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Surface nanocrystallization of metallic alloys with different stacking fault energy induced by laser shock processing

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ABSTRACT

Laser shock processing as a novel surface treatment technology, induces compressive residual stresses generation and microstructural transformation. However, compressive residual stresses will be relaxed under fatigue related conditions or elevated temperature conditions. Thus, we focus on the microstructural transformation especially surface nanocrystallization after LSP process. In this paper, the two typical alloys of TC6 titanium alloy and AISI 304 stainless steel were taken to study the surface nanocrystallization process, and the surface microstructures were characterized by transmission electron microscope (TEM) and electron back scattered diffraction (EBSD). The experiment results showed that nanostructure was formed in the surface layer with adequate laser parameters. In addition, we found that the more shock impacts or larger laser energy injected, the higher grain refinement degree was generated. Finally, surface nanocrystallization mechanisms of the two metallic alloys and the effects of different stacking fault energy on surface nanocrystallization were discussed in detail.

1. Introduction

Due to the maximal tensile stress always locates at the surface of components, where the fatigue crack is prone to initiate. In order to improve the fatigue resistance, surface treatment technologies, such as shot peening, deep rolling and laser shock processing (LSP), have been studied and successfully applied to some kinds of metallic materials [1]. They can induce high value compressive residual stresses generation and microstructural transformation.

As a superior surface treatment technology, laser shock processing (LSP) has been successfully applied to many alloys and proved to be effective in improving material properties including resistance against high cycle fatigue [1–8], foreign object damage (FOD) [9–12], wear [13,14]. C. Correa et al. [4] studied the effect of the pulse sequence during the LSP processing of stainless steel on the residual stress distribution and the fatigue life. The results indicated that fatigue life in laser peened specimens was increased from + 166% to + 471% by optimizing the pulse sequence. In addition, they developed a numerical model for the prediction of residual stress fields induced in real components by LSP [15]. Nie et al. [6] showed that LSP can effectively improve the HCF fatigue strength of TC11 titanium alloy from 483.2 MPa to 593.6 MPa. Wang et al. [14] discussed the effects of LSP on microstructure and mechanical properties. It is found that the fatigue life of laser-peened specimen was increased about 2.44 times compared with the original.

The above studies addressed the effects of LSP on HCF performance, in which compressive residual stresses induced by LSP are regarded to be a primary strengthening mechanism for HCF strength improvement [1–15]. But for thin specimens, such as the leading edge of compressor and fan blades, there is no sufficient material to restrain the lateral expansion of shock wave in the peened region, which leads to the compressive residual stresses induced by LSP extend through the thickness [16,17]. Moreover, residual stresses will be relaxed under fatigue related conditions or elevated temperature conditions [18,19]. On the other hands, surface microstructure and properties are sensitive to fatigue failures. Hence, optimization of the surface microstructure and mechanical properties can effectively improve the reliability of parts and prolong the service lifetime of components [20]. Results showed that LSP could not only significantly impart high value compressive residual stress and hardness in materials surface layer, but also induce obvious deformation of microstructures [21–34].

To characterize the deformation microstructures driven by LSP at high strain rates, Mordyuk et al. [21] conducted multiple LSP tests on AISI 321 stainless steel and found the generation of dislocation-cell structures and high tangled and dense dislocation arrangements in the surface layer. Similarly, Ye et al. [22,23] studied the dislocation structures in AISI 4140 stainless steel by warm laser shock peening and LSP treatment, they thought the stability of dislocation structures is an improvement factor for high temperature fatigue performance. Lu et al. [24] found that microstructure presents various configurations including high density dislocation, refined grain and even nanoscale grains at different depths of the LY2 aluminum alloy after multiple LSP impacts. H. Ding et al. [25] further studied the material strengthening

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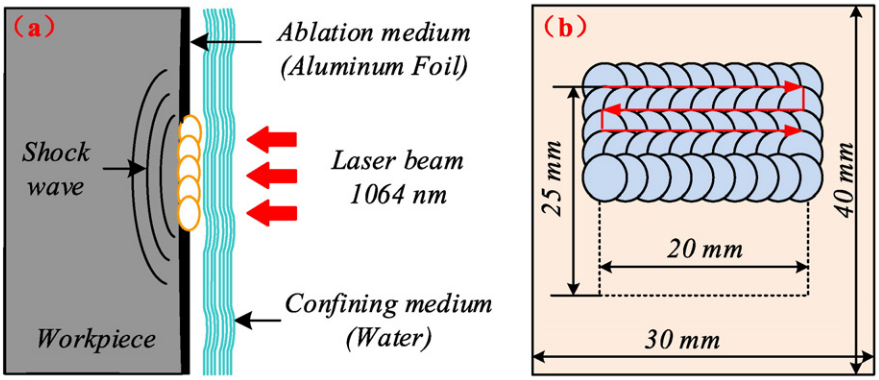

