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Full length article

Surface gradient microstructural characteristics and evolution mechanism of 2195 aluminum lithium alloy induced by laser shock peening

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ABSTRACT

The peak-aged 2195 aluminum lithium alloy was treated by laser shock peening (LSP). The surface gradient microstructural characteristics of this alloy induced by ultrahigh strain rate deformation during LSP were systemically examined with transmission electron microscope (TEM), the observed results suggested that the grains refined and precipitates partially dissolved in the surface after LSP. The original coarse grains with average size of about 16 μm in length and 5 μm in width were refined instantly to equiaxed grains with size of about 91 nm at the top surface after LSP. The quantitative calculation of recrystallization kinetics proved that the grain refinement was the result of rotation dynamic recrystallization (RDR). The adiabatic temperature increase, the generation of high-density dislocations around the precipitates, and the increase of grain boundary area caused by grain refinement provided the thermodynamics and kinetics conditions for partial dissolution of precipitates. The microhardness tested results showed gradient distribution characteristics of microhardness values after LSP, and the maximum of microhardness was at the top surface of this alloy. The refined grains and deformed substructures played important roles on the enhancement of surface microhardness.

1. Introduction

Aluminum lithium alloys are optimal structural material in the field of aerospace, as the third generation aluminum lithium alloy, the 2195 aluminum lithium alloy had become one of the widely applied aluminum lithium alloys due to it's high specific strength, good toughness and excellent resistance to stress corrosion [1,2]. 2195 aluminum lithium alloy is the typical precipitates hardening type alloy and different heat treatment processes can adjust the property in every aspect to fit the requirement of different fields [3–5].

Laser shock peening (LSP) is a new technique for surface modification of alloys. With the constant breakthrough of laser research and the continuous deepening of material science research in recent years, the LSP technique have developed rapidly [6]. The influence of LSP or other high strains deformation on microstructure and mechanical property has been extensively investigated. Apps and Mordyuk did a series of intensive research on the effect of dispersoids on the grain refinement mechanisms during deformation of alloys to high strains [7–9]; Peyre found that LSP contributed to a 36% increase in fatigue limit of Al alloy A356 [10]; Lu focused on the microstructural characteristics of the surface of LY2 alloy after LSP and proposed that the dynamic process of grain refinement was finished under the mechanism of dislocation evolution [11]; Wang investigated the improvement of stress corrosion resistance, and held that this enhancement should attribute to the grain refinement of surface and the induction of residual compressive stress [12]. Nevertheless, most of the present investigations of the influence of aluminum alloy processed by LSP were limited to the characterization of microstructures and properties, and there was no systematic interpretation of dynamic evolution mechanism of microstructure induced by ultrahigh strain rate deformation in LSP.

In this paper, the peak-aged 2195 aluminum lithium alloy was treated by LSP, The microstructural evolution of 2195 aluminum lithium alloy induced by LSP was systematically investigated by means of TEM and XRD. The mechanism of partial dissolution of precipitates and gradient distribution characteristics of microhardness induced by ultrahigh strain rate deformation in LSP were stated, and it was the first time that the dynamic mechanism of surface grains instant refinement of 2195 aluminum lithium alloy under LSP was quantitatively explained at the base of recrystallization kinetics of rotation dynamic recrystallization (RDR).

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2. Material and methods

2.1. Sample preparation

The material used in this study was 2195 aluminum lithium alloy with the chemical compositions shown in Table 1, the furnishing conditions was hot rolled aluminum plate. The rectangular sample dimensions were 40 mm × 15 mm × 5 mm. The specimen was been solution treated in a salt bath furnace at 510 °C for 10 min and quenched down to room temperature in water, after that, the artificial age treatment was put on the sample at 180 °C for 12 h. The metallograph shown in Fig. 2-1 revealed that the grain size of 2195 aluminum lithium alloy was hard to grow significantly after solution treatment due to the existence of trace alloy element Zr, the fine and dispersive Al_3Zr particles formed by alloy element Zr pinned the grain boundaries effectively and retard the growth of grain [13]. The grain before LSP which size was about 16 μm in length and 5 μm in width exhibited the appearance of elongation which was similar to the original rolled alloy.

2.2. LSP experiment

A high pulse repetition rate laser, operated with a wavelength of 1064 nm, pulse width of 20 ns and pulse energy of 5 J, was used to deliver the pulse laser energy needed by LSP. In LSP experiment, the laser beam diameter was 3 mm and the overlapping ratio was 50%, a black tape had been used as the thermo-protective layer and flowing water with thickness of 1 mm was taken as the confining layer. The processing parameters used in LSP were listed in Table 2.

