

Advances in Micro-Scale Laser Peening Technology

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Abstract

Recent advances in laser peening technology, also known as laser shock processing (LSP) are reported. Specific emphasis is placed on its development in the micro scale regime. LSP imparts desirable residual stress distributions into the target material in order to improve the fatigue life of the material. In modeling improvements, plasma expansion is modeled as laser supported combustion wave, in which radial and axial expansions are considered. Stress/strain analysis is extended to three-dimensional and takes into account of finite geometry, which is important for micro-scale LSP. Fatigue tests are designed to demonstrate that micro-scale LSP can improve fatigue performance of the materials while offering a level of flexibility. The influence of LSP on the microstructures of the materials is studied quantitatively using Orientation Imaging Microscope (OIM) technique, and grain size and subgrain structures are analyzed. The experimental results of strain/stress distributions are compared with that of simulations in overlapped LSP using conventional X-ray diffraction measurement. The potential of applying the technique to micro components, such as micro gears fabricated using MEMS is demonstrated. The investigation also lays groundwork for possible combination of the micro scale laser shock processing with laser micro-machining processes to offset the undesirable residual stress often induced by such machining processes.

1. INTRODUCTION

In recent decades, significant progress has been made in the design and fabrication of micro electro-mechanical systems (MEMS) via various methods. Failure and reliability of MEMS has been drawing increasing attention [1-2]. Some MEMS structures experience cyclic loadings in operation, such as micro-engines and micro-switches. Metals such as copper, nickel and aluminum are widely used in such

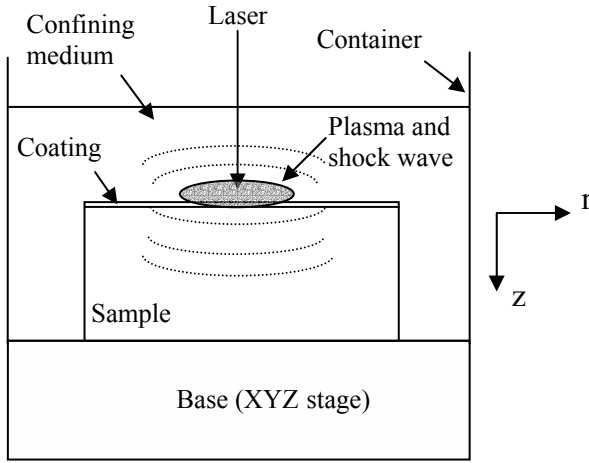
structures due to their better mechanical and electrical properties compared with silicon. Fatigue and wearing are important failure modes for such structures. Needs will arise to impart a desirable residual stress distribution or alter the existing distribution left by the fabrication process itself. LSP can increase the hardness of metallic surfaces thus improve the wearing resistance of the component. Microscale LSP can also alter the residual stress distribution thus improve the fatigue life of metal MEMS components. Little studies have been done for such methods in the micro scale.

In this paper, the expansion of plasma is modeled as 1D laser supported combustion (LSC) wave [3]. The 1D results are then modified to consider spatial expansion effects of the shock pressure. Copper and nickel samples are processed using microscale LSP and are compared with raw materials in terms of fatigue performance. 3D simulations of the shock induced deformation process are carried out, where the effects of finite sample size and irregular geometry are considered. The averaged strain map for the overlapped LSP is used to compare with X-ray diffraction measurements. The Orientation Imaging Microscope (OIM) techniques are used to quantitatively and statistically characterize the microstructures and especially the sub-grain structures of laser shock processed samples.

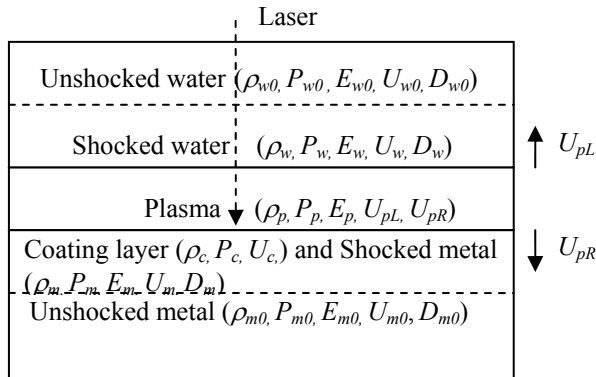
2. PRINCIPLE OF LASER SHOCK PROCESSING (LSP)

When a metallic target is irradiated by an intense ($>1\text{GW}/\text{cm}^2$) laser pulse, the surface layer instantaneously vaporizes into a high temperature and high pressure (1~10GPa) plasma. This plasma induces shock waves during expansion from the irradiated surface, and mechanical impulses are transferred to the target. If the plasma is not confined, i.e., in open air, the pressure can only reach several tenth of one GPa. If it is confined by water or other media, the shock pressure can be magnified by a factor of 5 or

more compared with the open air condition [4]. At the same time, the shock pressure lasts 2 to 3 times longer than the laser pulse duration. In most LSP a coating is used to protect the target from thermal effects so that nearly pure mechanical effects are induced. The coating could be metallic foil, organic paints or adhesives. These coatings can modify the surface loading transmitted to the substrate by acoustic impedance mismatch effects at the coating-substrate interface, and an additional 50% increase in the peak stress values can be achieved [5]. Pressures above 1 GPa are above the yield stress of most metals, thus plastic deformation can be induced. As a result, if the peak shock pressure is over the *HEL* (Hugoniot Elastic Limit) of the target material for a suitable time duration, compressive stress distribution in the irradiated volume can be formed [6].



