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Fabrication and Characterization of Micro Dent Array Produced by Laser Shock Peening on Aluminum Surfaces

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abstract

Surface micro dents may act as lubricant reservoirs to reduce friction and wear in sliding and rolling contact applications. Surface patterning has become a valuable technique for fabricating micro dents. Alternative methods such as micromachining present obvious limitations in comparison with laser shock peening (LSP). In this paper, the use of LSP along with an automatic X-Y table proves to be an attractive and reliable method for producing micro dent arrays with enhanced surface integrity and free of cracks. Surface topography and microhardness of the fabricated micro dent arrays on polished aluminum 6061-T6 have been characterized. It was found that low laser power produced deep micro dents. The hardness increased approximately 55% from the bulk material due to LSP induced strain and strain rate hardening.

terms

Surface Texturing, Micro Dent Array, Laser Shock Peening, Surface Integrity

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SME TECHNICAL PAPERS

FABRICATION AND CHARACTERIZATION OF MICRO DENT ARRAY PRODUCED BY LASER SHOCK PEENING ON ALUMINUM SURFACES

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ABSTRACT

Surface micro dents may act as lubricant reservoirs to reduce friction and wear in sliding and rolling contact applications. Surface patterning has become a valuable technique for fabricating micro dents. Alternative methods such as micromachining present obvious limitations in comparison with laser shock peening (LSP). In this paper, the use of LSP along with an automatic X-Y table proves to be an attractive and reliable method for producing micro dent arrays with enhanced surface integrity and free of cracks. Surface topography and microhardness of the fabricated micro dent arrays on polished aluminum 6061-T6 have been characterized. It was found that low laser power produced deep micro dents. The hardness increased approximately 55% from the bulk material due to LSP induced strain and strain rate hardening.

INTRODUCTION

Laser shock peening (LSP) is a proven technique for inducing deep compressive residual stress in the subsurface of a material. As a result, mechanical properties of a material are improved to prevent failure due to fatigue, wear and foreign object damage (FOD). The process of using elastic waves to plastically deform metals was first investigated in the early 1960s [White 1963]. Over several decades, significant progress toward understanding the mechanisms controlling wave propagation and their effects on residual stress and hardening have been studied [Clauer and Fairland 1979; Fairland et al. 1972; Ballard et al. 1991; Devaux et al. 1991; Peyre et al. 1996; Berthe et al. 1997]. Recently, the majority of LSP research is focused on simulating and predicting material responses [Berthe et al. 1999; Braisted and Brockman 1998; Zhang and Yao 2002; Ding and Ye 2003; Chen et al. 2004; Warren and Guo 2007, 2008; Fan et al. 2007]. Much of the attention in these studies was focused on laser parameters, confining layers and ablative coatings. All these parameters significantly influence the mechanical responses of a metallic material. Through these efforts, LSP was proven as a viable alternative to conventional shot peening to obtain deeper compressive residual stress in the subsurface of metals.

Typically, LSP is applied to metals as a form of surface treatment. It is well suited for localized regions under cyclic loading and fatigue.

Treating critical fatigue areas which have high stress concentrations can prevent cracking and spallation [Zhang and Yu 1998; Ruschau et al. 1999; Yang et al. 2000; Nalla et al. 2003]. Some applications for peening metallic components include gears, shafts, turbine blades, pumps etc. Another benefit of the compressive residual stress is improved resistance to corrosion and scuffing.

Lower energy lasers such as Nd: YAG are more suitable for microscale LSP as opposed to the high powered Nd: glass lasers. The use of Nd: glass lasers is considered mainly for covering large areas with macro size dents [Ding and Ye 2006]. The energy of Nd: glass lasers is on the order of Joules. As a result, the surface quality is compromised to impart deeper compressive stresses. In microscale LSP, the geometric goal for dents is to be small, on the order of microns, compared to the millimeter sized dents produced by macro LSP. As a result, the surface roughness is minimized which leads to improved tribological performance.