The thermo-protective layer material will vaporize and form a plasma instantaneously when laser pulse passes through the confining layer, and the constantly expanding plasma will creat a shock wave to the surface of target alloy because of the existence of confining layer. When the pressure of shock wave exceeds the dynamic yield strength of target alloy, it produces the evolution of surface microstructure and the enhancement of surface properties. The LSP principle and process route was schematically shown in Figs. 2-2 and 2-3 respectively.

Table 1
Chemical composition of 2195 Al-Li alloy.

Component	Cu	Li	Mg	Ag	Zr
wt/%	4.0	1.0	0.4	0.4	0.12

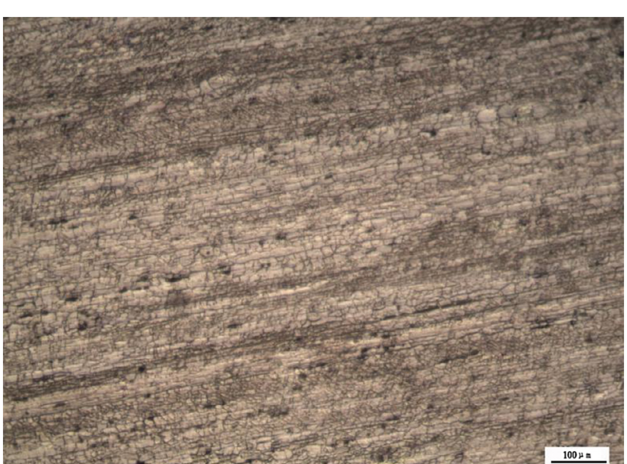

Fig. 2-1. Metallograph of 2195 aluminum lithium alloy before LSP.

Table 2
Processing parameters used in LSP.

Type	Value
Spot diameter/mm	3
Pulse energy/J	5
Pulse width/ns	20
Laser wavelength/nm	1064
Energy stability/%	≤±1.5
Overlapping ratio/%	50

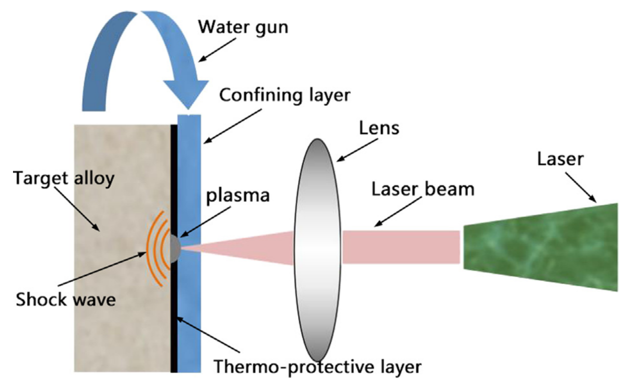

Fig. 2-2. Schematically principle of LSP.

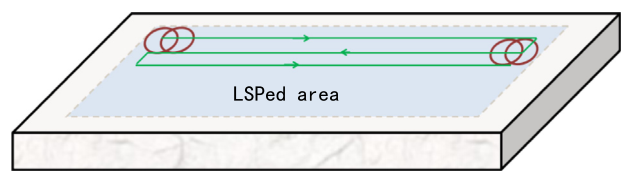

Fig. 2-3. Schematically process route of LSP.

2.2.1. Thermal/mechanical parameters of LSP

The laser power intensity (I_0) was calculated based on formula (1) [14], where E(J) is the pulse energy, τ(ns) is the laser pulse duration time, d (mm) is the laser pulse spot size. The E, τ and d in this study were set to 5 J, 20 ns and 3 mm, respectively. I_0 was calculated to be 3.54 GW/cm^2.

$$I_0 = \frac{4E}{\tau \cdot \pi d^2} \quad (1)$$

$$P = 0.01\sqrt{\frac{\alpha}{2\alpha + 3} \cdot Z \cdot I_0} \quad (2)$$

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \quad (3)$$

The peak pressure of laser-induced shock calculated by formula (2) [15] was 2.5 GPa, where α is the coefficient of internal energy conversion to thermal energy, the best value of α is 0.2 in water confined mode [16]. Z (g·cm^{-2}/s) is the synthetic shock acoustic impedance of target alloy and confining layer which is defined as formula (3) [15], where Z_1 is the shock acoustic impedance of target alloy of 2195 aluminum lithium alloy which is 1.7×10^6 g/cm^2/s, and Z_2 is the shock acoustic impedance of confining layer of water which is 0.165×10^6 g/cm^2/s [16].

The key point of LSP is that the peak pressure of laser-induced shock should be greater than dynamic yield limit of target alloy. Cao investigated the dynamic strain characteristics of 2××× aluminum alloys under pulsed laser by means of STSS-1 stress