

# Spallation-Like Phenomenon Induced By Laser Shock Peening Surface Treatment On 7050 Aluminum Alloy

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**ABSTRACT** Laser shock peening (LSP) is a promising surface treatment for fatigue life extension of metallic materials. The benefits include deeper residual stresses (>1 mm) and a smoother surface finish than conventional glass bead peening. However, fatigue tests on 7050 aluminium alloy specimens have shown that LSP may cause a reduction in life due to internal cracking generated during the process. A series of tests were carried out to identify any technological risks such as internal cracking associated with the use of LSP. Numerical modelling was also carried out and the results of this numerical prediction agreed well with the experimental results.

## 1 INTRODUCTION

Laser Shock Peening (LSP) is an innovative surface treatment method, which has been proven to greatly improve the fatigue life of many metallic components [Thompson, et al, 1997; Liu, et al, 2002a]. Compared to conventional Shot Peening (SP), the LSP process introduces a deeper layer of compressive residual stresses - up to a millimetre deep [Clauer and Lahrman, 2000] - whereas SP provides a compressive residual stress layer of about 250  $\mu\text{m}$  deep. LSP produces very little or no modification of the original surface roughness or dimensions of the component and has been successfully applied to increase fatigue life, reduce fretting fatigue, enhance resistance to corrosion and increase compressor blade foreign object damage resistance [Peyre, et al, 1995; Clauer, 1997; Dane, et al, 1997; Ruschau, et al, 1999]. The results of previous testing by the Defence Science and Technology Organisation (DSTO), Australia, have demonstrated LSP to be effective in extending the life of extruded 7075-T6 Al alloy coupons [Liu, et al, 2002a]. However, experimental results [Liu, 2002b] also revealed that some problems might arise under particular conditions, which will prevent the achievement of the full potential life extension. This paper reports the results of an investigation into the effect of laser power density on the fatigue life of 7050-T7451 aluminium alloy and the internal cracking phenomenon.

## 2 MATERIAL AND EXPERIMENTAL PROCEDURE

### 2.1 Material and Specimen Geometry

The material under investigation in this paper is a 7050-T7451 aluminium alloy which is mainly composed of ~2.07Cu, 2.05Mg, 6.05Zn and bal. Al in wt.%. The test specimens were manufactured from the 150 mm thick plate. The specimens were cylindrical with a reduced central area with a continuous radius in the form of an 'hour glass'. The diameter at the middle section was 10 mm.

### 2.2 Surface Treatment by LSP and SP

The laser system was a dual Q-switched high energy-pulsed neodymium (Nd)-glass phosphate laser with a wavelength of 1.054  $\mu\text{m}$  and pulse duration of 15 to 25 ns (nanoseconds). Its repetition rate was 0.125 to 0.25 Hz. The averaged laser beam diameter was about 5.5 mm. The system was configured to 'shot' simultaneously from two opposing sides and was used in this configuration to treat the specimens here. For comparison, a number of specimens received glass bead peened surface treatment with a coverage rate of 200% and Almen intensity of about 8A. Some of the specimens were tested in un-peened (as-machined surface) condition as benchmark.

### 2.3 Testing Procedure and Metallographic Analysis

The fatigue specimens used for this work were surface treated by LSP by LSP Technology, Inc, USA. The fatigue tests were conducted in a MTS 100kN, digitally controlled test machine, under load control mode, using a wing root bending moment load spectrum representative of about 300 hours of service for a military fighter aircraft. The applied stress was 390 MPa. The test frequency was 10 Hz. The fracture surface of the specimens treated by LSP was analysed using an optical microscope.

### 3 MODELLING OF LASER SHOCK PEENING PROCESS

A 3-D finite element model was developed to simulate the LSP process, where two laser pulses simultaneously impact both sides of the target surface. For simplicity, a square laser spot replaced the circular one. Since the model was symmetrical in geometry and subjected to a symmetric impulse pressure [Ding, et al, 2002], a “quarter model” was used instead of a full model to speed up analysis. A schematic of the configuration of the finite element (FE) model with finite and infinite elements as well as boundary conditions is shown in Figure 1, where the radius (R) is 6 mm. To simulate the two-sided LSP process, some assumptions were made for the FE calculation. These were: (1) Infinite elements being adopted for non-reflecting boundaries; (2) The specimen material would obey a Von Mises plasticity criterion; (3) The pressure pulse induced by the plasma was uniform over the entire surface of the laser spot; and (4) The dynamic yield strength ( $\sigma_y^{\text{dyn}}$ ) under uniaxial stress conditions defined in terms of Hugoniot elastic limit (HEL) [Johnson and Rohde, 1971]. In the FE analyses, the ABAQUS codes were used to calculate the propagation of the short duration shock wave and the dynamic stresses in the target [ABAQUS, 2001] The detail of the finite element analysis can be seen in [Ding, et al, 2002].