Since the primary goal for LSP has been to obtain high magnitude deep compressive residual stresses, little effort has been placed on evaluating dent geometry for surface tribological performance. The geometry of a dent is quantified by the largest diameter and depth. The ratio of the diameter to the depth is known as the dent aspect ratio (DAR). It is hypothesized that very shallow dents with relatively large diameters, or large DAR, will exhibit enhanced tribological performance compared to a low DAR. This work will focus on describing the fabrication method and the characterization of micro dents with a small DAR on AL 6061 T6 samples.

MICRO DENT FUNCTION AND FABRICATION

Functions of Dents

The controlled patterning of solid surfaces improves the wear, friction and lubrication [Anderson 2007]. Micro dents serve as fluid reservoirs that effectively retain lubricant. Also micro dents function as traps for wear debris, eliminating a potential plowing effect caused by entrapped particles. The long term benefit of surface patterning is to extend the life of contacting surfaces. Micro dents on the surface can improve the surface lifetime by a factor of 10 [Romano, Weber, and Dumitru 2003]. Experimental studies on the effect of dent patterns on micro-grooved sapphire discs in pin-on-disc tests [Blatter 1999], coated silicon discs in oscillating tests [Petterson and Jacobson 2003], steel discs with laser-textured micro dents in slow pin-on-disc tests [Dumitru 2000; Haefke 2000], steel against silicon nitride plates with micro dents in three-pin-on-disc tests [Wakuda 2003], micro dents produced by micro diamond pyramid on steel surfaces in rolling sliding contact [Nakatsuji and Mori 2001] or ceramic plates with micro dents in block-on-ring tests [Geiger 2002] lead to the conclusion that fabricated micro dents on metallic surfaces is a useful method to reduce friction in sliding contact. To generate controlled arrays of dents, different techniques can be applied. However, LSP is the most practical method that combines production efficiency and enhanced surface integrity. In combination with an automatic position system, LSP can be adapted to various peening patterns such as micro dents [Sealy and Guo 2008] or surface patterns.

Micro Dent Fabrication

To evaluate the effects of created micro dents on the surface tribological properties, various dimpling methods are investigated. Methods to obtain micro dents array on the surface can be classified into mechanical, lithographic, energy beam and coating techniques [Haefke 2000].

One mechanical method of micro dent fabrication is micro indentation. Nakatsuji and Mori successfully demonstrated dents produced by indentation had beneficial effects on suppressing pitting and improving scuffing resistance on surfaces in rolling-sliding contact [Nakatsuji 2002]. The dent array was obtained with a Vicker's indenter on S35C steel. The dent geometry follows the Vicker's tip imprint, an isosceles trapezoid, with a diagonal of 20 μm and a depth of 3 μm. Their research concluded dents manufactured by indentation positively affected metal to metal interactions and increased pitting durability.

Another mechanical technique for manufacturing micro dents is microdrilling. In microdrilling, holes less than 50 microns in diameter are produced on a surface with high accuracy and a high depth/diameter ratio up to 14 [Friedrich 2002]. The disadvantages of this method are resulting from the fact that surface integrity is mainly affected by the cutting process. Small chips are generated and cannot be completely removed from the hole. The chips could be released and cause further damage during surface interaction in an earlier stage than pitting onset. Microdrilling must be done in a peck cycle, wherein the drill is repeatedly inserted and withdrawn from the hole. The normal drilling speed is high since the feed rate is around 1 micron per peck cycle. Due to geometry constraints and fragile tooling under these operating conditions, where cutting forces are very high relative to the volume of material removed, microdrilling is not a suitable method for mass production.

