Improvement of Fatigue Life and Surface Properties of Metallic Materials of Biomedical Interest by Laser Shock Processing

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Improvement of Fatigue Life and Surface Properties of Metallic Materials of Biomedical Interest by Laser Shock Processing

OUTLINE:

• Introduction
• Summary on the Physical Basis of LSP Treatments
• Predictive Assessment Methods developed at CLUPM
• Experimental LSP Setup at CLUPM
• Sample results on the treatment of Metallic Materials of Biomedical Interest
  - Fatigue life enhancement of AISI 316L specimens
  - Surface modification of Ti6Al4V samples
  - Compressive Residual stresses fields induced in Ti6Al4V samples
  - Computational Design of LSP Treatment for a Hip Prosthesis
• Discussion and Outlook
  - LSP treatment of new/advanced materials of biomedical interest
Laser Shock Processing (LSP) is developed as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.

The highly beneficial effect of LSP treatments has been demonstrated in the extension of life of test specimens with induced surface notches.

The application of the LSP treatment to concrete high reliability components, particularly in the field of metallic materials of biomedical interest is envisaged.

In the present communication, several experimental examples of the effects introduced in this kind of materials are shown along with some computational design tools developed in relation with typical prosthetical components.

Additionally, the prospects for the application of the LSP treatment to new/advanced materials of biomedical interest are discussed.
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)
REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)
NUMERICAL SIMULATION. MODEL DESCRIPTION

The SHOCKLAS Calculational System

- DRUPT
  - SESAME PROPACEOS
  - Laser
  - Breakdown
  - Modified laser pulse
  - Plasma Evolution
  - Pressure
  - Heat Flux
  - $T_e$, $T_i$
  - $P_{ne}$, $P_i$
  - Ionization degree

- LSPSIM
  - P(t), H(t)
  - Target Confining Layer
  - Interface evolution
  - Pressure
  - Impulsion

- HELIOS
  - $\alpha$
  - P(t)

- HARDSHOCK 3D
  - Abaqus Explicit
  - 3D
  - Shock Wave Evolution
  - Dynamic and Residual Stresses
  - Plastic Deformation

- Target Geometry
- Overlapping strategy

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

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BRAMAT 2017
10TH INTERNATIONAL CONFERENCE ON MATERIALS SCIENCE & ENGINEERING
9 - 11 MARCH 2017, BRASOV, ROMANIA
HELIOS

Analysis of relative influence of confining material
CONSISTENT MODEL FOR CONFINED PLASMA EXPANSION IN LSP

HELIOS

Analysis of plasma for LSP conditions
SHOCK PROPAGATION AND DERIVED RESIDUAL STRESSES IN LSP
Ocaña, J.L. et al.: “Predictive assessment and experimental characterization of the influence of irradiation parameters on surface deformation and residual stresses in laser-shock-processed metallic alloys”.
Q-SWITCHED Nd:YAG LASER

\( \tau = 10 \text{ ns}; \ f = 10 \text{ Hz} \)
PROCESS EXPERIMENTAL SETUP
PROCESS EXPERIMENTAL SETUP
PROCESS EXPERIMENTAL SETUP
PROCESS EXPERIMENTAL SETUP
**EXPERIMENTAL PROCEDURE**

Equivalent Overlapping g ≡ EOD = \( \frac{\text{N}^\circ \text{ of pulses}}{\text{Total treated surface}} = \frac{x \cdot y}{\Delta s} = \frac{x \cdot y}{d \cdot d} = \frac{1}{d^2} \)

Equivalent Energy Density EED = \( \frac{\text{N}^\circ \text{ of pulses} \cdot \text{Pulse Energy}}{\text{Total treated surface}} = \frac{x \cdot y}{\Delta s} \cdot E = \frac{x \cdot y}{d \cdot d} \cdot E = \frac{E}{d^2} \)

Equivalent local overlapping factor ELOF = \( \frac{\text{N}^\circ \text{ of pulses} \cdot \text{Pulse Area}}{\text{Total treated surface}} = \frac{\pi \cdot \phi^2}{d^2} = \frac{\pi}{4} \left( \frac{\phi}{d} \right)^2 \)
EXPERIMENTAL RESULTS

Material: Al2024 T3
Pulses: \( \phi = 1.5 \text{ mm}; \tau = 10 \text{ ns}; f = 10 \text{ Hz}; \)
\( E = 1 \text{ J/pulse}; I = 1.41 \text{ GW/cm}^2 \)
Swept Area: \( 15 \times 15 \text{ mm}^2; 2500 \text{ pulses/cm}^2 \)
EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

Fatigue Life enhancement of AISI 316L specimens

Table 1: Percent Composition of AISI 316L Steel Used in the Reported Experiments

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Mn</th>
<th>Si</th>
<th>N</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>% wt</td>
<td>0.018</td>
<td>16.815</td>
<td>10.086</td>
<td>2.044</td>
<td>1.294</td>
<td>0.458</td>
<td>0.047</td>
<td>0.032</td>
<td>0.003</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2: Initial Mechanical Properties of AISI 316L Steel Used in the Reported Experiments