(a) Schematic of LSP



(b) Five regions in water confined LSP

Fig. 1 Laser shock processing (LSP)

Under typical conditions of LSP, the speed of plasma expansion is lower than the shock speed, thus

shock wave precedes plasma expansion. This resembles the case of laser supported combustion (LSC) wave [3]. LSC wave in air and vacuum has been studied [8] and will be extended in this paper to LSP modeling.

As illustrated in Fig. 1(a), laser irradiation first vaporizes the surface layer of the coating, and the vaporized material quickly evolves into plasma. The plasma irradiation is primarily in the extreme ultra-violet. At such short wavelengths ($<200\text{nm}$), multi-photon ionization (MPI) mechanism of water breakdown is dominant. Water near the plasma outer edge is quickly ionized and becomes strongly absorbent to incident laser irradiation. Thus water is changed into plasma due to plasma irradiation and direct laser irradiation. At the same time, the coating is continuously vaporized into the plasma. The pressure of the plasma increases quickly and the expansion of the plasma imparts shock pressure into water and target. Mass, momentum and energy are conserved across the shock wave.

Let subscripts *w* denote water, *m* metal, *c* the coating layer, *p* plasma, *L* the side of plasma near water, *R* the side of plasma near solid, and θ the property of unshocked region. Also let *D* be shock velocity, *U* particle velocity, *E* internal energy, ρ density, and *P* pressure. For convenience, the water-plasma-target system is divided into five regions (Fig. 1(b)): unshocked water ($\rho_{w0}, P_{w0}, E_{w0}, U_{w0}, D_{w0}$), shocked water ($\rho_w, P_w, E_w, U_w, D_w$), plasma ($\rho_p, P_p, E_p, U_{pL}, U_{pR}$), coating layer and shocked solid ($\rho_c, P_c, U_c, \rho_m, P_m, E_m, U_m, D_m$), and unshocked solid ($\rho_{m0}, P_{m0}, E_{m0}, U_{m0}, D_{m0}$). The unshocked properties are known.

The shocked and unshocked properties of water are related by mass, momentum, and energy conservation, and shock speed constitutive relations:

$$\rho_{w0} / \rho_w = 1 - (U_w - U_{w0}) / (D_w - U_{w0}) \quad (1)$$

$$P_w - P_{w0} = \rho_{w0} (D_w - U_{w0}) (U_w - U_{w0}) \quad (2)$$

$$(E_w + U_w^2 / 2) - (E_{w0} + U_{w0}^2 / 2) = \frac{1}{2} (P_w + P_{w0}) \left(\frac{1}{\rho_{w0}} - \frac{1}{\rho_w} \right) \quad (3)$$

$$D_w = D_{w0} + S_w U_w \quad (4)$$

For water, $U_{w0} = 0 \text{ m/s}$, $P_{w0} = 10^5 \text{ Pa}$, $E_{w0} = 0 \text{ J/kg}$, $\rho_{w0} = 997.9 \text{ kg/m}^3$, $D_{w0} = 2,393 \text{ m/s}$, and $S_w = 1.333$ [7]. S_w is a coefficient relating shock speed D_w to U_w , the particle velocity and D_{w0} , the shock speed at infinitesimally small particle velocity.

Substituting subscript *m* for *w* in Eq. 1-4, one obtains four more equations between shocked and unshocked properties of metals

The above equations can be solved after considering their interactions with the plasma. Mass and momentum conservation at the interfaces at any instant requires:

$$\rho_w(U_{pL} - U_w) = \rho_p U_{pL} \quad (5)$$

$$\rho_c(U_{pR} - U_c) = \rho_c V_{rec} = \rho_p U_{pR} \quad (6)$$

$$P_p + \rho_p U_{pR} U_c = P_c \quad (7)$$

$$P_p + \rho_p U_{pR} U_w = P_w \quad (8)$$

The current mass of the plasma is equal to the integration of the mass flows into plasma. The mass flow from water is $MF_w = \rho_w(U_{pL} - U_w)$. The mass flow from the coating layer is

$$MF_c = \rho_c(U_{pR} - U_c) = \rho_c V_{rec}$$

Where V_{rec} is the recess velocity of the melting coat surface. In this paper, the coating layer is aluminum foil, $\rho_c = 2,700 \text{ Kg/m}^3$, $U_m = U_c$, and $P_m = P_c$. The mass conservation of plasma requires:

$$\rho_p(t) \int_0^l (U_{pL} + U_{pR}) dt = \int_0^l (MF_w + MF_c) dt \quad (9)$$

The energy conservation of plasma should consider the absorption of incident laser irradiation, the total energy stored in the plasma, the work done by the plasma, and energy exchanges through mass flow. The total energy consists of kinetic energy and internal energy. Based on the assumption of linear distribution of particle velocity, the unit mass kinetic energy of plasma is

$$E_{pk} = (U_{pL}^2 + U_{pR}^2 - U_{pL} U_{pR}) / 6.$$

Using the ideal gas law, the internal energy of plasma is related to its density, specific heat ratio γ (about 1.3), and pressure:

$$E_p = \frac{\gamma P_p}{(\gamma - 1) \rho_p} \quad (10)$$

So the total energy in plasma is:

$$E_{pt} = \rho_p L (E_{pk} + E_p),$$

where $L(t) = \int_0^l (U_{pL} + U_{pR}) dt$ is the plasma length.

