REVISTA MEXICANA DE FÍSICA **51 SUPLEMENTO 1**, 16–18 MAYO 2005

Effect of laser shock processing on fatigue crack growth of 6061-T6 aluminum alloy

C. Rubio-González[1,*], G. Gomez-Rosas, M. Paredes, and A. Banderas
Centro de Ingeniería y Desarrollo Industrial
Pie de la cuesta No. 702, Desarrollo San Pablo, 76130 Querétaro, Qro., Mexico
e-mail: [1]*crubio@cidesi.mx*

J.L. Ocaña, C. Molpeceres, and J. Porro
Departamento de Física Aplicada a la Ingeniería Industrial, E.T.S.I.I. Universidad Politécnica de Madrid. Spain

Recibido el 22 de septiembre de 2003; aceptado el 15 de julio de 2004

Laser shock processing (LSP) or laser shock peening is a new technique for strengthening metals. This process induces a compressive residual stress field which increases fatigue crack initiation life and reduces fatigue crack growth rate. Specimens of 6061-T6 aluminum alloy are used in this investigation. A convergent lens is used to deliver 1.2 J, 8 ns laser pulses by a Q-switch Nd:YAG laser, operating at 10 Hz. The pulses are focused to a diameter of 1.5mm onto a water-immersed type aluminum samples. The effect of pulse density in the residual stress field is evaluated. Residual stress distribution as a function of depth is assessed by the hole drilling method. It is observed that the higher the pulse density, the larger the area with compressive residual stress. Densities of 900, 1350 and 2500 pulses/cm^2 with infrared (1064 nm) radiation are used. Pre-cracked compact tension specimens were subjected to LSP process and then tested under cyclic loading with $R = 0.1$. Fatigue crack growth rate is determined and the effect of LSP process parameters is evaluated. Fatigue crack growth rate is compared in specimens with and without LSP process.

Keywords: Fatigue test; laser shock processing; residual stress

El proceso denominado impacto por láser (LSP, por sus siglas en inglés), o granallado por impacto láser, es una nueva técnica para aumentar la resistencia de los metales. Este proceso induce un campo de esfuerzos residuales de compresión, que incrementa la vida previa a inicio de fractura bajo fatiga y reduce el rango de crecimiento de fractura por fatiga. En esta investigación se usan especímenes de aleación de aluminio 6061-T6. Se utiliza una lente convergente para generar una energía de 1.2 J, con pulso láser de 8 ns, mediante un interruptor Q-Nd; Láser YAG, operando a 10 Hz, los pulsos son enfocados a un diámetro de 1.5 mm sobre especímenes de aluminio sumergidos en agua. El efecto de la densidad del pulso en el campo residual de esfuerzos es evaluado. La distribución residual de esfuerzos, como una función de la profundidad, es determinada mediante la perforación de un agujero. Se observa que entre más alta sea la densidad del pulso, más grande es el área con esfuerzos residuales de compresión. Se usan densidades de 900, 1350 y 2500 pulsos/cm^2 con radiación infraroja (1064 nm). Especímenes compactos de tensión pre-fractutrados fueron sujetos al proceso LSP y después probados bajo carga cíclica con $R = 0.1$. El rango de crecimiento de fractura en fatiga, es determinado y el fecto de los parámetros del proceso evaluado. El rango de crecimiento de fractura por fatiga, es comparado entre especímenes con y sin proceso LSP.

Descriptores: Prueba de fatiga; proceso de impacto por láser; esfuerzo residual

PACS: 46.50.+a; 81.40.Jj

1. Introduction

Laser Shock Processing (LSP) is a new and promising surface treatment technique and has been shown to be effective in improving the fatigue properties of a number of metals and alloys. Potential applications are aimed at the aerospace and automotive industries. The beneficial effects of LSP on static, cyclic, fretting fatigue and stress corrosion performance of aluminum alloys, steels and nickel-based alloys have been demonstrated [1–5]. 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. In the laser shock processing of metals, the sample is completely immersed either in water or in air. The laser pulse is then focused onto the sample. The description of the operating principle may be seen in Ref 6.

The objective of this work is to examine the effect of laser shock processing on the fatigue behavior of 6061-T6 aluminum alloy specimens. Process parameters such as pulse density are varied. The effects of LSP on fatigue crack growth rate, micro-hardness, and residual stresses are investigated.