Laser surface texturing (LST) is probably the most advanced technique in obtaining dent arrays. The process uses high energy laser pulses to ablate localized surface regions by rapid melting and vaporization [Kulkani and Lei 2004; Etsion 2005]. The design parameters critical for creating a dent array is depth, diameter and dimple density. Etsion et al. [2003] investigated the effects of LST on mechanical seals and reciprocating automotive parts. Their work concluded dents obtained by LST improved the surface interaction resulting in less wear and fatigue. There is a proven dependence between LST and increased load capacity, reduced friction coefficient, and reduced wear [Etsion 2005]. The main problem of LST is the alteration of surface integrity by the process of ablation. The high temperatures encountered during ablation cause melting, cracking and changing of the surface microstructure [Iordanova 2002]. According to Iordanova, the effects of LST on cold rolled low carbon steel revealed that the residual stress distribution was not affected in rolling direction and negatively affected in transverse direction. The changes in surface integrity can drastically shorten the fatigue life of the material.

FABRICATION PROCEDURE OF MICRO DENTS BY LSP

Sample Preparation

For the following study, Al 6061 T6 samples were sectioned ¼ inch thick from a 3 inch diameter round bar. Aluminum was chosen due to its wide application across multiple fields in industry. To improve surface finish, each sample was turned and later polished to a mirror finish. The Al samples underwent three stages of polishing using various polishing pads; 1200 grit, nylon, and Lecloth™. To prevent and remove any micron-sized pits and scratches induced by polishing, 1 μm diamond liquid in conjunction with lapping oil and/or water was used at low polishing speeds to final polish to a mirror finish. The surface roughness, R_a, was measured along 10 mm spans at random locations across the surface. The average surface roughness measured is less than 0.01 μm.

Process Mechanism of Micro Dent Formation

Laser Shock Peening (LSP) is a mechanical process where pressure waves caused by expanding plasma plastically deform the surface of a material. LSP uses a thin layer of ablative material that is opaque to the laser. The opaque ablative material, typically black spray paint or tape, is a sacrificial layer [Fairand and Clauer 1976]. The sacrificial layer also minimizes undesirable thermal effects on the surface caused by the laser. The laser vaporizes the ablative layer to form a high pressure plasma [Fan et al. 2005]. The plasma, confined by a thin layer of water film, expands rapidly resulting in a recoiling pressure wave on the order of GPa [Masse and Barreau 1995; Berthe et al. 1997; Fabbro 1990; Fairand et al. 1972]. The pressure wave is the mechanical process that plastically deforms the surface. The resulting pressure in confined ablation mode is much larger than the dynamic yield strength. Once the pressure exceeds the dynamic yield stress, plastic deformation occurs and forms a dent. Figure 1 is a process schematic of LSP.

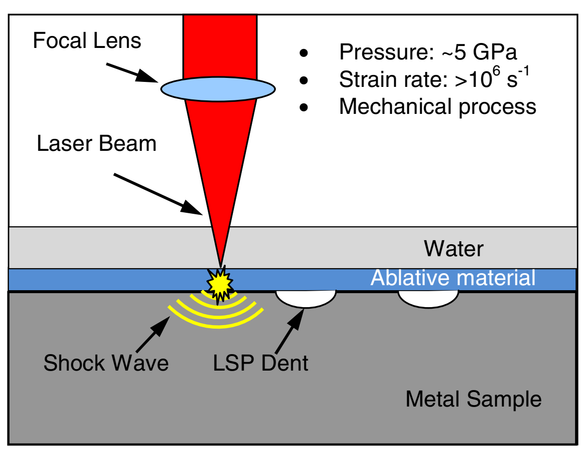

FIGURE 1. SCHEMATIC OF DENT FABRICATION MECHANISM.

Experimental Setup

The experiments were performed with a Q-switched Nd: YAG (neodymium-doped yttrium aluminum garnet) laser with a wavelength of 1064 nm and a frequency of 30 Hz. The laser emitted a 5-7 ns Gaussian distributed pulse. The laser beam was focused to a diameter of 32.5 μm using a 75 mm focal length lens. The energy was measured using an Ophir 30 A-HE power meter and ranged from 33 to 133 mJ.

