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Effect of laser shock peening on the stress corrosion cracking of AZ31B magnesium alloy in a simulated body fluid

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ABSTRACT

Stress corrosion cracking (SCC) behavior of AZ31B Magnesium (Mg) alloy with and without Laser Shock Peening (LSP) was studied using slow strain rate tension (SSRT) method in a simulated body fluid (SBF) at 36.5 ± 0.5 °C. The effects of two-sided simultaneous LSP on microstructure, residual stress, surface roughness and electrochemical property of AZ31B samples were investigated by using optical microscopy, X-ray diffraction (XRD) method, true color material confocal microscopy, transmission electron microscopy (TEM) and electrochemical polarization experiment. The experimental results show that based on the optimal laser processing parameters, surface nanocrystallization could be induced in the AZ31B surface layer. Comparing with the original samples, the corrosion potential increased 131 mV, the corrosion current density decreased by 85.4% and the SCC susceptibility index (I_{SCC}) decreased by 47.5% after LSP. Based on the experimental observations, the improvement mechanism of SCC resistance for AZ31B with LSP was also analysed and revealed.

1. Introduction

Magnesium (Mg) is a necessary element to human body, and its daily intake is around 300–400 mg for a normal adult [1]. Mg alloys, as an implant, can greatly reduce stress shielding effects because its density (1.74–2 g/cm^3) and elastic modulus (42–45 GPa) mostly approximate those (1.8–2.1 g/cm^3, 40–57 GPa) of human bone [1–3]. Therefore, Mg alloys have much better biocompatibility than traditional implant materials such as Titanium alloys and stainless steels. Moreover, the biodegradable Magnesium alloy implant can effectively avoid secondary removal surgery [2]. Thus Mg alloys are ideal biodegradable implant materials. However, rapid corrosion of Mg alloys in the human body restricts their application as human implant materials. Especially, Mg alloys are highly sensitive to SCC even in very moderate environments such as deionized water and distilled water [4,5]. Usually, SCC occurs suddenly which may result in catastrophic accidents. Therefore, it is indispensable to enhance the anti-corrosion ability for Mg alloys without losing their main properties in the human body.

LSP is a nontraditional and non-contacting surface modification technique. When a laser beam with high power density and short duration irradiated at a metal target surface can create a high temperature and pressure plasma medium, this laser-induced plasma is rapidly expanded due to continuous absorbing laser pulsed energy, and then produces a high-pressure shock wave, which can result in severe plastic deformation in the metal target and consequently induce microstructural change and compressive residual stress. So fatigue behavior [6–8], corrosion attributes [3,5,9–11] and wear resistance [12] of metal materials can be significantly improved by LSP. Guo et al. [3] found that LSP significantly reduced the corrosion rate of Ma-Ca alloy from about 17 mm/year to 0.001 mm/year in Lonza™ Hank's balanced salt solution. Amar et al. [10] and Peyre et al. [11] demonstrated that LSP remarkably enhanced pitting resistance of AA2050-T8 aluminum alloy in 0.1 M NaCl and 316L stainless steel in 0.05 M NaCl, respectively. In addition, the advantage of LSP treatment over the conventional peening technologies is that LSP can produce much finer grain and deeper residual stresses in the surface layer of metal target relative to shot-peening [13], which is attributed to ultra-strong stress wave induced by high-energy pulsed laser. Severe plastic deformation is reported to produce a refined microstructure. Meanwhile, LSP is also reported not to lead to increasing surface roughness. In fact, residual stress and microstructure are also two significant factors governing SCC behaviors of metal materials. So far, some researches about the influences of LSP on SCC behaviors of metal materials have already been carried out [14,15].

Zhang et al. [14] indicated that LSP could restrict the SCC initiation and crack propagation in AZ31B Mg alloy in 1 wt.% NaOH solution at room temperature using three-points loading method. Li et al. [15] found that LSP could prolong failure time and increase SCC strength of AZ31B in 3.5 wt.% NaCl solution by SSRT test. Although the above authors realized grain refinement in AZ31B Mg alloy surface layer using LSP, the grain size did not reach nanometer scale. If nanometer grains

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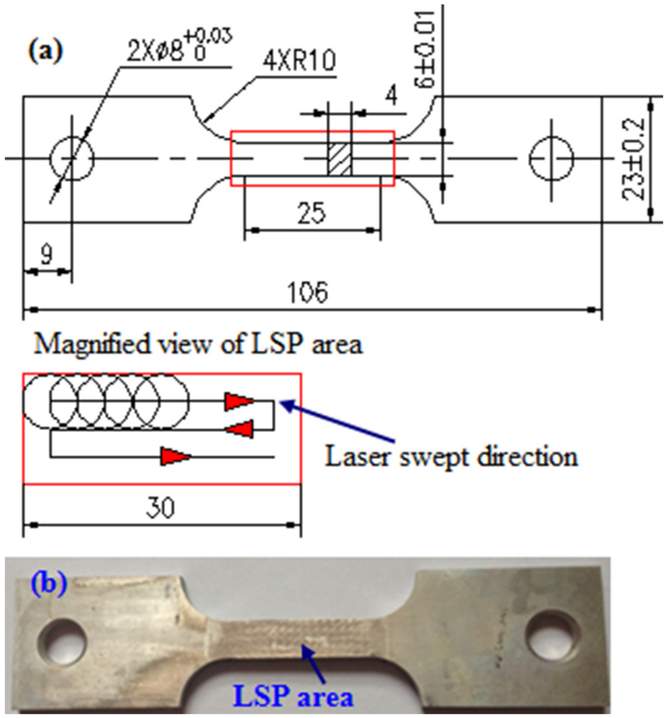