2. Experimental Procedure

2.1. Material

Plates of 6061-T6 aluminum alloy with a thickness of 6.3 mm were machined to obtain the specimens. The T6 condition

FIGURE 1. Compact tension test specimens used in the fatigue crack growth tests. Dimensions in mm. Specimen thickness is 6.3 mm.

consists of a solution treatment and natural aging. Its chemical composition (wt%) was: 0.52 Si, 0.27 Fe, 0.13 Cu, 0.03 Mn, 0.46 Mg, 0.011 Zn, 0.27 Cr, 0.022 Ti. Chemical composition was determined using a spark emission spectrometer. The mechanical properties, reported in Ref. 7, are as follows: tensile yield stress of 300 MPa, ultimate tensile strength of 328 MPa and elastic modulus of 69 GPa.

The specimens used for residual stress measurement were blocks of $60 \times 60 \times 6.3$ mm. The specimen used for fatigue crack growth tests were compact tension specimens as illustrated in Fig. 1. All fatigue crack growth test specimens were machined with the loading axis parallel to the rolling direction (L). Figure 1 also shows pulse swept direction.

2.2. Laser shock processing

The LSP experiments were performed using a Q switched Nd:YAG laser operating at 10 Hz with a wave length of 1064 nm and the FWHM of the pulses was 8 ns. A convergent lens is used to deliver 1.2 J. Spot diameter was 1.5 mm. Three pulse densities were used: 900, 1350 and 2500 pulses/cm^2. Specimens were submerged into a water bath when they were irradiated. Water was the confined medium. Specimen treatment area was 20×15 mm on both sides. A 2D motion system was used to control specimen position and generate the pulse swept. The desired pulse density was obtained by controlling the velocity of the system.

2.3. Characterization of the effects induced by LSP

Micro-hardness measurement was made with 50 g load and 10 s hold time. Residual stress distribution was determined by the hole drilling method according to the ASTM standard E837 [8]. Strain gage rosettes EA-13-062RE-120 along with a RS-200 Milling Guide from Measurements Group were used.

FIGURE 2. Micro-hardness profile on the specimen cross section.

2.4. Fatigue crack growth test

Fatigue crack growth tests were performed on a MTS 810 servo-hydraulic system at room temperature in the air. Load ratio $R = P_{\min}/P_{\max}$ was maintained at $R = 0.1$. A frequency of 20 Hz with a sine wave form was used in the experiments. Two specimen groups with 900, 1350 and 2500 pul/cm^2 pulse densities were formed. One specimen in each group was tested to a maximum load of 3000 N and another to 5000 N. Crack lengths were measured at a magnification of 10x using a CCD camera.

Stress intensity factor K_I due to external load P was determined using the following equation $[9, 10]$:

$$K_I = \frac{P}{B\sqrt{W}} \frac{2 + \frac{a}{W}}{\left(1 - \frac{a}{W}\right)^{3/2}} \left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4\right]. \quad (1)$$

3. Results and Discussion

Micro-hardness profiles of the specimen cross section are shown in Fig. 2. First, note that far from the surface, on the untreated material, hardness takes a constant value of 83 HV. On surface, hardness reaches a larger value than that reached on the untreated material. At the surface micro-hardness values are 95.8, 94.4 HV, for pulse densities of 900 and 2500 pulses/cm^2, respectively.

Residual stress distributions as a function of depth are shown in Fig. 3. It is observed that the higher the pulse density, the larger the compressive residual stress S_2, which is perpendicular to pulse swept direction. From residual stress distribution plot, it seems that there is an effect of pulse swept direction, *i.e.*, compressive stress component perpendicular to the swept direction is much higher than that parallel to that direction.

Figure 4 shows the fatigue crack growth rates for the aluminum alloy. A comparison of results without and with LSP treatment is illustrated. Solid lines are the least square fitting curves. First, note that as pulse density is increased, fatigue crack growth rate da/dN decreases for constant ΔK_I. Sec-

FIGURE 3. Residual stress distribution.

ond, da/dN values are lower for samples with LSP treatment than for samples without the treatment on fatigue crack growth, which is derived from the compressive residual stress field induced at the surfaces of the specimens. Fitting the experimental results with the well known Paris rule

$$\frac{da}{dN} = C(\Delta K)^m$$

it is observed (see Table I) that C increases as pulse density increases and m decreases, increasing pulse density.

