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Dislocation polymorphism transformation of 6061-T651 aluminum alloy processed by laser shock processing: Effect of tempering at the elevated temperatures

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ABSTRACT

The effects of tempering on surface topography and dislocation configuration of 6061-T651 aluminum alloy by laser shock processing (LSP) were investigated at the elevated temperatures. Surface topography and surface roughness were tested by a Surfcom 130A-Monochrome surface rough-meter. Morphologies of precipitated phases were monitored by scanning electron microscopy (SEM), and the dislocation configurations of samples after LSP were characterized by transmission electron microscope (TEM). The results showed that LSP had a beneficial effect on micro-hardness at elevated temperature. There was a little change of the surface roughness as subjected to LSP. The main strengthening mechanism of micro-hardness was dislocation strengthening and fine grain strengthening, and precipitated phase strengthening was the main strengthening mechanism at elevated temperature. “Dislocation polymorphism transformation” (DPT) effect was affirmed at elevated temperature, and the elevated temperature was principal element for inducing the DPT effect of 6061-T651 aluminum alloy by LSP.
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1. Introduction

Aluminum–magnesium–silicon (Al–Mg–Si) denoted as 6XXX series alloys are desirable in many industries such as aircraft, automotive, appliances and food packaging due to their light weight with good mechanical properties [1], such as good strength [2], formability [3], and corrosion resistance [2–4].

Compared with the traditional process such as shot peening [5], deep rolling [6] and cold extrusion [7], laser shock processing (LSP) is a new surface modification technology to improve the mechanical properties of metal, especially the metallic material of hardness [8], residual stress [9,10] and fatigue life [11,12]. The principle of LSP is shown in Fig. 1. As the power density of the laser pulse from a Q-switched laser is sufficiently high, the shock waves would be induced. When the shock wave propagates into the metal target, the compressive residual stress would be generated near the target surface due to the plastic deformation. Fribourg et al. [13] investigated the effect of laser treatment on the microstructure of AA7449 aluminum alloy. Rubio-Gonzalez et al. [10] obtained the effects of the pulse density on mechanical properties of 6061-T6 aluminum. Zhang et al. [14] evaluated improvement of fatigue life of Ti–6Al–4V alloy by laser shock peening. Dorman et al. [15] showed the effect of laser shock peening on residual stress and fatigue life of 2024 aluminum alloy. Ocana et al. [16] examined the effects of different processing parameters on the strengthening effect induced by two-sided LSP. However, most of above researches focused on the effects of LSP on the surface deformation, residual stress and fatigue life of metallic material at room temperature. There is a lack of consideration of the influences of elevated temperature on the effect of LSP. The strengthening mechanism of LSP on the components at elevated temperature would have a difference as compared with room temperature. The aim of this paper is to study the influences of elevated temperature on surface topography, micro-hardness and microstructure of 6061-T651 aluminum alloy by LSP. Furthermore, the strengthening mechanisms of LSP on micro-hardness and dislocation configuration evolution at elevated temperature are also revealed.

2. Experimental procedures

2.1. Experimental material and parameters

6061-T651 aluminum alloy specimens were cut into a circular shape with dimensions of ϕ 16 mm × 5 mm (diameter × thickness). The chemical composition and photograph of 6061-T651 aluminum alloy taken by LSP are shown in Table 1 and Fig. 2(a), respectively.

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First, the 6061-T651 aluminum alloy specimens were treated by LSP. High energy shockwave was induced by Nd:Glass laser with a wavelength of 1064 nm and a pulse of 10 ns. Laser spot diameter was 3 mm and the overlapping rate of laser spot was 50%. The specimen surface in laser shock region was covered with the absorbing layer and the confining layer. Al foil with a thickness of 0.12 mm was used as an absorbing layer to protect the specimen surface from thermal effect, and the 2 mm thickness water was used as the transparent confining layer. Laser energy was 6 J. The parameters used in LSP are shown in Table 2, and the LSP shock region as well as scan direction of the sample is shown in Fig. 2. Then, all the samples after LSP were heated at the temperatures of 200 °C, 300 °C, 400 °C and 500 °C in chamber type electric resistance furnace for 30 min, finally air cooling 1 h.

2.2. Surface topography and roughness

Two-dimensional surface topography and surface roughness were tested by Surfcom 130A-Monochrome surface roughometer. The arithmetic average deviation of profile (R_a) is treated as the main parameter to evaluate surface roughness. $R_a=(1/l)\int_0^1 y(x)|dx$ [17], where l is the sample length, $y(x)$ is the deflection distance of profile. The tested length l was a 6 mm line segment along the laser spot center.