Fig. 1. Schematic illustrations of LSP process. (a) The plasma shock wave generated by nanosecond pulse laser; (b) dimensions, LSP processed area of samples for microstructure observation and laser shock paths (the dashed region is the LSP processed area with a 25 × 20 mm dimension on one side).

mechanism based on the dislocation density-based predictive mode. Nanoscale grains were also found after LSP treatment in titanium alloys [6–8], magnesium alloy [26] and stainless steel [27,28]. The microstructure changes [6–8,21–34] and the process of grain refinement [24,30] induced by LSP treatment have been explored in these years, and the surface nanocrystallization mechanisms for different stacking fault energy (SFE) induced by low strain rate plastic deformation were discussed [35]. However, little work exists in the open literatures regarding systematic research on the surface nanocrystallization mechanism of metallic alloys with different stacking fault energy induced by ultra-high strain rate plastic deformation. Understanding of this formation mechanism is crucial for the application of the LSP technology.

In this paper, the two typical materials of TC6 titanium alloy and AISI 304 stainless steel were taken to study the surface nanocrystallization process by the LSP treatment. The microstructure characteristics were characterized via transmission electron microscope (TEM) and electron back scattered diffraction (EBSD). Then the surface nanocrystallization mechanisms of the two metallic alloys induced by LSP were discussed, and the deformation mechanisms of metallic alloys with different stacking fault energy were further analyzed.

2. Experimental setups

2.1. Experimental process of LSP

The samples of TC6 titanium alloy and AISI 304 stainless steel for microstructure observation were cut into rectangular shapes with dimensions of 30 × 40 × 4 mm (width × length × thickness) are schematically shown in Fig. 1(b), and the composites of the two alloys are shown in Table 1.

In the LSP process, a water layer with about 1 mm thickness was used as the transparent confining layer and an Al foil with a thickness of 100 μm was used as the absorbing layer, as shown in Fig. 1(a). The detailed principle of LSP is described by Ye et al. [2]. The laser beam with a wavelength of 1064 nm and a pulse of around 20 ns was generated by a Q-switched Nd:YAG laser designed by ourselves (SGR-EXTRA/25J). To investigate the effects of laser power density and laser impacts on the microstructural transformation, considering the relationship between shock wave pressure and dynamic yield strength [2], the laser parameters of TC6 titanium alloy and AISI 304 stainless steel are chose and listed in Table 2. Due to the difference in dynamic yield strength of the two alloys, the different LSP parameters were chose in this work. The paths of laser spots were confirmed by our previous works [7,31] and laser-shocked area are shown in Fig. 1(b).

2.2. Microstructure observation methods

The microstructural characteristics in the different layers of the treated samples subjected to multiple LSP impacts were characterized by TEM-3010 transmission electron microscopy (TEM) and electron back scattered diffraction (EBSD). The cross-sectional TEM samples were made as follows: both sides of the samples were ground to make its thickness <100 μm. By means of lowering the Ion Milling (Gatan 691) from 4.8 kV to 3.2 kV and decreasing the angle from 15° to 4° to prepare the thin zone. This step takes 30 min. The TEM foils at different depths were made as follow: TEM foils at different depths into the surface were prepared by a combination of single and twin-jet electro polishing.

3. Results and discussion

3.1. Microstructure characteristics

3.1.1. TC6 titanium alloy

The microstructure changes of TC6 titanium alloy in the surface layer after LSP process with different parameters are shown in Fig. 2. The original features of the samples without LSP as illustrated in Fig. 2(a). Fig. 2(b) displays the high density dislocation generating near the grain boundary at the depth of 5–20 μm after one LSP impact with 4.24 GW/cm^2. According to the homogeneous nucleation theory [36], the generation of dislocation is contributed to the fact that the shock wave pressure is larger than the dynamic yield strength of the material. Due to higher shock wave pressure on the surface compared to the subsurface, high density dislocations change into dislocation walls and dislocation cells by slip, accumulation, and interaction as is shown in Fig. 2(c). Increasing the LSP impacts from one to three while keeping the laser power density at 4.24 GW/cm^2, the grains are refined to nanoscale, ranging from 60 to 300 nm, as shown in Fig. 2(d). This is attributed to the multiple plastic deformation caused by multiple LSP impacts, and thus nanocrystallines are generated on the surface of TC6 titanium alloy. The nanocrystals are smaller and more uniformity with the LSP impacts increasing. As is shown in Fig. 2(e), increasing the LSP impacts

Table 1
The composites of TC6 titanium alloy and AISI 304 stainless steel (mass fraction, %).

TC6 titanium alloy	Composition	Al	Mo	Cr	C	Fe	Si	Ti
	Percentage (wt.%)	5.5–7.0	2.0–3.0	0.8–2.3	0.10	0.2–0.7	0.15–0.40	Balance
AISI 304 stainless steel	Composition	C	Si	Mn	P	Cr	Ni	Fe
	Percentage (wt.%)	0.08	1.00	2.00	0.045	18.0–20.0	8.0–10.5	Balance