Fig. 1. (a) Dimensions of SSRT specimen (unit: mm) and (b) photograph of laser treated sample.

can be produced in AZ31B Mg alloy surface layer by using the optimal laser processing parameters, which may have an important effect on the SCC susceptibility due to superior physical and chemical properties of nanocrystalline materials. Furthermore, the thickness of AZ31B Mg alloy sheet used in Ref. [15] was 2.5 mm. However, the depth of compressive residual stress reached around 1 mm when AZ31B Mg alloy sample treated by one-sided LSP [14]. So when AZ31B Mg alloy samples with 2.5 mm in thick were processed by two-sided LSP, two opposite and simultaneously produced laser shock wave would meet and interact inside the AZ31B, then producing harmful coupling action, which can greatly decrease mechanical properties of AZ31B Mg alloy samples [16,17]. In addition, 1 wt.% NaOH solution and 3.5 wt.% NaCl solution were only chosen to be corrosive medium in the above tests. Nevertheless, the SCC behavior of AZ31B Mg alloy subjected to LSP in the stimulated body fluid is quite few so far.

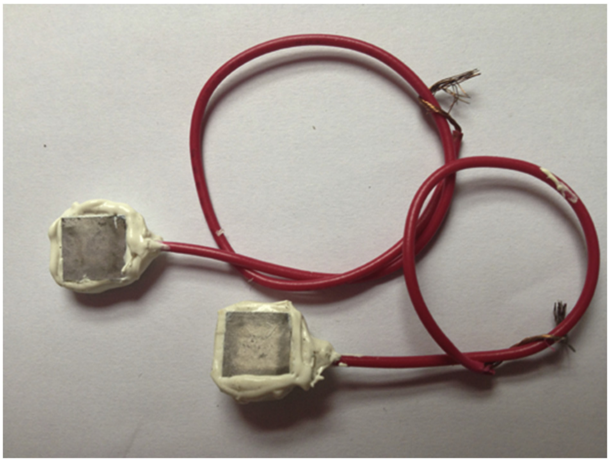

Fig. 2. Samples for polarization tests.

Table 1
The ion concentrations in the simulated body fluid (±0.05 mmol/l).

K^+	Na^+	HCO_3^-	HPO_4^{2-}	Cl^-	Mg^{2+}	Ca^{2+}	SO_4^{2-}
5.0	142.0	4.2	1.0	147.8	1.5	2.5	0.5

This paper focused on studying the SCC behavior of AZ31B Mg alloy peened by the optimal laser processing parameters in a stimulated body fluid by SSRT test. Potentiodynamic polarization tests were used to examine the influence of LSP on the electrochemical corrosion behavior of AZ31B. To investigate the improvement mechanism of LSP on the stress corrosion resistance of AZ31B, the microstructure, residual stress and surface roughness of AZ31B after LSP were also revealed. The above topics studied could offer an alternative SCC resistance measure for Mg alloys implant materials.

2. Experimental procedure

2.1. Sample preparation

All samples are cut by an electrical spark liner cutting machine from a plate (thickness 4.2 mm) of wrought AZ31 Mg alloy, which has the following chemical compositions: Mg-3.19Al-0.81Zn-0.334Mn-0.005Fe (wt.%). The dimensions of specimen used for SSRT test are shown in Fig. 1. It should be noted that the gauge length is 25 mm, and plate rolling direction is parallel to each sample loading direction. The dimensions of the sample used for potentiodynamic polarization test are 10 mm × 10 mm × 4 mm. Prior to LSP treatment, each sample should be polished using SiC paper with the different roughness ranging from 150 # to 1000 #, degreased in acetone using ultrasonic vibration method, and then dried with air-drying.

2.2. Laser shock processing parameters

The massive LSP treatments were performed on a Q-switched Nd:YAG laser system, which operates at a wavelength of 1064 nm, a repetition rate 5 Hz and a pulse width of 15 ns. In our present study, the round laser spot was set to 3 mm in diameter, the laser pulse energy was 10.2 J and its optimization process was presented in Ref. [6]. During laser irradiation, the sample surface to be peened by laser was first covered by a professional Aluminum foil with 100 μm in thick, which was used as the ablative layer to keep the sample surface from heat damage caused by high temperature plasma. Consequently, the protective layer surface was covered by a uniform water curtain with 3 mm in thick, which was served as the confining layer to restrict the propagation of high pressure and temperature plasma produced by the protective layer vaporized and to enhance the peak pressure of stress wave. Plate rolling direction was parallel to laser swept direction, which is shown in Fig. 1. Laser overlapping rate between two adjacent spots along the sample length and width was 50%. The laser treated area of samples was 30 mm × 6 mm on both sides. During LSP treatment, the same locations on both sides of sample were impacted simultaneously by two opposite laser beams with the same laser processing parameters.

2.3. Measuring equipment of microstructure, surface roughness and residual stress

The microstructure of original AZ31B Mg alloy was measured by optical microscopy (Model XJL-02). The microstructure after LSP was characterized by TEM (Model JEM-2100, Japan). TEM specimens were cut off from the laser peened sample surface layer. Only the laser untreated side was ground to about 40 um in thick using different grit papers, and then the laser un-peened surface were ion milled in a Gatan 691 Precision Ion Polishing System with an incident angle of 8° till perforation. Nevertheless, the laser peened surface was ion milled using a small incident angle of 4°. The grain size of original AZ31B Mg alloy