The total work done by plasma to the surrounding is: $W_p = \int_0^l P_p (U_{pL} + U_{pR}) dt$. The mass exchange induced

energy exchange equals mass flow times the energy difference:

$$E_{MF} = \int_0^l [MF_c (E_{pk} + E_p - U_c^2 / 2 - Q_c) + MF_w (E_{pk} + E_p - U_w^2 / 2 - Q_w)] dt$$

where Q_w and Q_c are the phase change energy of water and coating layer, respectively. The internal energy is incorporated in the phase energy term.

Let AP be the fraction of laser energy absorbed by plasma, and $I(t)$ the laser intensity, the energy conservation of plasma requires:

$$E_{pt} + W_p - E_{MF} = \int_0^l AP \times I(t) dt \quad (11)$$

AP can be decided from experiments. Now the equations of this 1D model are closed and all the

variables involved can be solved as a function of time.

Radial expansion of plasma is a more significant concern in microscale LSP than in mm-scale LSP because such expansion may not be neglected because of the small beam size. Once plasma is created, radial expansion of plasma commences. A rarefaction wave propagates into the plasma from the edge at the sound speed of the plasma. After a characteristic time $T_r = R_0 / a$, where R_0 is the radius of the laser beam and a is the sound speed of the plasma, the rarefaction wave coalesces at the center of the spot. The pressure of the plasma drops and deviates from the 1D values afterwards. Axial relaxation starts after the laser pulse terminates, thus the characteristic time for axial expansion is $T_z = T_p$, where T_p is pulse duration. The temporal evolution of the plasma depends on the values of T_r and T_z . For the laser used in current research, $R_0 = 6$ microns, $T_z = T_p = 50$ ns, and sound speed of plasma $a = 300$ m/s, $T_r = 20$ ns, thus radial relaxation occurs earlier than axial relaxation. Based on the work of Pirri[8], Simons[9], and Root[3], the following power scaling laws are used in this paper.

$$\begin{aligned} t < T_r & \quad P = P_{1D} \\ & \quad R = R_0 \\ T_z > t > T_r & \quad P = P_{1D} (t / T_r)^{-4/5} \\ & \quad R = R_0 (t / T_r)^{1/2} \\ t > T_z & \quad P = P_{1D} (T_r / T_z)^{4/5} (T_z / t)^{6/5} \\ & \quad R = R_0 (T_z / T_r)^{1/2} (T_z / t)^{-4/5} \end{aligned} \quad (12)$$

where P_{1D} is the plasma pressure from 1D model described above.

For laser shock processing on micron scale, the spatial profile of the laser beam should also be considered. Following the work of Zhang and Yao [10], shock pressure obeys Gaussian spatial distribution, but with its $1/e^2$ radius equals to $\sqrt{2}R(t)$, where $R(t)$ is the radius of plasma in Eq. 12. Let r be the radial distance from the center of the laser beam, the spatially uniform shock pressure $P(t)$ relates to the spatially non-uniform shock pressure as

$$P(r, t) = P(t) \exp\left(-\frac{r^2}{2R^2(t)}\right) \quad (13)$$

3. EXPERIMENT AND SIMULATION CONDITIONS

(1) Selection of Materials and Experimental Conditions

Copper foils of 90-micron thickness and nickel foils of 120-micron thickness were used in LSP

experiments. The samples were adhesively attached to bulk copper columns for rigid support and easy handling. The samples were polished and the sample size was about 8 mm square. To apply the coating, a thin layer of high vacuum grease (about 10 microns) was spread evenly on the polished sample surface, and the coating material, aluminum foil of 25 microns thick, which was chosen for its relatively low threshold of vaporization, is then tightly pressed onto the grease. The sample was placed in a shallow container filled with distilled water around 3 mm above the sample. A frequency tripled Q-switched Nd:YAG laser in TEM₀₀ mode was used, the pulse duration was 50 ns, and pulse repetition rate could vary between 1 KHz to 20 KHz. Laser beam diameter is 12 microns. After shock processing, the coating layer and the vacuum grease were manually removed. Pulse number at each location was varied from 1 to 6 at 1 KHz repetition rate, and pulse energy was varied from 160 μJ to 240 μJ corresponding to laser intensity of 2.83 to 4.24 GW/cm^2 . LSP at individual locations (similar to drilling) and overlapped locations (similar to grooving) was carried out.

The geometry of the shocked region was observed and measured using optical microscopy, scanning electron microscopy (SEM), and interferometry-based optical profilometry. The strain/stress distributions are compared with that of simulations in overlapped LSP using conventional X-ray diffraction measurement. Fatigue tests of unshocked and shocked samples were carried out using a material testing system. Orientation Imaging Microscopy (OIM) measurements of microstructures and especially sub-grain structures were carried out.

(2) Simulation Conditions

The spatial and temporal dependent shock pressure was solved numerically based on what was outlined in Section 2 and used as the loading for the subsequent stress/strain analysis. In the stress/strain analysis, work hardening, strain rate and pressure effects on yield strength are assuming room temperature [10]. This is reasonable because only the coating is vaporized and minimal thermal effects are felt by the sample. A commercial FEM code, ABAQUS, is used for the stress/strain analysis as a dynamic implicit nonlinear process. First, axisymmetric modeling was carried out to compare the effects of the current shock pressure model with the previous model on deformation assuming semi-infinity in geometry [10]. Single and multiple pulses at individual locations were simulated. Secondly, 3D simulation was carried out assuming finite geometry (100 microns in thickness, 1 mm in width, and 2 mm in length). Pulses at overlapped locations with 50 micron spacing were simulated. Shocks are applied

on the top surface along a narrow strip in the width direction. The bottom surface is fixed in position, while all the other side surfaces are set traction free. The 3D simulations were extended to consider the specimen geometry used in the fatigue tests. The geometry and finite size effects were studied to explain the fatigue test results.

