Materials Science & Engineering A 704 (2017) 459–468

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of laser shock peening on the high-temperature fatigue performance of 7075 aluminum alloy

J.T. Wang[a,b,*], Y.K. Zhang[b,c], J.F. Chen[a], J.Y. Zhou[a], K.Y. Luo[b], W.S. Tan[d], L.Y. Sun[a], Y.L. Lu[a]

[a] School of Materials Engineering, Jiangsu University of Technology, Changzhou 213001, PR China
[b] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, PR China
[c] School of Mechanical Engineering, Southeast University, Nanjing 211189, PR China
[d] Changzhou Key Laboratory of Large Plastic Parts Intelligence Manufacturing, Changzhou 213164, PR China

ARTICLE INFO

Keywords:
Aluminum alloy
Laser shock peening
Microstructural observation
High temperature fatigue
Fracture

ABSTRACT

7075 aluminum alloy was subjected to intensive laser shock peening (LSP), and the effect of LSP on the microstructure and high-temperature fatigue properties of the alloy at various elevated temperatures was investigated. Microstructural characterization of the laser-shock-peened (LSPed) material was performed with scanning electron microscopy (SEM) and transmission electron microscopy. The LSPed sample exhibited an improved high-temperature fatigue performance. Its fatigue life increased by 110% at 150 °C. Grain refinement, work hardening, and precipitates were detected through SEM. After LSP, significant changes in surface morphology in three stages of high-temperature fatigue were examined. Results suggested that the highly dense dislocation structure and high compressive residual stress induced by LSP significantly improved the high-temperature fatigue performance of the 7075 aluminum alloy.

1. Introduction

Aluminum alloys are currently used in critical components subjected to thermal and mechanical fatigue loading conditions in industrial applications. During service, aluminum alloys are often required to withstand high-temperature alternating loads. Therefore, the high-temperature fatigue performance of aluminum alloys has gained much attention and has been investigated comprehensively [1–3]. Researchers are interested in various process parameters and their effects on high-temperature fatigue. Increasing the performance of a selected material is also important in actual practice. Laser shock peening (LSP) is an effective mechanical surface treatment technique that not only enhances the wear [4] and corrosion resistance [5–8] of metallic parts but also effectively increases the high-temperature fatigue tolerance of these parts [9–13]. Many studies [9–11] have proven that LSP provides better resistance to thermal relaxation of residual compressive stress under simulated service conditions compared with conventional mechanical surface treatments, such as shot peening. However, Zhou et al. found that the residual compressive stress induced by LSP exhibits thermal relaxation when LSP is applied to high-temperature components of aircraft engines [12,13].

7075 aluminum alloy is an important material in automotive and defense-related industries. Under service conditions, its weight needs to be reduced, and its strength must be improved. This alloy can be effectively used as structural parts because of its excellent characteristics of low density, high strength, and high specific stiffness [14]. However, only a few researchers have investigated the effect of LSP on the high-temperature fatigue performance of 7075 aluminum alloy. Therefore, the focus of the present work is to systematically reveal the positive effects of LSP on the fatigue performance of 7075 aluminum alloy under high temperatures. We also examine the salient microstructural mechanisms underlying such a behavior.

2. Experimental details

2.1. Materials selected

The material investigated was 7075 aluminum alloy with a chemical composition of 5.5 Zn, 2.0 Cu, 2.1 Mg, 0.3 Mn, 0.5 Fe, 0.4 Si, 0.19 Cr, and 0.2 Ti–Al (wt%). The samples subjected to T6 heat treatment had a tensile strength, yield strength, and elongation of 538 MPa, 476 MPa, and 8%, respectively.

All samples were fabricated according to ASTM: E466–07(2007), and the dimensions and schematic of standard stretched fatigue specimens are shown in Fig. 1. The specimens were cut from the same rods. Half of the samples were directly machined without LSP treatment. The

* Corresponding author at: School of Materials Engineering, Jiangsu University of Technology, Zhongwu Road 1801, Zhonglou District, Changzhou 213001, PR China.
E-mail address: jiasqq1225@126.com (J.T. Wang).

http://dx.doi.org/10.1016/j.msea.2017.08.050
Received 6 February 2017; Received in revised form 13 August 2017; Accepted 14 August 2017
Available online 15 August 2017
0921-5093/

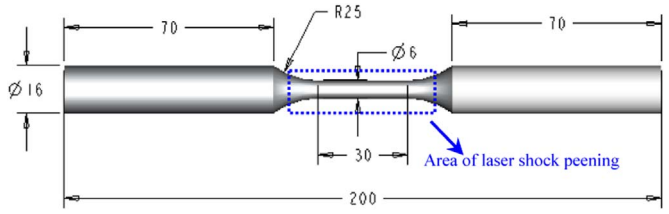

Fig. 1. Dimensions of the specimens used in the test (unit: mm).

specimens were initially polished with silicon carbide paper of 1000, 1200, and 1600 grits and subsequently polished with a cotton mop. Before each experimental measurement, the surface of the specimens showed low roughness and good brightness, and no small scratches existed on the surface.

