Short communication

Laser shock peening on fatigue behavior of 2024-T3 Al alloy with fastener holes and stopholes

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Abstract

The effect of laser shock peening on the fatigue behavior of 2024-T3 aluminum alloy with a fastener hole, multiple crack stopholes and single-edge notch was investigated. Laser shock peening (LSP) was performed under a ‘confined ablation mode’ using a Nd:glass laser at a laser power density of 5 GW cm⁻². The fatigue crack initiation life and fatigue crack growth rates of the Al alloy, with different preexisting notch configurations, were characterized and compared with those of the unpeened material. The results clearly show that LSP is an effective surface treatment technique for improving the fatigue performance of Al alloys having various preexisting notch configurations. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Laser shock peening (LSP) is a promising surface treatment technique and has been shown to be effective in improving the fatigue properties of a number of metals and alloys. The process was originally developed at the Battelle Columbus Laboratory in the 1970s [1–6]. Since then considerable attention has been paid to potential applications of LSP in the aerospace and automotive industries. The beneficial effects of LSP on static, cyclic, fretting fatigue and stress corrosion performance of aeronautical and automotive aluminum alloys, steels and nickel-based alloys have been demonstrated [7–14]. LSP has also been successfully used for improving the resistance to foreign object damage of aircraft gas turbine engine blades. Since laser beams can be easily directed to fatigue-critical areas without masking LSP technology is expected to be widely applicable for improving the fatigue properties of metals and alloys, particularly those that show a positive response to shot peening.

The objectives of this work was to examine the effect of laser shock peening on the fatigue behavior of Al alloy specimens having a fastener hole, crack stop-holes and single-edge notch. It is well-known that cracks initiate at the fastener holes in aircraft structures under fatigue loading. It is also known that stopholes can be used to arrest fatigue cracks and to extend the fatigue life of aircraft structures. In practice, one stophole at each end of a fatigue crack is usually used to immediately slow down its propagation rate for tolerable cracks. However, a previous study indicated that multiple in-line end holes at each end of a straight crack with the axes perpendicular to the crack and parallel to the loading direction may reduce the stress concentration further than for the case of a single stophole at each end [15]. Therefore, multiple stopholes would be an useful repair method to increase the fatigue life of aircraft structures. The introduction of residual compressive stress through LSP is expected to further suppress the fatigue crack initiation and to extend the fatigue life of aircraft structures.
2. Physics and mechanics of laser shock peening

With the advent of pulsed laser it was soon recognized that relatively high amplitude shock waves required for peening could be achieved by means of tamped (confined) plasma. For the ‘confined plasma’ laser shock a dual layer coating is applied to the surface over the area being treated. This consists of a thin film of material opaque to the laser beam (such as black paint, metallic foils), which is placed directly on the surface of the part and a second layer, transparent to the laser beam (such as water, glass), which is placed over the opaque film. As the high-energy laser beam strikes the material it passes through the transparent film and is absorbed by the opaque film, causing a thin layer of the material on the surface of the opaque film to vaporize. As the vapor continues to absorb the laser energy it is readily heated and ionized into a plasma. The rapidly expanding plasma is confined against the surface of the material by the transparent overlay, creating a high surface pressure which propagates into the material as a shock wave. The resulting shock wave plastically deforms the material below the surface to a depth at which the peak stress no longer exceeds the Hugoniot elastic limit (HEL, the compressive yield strength of a material under a shock condition) of the metal, and produces a residual compressive stress throughout the affected depth. This process is referred to as laser shock peening. Since the opaque coating protects the material from melting and vaporization, LSP is a pure mechanical treatment inducing plastic flow and compressive residual stress. Also, an important feature of this residual stress is that it extends more than 1.0 mm below the surface, compared with a typical depths of 0.25 mm for conventional shot peening.