4. RESULTS AND DISCUSSION

(1) Deformation and Model Validation

Fig. 2 shows a dent on a copper sample induced by 3 laser pulses with pulse energy 220 μJ (3.89 GW/cm^2). The dent is a clear indication of plastic deformation.

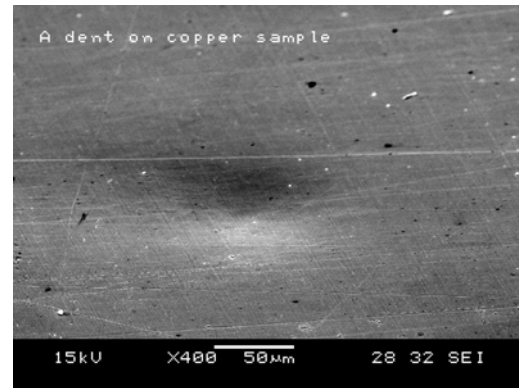


Fig. 2 A dented area made by LSP on copper foil

To quantitatively characterize the deformation, an interferometry based optical profilometer with a vertical resolution of 3 nm is used to profile deformed regions under this and other conditions.

Fig. 3(a) and (b) show the variation of dent depth and slope angle with the increase of pulse number at $E = 220 \mu\text{J}$ (3.89 GW/cm^2) for copper and nickel samples, respectively. Each experimental data point is the average of more than three features and the error bar represents standard deviation. Simulation results of current and previous shock pressure model are also superposed [10]. The stress/strain analysis of the simulation is the same as reported in [10].

The current model agrees well with the experimental results while the previous model overestimates the dent depth especially at the larger number of pulses. This is primarily due to the fact that the previous model overestimated the shock pressure duration by neglecting the radial and axial expansions of the plasma. When the number of pulses increases, the effect of such overestimation accumulates. This explains why the discrepancy gets larger with the number of pulses. The discrepancy in the slope angle can be similarly explained. Simulations and experi-

ments under a wide range of other conditions showed similar trends.

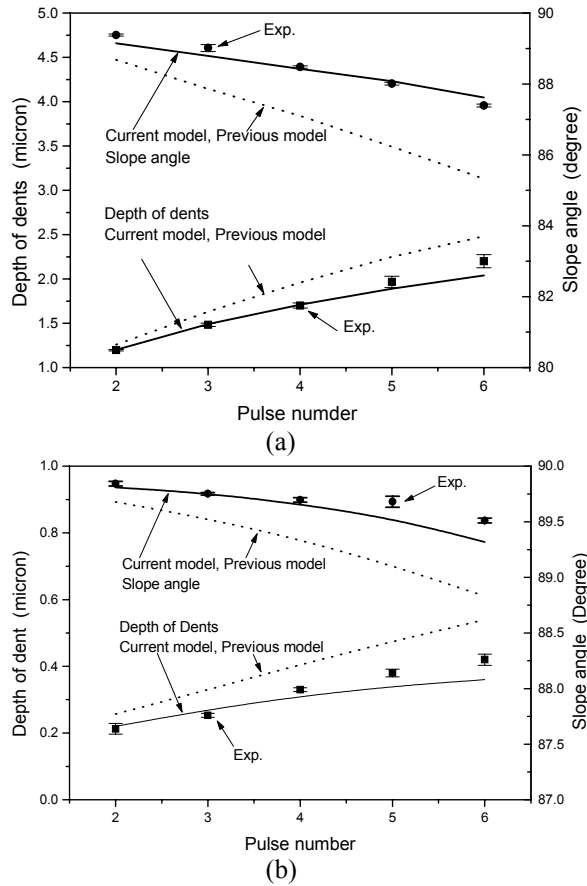


Fig. 3 Dent geometry comparisons

(2) Overlapped LSP and X-ray diffraction measurements

Besides geometry comparison, it is highly desirable to directly compare the experimental results of strain/stress distributions of the shocked area with that of simulations. Traditional X-ray diffraction measurement, however, is limited by its spatial resolution (~ 1 mm) and cannot be used directly to measure the micron scale strain distributions. Experiments were carried out, in which an array of equally spaced locations on a sample is consecutively shocked by laser pulses. It is termed as overlapped laser shock processing.

The 2D strains from simulations are first averaged along the depth direction corresponding to specific lattice planes to be examined in the X-ray diffraction. The strain values expressed in the cylindrical coordinates (r, z) at each shocked location are then transformed into Cartesian coordinates. Assuming individual shocks are independent, the strains at various shocked locations on the sample are finally summed

up to obtain averaged strain map for the overlapped LSP, which is used to compare with the X-ray diffraction measurements.

Fig. 4 shows an optical micrograph of the copper sample shock processed by overlapping laser pulses. The overlap spacing is 50.8 microns. The left side is the dented region and the right side is the unprocessed, original copper surface. Holes were drilled on the unprocessed region to assist locationing in subsequent X-ray diffraction measurements. The grain size of the copper sample is between 10 to 15 microns, and the grains are randomly oriented. For such grain sizes, a 2 mm by 2 mm X-ray beam covers a large number of grains.

