Laser Shock Processing: An Emerging Technique for the Improvement of Fatigue Life and Surface Properties of High Reliability Metallic Components

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Laser Shock Processing: An Emerging Technique for the Improvement of Fatigue Life and Surface Properties of High Reliability Metallic Components

OUTLINE:

• Introduction
• Process Experimental Setup
• Experimental Procedure
• Experimental Results for Al2024-T351, Ti6Al4V and AISI 316L
  - Surface Roughness and Compactation
  - Residual stresses
  - Tensile Strength
  - Fatigue Life
• Discussion and Outlook
  - Prospects for technological applications of LSP
INTRODUCTION

Laser Shock Processing (LSP) is being increasingly applied 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.

According to the inherent difficulty for the prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability coupled to a readily controllable experimental setup for a correct application of treatment parameters and an associate material properties characterization capability.

In the present communication, the practical LSP treatment and associate specimens characterization capabilities developed at CLUPM (Spain) are presented along with selected results obtained in several relevant aerospace and nuclear industry alloys.
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)
REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)
PROCESS EXPERIMENTAL SETUP

Q-SWITCHED Nd:YAG LASER

\[ \begin{align*}
\lambda &= 1064 \text{ nm}; \ E = 2.5 \ J/\text{pulse} \quad \tau = 10 \ \text{ns}; \ f = 10 \ \text{Hz} \\
\lambda &= 532 \ \text{nm}; \ E = 1.4 \ \text{J/pulse}
\end{align*}\]
PROCESS EXPERIMENTAL SETUP

**LSP TREATMENT PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength (nm); Q-switched Nd:YAG</td>
<td>1064</td>
</tr>
<tr>
<td>Energy per pulse (J/pulse)</td>
<td>2.0</td>
</tr>
<tr>
<td>Pulse temporal width (ns)</td>
<td>9</td>
</tr>
<tr>
<td>Laser spot diameter (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Ratio x-y pitch</td>
<td>1</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Water jet ≈ 2 bar</td>
</tr>
<tr>
<td>Absorbing coating overlay</td>
<td>No</td>
</tr>
</tbody>
</table>
PROCESS EXPERIMENTAL SETUP
EXPERIMENTAL PROCEDURE

[Images of experimental procedure]
**EXPERIMENTAL PROCEDURE**

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

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

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

Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

<table>
<thead>
<tr>
<th>Overlapping pitch Y (mm)</th>
<th>Equivalent overlapping density (pulses/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.588</td>
<td>289</td>
</tr>
<tr>
<td>0.33</td>
<td>900</td>
</tr>
<tr>
<td>0.285</td>
<td>1225</td>
</tr>
<tr>
<td>0.2</td>
<td>2500</td>
</tr>
<tr>
<td>0.141</td>
<td>5000</td>
</tr>
</tbody>
</table>
Material: Al2024 T3
Pulses: \( \phi = 1.5 \text{ mm}; \tau = 10 \text{ ns}; f = 10 \text{ Hz}; \)
E = 1 J/pulse; \( I = 1.41 \text{ GW/cm}^2 \)
Swept Area: 15x15 mm\(^2\); 2500 pulses/cm\(^2\)
## EXPERIMENTAL RESULTS

### Reported Analysis

<table>
<thead>
<tr>
<th></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 Roughness (Microscopy): Al2024-T351

900 pulses/cm² 1600 pulses/cm² 2500 pulses/cm²
EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Al2024-T351

<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>

900 pulses/cm²  1600 pulses/cm²  2500 pulses/cm²
EXPERIMENTAL RESULTS

Microscopic material compactation: Al2024-T351

900 pulses/cm²  
1600 pulses/cm²  
2500 pulses/cm²
EXPERIMENTAL RESULTS

Surface Roughness (Microscopy): Ti6Al4V

900 pulses/cm²

2500 pulses/cm²

5000 pulses/cm²
Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Pa (μm)</th>
<th>900 pulses/cm²</th>
<th>1600 pulses/cm²</th>
<th>2500 pulses/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>No treatment</td>
<td>9.98</td>
<td>3.62</td>
<td>3.87</td>
<td>3.87</td>
</tr>
<tr>
<td>Pa (μm)</td>
<td>&lt;Δz&gt;</td>
<td>2.81</td>
<td>7.40</td>
<td>5.80</td>
</tr>
</tbody>
</table>