Each experiment was performed in water confined regime (WCR) at a depth of 2 mm. The ablative material was black tape which has a thickness of 0.13 mm. Figure 2 shows the experimental setup.

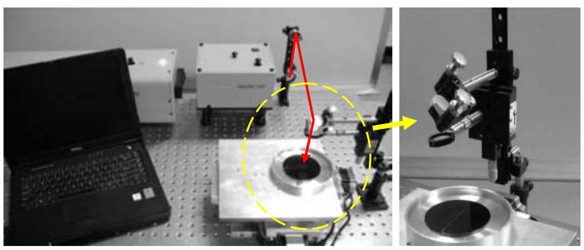

FIGURE 2. EXPERIMENTAL SETUP OF LSP.

Laser Intensity Calculation

To characterize the laser intensity the optical characterization of laser beam is required. The amplitude distribution of the electromagnetic field in a plane perpendicular to the axis of the optical cavity is described as "transverse electromagnetic (TEM) modes," which are actually cross sections of the beam. The transverse mode which is most commonly observed and used for our application is the TEM_{00}. This pattern has the circular spot cross section. For the transverse mode TEM_{00}, the intensity of laser beam does not fall to a minimum in either coordinate direction.

The beam characterization with respect to pulse time is necessary to understand the effect of pulsed type on laser intensity. Three main categories of pulsed types and their corresponding intensity distributions could be defined based on the pulse time [Winburn 1987]. A constant beam laser, known as a "continuous wave" or "constant wattage" (CW) laser, is differentiated from a pulsed laser that provides bursts of energy. A continuous wave is defined as the output of laser which is operated with a continuous output for a period larger than 0.25 seconds. The intensity of a CW is measured in units of watts per square centimeter (W/cm^2). This unit is often referred to as "power density". So, the term power density is used to describe the intensity of a CW beam.

A pulsed laser delivers its energy in the form of a single pulse or train of pulses [Winburn 1987]. The pulse duration is less than 0.25 seconds. By Q-switching, the burst of energy is released in much shorter periods of time, usually on the order of nanoseconds. Using specialized equipment like faster Q-switches could decrease the periods into the range of picoseconds. For pulsed lasers and Q-switched lasers, the laser intensity is calculated as the peak pressure delivered onto the laser spot area. The peak pressure is the pressure delivered in one shot in a very short period of time (10ns). In literature, laser energy represents the peak pressure delivered in one pulse time or it could be calculated as the average pressure delivered at the given frequency [Zhang and Yu 1998]. In this respect the energy could be calculated as:

$$E = \frac{P_{avg}}{f}; \qquad E = P_{peak} * p_t \tag{1}$$

where

P_{avg}	Average power output in Watts
P_{peak}	Peak power in watts
E	Pulse energy in Joules
F	Laser frequency in Hertz
p_t	Pulse time in seconds

Laser intensity I as calculated in Eq. (2) can be obtained in terms of GW/cm^2, either directly from the laser energy or calculated in power increments. So, laser intensity can be calculated using the formula:

$$I = \frac{P_{peak}}{A} = \frac{E}{p_t \cdot A} = \frac{P_{avg}}{f \cdot p_t \cdot A} \tag{2}$$

where

I	Laser intensity in GW/cm^2
E	Pulse energy in Joules
P_{avg}	Average power output in watts
P_{peak}	Peak power in watts
F	Laser frequency in Hertz
p_t	Pulse time in nanoseconds
A	Laser spot area in cm^2 [Zhang and Yu 1998]

In Eq. (2) the laser spot area A is calculated through "Thin Lens Theory" [Winburn 1987].

