast shock applied by electron beams.
- 3) Shock hardening improved wear resistance by stabilizing the coefficient of friction.

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