4. Conclusions

It has been demonstrated that laser shock processing (LSP) is an effective surface treatment technique to improve fatigue properties of 6061-T6 aluminum alloy. This is due to the residual stress field induced at the surface. It has been shown that increasing the pulse density, fatigue crack growth rate

FIGURE 4. Fatigue crack growth rates for 6061-T6 aluminum alloy without LSP and with LSP treatment with different pulse densities.

TABLE I. Parameters of the fatigue crackgrowth rate model.

Pulse density (pul/cm^2)	C	m
No LSP	4×10^{-13}	7.664
900	8×10^{-13}	6.818
1350	2×10^{-11}	5.733
2500	3×10^{-10}	4.723

is reduced. Fatigue crack growth rate has been quantified through the determination of Paris rule parameters for loading rate $R = 0.1$.

Acknowledgement

Support for this work provided by the Centro de Ingeniería y Desarrollo Industrial and the Centro Laser UPM Spain is gratefully acknowledged.

∗. Corresponding author, fax: +52(442)2119839.

1. J.M. Yang, Y.C. Her, N. Han, and A. Clauer, *Mater. Sci. Eng.* **A298** (2001) 296.
2. Z. Hong and Y. Chengye, *Mater. Sci. Eng.* **A257** (1998) 322.
3. L.W. Tsay, M.C. Young, and C. Chen, *Corrosion Science*. In press (2003).
4. J.E. Rankin, M.R. Hill, and L.A. Hackel, *Mater. Sci. Eng.* In press (2003).
5. J.P. Chu, J.M. Rigsbee, G. Banas, and H.E. Elayed-Ali, *Mater. Sci. Eng.* **A260** (1-2) (1999) 260.
6. T. Schmidt-Uhlig *et al.*, *The European Physical Journal, Applied Physiscs* **9** (2000) 235.
7. Fatigue and Fracture Resistance of non-ferrous alloy. ASM Handbook v19, ASM International, Materials Park, OH, (1996).
8. ASTM 2002 Annual book of ASTM Standards, v.03.01 No. E837-01 Standard Test Method for Determining Residual Stresses by the Hole–Drilling Strain Gage Method
9. ASTM 2002 Annual book of ASTM Standards, v.03.01 No. E647-00 Standard Test Method for Measurement of Fatigue Crack Growth Rates
10. T.L. Anderson, Fracture mechanics, fundamentals and applications CRC Press, New York (1995).

Laser shock peening (LSP) is an innovative surface treatment process with the potential to change surface microstructure and improve mechanical properties of additively manufactured (AM) parts. In this paper, the influences of LSP on the microstructure and properties of Tiâ€"6Alâ€"4V (Ti64) titanium alloy fabricated via selective laser melting (SLM), as an attractive AM method, were investigated. The microstructural evolution, residual stress distribution and mechanical properties of SLM-built Ti64 samples were characterized before and after LSP.Â Irizalp, S.G.; Saklakoglu, N. High strength and high ductility behavior of 6061-T6 alloy after laser shock processing. Opt. Laser Eng. 2016, 77, 183â€"190. [Google Scholar] [CrossRef]. Laser shock processing (LSP) or laser shock peening has been proposed as a competitive alternative technology to classical treatments for improving fatigue and wear resistance of metals. This process induces a compressive residual stress field which increases fatigue crack initiation life and reduce fatigue crack growth rate. We present a configuration and results in the LSP concept for metal surface treatments in underwater laser irradiation at 1064 nm with and without a thin surface paint layer.Â A LSP configuration with experimental results using a pulse density of 5000 pulses/cm2 in 6061-T6 aluminum samples are presented. Â© (2007) COPYRIGHT Society of Photo-Optical Instrumentation Engineers (SPIE). 6061-T6 Aluminum Standard Heat Treating Process. T6 temper 6061 has been treated to provide the maximum precipitation hardening (and therefore maximum yield strength) for a 6061 aluminum alloy. It has an ultimate tensile strength of at least 290 MPa (42 ksi) and yield strength of at least 240 MPa (35 ksi). More typical values are 310 MPa (45 ksi) and 270 MPa (39 ksi), respectively.[10] This can exceed the yield strength of certain types of stainless steel.[11] In thicknesses of 6.35 mm (0.250 in) or less, it has elongation of 8% or more; in thicker sections, it has elongation of 10%.Â Also note the actual value of fatigue limit for an application can be dramatically affected by the conventional de-rating factors of loading, gradient, and surface finish. Microstructure[edit].