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Near surface modification of aluminum alloy induced by laser shock processing

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ABSTRACT

This paper investigates the influences of near surface modification induced in 6061-T6 aluminum alloy by laser shock processing (LSP). The present study evaluates LSP with a Q-switched Nd:YAG low power laser using water confinement medium and absorbent overlay on the workpiece. The near surface microstructural change of 6061-T6 alloy after LSP was studied. The residual stress variation throughout the depth of the workpiece was determined. The results showed an improvement of the material resistance to pit formation. This improvement may be attributed to compressive residual stress and work-hardening. The size and number of pits revealed by immersion in an NaOH–HCl solution decreased in comparison with the untreated material.

1. Introduction

Laser shock processing (LSP) has been proposed as a promising alternative technology to conventional treatments for improving wear, fatigue and corrosion resistance of metallic materials [1]. During LSP, material is mostly irradiated by a Q-switched Nd:YAG laser with short pulses (several ns) and a peak intensity greater than 109 W/cm^2 [2–5]. The irradiated surface is generally coated with an opaque overlay that acts as protective coating, such as black paint, plastic or metallic foil tape. The target material is submerged in a transparent medium. The laser beam passes through the transparent medium and first interacts with the opaque overlay. The opaque overlay evaporates and a plasma is generated on the target material. The plasma causes the generation of a high pressure at the evaporated surface because it is confined by the transparent medium which is called "confined ablation". The plasma continues absorbing laser energy until the end of the laser pulse length. Shock waves are generated in the material and the confining medium, because the process is very fast and the magnitude of the pressure is very high. Plastic deformation occurs in the material subjected to the effect of the shock waves. Elastic deformation surrounds the plastic deformation area in the LSP-affected zone. When the laser pulse is switched off, the pressure recoils and the surrounding matter react to the plastically deformed volume; thus a compressive residual stress field is created in the target material [4,6–8]. LSP has many advantages over conventional methods. Some of these advantages include non-mechanical contact between the workpiece and the laser source, local treatment, precision of operation and low cost, furthermore, the first atomic layers of the opaque overlay protect the surface from thermal rise.

Aluminum alloy is widely used in the automotive and aerospace industries, but its moderate strength and corrosion resistance restrict wider applications [9]. The alloys are exposed to corrosion attack in aggressive environments especially in a chloride environment [10–13]. The attack can lead to problem which is well known as the pit initiation in the aluminum alloy. Some applications such as surface treatments and alloying overcome the major corrosion problems. The conventional laser surface treatments are predominantly thermal or thermo-chemical. In contrast, LSP is a mechanical surface treatment which uses pulsed lasers. LSP has been effective in improving the properties of metals such as tensile strength, hardness, wear resistance and corrosion resistance [14–17]. A few studies have considered the effect of LSP on the corrosion behavior, and mechanical and metallurgical properties of some aluminum alloys. Yue et al. [13] investigated the excimer laser surface treatment of aluminum alloy 7075 and they found that the excimer laser surface treatment was an effective method for improving the pitting resistance. Sathyajith et al. [18] investigated laser shock processing without coating on aluminum alloy 6061-T6. The study showed that compressive residual stress and micro-hardness were induced in the alloy. Yilbas and Arif [7] studied the laser shock processing of aluminum and examined the microstructural changes in the plastically deformed region. They showed that the von Mises stress remained

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high in the vicinity of the surface and SEM micrographs showed that a crack-free shock hardened layer was generated at the LSP-affected area. Zupanc and Grum [19] stated the importance of pitting corrosion on high strength aluminum alloys and their results showed the improvement of corrosion fatigue properties of induced compressive residual stress in consequence of shot peening which is purely mechanical surface treatment. He et al. [20] investigated microstructure evolution and micro-hardness changes of commercial purity ultra-fine grained (UFG) aluminum caused by ultra-high strain rates during a single pass LSP. They found that after LSP many sub-grains formed at the center of the laser shock wave after a single pass LSP, while high density dislocation networks were observed in some grains at the edge of the laser shock wave. Luo et al. [21] investigated the effects of LSP on nano-hardness and elastic modulus of the sample manufactured by LY2 aluminum alloy. They found that in the laser-shocked region (i) the grains were clearly refined, (ii) there were numerous dislocation tangles in the vicinity of grain boundaries and (iii) a small amount of twins was also found.

On reviewing related research work, the trend has been generally inclined to highlight the mechanical properties of the laser shock processed materials, but few papers concentrate on the effects of LSP treatment on pit formation. On the other hand, many materials, such as aluminum alloys, titanium alloys and stainless steels, were investigated when these alloys were irradiated with high power lasers, but, this study covers use of a low power Nd:YAG laser. In our study, we intend to explain how LSP treatment affects on 6061-T6 aluminum alloy in terms of both work hardening and pit formation and it consists of their correlations.