### 4 EXPERIMENTAL RESULTS AND DISCUSSION

#### 4.1 Fatigue Testing Result

A previous study found a spallation-like phenomenon (i.e. internal cracking) [Liu, et al, 2002b]. In order to further understand the effect of laser power density on the fatigue life, a series of tests with a range of laser power densities, from 2 GW/cm<sup>2</sup> to 7 GW/cm<sup>2</sup>, were performed on the 7050 Al specimens, with the same geometry as in the previous study. Figure 2 shows the experimental results of the fatigue life as a function of laser power density. This result clearly shows that when the laser power density is 5 GW/cm<sup>2</sup> or higher, the fatigue life is dramatically reduced. The reason for this reduction of the fatigue life is the formation of internal cracks in the specimens during the laser treatment, which act as large crack initiators, larger than any surface discontinuities. Below this 5 GW/cm<sup>2</sup> value, internal crack was only found at 3 GW/cm<sup>2</sup> level. The causes of the internal crack in some 3 GW/cm<sup>2</sup> specimens are still being analysed. As Figure 2 clearly shows when LSP is optimal, a 3 times increase in fatigue life can be achieved over un-peened specimens compared to 1.5 – 2 times for glass bead peened specimens at this high peak fatigue stress of 390 MPa. However, under some conditions the fatigue life is equal to or less than the as-machined mean value.

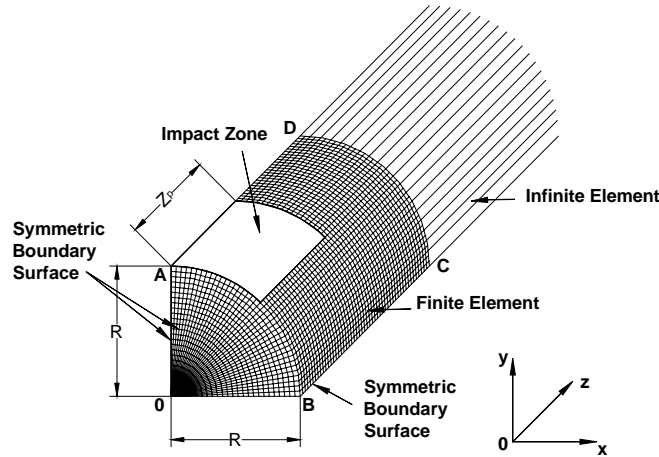


Fig.1 Three-dimensional (3D) Finite element model with symmetric boundary conditions

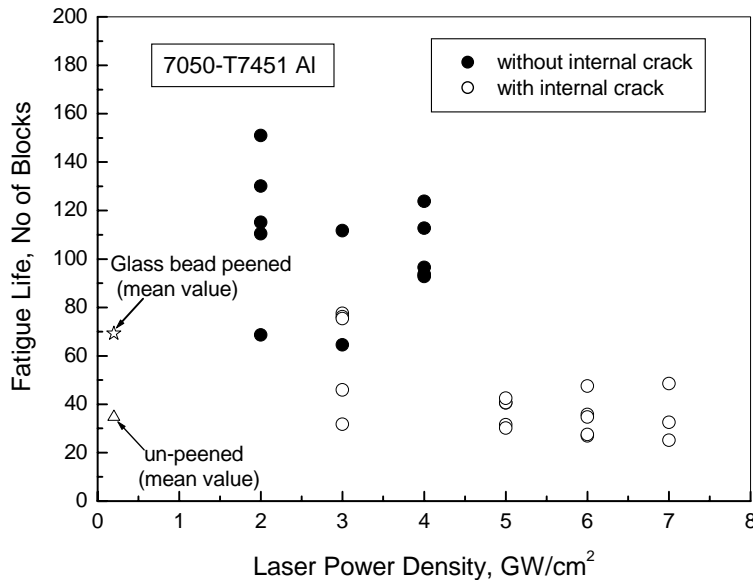


Fig.2 Fatigue life as a function of laser power density on LSP 7050 Al specimens under spectrum loading at applied peak stress of 390MPa.

#### 4.2 Fracture Surfaces

A typical macroscopic fracture appearance of a LSP fatigue specimen is shown in Figure 3. In this figure, (a) shows the overall appearance of a fracture and (b) shows the detail of internal cracking near the central axis of the specimen. The bright area shown by dashed line in Figure 3 was the fatigue zone. Except for the central internal cracking, there existed multiple surface cracks in new 7050 Al series specimens. The main reason for this was the presence of surface black ‘burnt’ spots (defects). The large in-plane cracks initiated perpendicular to the fatigue cracks. The overall fracture profiles in the LSP specimens were typically extremely uneven since many fatigue cracks on different planes were initiated by these large laser induced cracks. More details of fractographic analysis can be found in a DSTO report [Liu, et al, 2004].