Figure 3 presents a "diffraction limited" beam focused through a bi-convex lens with the focal length *F* and the diameter of the spot size *d.* According to Winburn, the equation used to calculate laser spot size for a circular beam in TEM_{00} mode is:

$$d = 2.44 \frac{F\lambda}{D} \quad (3)$$

where

d Laser spot diameter at the focal distance in mm

F Focal distance in mm

Λ Wavelength in μm

D Unfocused beam diameter in mm

With the laser spot size calculated in Eq. (3) the laser spot area *A* is calculated with the formula:

$$A = \frac{\pi d^2}{4} \quad (4)$$

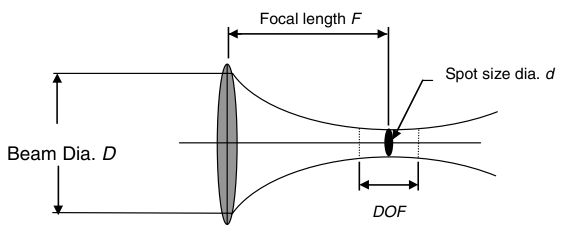

FIGURE 3. LASER THROUGH A BI-CONVEX LENS.

In Figure 3 depth of focus (*DOF*) is defined as the distance over which the focused beam has about the same intensity, it is defined as the distance over which the focal spot size changes –5% ~ +5%. The formula used to calculate the depth of focus in μm is:

$$DOF = 2.44\lambda \left(\frac{F}{D}\right)^2 \quad (5)$$

where

λ Wavelength in μm

F Focal distance in mm

D Unfocused beam diameter in mm

For a higher accuracy in laser machining, a longer depth of focus is desired. To increase this parameter, either lenses with a longer focal length are used or wavelength is decreased where this possibility exists.

Based on the above method of laser intensity, the calculated laser intensities were between 575 and 2300 GW/cm^2 for the power range from 1 to 4 watts.

CHARACTERIZATION OF MICRO DENT GEOMETRY AND PROPERTIES

Dent Profile

Figure 4 shows surface topography of the fabricated micro dents at different power levels. To investigate dent geometry, experiments were carried out on four rows where each row corresponds to a different power setting. To examine repeatability, six dents were produced at each power level and then measured to determine average dent properties. The dent geometry was measured using a Dektak profiler. Figure 5 depicts the dent profiles for the various laser powers.

Each dent was measured at the deepest diameter. The deepest part of the dent was found by iterating across the bottom surface. The deepest dent occurred at the lowest power setting of 1 W. The depth at different power levels decreased nonlinearly with increasing power. These results suggest that increasing the power past a saturation point does not increase the depth of a dent.

The power level had a negligible effect on the dent diameter. The laser spot size is controlled by the optical setup and therefore is not influenced by the power level. Increasing the power did not increase the radial stress required to produce wider dents. The average dent diameter is approximately 400 μm.

As for the little influence of power level on dent diameter, one possibility is that all laser power levels are above the ablation threshold and thus the same diameter will always be affected.

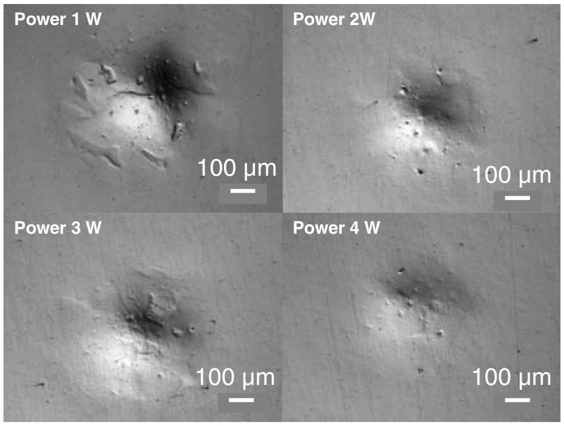

FIGURE 4. TOPOGRAPHY OF MICRO DENTS.