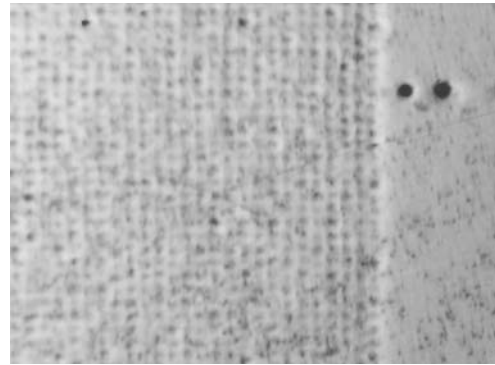


Fig. 4 Typical micrograph of dented region

Fig. 5 shows the in-depth strain maps resulted from summing up the Cu (311) averaged elastic of different shocked locations. The spacing is 50.8 microns. Only a 4 by 4 matrix of the shocked locations are shown, but it is representative of the entire shocked region. The overlapping results of the averaged in-depth strain E_z are all tensile with the grand average being 4.1464×10^{-4} for the spacing of 50.8 microns. The averaged E_z is 1.9743×10^{-4} for the spacing of 76.2 microns (not shown). This results in compressive average strains of E_x and E_y assuming they are equal-biaxial and under the constant volume principle. It is observed that the elastic strains induced by overlapping at 50.8-micron spacing are about twice as large as that at 76.2-micron spacing, and the range of variation for 50.8 microns is smaller than that of 76.2 microns. So the overlapping spacing can be used to influence the values as well as the uniformity of the strain distribution. Because of the compressive average in-plane stresses as just mentioned above, it can be expected that large areas of compressive average in-plane residual stress distributions will be the result of the shock overlapping. Such in-plane compressive residual stress distribution is desired for the prevention of crack formation and propagation.

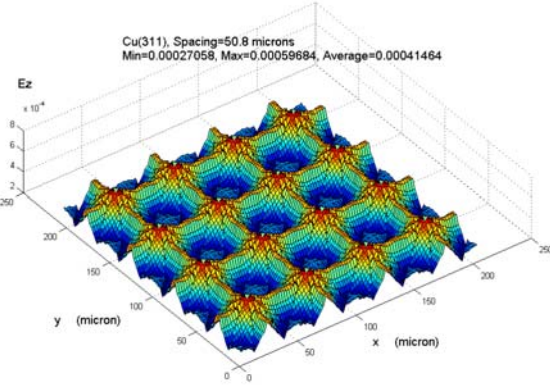


Fig. 5 Overlapping results of the depth-direction elastic strain

Similar calculations were carried out for Cu (111) diffraction and for other strain components. The strain values of Cu (111) diffraction are smaller than the strain values of Cu (311) diffraction due to the fact that Cu (111) diffraction is the average of a shallower top layer than Cu (311) diffraction, and the in-depth residual stress is close to zero near the top.

Table 1: Comparison of X-ray diffraction measurements with simulation predictions

Diffraction plane and overlapping spacing (μm)	θ (Degrees)	θ_0 (Degrees)	E_z (experiment, $\times 10^{-4}$)	E_z (simulation, $\times 10^{-4}$)
Cu (111), 50.8	43.5802 ± 0.0004	43.5865 ± 0.0005	1.4844 ± 0.2800	1.79
Cu (111), 76.2	43.5640 ± 0.0004	43.5678 ± 0.0003	0.8233 ± 0.0858	0.8935
Cu (311), 50.8	90.1317 ± 0.0019	90.1609 ± 0.0020	2.5449 ± 0.1619	4.1464
Cu (311), 76.2	90.1267 ± 0.0032	90.1443 ± 0.0020	1.5298 ± 0.2820	1.9743

The averaged elastic strain E_z values are compared with the results from X-ray diffraction measurements as shown in Table 1. The X-ray diffraction spectra of the unprocessed sample and the shocked regions of 50.8-micron and 76.2-micron spacing were recorded. Measurements were repeated three times under each condition and the repeatability is indicated in Table 1 in terms of the standard errors. From Table 1 it is seen that X-ray measurement results show the same trends as the simulation predictions but are lower than the simulation predictions especially in case of Cu (311). The overestimation by the simulation is perhaps due to some of the assumptions made in the simulation and subsequent data processing. In simulation the strain contributions from neighboring locations were directly summed up, while in experiments the accumulation of strains is nonlinear due to work hardening effects. Energy dissipation into the coating layer was neglected in simulation, and the bottom surface was not absolutely fixed in position in experiments. All these factors lead to the overesti-

mation of simulation predictions, but the trends of variation agree with that measured by X-ray diffraction. Thus, in addition to the geometry comparison presented in an early section, this comparison further validates the simulation process.

(3) Fatigue Performance Improvement through Microscale LSP

It has been shown that millimeter scale LSP can improve fatigue life of metals [6]. However, it requires the use of high-energy laser pulses [11] and has a limited spatial resolution and not suited for microscale device treatment. Lasers that are used in microscale LSP having much smaller beam have two advantages. First, it delivers laser intensities comparable to that used in the millimeter scale LSP but allows for a higher repetition rate (1KHz or higher in this paper). More importantly, the smaller footprint of treatment made possible by the smaller beam size provides greater flexibility in treating smaller devices and devices with complex geometry. It can selectively treat critical regions such as regions around stress raisers on microscale devices at high speeds. Microscale LSP can be overlapped to treat large areas (Fig.6), at the same time the geometry of the laser shocked area can be controlled with micron accuracy.

