Applied Surface Science 457 (2018) 342–351

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Full Length Article

Gradient twinning microstructure generated by laser shock peening in an AZ31B magnesium alloy

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ARTICLE INFO

Keywords:
Mg alloys
Laser shock peening
Gradient microstructure
Deformation twinning

ABSTRACT

Mg alloys are lightweight structural metals that are promising for a variety of engineering applications. However, use of Mg alloys is often restricted by their poor mechanical properties. Recent studies indicate that a novel laser-based surface processing technology, laser shock peening (LSP), is promising to improve the engineering performance of Mg alloys by enhancing their surface strength, biocompatibility, fatigue resistance, and anti-corrosion ability. Despite these experimental efforts, little attention has been paid to study the surface microstructure evolution in the LSP process, particularly the formation of high density deformation twins. Deformation twinning in hexagonal closed-packed (HCP) crystal structure plays a fundamental role in enhancing mechanical performance of Mg alloys. This research is to establish the process-microstructure relationship of Mg alloys as processed by LSP. A focus is placed on understanding the deformation twinning mechanism. LSP experiments are conducted on a rolled AZ31B Mg alloy. The microstructures before and after laser processing are characterized. The effect of laser intensity on the twin volume fraction is investigated. The surface hardness as associated with the twin density is measured. The mechanism responsible for the formation of gradient twinning microstructure and the twinning-induced hardening effect are discussed. The anisotropic response to LSP in terms of grain orientation and the resultant microstructure and hardness improvement in the Mg samples are discussed.

1. Introduction

Mg alloys are lightweight structural metals that are promising for a variety of engineering applications in aerospace, automotive, and biomedical industries [1–4]. However, use of Mg alloys is often restricted by their limited ductility, formability, and fatigue strength [5]. These poor mechanical properties of Mg alloys are attributed to their hexagonal closed-packed (HCP) crystal structure, which exhibits a limited number of easy slip systems to accommodate deformation strain [6,7].

In order to improve the mechanical performance of Mg alloys, several manufacturing approaches have been proposed, including micro-alloying [8], equal-channel angular extrusion (ECAE) [9], and surface mechanical attrition treatment (SMAT) [10]. In addition to these processing approaches, a laser-based surface processing technology, laser shock peening (LSP), is exceptional due to its high process efficiency, flexibility, and controllability [11,12]. LSP is a surface processing process utilizing pulsed laser energy to introduce compressive residual stresses and a work-hardened layer to the surfaces of metallic materials for enhanced durability [13,14]. Recent studies indicate that LSP is promising to improve the engineering performance of Mg alloys by enhancing their surface strength [15], biocompatibility [16], fatigue resistance [17], and anti-corrosion ability [18]. For instance, Ye et al. [15] showed that LSP resulted in the increase of surface hardness of AZ31B Mg alloy from 57 to 69 HV and the yield strength from 128 to 152 MPa. Vinodh [16] et al. reported that the corrosion rate of the Mg–calcium (Mg-Ca) alloy samples without laser processing was 2.5 times higher than that of the samples processed by LSP. In addition, laser processed samples exhibited a significantly improved biocompatibility. Ge et al. [19] investigated the effect of LSP on the stress corrosion cracking behavior of AZ31B Mg alloy and showed that the SCC susceptibility index of the LSP treated samples was decreased by 47.5% as compared to the as-received samples. Sealy et al. [20] studied the fatigue performance of Mg-Ca alloys subjected to LSP and found that the rotating bending fatigue life of the laser peened samples was ten times higher than that of the untreated samples.

Despite these experimental efforts on understanding the effect of LSP on enhancing performance of Mg alloys, little attention has been paid to study the surface microstructure evolution during LSP. Although surface grain refinement of Mg alloys during LSP was reported in [21,22], no particular investigation has been focused on elucidating the

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https://doi.org/10.1016/j.apsusc.2018.06.176
Received 30 March 2018; Received in revised form 4 June 2018; Accepted 19 June 2018

formation of high density deformation twins as a result of surface plastic deformation with an ultrahigh strain rate of 10^6–10^7/s in the LSP process. Deformation twinning in HCP structure plays a fundamental role in enhancing mechanical performance of Mg alloys [23,24]. In addition, the microstructural anisotropic response to LSP should be considered. A better understanding of twining mechanisms in Mg alloys as subjected to LSP may lead to improved process development and control for optimized mechanical performance.

This research is to establish the process-microstructure relationship of Mg alloys as processed by LSP. A focus is placed on understanding deformation twinning mechanism. LSP experiments are conducted on a rolled AZ31B Mg alloy. The microstructures before and after laser processing are characterized using optical microscopy, electron backscatter diffraction (EBSD), and scanning electron microscope (SEM). The effect of laser intensity on the twin volume fraction is investigated. The surface hardness as associated with the twin density is measured. The mechanisms responsible for the formation of gradient twinning microstructures and the twinning-induced strain hardening effect are discussed. The anisotropic response to LSP in terms of grain orientation and the resultant microstructure and hardness improvement in Mg samples are compared and discussed.