2.3. Measurements of micro-hardness

The micro-hardness was measured by HXD-1000TMSC/LCD Micro-hardness Tester. 0.49N was applied for micro-hardness measurements, and the loading time was 10 s. Micro-hardness results were obtained by taking the average values of ten different hardness measurements from each sample.

2.4. Microstructure observations

The metallographic structures were etched with the Keller reagent (2 ml HF+3 ml HCl+5 ml HNO_3+90 ml H_2O). The morphologies of precipitated phases in 6061-T651 aluminum alloy after LSP were monitored by scanning electron microscopy (SEM). The microstructures after LSP at different temperatures were characterized by JEM-2100(HR) transmission electron microscope (TEM) with a voltage of 200 kV.

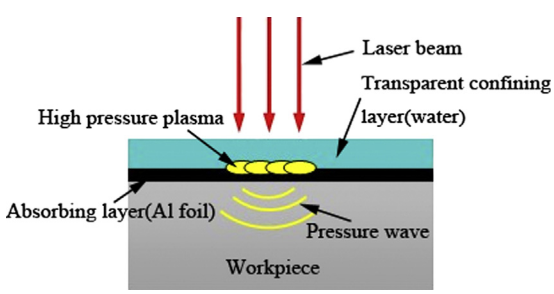

Fig. 1. Schematic of laser shock processing.

3. Results and discussions

3.1. Surface topography and roughness

Surface morphology of the metal material has a great effect on fatigue behavior [18]. Full investigation of surface topography by LSP treatment at elevated temperature has never been conducted in the previous studies, it is crucial to study the effect of LSP on the surface topography of 6061-T651 aluminum alloy.

Fig. 3 shows the 2D surface topography of 6061-T651 aluminum alloys with LSP and un-LSP. The microscopic surface without LSP is very smooth, whose height of peak and valley scatters from −0.5 μm to 0.5 μm. The height of peak and valley is enlarged rapidly (from −2.5 μm to 2.5 μm) after LSP, which illustrates that LSP changes the surface topography. The 2D surface topography of 6061-T651 aluminum alloy by LSP in the temperature range of 200–500 °C is shown in Fig. 4, which shows the absolute value of microscopic surface height of peak and valley increases gradually as the temperature increases. But all of the microscopic height distributes from −5 μm to 7 μm, illustrating that elevated temperature has a little change on the 2D surface topography of 6061-T651 aluminum alloy after LSP between 200 °C and 500 °C.

It could be observed from Fig. 5 that the surface roughness of 6061-T651 increases gradually in the temperature range of 25–500 °C.

Table 1
Chemical compositions of 6061-T651 aluminum alloy (wt%).

Cu	Mn	Mg	Zn	Cr	Ti	Si	Fe	Al
0.15–0.4	0.15	0.8–1.2	0.25	0.04–0.35	0.15	0.4–0.8	0.7	Bal.

Table 2
The parameters used in laser shock processing.

Type	Valve
Beam divergence of output (mrad)	≤0.5
Pulse energy (J)	6
Spot diameter (mm)	3
Laser pulse width (ns)	10
Repetition-rate (Hz)	5
Laser wavelength (nm)	1064

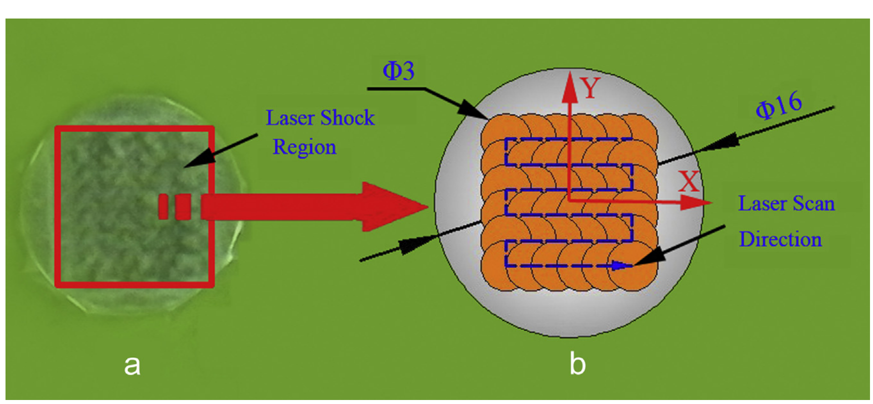

Fig. 2. Photograph of the specimen treated by LSP: (a) laser shock region and (b) laser scan direction.

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