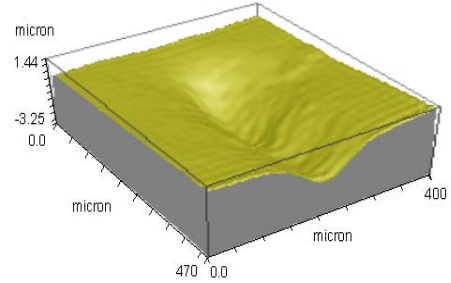


Fig. 6 Optical profilometer measurement of laser shock induced deformation (groove) on copper

The geometry of the fatigue test specimen is shown in Fig. 7 (a). It is a scale down version of the standard tensile test specimen. The copper sample is 0.8 mm in thickness with two half-circle notches of radius of 0.5 mm to introduce stress concentration and more complex geometry effects. Micro scale LSP is used to treat the dotted region between and around the notches and both sides of the specimen are shock processed. Laser pulse energy is 220 μJ . 2, 3 or 4 laser pulses at repetition rate of 1KHz are applied at each location and the shocked locations in the dotted region are spaced by 50 microns. The fatigue test was done on a material testing machine and a 80Hz sinusoidal load was applied axially. To prevent backlash, a positive mean load is applied

such that the total load always oscillates in the tensile territory. It is mainly the tensile stress that is responsible for the initiation and propagation of cracks. Five pairs of tests were conducted covering the range from the fatigue strength to the ultimate strength of copper. Fig. 7(b) compares the typical fatigue curves of identical specimens with LSP and without LSP. It is seen that the fatigue life of the specimen with LSP is about 3 times that of the specimen without LSP, noting the logarithmic scale used.

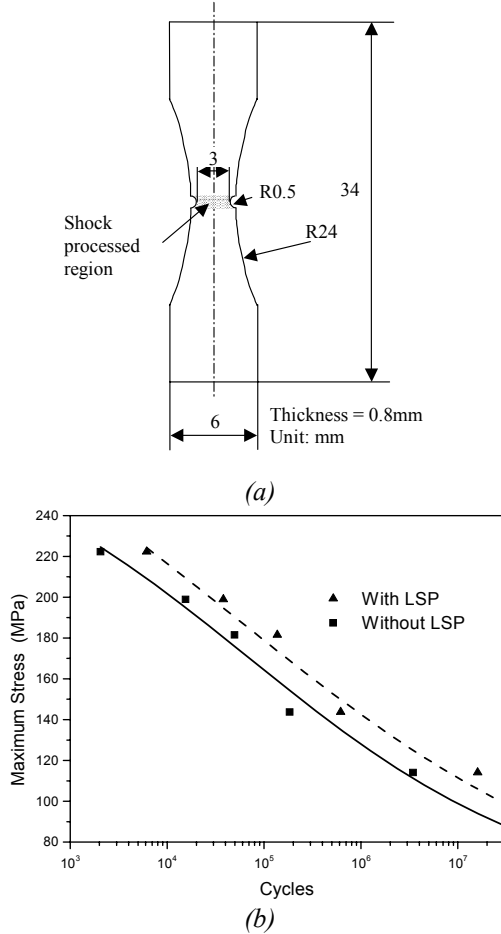


Fig. 7 (a) Geometry of the fatigue test sample, and (b) Results of fatigue test.

Although it is difficult to directly compare the fatigue test results of mm-scale LSP and microscale LSP due to different process conditions involved, microscale LSP can increase the fatigue life of metal components as mm-scale LSP does, but its high repetition rate and high spatial resolution makes it more flexible for treating normal size samples especially the ones with more complex geometry. More importantly, only the microscale LSP offers the capability to treat micro-devices. It appears that the fatigue prevention mechanism does not differ

significantly between the mm-scale LSP and microscale LSP.

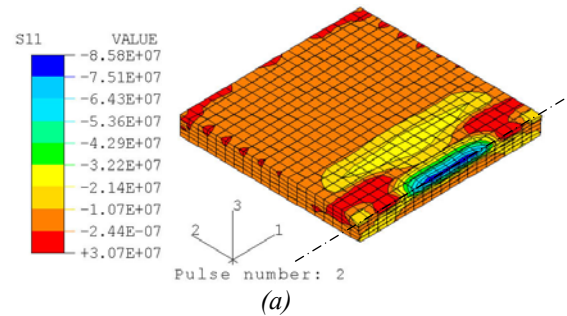
Table 2 Influence of pulse numbers on the fatigue life of copper

	2 pulses	3 pulses	4 pulses
With LSP	60,873±730 cycles	76,845±610 cycles	53,458 ±692 cycles
Without LSP	25,506±588 cycles		
With/Without Ratio	2.39±0.03	3.01±0.02	2.10±0.02

Table 2 shows the influence of pulse numbers on the fatigue life of copper under one of the five testing conditions (mean stress=103.5 MPa and stress oscillation amplitude=95.5MPa). 2, 3, and 4 pulses were applied at each location and each test was repeated three times. Contrary to intuition, the fatigue life deteriorated when more than 3 shock pulses were used although it is still much better than that without LSP. This phenomenon will be explained in conjunction with the 3D simulation results in Section 4.4.

(4) Three-dimensional Stress/Strain Analysis with Finite Geometry

Axisymmetric stress/strain analysis was conducted for microscale LSP at individual locations [10, 12], in which semi-infinite geometry was also assumed. Such analysis results are used in Fig. 4 of this paper to compare with experimental measurements. For LSP at overlapped locations as in the case of fatigue specimen described in the last section, 3D stress/strain analysis will be necessary. In addition, for such geometry and for small-scale specimen, the semi-infinite geometry assumption needs to be removed. Such simulation helps examine the residual stress states and understand the fatigue performance. Figs. 8 and 9 show typical 3D stress/strain analysis results where finite geometry is considered.