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus [GPa]</td>
<td>177.2</td>
</tr>
<tr>
<td>Offset Tensile Yield Strength [MPa]</td>
<td>355.4</td>
</tr>
<tr>
<td>Ultimate Tensile Strength [MPa]</td>
<td>633.6</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

Process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1064</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>10</td>
</tr>
<tr>
<td>Energy (J/pulse)</td>
<td>2.0</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
<td>~ 9</td>
</tr>
<tr>
<td>Spot diameter (mm)</td>
<td>~ 1.5</td>
</tr>
<tr>
<td>Overlapping (pulses/cm²)</td>
<td>900</td>
</tr>
<tr>
<td>Overlapping (pulses/cm²)</td>
<td>1600</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Water jet</td>
</tr>
<tr>
<td>Absorbent coating</td>
<td>No</td>
</tr>
</tbody>
</table>

900 pulses/cm² + Heat treat.: 500 °C, 8h

1600 pulses/cm² + Heat treat.: 500 °C, 8h

Experimental setup LSP CLUPM
Residual Stresses:

Residual stresses (MPa) vs. Depth (mm)

Steel AISI 316L, 900 pulses/cm², λ = 1064 nm
2.8 J/pulse, spot diameter = 1.5 mm, water jet, no paint

Smax, As LSP treated
Smax, LSP treated + thermal aging

Steel AISI 316L, 1600 pulses/cm², λ = 1064 nm
2.8 J/pulse, spot diameter = 1.5 mm, water jet, no paint

Smax, As LSP treated
Smax, LSP treated + thermal aging

EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L
Fatigue Tests:

![Graph showing fatigue life enhancement of AISI 316L](image)

**Experimental Results.** Fatigue life enhancement of AISI 316L.
EXPERIMENTAL RESULTS. Fatigue life enhancement of AISI 316L

Fatigue Tests:

Steel AISI 316L, 900 pulses/cm², λ = 1064 nm
2.8 J/pulse, spot diameter = 1.5 mm, water jet, no paint

Steel AISI 316L, 1600 pulses/cm², λ = 1064 nm
2.8 J/pulse, spot diameter = 1.5 mm, water jet, no paint

Pristine AISI 316L
LSP 900
LSP 900 + Thermal Aging
**EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples**

### Reported Analysis

<table>
<thead>
<tr>
<th>Surface Modification</th>
<th>Al2024-T351 30x20x8 mm³</th>
<th>Ti6Al4V 30x20x10 mm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 pulses/ cm²</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>1600 pulses/ cm²</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>2500 pulses/ cm²</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>5000 pulses/ cm²</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Microscopy): Al2024-T351

900 pulses/cm² 1600 pulses/cm² 2500 pulses/cm²
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Topographic Confocal microscopy): Al2024-T351

900 pulses/cm²  1600 pulses/cm²  2500 pulses/cm²

<table>
<thead>
<tr>
<th></th>
<th>No treatment</th>
<th>900 pulses/cm²</th>
<th>1600 pulses/cm²</th>
<th>2500 pulses/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa (µm)</td>
<td>7.96</td>
<td>5.23</td>
<td>4.82</td>
<td>4.96</td>
</tr>
<tr>
<td>&lt;Δz&gt;</td>
<td>----</td>
<td>10.30</td>
<td>20.00</td>
<td>26.82</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Microscopic material compactation: Al2024-T351

900 pulses/cm²

1600 pulses/cm²

2500 pulses/cm²
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Microscopy): Ti6Al4V

900 pulses/cm²  2500 pulses/cm²  5000 pulses/cm²
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

<table>
<thead>
<tr>
<th>Treatment</th>
<th>900 pulses/cm²</th>
<th>2500 pulses/cm²</th>
<th>5000 pulses/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa (μm)</td>
<td>9.98</td>
<td>3.62</td>
<td>3.87</td>
</tr>
<tr>
<td>&lt;Δz&gt;</td>
<td>----</td>
<td>2.81</td>
<td>7.40</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Microscopic material compactation: Ti6Al4V

900 pulses/cm²  2500 pulses/cm²  5000 pulses/cm²
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Microhardness (HV)

Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatment intensity

No apparent hardening effect in Ti6Al4V.
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Wear resistance (According to ASTM G99-04)

Al2024-T351

Slight wear improvement in Al2024-T351 at low loads

Considerable wear improvement in Al2024-T351 at moderate loads
EXPERIMENTAL RESULTS. Surface modification of Ti6Al4V samples

Wear resistance (According to ASTM G99-04)

Ti6Al4V

Slight negative wear impact in Ti6Al4V at low loads

Inappreciable wear improvement in Ti6Al4V at moderate loads
EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V

Residual Stresses Measurement Equipment (According to ASTM E837-08)
EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V

Residual Stresses (According to ASTM E837-08)