The mechanical effects of a laser-induced shock wave have also been evaluated to predict the plastic strain and residual stress fields induced by an impact pressure and the pressure pulse duration. A simple elastic-plastic model was developed based on a calculation of the elastic-perfectly plastic response of a material to both longitudinal and planar shock wave systems. The calculated plastically affected depth, the surface plastic strain and the surface residual stress induced by LSP of an elastic-perfectly plastic materials are summarized in Ref. [10].

3. Experimental procedure

The material used in this study was 2024-T3 aluminum alloy. The T3 condition consists of a solution heat treatment, cold working and natural aging. The yield strength and ultimate tensile strength of the alloy is 345 and 483 MPa, respectively. Specimens with dimensions of 15.2 × 5.08 × 0.25 cm were prepared. The geometries of the specimens having a fastener hole, one and three in-line crack stop-holes are shown in Fig. 1. The stress concentration factor in the specimens with single and multiple stop-holes was calculated using finite element analysis [15]. The fastener hole and crack stop-holes were prepared using electrical discharge wire machining.

The laser used in this study was a solid state Nd:glass laser with a wavelength of 1.054 µm and a pulse duration of 18 ns. The laser beam spot size was maintained at 10 mm at the full width at half maximum of the near-Gaussian intensity profile. The LSP was conducted using a confined plasma configuration. A thin layer of black paint was used as the sacrificial, energy-absorbing layer. A thin water tamping layer was used as the plasma confinement layer. Both sides of the specimens were shocked under the same condition. The laser power density used was 5 GW cm⁻². After LSP the black paint sacrificial coating was removed using acetone.

The residual stress generated by LSP was measured using the X-ray diffraction technique. The surface morphology and microstructure was analyzed by electron microscopy. The fatigue behavior of the laser-peened aluminum alloys was conducted under a tension–tension mode at room temperature with a stress ratio (R) of 0.1 and a frequency of 10 Hz. The maximum stress used in this study was 100 MPa. The fracture morphology of the laser-peened and unpeened Al alloy after fatigue loading was examined by scanning electron microscopy.

4. Results and discussion

After LSP a homogeneous impression was generated on the surface of the specimen. The surface residual compressive stress measured by X-ray diffraction was found to be 385 MPa. As expected, a high compressive residual stress was generated by LSP. An earlier TEM
The fatigue crack lengths as a function of fatigue cycles for the laser-peened and unpeened 2024-T3 Al with various pre-existing notches. The results clearly demonstrate that three in-line holes at each end of the crack is more effective for stress reduction and crack stopping than the typical one-stophole at each end of a fatigue crack.

Second, it is evident that LSP has a significant effect on the fatigue behavior of the Al alloy. As shown in Fig. 2 and Table 1 the fatigue crack initiation life and fatigue life for the laser-peened materials are substantially higher than those of the unpeened material. The ratio of fatigue crack initiation life for the laser-peened and unpeened specimens was found to be 5.7, 1.6 and 1.6 for specimens having a center hole, three in-line crack stop-holes and single crack stop-hole, respectively. The improvement of fatigue crack initiation life decreases gradually as the stress concentration factor, near the notch root, increases. Furthermore, the fatigue crack growth rates in the laser-peened specimens are an order of magnitude lower than those of the unpeened specimens. The combination of longer crack initiation life and slower crack growth rates would greatly enhance the fatigue life of the Al alloy.

In order to examine the fatigue crack growth behavior the laser-peened Al alloy specimens were loaded to fracture under static tensile loading. The fracture morphology of the laser-peened Al specimen is shown in Fig. 3a and b. Fatigue striation patterns were clearly observed on the fracture surface of both the laser-peened and unpeened Al alloys. However, the spacing of the fatigue striations in the laser-peened specimen is less than those observed on the unpeened one. This is indicative of a slower fatigue crack growth rate. The reduction of fatigue crack growth rates can be at-
tributed to an introduction of residual compression stress. As a result, the effective stress intensity factor that controls the fatigue crack growth in the laser-peened specimen is lower than that of the unpeened case.

5. Summary

The results show that LSP is an effective surface treatment technique for improving the fatigue life of Al alloys having various preexisting notch configurations.

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References