2.2. LSP

The specimens were subjected to shock provided by a Q-switched Nd: YAG laser system at Laser Technology Institute, Jiangsu University. The specimens were covered by a layer of aluminum tape (ablative layer) with a thickness of 0.1 mm and a tamping layer of flowing water with a thickness of about 2 mm before LSP treatment to improve the absorption of laser energy and protect the surface from thermal damage caused by the high-temperature plasma. A beam laser with a pulse energy of 9 J, spot diameter of 1 mm, and pulse duration of 18 ns was employed. The overlap rate between the two adjacent round spots was 50%, and the shock area was 12.274 mm × 60 mm (Fig. 1).

As shown in Fig. 2(a), the radial route of LSP was a circle, and the axial route contained two arcs and one line. The LSP effects began from the intersection point of these two routes. The specimen contrarotated around the A-1 axis by 6.6°, and the LSP effects continued. They were repeated until the circle route was completed. The laser beam moved by 1 mm along the axial route and continued. The full expansion plane of the LSPed zone is shown in Fig. 2(b). The overlapping rate was ensured by changing the angle of rotation (θ) of the specimen, as shown in Fig. 2(c).

2.3. Micro-structural observations

After LSP treatment, the sections perpendicular to the sample surface obtained from the two groups of samples were cut for metallographic investigation and subjected to several successive steps of grinding and polishing. Then, the samples were died on a circular plate with a thickness of about 40 μm and a diameter of 3 mm. The microstructures of these two groups of samples were analyzed with a transmission electron microscope (JEM-2100) operated at 200 kV after being electro-polished by a DJ2000 device with a solution consisting of 5 ml of $HClO_4$ and 95 ml of alcohol.

2.4. Measurements of residual stress

The residual stresses on the surface of specimens and along the depth were measured with a commercial X-350A X-ray diffractometer (XRD) via the sin2ψ method and by employing Ni filtered Cu-Kα radiation. The diffraction peak was a phase (311) plane at 10 different tilt angles. The measurement angle was from 144° to 135°, with 0.01° per step and 1 s stop per step. The electro-polishing material removal method was used to measure the residual stress along the depth direction. The surfaces were etched by a solution that consisted of 10 ml of $HClO_4$ and 90 ml of alcohol for 10 s at room temperature. The device operated at 23 V and 1.0 A. These tests were repeated when the deviation exceeded 20 MPa. The measurements were repeated five times for each condition, and the average value was used.

2.5. Procedure for fatigue testing

All samples were ultrasonically cleaned in ethanol to remove contaminants from the LSP process and ensure test reliability. The high-temperature fatigue test was performed on a MTS fatigue testing machine (model 809) equipped with an MTS extensometer at 25 °C and 250 °C. The load-control system of the test was used. Smooth fatigue specimens with a 6 mm diameter were subjected to tensile loading according to a closed-loop actual stress strain control to determine the fatigue strength at high temperatures (i.e., 150 °C, 200 °C, and 250 °C). Each stress level was implemented with a constant amplitude at a load frequency of 30 Hz (sinusoidal loading) and a load ratio of R = 0.1. The untreated samples and those with massive LSP effects with pulse energies of 9 J were fatigue tested. The measurements for the fatigue test were repeated three times for each condition, and the average value was selected. The fatigue fracture surfaces were then examined through scanning electron microscopy (SEM).

3. Results and discussion

3.1. Residual stress distribution

The residual stresses were measured in longitudinal directions at 13 locations in the sample, as shown in Fig. 3. The surface residual stresses before and after LSP are shown in Fig. 4. The figure shows that LSP treatment changed the residual stress from tensile (about 15 MPa) to compressive (about −175 MPa) at room temperature.

Measurements of the depth profiles of the residual stresses were conducted to assess the stress of the samples exposed to different temperatures with a duration time of 180 min [Fig. 5(a)]. The distribution of the residual stress on the surface under different duration times was also examined [Fig. 5(b)]. Fig. 5(a) shows that the residual stress relaxations were not evident when the temperature increased from room temperature to 200 °C. When the temperature reached 250 °C, the residual compression stress on the surface layer decreased

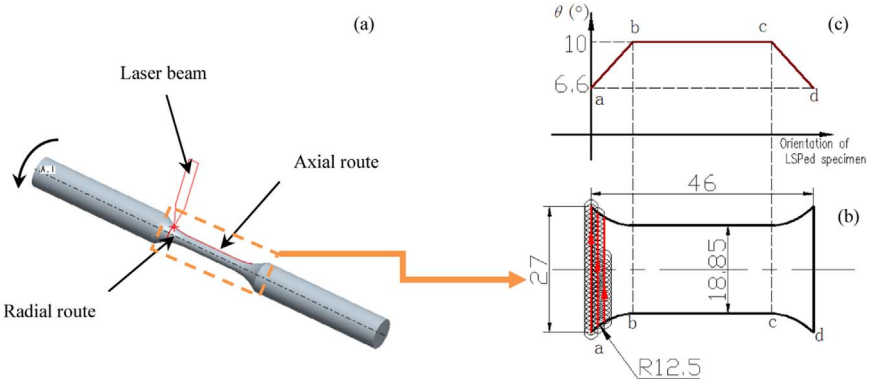

Fig. 2. Schematic of LSP on the specimen (unit: mm).