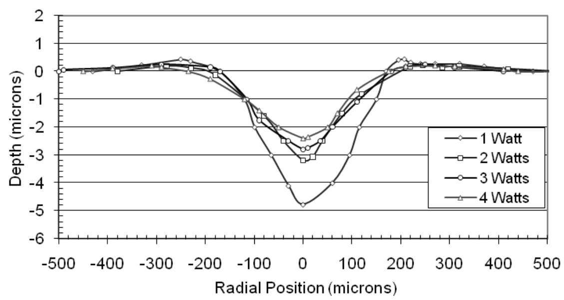

FIGURE 5. DENT PROFILES AT DIFFERENT POWER SETTINGS.

Microhardness Profiles

To investigate hardness produced by LSP, experiments were carried out to measure microhardness on four rows of dents, where each row corresponds to a different power setting. A Knoop indenter with a load of 50 g was used to measure hardness in and around the dents. Hardness was measured consecutively along a radial path on the top surface. The size of the imprint was approximately 30 µm which allowed for multiple measurements within the same dent. The equipment used was a microhardness tester 401/402 MVD. Figure 6 shows the microhardness profiles on the surface for various laser powers. As expected, LSP increased the hardness within the dent. The average hardness at the center and exterior of a dent was 423 and 272, respectively. On average, the hardness in the center increased 56% from the bulk material. A comparative study by Zhang and Yu [1998] found similar results on increasing the hardness of Al 2024-T62 by as much as 52%.

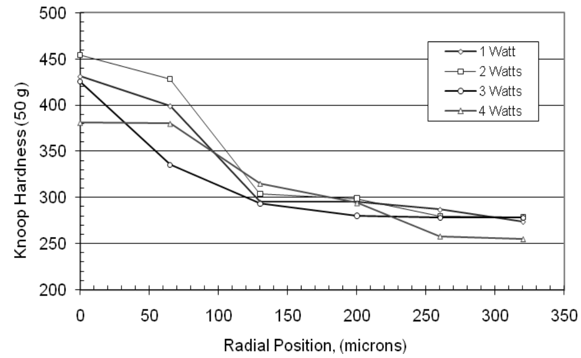

FIGURE 6. MICROHARDNESS PROFILES.

The main concern for measuring microhardness in dents produced by LSP is dealing with curved surfaces. Since 3D topography for a LSP dent is similar to a hemisphere, measurement error is unavoidable when measuring hardness. As a result, a drag like effect as shown in Figure 7 elongates the Knoop indentations which will inaccurately reflect hardness. To minimize the experiment error, the Knoop indenter was oriented to measure hardness along the y-direction. Therefore, the long diagonal, critical to measuring hardness, was unaffected by the curved surface. In this setup, there is still a dragging effect on the short diagonal; however, the hardness measurements are unaffected.

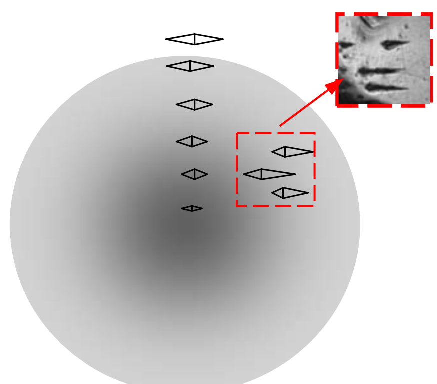

FIGURE 7. SCHEMATIC OF DRAGGING EFFECT ON HARDNESS MEASUREMENT ON CURVED SURFACE.

CONCLUSIONS

Microscale laser shock peening was performed on Al 6061-T6 to explore the feasibility of fabricating micro dents. The effects of laser power on dent topography and hardness were characterized. In WCR with black tape as the ablative medium, using higher laser power did not increase dent depth. An average laser power of 1 Watt, which corresponds to a laser intensity of 576 GW/cm^2, produced the deepest dent. As the average power increased, the depth of each dent decreased nonlinearly. The diameter of the dent was unaffected by changing the power. The hardness in the center of the dent increased approximately 55%. It is believed hardening effect in the dented area is caused by large strains and high strain rates.

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