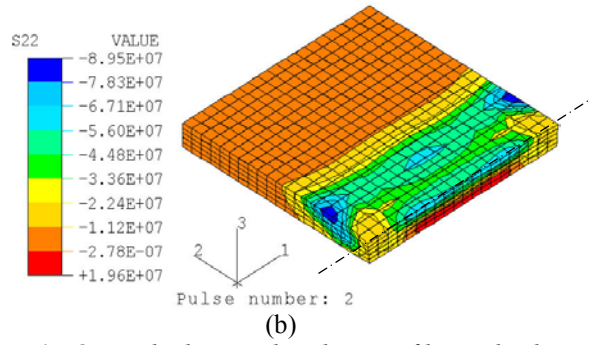
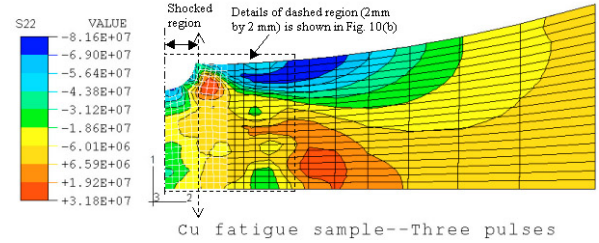


Fig. 8 Residual stress distribution of laser shock processed copper plate

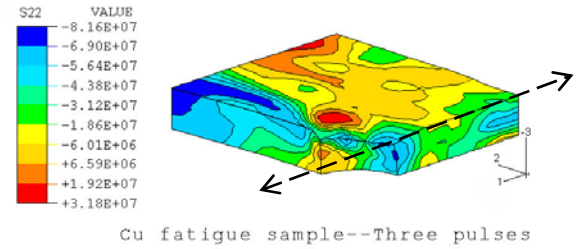
Fig. 8(a) and (b) illustrate the residual stress distributions of S_{11} (along laser scanning direction) and S_{22} (vertical to laser scanning direction), respectively. Two observations can be made. First, the stress state at the edge areas is more complex than that in the interior area. This is obviously due to the effect of finite geometry. Typically less resistance to deformation is experienced at the edge areas. The residual stress state at the edge areas has significant influence on crack initiation and propagation. Secondly, S_{22} is more uniformly distributed than S_{11} . Fig. 8(b) shows that LSP induced an area of surface compressive residual stresses perpendicular to the scanning direction, and the area extends 300 microns from the centerline. The maximum compressive stress is close to -90 MPa. If the specimen experiences a periodic load along the S_{22} direction, the surface compressive residual stress will help improve its fatigue life. In fact the compressive stress extends into the depth direction, which will be further discussed when Fig. 9 is explained.

Fig. 9(a) shows the geometry of the fatigue sample and the distribution of S_{22} on the top surface for three pulses. The simulation condition was similar to that used to process the fatigue specimen. S_{22} is compressive in the shocked region including the notched area. A 2mm by 2mm region close to the notched area is shown in detail in Fig. 9(b). As seen, S_{22} is compressive around the notched area and throughout the depth direction reaching a peak value of -80 MPa. Such compressive stress distribution is favorable for crack prevention and fatigue life improvement. The distribution of S_{22} is similar to that of three pulses when two pulses were used, but the compressive stress level is lower (-57 MPa). When four pulses were used, S_{22} becomes partially tensile in the shocked region as shown in Fig. 9 (c). This counter-intuitive change is due to overly large plastic deformations in the shocked region. Large downward (33 direction) pressure primarily causes excessive deformation in the outward (11 direction) in which least resistance is experienced. Based on

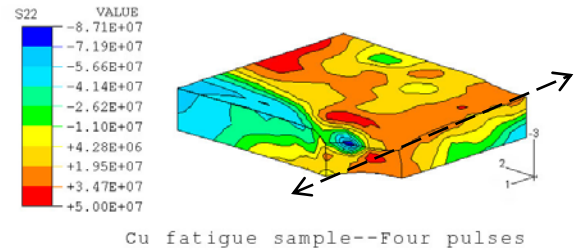
the constant volume principle of plastic deformation, the stress in the 22 direction becomes slightly tensile. This explains why the fatigue specimen treated with 4 pulses at each location did not perform as well as that treated with 2 and 3 pulses (Table 1). More generally, this is indicative of the effects of shock processing conditions on residual stress distributions.



(a)



(b)



(c)

Fig. 9 Residual stress distribution of the laser shock processed fatigue specimen

5. MICROSTRUCTURE STUDY OF LASER SHOCK PROCESSED SAMPLES

The effects of LSP on the target material can be better understood through the study of its microstructures, which are responsible for its macroscopic properties.

In this paper, Orientation Imaging Microscopy (OIM) was used to study the microstructure changes quantitatively. In an OIM system, the Electron Back-Scatter Diffraction (EBSD) patterns are recorded, and the bands in these patterns are termed Kikuchi bands. Kikuchi bands are representative of lattice planes in

the diffracting crystal. Such patterns are auto-indexed to extract the lattice orientation information.

Grain size and uniformity Grain boundaries were distinguished by defining the corresponding misorientation angles and the grain size distribution of the sample were found using the OIM post processing software. For instance, by setting misorientation angle of grain boundary to be 10 degrees, it was found that the grain size after microscale LSP did not change significantly, and this agrees with previous studies which found grain sizes change significantly only when very high pressures are applied [13]. The standard deviations of grain size, however, for both copper and nickel were reduced by more than 20% after LSP, which means the grains become more uniform after LSP. When the mean grain size is the same, the material with more uniform distribution of grain size has higher yield strength compared with the material with more scattered grain size distribution. The reason is that plastic strain is unevenly distributed among grains of different sizes [14]. Uniform grain size tends to share the external load more uniformly and is desirable for neutralizing weak spots and thus stress concentration.