**Al2024-T351**

Relatively broad difference between $S_{\text{max}}$ and $S_{\text{min}}$ in Al2024-T351

**Ti6Al4V**

Relatively small difference between $S_{\text{max}}$ and $S_{\text{min}}$ in Ti6Al4V
Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening

EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V

Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities
EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V

Table 1. Ti6Al4V specimens composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>V</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight percentage</td>
<td>6.1</td>
<td>4.2</td>
<td>0.01</td>
<td>0.12</td>
<td>0.006</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2. Samples designation and processing conditions

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial treatment (pre LSP)</th>
<th>LSP treatment EOD (cm²)</th>
<th>Thermal aging treatment (post LSP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>710ºC / 2h</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>T-LSP</td>
<td>710ºC / 2h</td>
<td>5000</td>
<td>No</td>
</tr>
<tr>
<td>T-LSP5</td>
<td>710ºC / 2h</td>
<td>5000</td>
<td>595ºC / 1h</td>
</tr>
<tr>
<td>T-LSP7</td>
<td>710ºC / 2h</td>
<td>5000</td>
<td>710ºC / 2h</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V

Typical SEM views of surfaces on T (a), T-LSP (b), T-LSP5 (c), and T-LSP7 (d) specimens.
RESIDUAL STRESSES FIELDS FOR THE DIFFERENT CONDITIONS
(Measured by energy-dispersive diffraction using synchrotron X-ray radiation at the EDDI beam line of BESSY II (Berlin, Germany); 10-150 keV; 2θ =16º)

EXPERIMENTAL RESULTS. Compressive RS’s fields induced in Ti6Al4V
Computational Design of LSP Treatment for a Ti6Al4V Hip Prosthesis

Typical geometry of a Charnley hip replacement prosthesis (adapted from Charnley, 1977)
Treatment geometry and FEM mesh used in the treatment of the considered hip replacement by LSP.

Colour scale presentation of the minimum principal superficial residual stresses induced in the considered hip replacement by LSP.

Sample result showing the internal residual stresses fields induced in a hip replacement prosthesis by LSP.

• Important surface resistance and life cycle extension improvements in critical high reliability components by LSP have been experimentally demonstrated. The associate predictive assessment capabilities needed for adequate process design have also been developed and used for theoretical-experimental contrast.

• In view of the important improvements reached in wear behaviour, surface roughness (precursor of improved corrosion resistance) and fatigue life (all of them resulting from the deep compressive residual stresses fields introduced by the process), the LSP technique has to be recognized as a key technology for the enhancement of materials and systems durability and reliability.

• Important technological implementations of LSP in the aerospace, automotive, nuclear and biomedical sectors are under course, anticipating relevant improvements in service reliability and in material preservation and (eco-friendly) efficient use.

• Of special interest is the LSP treatment of new/advanced materials of biomedical interest as a means of improving the effective life of high risk/reliability components (i.e. prosthetic replacements in aged persons).
Due to their excellent biodegradability characteristics, Mg and Mg-based alloys have become an emerging material in biomedical implants, notably for repair of bone as well as coronary arterial stents. However, the main problem with Mg-based alloys is their rapid corrosion in aggressive environments such as human body fluids.

(M. Peuster et al.: doi:10.1017/S1047951106000011)

(B. Denkena, A. Lucas.: doi:10.1016/j.cirp.2007.05.029)
DISCUSSION AND OUTLOOK

\[ \varnothing = 2.5 \text{ mm} \]

- 178 pulsos/cm²
- 223 pulsos/cm²
- 278 pulsos/cm²
- 400 pulsos/cm²
ACKNOWLEDGEMENTS

Work partly supported by MINECO (Spain; Projects MAT2012-37782 and MAT2015-63974-C4-2-R).

REFERENCES

The UPM Laser Centre Approach to LSP Development

EXPERIMENTAL CHARACTERIZATION OF MATERIAL PROPERTIES

LASER PLASMA INTERACTION SIMULATION AND DIAGNOSIS

NUMERICAL SIMULATION OF SOLID BEHAVIOUR
Thank you very much for your attention!

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Major Facilities (1/2)
Major Facilities (2/2)
Evaluation of relative effects of thermal and mechanical waves on shocked material

Water / Aluminium; Nd:YAG (1064 nm),
\[ \tau = 9 \text{ ns}, F = 84 \text{ J/cm}^2, \text{radius} = 1.5 \text{ mm} \]

EXPERIMENTAL RESULTS

A typical prospective LSP application to welding technology
DISCUSSION AND OUTLOOK

Fig. 10. (a) Tensile properties at different regions of the weld (b) Strain fields in the x-direction for the specimen before failure.

Fig. 11. Residual stresses for the various peened FSW specimens.

Fig. 12. Two-dimensional map of the measured residual stress for the unpeened FSW specimen.

Fig. 13. Two-dimensional map of the measured residual stress for the shot peened FSW specimen.

Fig. 14. Two-dimensional map of the measured residual stress for the laser peened FSW specimen.