900 pulses/cm²  2500 pulses/cm²  5000 pulses/cm²
EXPERIMENTAL RESULTS

Microscopic material compactation: Ti6Al4V

900 pulses/cm²  
2500 pulses/cm²  
5000 pulses/cm²
Microhardness (HV)

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

No apparent hardening effect in Ti6Al4V.
EXPERIMENTAL RESULTS

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

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

Residual Stresses (According to ASTM E837-08)

CEA-XX-062UM-120
EA-XX-062RE-120
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)

**EXPERIMENTAL RESULTS**

- **Al2024-T351**
  - $S_{\text{max}}$ in Al2024-T351 for different irradiation intensities

- **Ti6Al4V**
  - $S_{\text{max}}$ in Ti6Al4V for different irradiation intensities
Residual Stresses (According to ASTM E837-08)

**Al2024-T351**

- $S_{\max}$ and $S_{\min}$ extremes reached in Al2024-T351 for different irradiation intensities
- Compressively protected depth (100 MPa) reached in Al2024-T351 for different irradiation intensities
Residual Stresses (According to ASTM E837-08)

**Ti6Al4V**

**S\text{max} and S\text{min}** extremes reached in Ti6Al4V for different irradiation intensities

Compressively protected depth (100-200 MPa) reached in Ti6Al4V for different irradiation intensities
Residual Stresses (According to ASTM E837-08)

**Ti6Al4V: Comparison LSP-Shot Peening**

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

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities
Residual Stresses Permanence upon Thermal Treatment

AISI 316L Steel

S_{\text{max}} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 900 pulses/cm² LSP Treatment Intensity

S_{\text{max}} permanence in AISI 316L Steel after different Thermal Treatment Temperatures for a 1600 pulses/cm² LSP Treatment Intensity
EXPERIMENTAL RESULTS

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>2.8</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, 1600</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Water jet</td>
</tr>
<tr>
<td>Absorbent coating</td>
<td>No</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

- Experimental setup LSP CLUPM
- 900 pul/cm²
- 1600 pul/cm²

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

Residual Stresses:

AISI 316L Stainless steel, $\lambda = 1064\,\text{nm}$
2.8 J/pulse, Spot diameter = 1.5 mm, Water jet, without paint

Residual Stresses:

AISI 316L Stainless steel, 900 pulses/cm$^2$, $\lambda = 1064\,\text{nm}$
2.8 J/pulse, Spot diameter = 1.5 mm, Water jet, without paint

Residual stresses (MPa)
Depth (mm)
Smin, 25ºC
Smin, 500ºC - 8 h
Smax, 25ºC
Smax, 500ºC - 8 h
EXPERIMENTAL RESULTS

“Sub-size” Tensile Specimen
ASTM E 8M

“Bone” Fatigue Specimen
ASTM E 466
EXPERIMENTAL RESULTS

Tensile Tests:

![Tensile Test Graph]

<table>
<thead>
<tr>
<th>Property</th>
<th>Base material</th>
<th>LSP 900</th>
<th>LSP 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Modulus (GPa)</td>
<td>177.205</td>
<td>182.099</td>
<td>185.446</td>
</tr>
<tr>
<td>Engineering elastic limit (MPa)</td>
<td>355.410</td>
<td>356.390</td>
<td>359.930</td>
</tr>
<tr>
<td>Maximum tensile stress (MPa)</td>
<td>633.608</td>
<td>629.700</td>
<td>626.870</td>
</tr>
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</table>
EXPERIMENTAL RESULTS

Fatigue Tests:

<table>
<thead>
<tr>
<th>$S_a$ (Mpa)</th>
<th>$S_{max}$ (Mpa)</th>
<th>$F_{max}$ (kN)</th>
<th>$F_{mean}$ (kN)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>622</td>
<td>54.507</td>
<td>29.979</td>
<td>37752</td>
</tr>
<tr>
<td>270</td>
<td>600</td>
<td>52.560</td>
<td>28.908</td>
<td>49580</td>
</tr>
<tr>
<td>260</td>
<td>578</td>
<td>50.613</td>
<td>27.837</td>
<td>51513</td>
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<tr>
<td>250</td>
<td>556</td>
<td>48.667</td>
<td>26.767</td>
<td>71850</td>
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<tr>
<td>240</td>
<td>533</td>
<td>46.720</td>
<td>25.696</td>
<td>92466</td>
</tr>
<tr>
<td>230</td>
<td>511</td>
<td>44.773</td>
<td>24.625</td>
<td>105771</td>
</tr>
<tr>
<td>220</td>
<td>489</td>
<td>42.827</td>
<td>23.555</td>
<td>131677</td>
</tr>
<tr>
<td>210</td>
<td>467</td>
<td>40.880</td>
<td>22.484</td>
<td>157696</td>
</tr>
<tr>
<td>200</td>
<td>444</td>
<td>38.933</td>
<td>21.413</td>
<td>184158</td>
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<tr>
<td>190</td>
<td>422</td>
<td>36.987</td>
<td>20.343</td>
<td>260974</td>
</tr>
<tr>
<td>180</td>
<td>400</td>
<td>35.040</td>
<td>19.272</td>
<td>264889</td>
</tr>
<tr>
<td>170</td>
<td>378</td>
<td>33.093</td>
<td>18.201</td>
<td>661126</td>
</tr>
<tr>
<td>160</td>
<td>356</td>
<td>31.147</td>
<td>17.131</td>
<td>1000000</td>
</tr>
</tbody>
</table>

Base Material: AISI 316L Stainless Steel
EXPERIMENTAL RESULTS

Fatigue Tests:

<table>
<thead>
<tr>
<th>S&lt;sub&gt;a&lt;/sub&gt; (MPa)</th>
<th>S&lt;sub&gt;max&lt;/sub&gt; (MPa)</th>
<th>F&lt;sub&gt;max&lt;/sub&gt; (kN)</th>
<th>F&lt;sub&gt;mean&lt;/sub&gt; (kN)</th>
<th>Cycles 900</th>
<th>Cycles 1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>622</td>
<td>54.507</td>
<td>29.979</td>
<td>35574</td>
<td>60199</td>
</tr>
<tr>
<td>260</td>
<td>578</td>
<td>50.613</td>
<td>27.837</td>
<td>57777</td>
<td>75105</td>
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<tr>
<td>240</td>
<td>533</td>
<td>46.720</td>
<td>25.696</td>
<td>91471</td>
<td>107098</td>
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<td>230</td>
<td>511</td>
<td>44.773</td>
<td>24.625</td>
<td>130302</td>
<td>165560</td>
</tr>
<tr>
<td>220</td>
<td>489</td>
<td>42.827</td>
<td>23.555</td>
<td>233301</td>
<td>185802</td>
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<tr>
<td>210</td>
<td>467</td>
<td>40.880</td>
<td>22.484</td>
<td>268180</td>
<td>444006</td>
</tr>
<tr>
<td>200</td>
<td>444</td>
<td>38.933</td>
<td>21.413</td>
<td>1000000</td>
<td>1000000</td>
</tr>
</tbody>
</table>

Log<sub>N</sub><sup>2</sup> = 21.09071 - 0.01178<sub>S<sub>a</sub></sub><sup>2</sup><sup>2</sup>  \( R^2 = 0.99760 \)

Log<sub>N</sub><sup>2</sup> = 22.51020 - 7.35620<sub>Log</sub><sub>S<sub>a</sub></sub><sup>2</sup> \( R^2 = 0.98967 \)

Log<sub>N</sub><sup>2</sup> = 16.33764 - 4.79302<sub>Log</sub><sub>S<sub>a</sub></sub><sup>2</sup> \( R^2 = 0.99760 \)
**EXPERIMENTAL RESULTS**