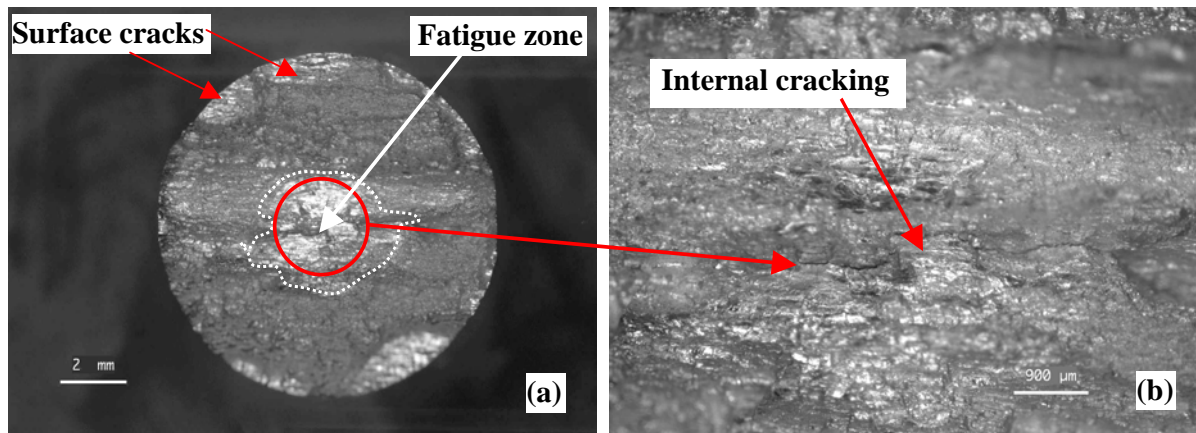


Fig.3 Macroscopic appearance of 7050-T7451 aluminium alloy (new series) induced by LSP at the applied peak stress of 390MPa laser power density of  $7\text{GW}/\text{cm}^2$ : (a) the overall appearance of the fracture and (b) the macroscopic cracks are clearly shown across the centre of the specimen.

### 4.3 Numerical Analysis

As stated previously, laser power density has a significant influence on fatigue life of LSP 7050 specimens through the occurrence of internal cracking. These cracks are closely related to the dynamic tensile stresses and material properties. The former is dependent on the plasma pressure generated on the surface of the specimen. If the laser power density is increased, the plasma pressure is also increased. Consequently, the amplitude of the dynamic tensile stress wave is increased.

Figure 4 shows the distribution of the predicted dynamic stresses along the y-direction (refer to Figure 1) at different times with different pressures applied to the surface of the specimen. The results show that at the beginning, the compressive stresses occur near the treated surfaces. The peak compressive stress is about -2000 MPa. However, the peak compressive stress is reduced with time. Increasing the peak pressure leads to an increase in amplitude of both compressive and tensile stresses. At the same time (i.e. 1200 ns after the peening) near the centre of a specimen, the dynamic tensile stress can reach a very high level, which may exceed the critical stress of the material.

Once the tensile stress exceeds the critical stress, a crack can form. For example, Figure 4 shows the numerical results under the peak surface pressure of 2.7 GPa (corresponding to a laser power density of  $7\text{GW}/\text{cm}^2$ ). At the solution times<sup>1</sup> of 800, 1000 and 1200 ns, the peak tensile stress reaches 1200, 1060 and 1210 MPa at 2.27, 1.01 and 0 mm from the centre of the specimen, respectively. With decreasing surface pressure (i.e. laser power density), the corresponding stresses are reduced. The dynamic fracture strength of the 7050 Al specimens is  $\sim 900\text{MPa}$ . [Liu, et al, 2004]. Figure 5 shows the relationship between the predicted dynamic tensile stress and peak surface pressure during the LSP process. Clearly, when the pressure is higher than about 2.2GPa (corresponding to a laser power density of  $4.65\text{GW}/\text{cm}^2$ ), the local tensile stress can easily reach the critical tensile stress ( $\sim 900\text{MPa}$ ), leading to the formation of a crack.

<sup>1</sup> The solution time means the time that is simulated by the analysis. The analysis can simulate the stress states that would exist at specific time after the peening.