2. Experiments

2.1. Materials

Rolled AZ31B Mg alloy block (3.0 wt% Al, 1.0 wt% Zn, Mg balance) purchased from Metalmart.com was used for experiments. Cubic samples with a dimension of 1 in. by 1 in. were machined from the block for LSP processing. Prior to laser processing, the samples were grinded using SiC sandpapers with different grit numbers (from 320 to 1200), followed by fine polishing using 3 µm diamond suspension. Afterwards, the samples were ultrasonically cleaned in an ethanol solution.

2.2. LSP experiments

Fig. 1a shows a schematic view of the LSP configuration. In this work, a Q-switched Nd-YAG laser (Surelite III from Continuum, Inc.), operating at a wavelength of 1064 nm and a pulse width of 5 ns (full width at half maximum), was used to deliver the laser energy. The laser beam diameter was 2 mm. The laser power intensity was adjusted by adjusting the Q-switched delay time. Black tape with a thickness of 100 µm was used as the ablative coating material. BK7 glass with a high shock impedance was used as the transparent confinement. LSP experiments were performed along the rolling direction (RD) of the specimen (Fig. 1b).

2.3. Microstructure characterization

The microstructure before and after LSP was characterized using Leica DM2700 optical microscope (OM), SM-7100FT field emission scanning electron microscope (FESEM), and electron backscattered microscope (EBSD). Samples for optical microscope characterization were prepared by sectioning, mounting, polishing, and etching with the acetic picral solution. (10 ml acetic acid + 4.2 g picric acid + 10 ml distilled water + 70 ml ethanol). EBSD characterization was performed in the stage control model with TSL data acquisition software on an area of 200 µm by 200 µm with a step size of 0.5 µm. All the microstructure characterization was performed on a cross-section perpendicular to the ND.

2.4. Mechanical properties test

The surface micro-hardness of samples before and after laser processing were measured using a Wilson Hardness tester with a 500 g load and 10 s holding time. In order to study the effect of the gradient twinning microstructure on the material strength, in-depth hardness was measured from the top surface to a depth of 2300 µm on TD-ND planes in Fig. 1b. An electrolytic polisher was used to remove the material layer by layer for in-depth hardness testing. At each depth, the hardness values were measured 5 times.

3. Results and discussion

3.1. Laser-induced shockwave pressure and propagation

In order to understand the process-microstructure relationship, first the shockwave pressure during LSP is theoretically estimated. According to the widely accepted Fabbro's laser shock processing mode (Eqs. (1)–(3) [13,25], the magnitude of shockwave pressure $P(t)$can be estimated as a function of the shock impedance Z (confining media $Z_1$and target material Z_2) and the laser intensity $I(t)$, where $L(t)$is the layer thickness of laser-induced plasma, α is the efficiency of the interaction (≈ 0.1), and t is the time.

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{1}$$

$$\frac{dL(t)}{dt} = \frac{2}{Z}P(t) \tag{2}$$

$$I(t) = P(t)\frac{dL(t)}{dt} + \frac{3}{2\alpha}\frac{d}{dt}[P(t)L(t)] \tag{3}$$

In this work, $Z_1 = \mathrm{Z}_{glass} = 1.44 \times 10^6\ \mathrm{g/cm^2{\cdot}s}$ $Z_2 = \mathrm{Z}_{\mathrm{AZ31b}} = 1.01 \times 10^6\ \mathrm{g/cm^2{\cdot}s}$[26], and $I(t)$is given by Eqs. (4) and (5) [27]:

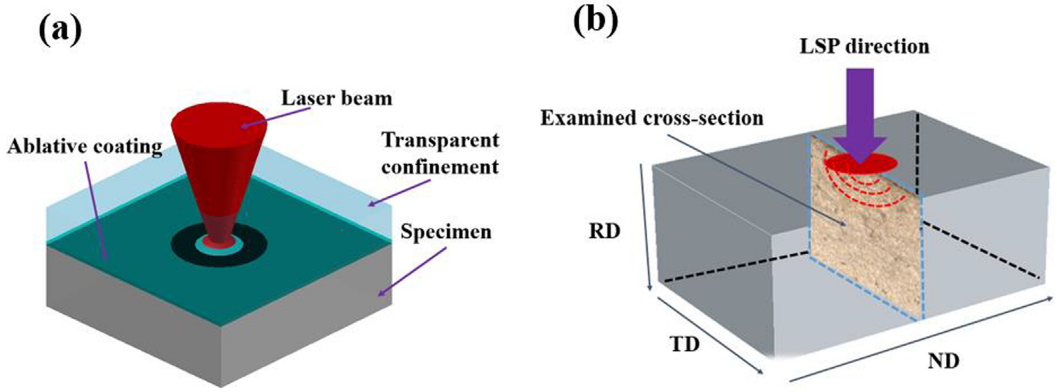

Fig. 1. Schematic illustrations of: (a) LSP experimental set up, and (b) LSP direction and examined cross-section of the processed specimen, where the RD, TD, and ND are rolling, transverse, and normal direction, respectively.