**Fatigue Tests:**

<table>
<thead>
<tr>
<th>S_a (Mpa)</th>
<th>S_max (Mpa)</th>
<th>F_max (kN)</th>
<th>F_mean (kN)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>622</td>
<td>54.507</td>
<td>29.979</td>
<td>6000</td>
</tr>
<tr>
<td>230</td>
<td>511</td>
<td>44.773</td>
<td>24.625</td>
<td>128632</td>
</tr>
<tr>
<td>200</td>
<td>444</td>
<td>38.933</td>
<td>21.413</td>
<td>259987</td>
</tr>
<tr>
<td>180</td>
<td>400</td>
<td>35.040</td>
<td>19.272</td>
<td>1000000</td>
</tr>
</tbody>
</table>

**Graph:**

- Base Material
- LSP 900
- LSP 900 Heat Treatment

Equations:

- \( \log N = 16.33764 - 4.79302 \log S_a \) with \( R^2 = 0.99760 \)
- \( \log N = 22.51020 - 7.35620 \log S_a \) with \( R^2 = 0.98967 \)
- \( \log N = 17.00022 - 5.03482 \log S_a \) with \( R^2 = 0.99 \)
EXPERIMENTAL RESULTS

A typical prospective LSP application to welding technology

Fig. 4. Dimensions of the tensile specimen.
DISCUSSION AND OUTLOOK

With the aid of the experimental irradiation and process diagnosis system implemented at CLUPM (Spain), a complete feasibility of the LSP technique at laboratory scale for the induction of improved material surface properties has been accomplished. The implementation of the appropriate experimental diagnosis methods enables a reliable process predictive assessment capability in view of process industrial implementation.

On the other side, the need for a practical capability of LSP process control in practical applications has led to the joint development of comprehensive theoretical/computational models and related material properties characterization capabilities able to properly assess the complex material issues arising in the process.

With the aid of the developed experimental testing capability, a specifically targeted analysis of LSP induced effects (such as surface morphology, surface composition transformations, surface mechanical behaviour, deep residual stress fields and others) is made possible, thus allowing a practical development of the technique from an industrial point of view.

Representative applications of the LSP technique to the treatment of typical aeronautic grade alloys (typically Al and Ti) and stainless steels characteristic of the aerospace, nuclear, biomedical and equipment industries, as well as to the post-treatment of welded metallic joints have been successfully conducted to the induction of compressive residual stresses fields decisively improving their fatigue life.
DISCUSSION AND OUTLOOK

EXPERIMENTAL CHARACTERIZATION OF MATERIAL PROPERTIES

LASER PLASMA INTERACTION SIMULATION AND DIAGNOSIS

NUMERICAL SIMULATION OF SOLID BEHAVIOUR
ACKNOWLEDGEMENTS

Work supported by MEC/MCINN (Spain; Projects DPI2005-09152-C02-01; MAT2008-02704/MAT), UPM (Spain, Project CM CCG07-UPM/MAT-1964) and EADS-CASA (Spain)

REFERENCES

DISCUSSION AND OUTLOOK

LSP: An emerging industrial technology
LSP: An Emerging Sustainability Supporting Technology

Next event on LSP:

4th International Conference on Laser Peening and Related Phenomena

May 6th-10th 2013
ETS de Ingenieros Industriales, Universidad Politécnica de Madrid, SPAIN

Contact: jlocana@etsii.upm.es
http://www.upmlaser.upm.es/4-ICLPRP
In Memoriam

Prof. Dr. Ing. Danut IORDACHESCU
(Passed away W03.JAN.2012)
Thank you very much for your attention!

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Major Facilities (1/4)
Major Facilities (2/4)
Major Facilities (3/4)
Major Facilities (4/4)
The SHOCKLAS Calculational System

- Interface evolution
- Pressure
- Impulsion

- Breakdown
- Modified laser pulse

- Plasma Evolution
- Pressure
- Heat Flux
- \( T_e, T_i \)
- \( P_{\text{D}} \)
- Ionization degree

- Hardshock 1D
- ABAQUS Explicit
- ABAQUS Standard

1D
- Shock Wave Evolution
- Plastic Deformation

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

Target Geometry
Overlapping strategy