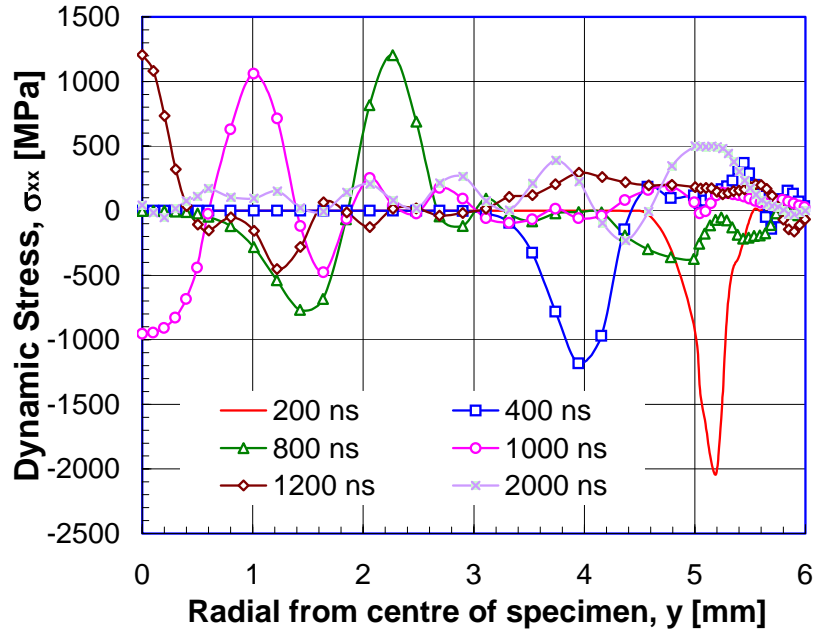


Fig. 4 Dynamic stress distributions,  $\sigma_{xx}$ , in the radial direction ( $y$ ) at the end of six increments at the surface pressure of  $P = 2.7$  GPa (corresponding to laser power density of  $7 \text{ GW/cm}^2$ ).

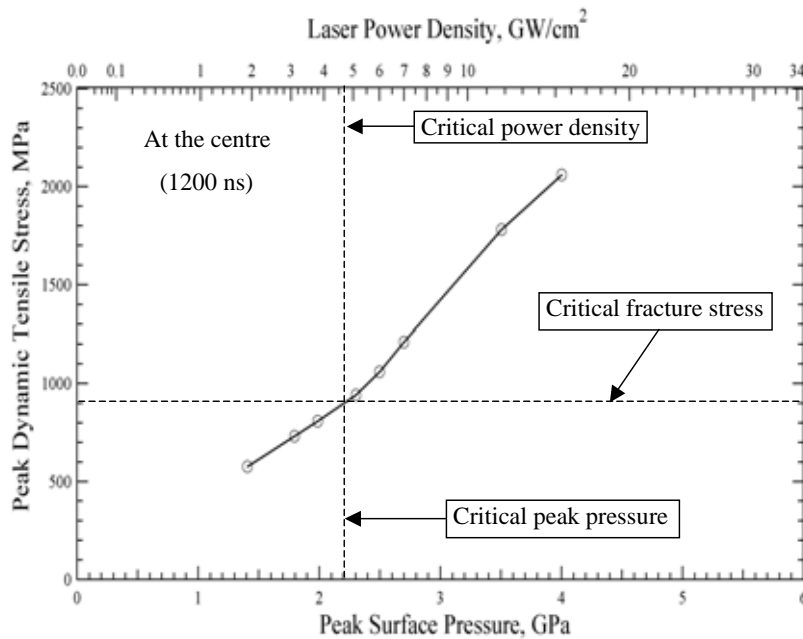


Fig. 5 Peak tensile stress as a function of peak surface pressure during the LSP process on 7050 Al specimens predicted by the 3D finite element analysis

## 5 CONCLUSIONS

The phenomenon of the internal cracking in 7050-T7451 aluminium alloy induced by LSP was investigated. One of the main factors causing the internal cracking was studied by experimental and numerical analysis. Conclusions can be drawn as follows:

- (1) The internal cracking caused by LSP in 7050 Al specimens was responsible for their shorter-than-expected fatigue life.

- (2) The numerical model developed to predict what power density levels could cause internal cracks was verified by the experimental results.
- (3) The laser power density is one of main factors causing the internal cracking in LSP specimens of 7050 aluminium alloy. When the laser power density is higher than a critical value, internal cracking can take place within the material, which shortens its fatigue life. In this investigation, the critical value was found to be about  $4 \sim 5 \text{ GW/cm}^2$  obtained from both experimental and numerical results, although unaccounted for geometry effects may make the safe critical power density lower.
- (4) The causes of anomalous results from the  $3 \text{ GW/cm}^2$  power density level are being investigated.
- (5) If LSP process is optimised for the material/configuration, fatigue life extension can be achieved.

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