Crystallographic texture Crystallographic texture refers to the preferred orientation. Misorientation angle between two points (or two directions) is defined as the minimum rotation angle needed to bring their lattice coordinates (or two directions) into coincidence. In OIM, the misorientation angle can be statistically analyzed as shown in Fig. 10, which compares the changes of {001} direction misorientation angle distribution with and without LSP for copper (Fig. 10(a)) and nickel (Fig. 10(b)), respectively. The misorientation angle is relative to the surface normal of the sample. The angle distribution curves for both nickel and copper in Fig. 10 show very low intensities at low angles before LSP. The reason is that for face centered cubic (FCC) metals such as nickel and copper, there are three perpendicular {001} pole-directions for each grain. Even if one pole is low angle (close to surface normal direction), the other two poles are high angles. The sample as received has slight textures, which rotate the lattice and make the low angle intensity even smaller. Texture variations of copper and nickel after LSP share a common feature, that is, trending towards the ideal {001} direction (low angle). Especially for angles less than 10 degrees, both copper and nickel show an obvious intensity increase after LSP. A striking difference between nickel and copper is that the {001} texture of nickel has a sharper density increase at small angles.

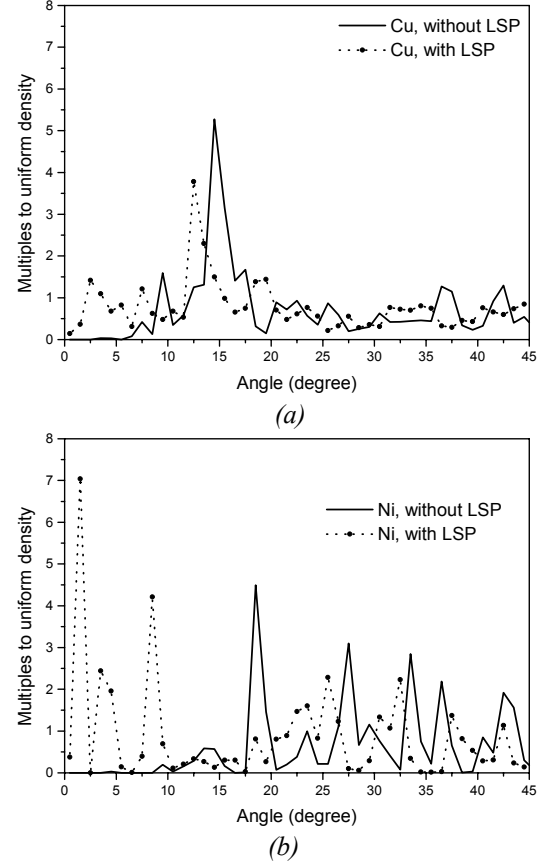


Fig. 10 Misorientation angle distribution of {001} lattice direction

Subgrain structures Subgrain structures can be quantitatively analyzed through OIM measurements because OIM is based on sub-micron spatial accuracy data acquisition of misorientation angles, and the misorientation angle accuracy is less than one degree. It is observed that copper has a larger increase in substructure and in highly deformed region after LSP than nickel, while both show substantial increase in substructure and highly deformed regions with LSP compared with that without LSP. Table 3 gives a quantitative comparison.

Table 3 Quantitative Comparison of Subgrain Structures

% of Area	Cu, without LSP	Cu, with LSP	Ni, without LSP	Ni, with LSP
With substructures	11±2.1%	46.3±2.5%	13±2.0%	39.4±1.8%
Highly deformed	4.4±0.9%	11±1.3%	0.5±0.5%	4.2±0.7%
Fully recrystallized	82.6±3.0%	42.7±3.2%	86.5±2.9%	56.4±2.5%

The substantial increase of substructures is the major cause of strength and hardness improvement in LSP. With the increase of substructures, the subgrain

size decreases, which has an effect similar to grain refinement. According to Murr [15], the flow stress

$$\sigma = \sigma_0 + k_1 D^{-1/2} + k_2 d^{-1} \quad (14)$$

where σ_0 , k_1 and k_2 are material constants, D is grain size, d is the subgrain size. As a result, the yield strengths of copper and nickel increase after LSP. Both the compressive surface residual stress and the refined microstructure in LSP contribute to the fatigue life improvement.

6. CONCLUSIONS

Laser shock processing at the scale of microns for the purpose of residual stress distribution alteration was discussed in this paper. A shock pressure model taking into account of mass, energy and momentum conservation was formulated with plasma modeled as laser supported combustion wave and its spatial expansion effects accounted for. Stress and strain analysis was extended to 3D and considered finite geometry, which again is important for microscale LSP. Tests showed microscale LSP more than doubled the fatigue life of copper and nickel specimens under the test condition. OIM measurements quantitatively showed LSP improved grain size uniformity and slightly increased texture. Increase of subgrain structures was also quantified and used to help explain the fatigue performance improvement by LSP. The differences between copper and nickel were explained in terms of their properties and response to shock waves.

It is shown that it is possible to impart desirable residual stress distributions into micro scale metallic components by properly choosing laser intensity, number of pulses and spacing. Fatigue life of metallic micro-devices can be improved if their residual stress distribution can be purposely altered. Micro scale laser shock processing has the potential to alter the mechanical properties of such metallic micro-devices. It may also be combined with laser micro-machining processes, which alone often leave an undesirable residual stress distribution in the machined components, to allow the net residual stress distributions in favor of improved fatigue life of the components.

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