2. Experimental

LSP experiments were performed using 6061-T6 aluminum alloy. The chemical composition of the alloy is shown in Table 1. It was determined using a spark emission spectrometer. The thickness of material was 2 mm. Specimens were cleaned ultrasonically in ethanol. Prior to LSP, the specimens were covered with a 130 μm thick black tape which is called opaque overlay. It also protects the surface of the sample from a thermal effect. Specimens were immersed in water, which was the confining medium, with a thickness of 2 mm. Experiments were carried out by using the Q-switched Nd:YAG laser operating a 10 Hz repetition rate, a wavelength of 1064 nm and a pulse duration of 6 ns. Pulse energy of the laser system was 750 mJ and the focal length of the lens was 150 mm. The laser beam spot diameter was set to 1 mm with an overlapping ratio of 50%. The LSP treatment was performed in single and two-LSP impacts.

X-ray diffraction (XRD) was used to estimate the degree of plastic work. The broadening of the full width at half-maximum (FWHM) of the diffraction peak was measured to calculate the crystallite size. The FWHM was measured from the treated surface for five lattice reflections which were α-Al {220}, {311}, {400}, {331} and {420} planes. The crystallite size was calculated by the Scherrer equation. The XRD patterns were collected using Phillips X'Pert Pro equipped with a CuKα radiation source whose wavelength was 1.542 Å.

A hole-drilling/ESPI technique (PRISM) was used for the measurement of residual stress. Residual stress as a function of depth can be estimated using the hole-drilling method [22]. Hole-drilling is the most widespread method for measuring the residual stress profile. The method is based on a small hole drilled in the residual stress area in question and then the deformation, which occurred after the hole had been drilled in the area, was measured and this measurement was used for residual stress calculation. ESPI (electronic speckle pattern interferometer) is an adaption of the hole-drilling method in which the measured deformation around the hole is converted to a value of in-plane residual stress [23,24]. Specimens were placed on an optical table to minimize the vibrations of the drill, lighting and camera during the measurement. The hole was drilled at 30,000 rpm. The nominal diameter of the drill, which was made of tungsten coated with TiN, was 0.8 mm. Since the hole drilling technique destructively measured residual stress by drilling on the material surface, the data could be imported from depth of 20 μm minimum.

The LSP-treated and untreated specimens were cut in a micro-cut machine. After cutting, the samples were mounted from cross-section surfaces in cold molding for metallographic examination. The samples were ground with silicon carbide papers down to 1200 grit and polished with diamond pastes in steps of 3 and 1 μm. Samples were immersed in NaOH 1 g–HCl 1 ml–water 50 ml solution for 5 min and then the microstructures were observed using scanning electron microscopy (SEM). The morphology of the pits observed in the microstructure was analyzed in Clemex image analysis software.

Table 1
Composition of 6061-T6 alloy.

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
0.62	0.46	0.29	0.09	0.88	0.17	0.01	0.04	0.05	97.39

3. Results and discussion

It is known that laser intensity (I_0) is an important parameter of LSP to produce desirable residual stress [25,26]. Pressure (P), which is imposed on the material surface during LSP, is a function of the laser intensity ($P(\text{GPa}) = 1.02\sqrt{I_0(\text{GW cm}^{-2})}$) [27]. In our study, laser intensity is 16.025 GW/cm^2; according to the equation, peak pressure magnitude imposed on the material surface is calculated as 4.08 GPa.

3.1. Plastic work

The grains consist of crystallites which have differences in orientation. And so, the crystallites are separated by the small angle between lattice planes. A grain may be composed of multiple crystallites. Determination of crystallite size by XRD is ideal when crystallites are too small for optical methods. By the effect of a very short interaction time and high plasma pressure during LSP, the crystalline grains can be separated into several coherently diffracting domains. Inferences regarding the work hardening effect can be drawn from X-ray diffraction peak broadening which is indicated using the full width at half-maximum (FWHM) measurement data [28]. X-ray diffraction was used to characterize the crystallite size, dislocation line density in the LSP-treated specimens by using a Williamson–Hall plot [29]. As the peak width increased, crystallite size decreased according to the Scherrer formula from the FWHM of the diffraction peak [30]:

$$\beta = \frac{K\lambda}{L\cos\theta} \quad (1)$$

where the peak width β consists of the contribution of the crystallite size L. λ is the wavelength of the X-ray and K is the Scherrer constant, which is assumed to be approximately 0.94. The value of the constant C is typically 4.

X-ray line profile analysis has been also used to indirectly determine dislocation density [31–33]. The dislocation density is defined as the length of dislocation lines per unit volume of the crystal. The dislocation line density δ can be calculated from the