Improvement of Mechanical Properties and Life Extension of High Reliability Structural Components by Laser Shock Processing

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Improvement of Mechanical Properties and Life Extension of High Reliability Structural Components by Laser Shock Processing

OUTLINE:

• Introduction. Fundamental Physics of Laser Shock Processing
• Experimental Procedure
• Experimental Results for Al2024-T351 and Ti6Al4V
  - Surface Roughness
  - Microstructure
  - Microhardness
  - Wear
  - Residual stresses
  - Fatigue crack growth
• Discussion and Outlook
INTRODUCTION

- 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.

- However, 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.

- Despite the availability of the LSP technique at laboratory level, practical developments at industrial level still need to be further accomplished.

- 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 two relevant aerospatial alloys (Al2024-T351 and Ti6Al4V).
REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)
NUMERICAL SIMULATION RESULTS

Ti6Al4V

Nd:YAG (1064 nm)
$P_w = 5.7 \text{ W/cm}^2$
Spot radius = 0.75 mm
FWHM = 0 ns
$\alpha = 0.15$

Multiple shocks
dynamic analysis

HARDSHOCK-2D Semi-infinite
NUMERICAL SIMULATION RESULTS

HARDSHOCK-2D Semi-infinite

Ti6Al4V

Nd:YAG (1064 nm)
P_w = 5.7 W/cm²
Spot radius = 0.75 mm
FWHM = 0 ns
α = 0.15

Multiple shocks
dynamic analysis

Residual radial stress (GPa)

Depth (mm)
NUMERICAL SIMULATION RESULTS

HARDSHOCK-2D Semi-infinite

Ti6Al4V

Nd:YAG (1064 nm)
$P_w = 5.7 \, \text{W/cm}^2$
Spot radius = 0.75 mm
FWHM = 0 ns
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Multiple shocks
dynamic analysis
NUMERICAL SIMULATION RESULTS

HARDSHOCK-3D (full scope)

Ti6Al4V

Nd:YAG (1064 nm)

$P_{av} = 5.7 \text{ W/cm}^2$

Spot radius = 0.75 mm

FWHM = 0 ns

$\alpha = 0.15$

Overlapping = 900/cm$^2$

1 9

17 25
NUMERICAL SIMULATION RESULTS

HARDSHOCK-3D (full scope)

Ti6Al4V

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$P_{av} = 5.7\ \text{W/cm}^2$

Spot radius = 0.75 mm

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- $P_{av} = 5.7$ W/cm$^2$
- Spot radius = 0.75 mm
- FWHM = 0 ns
- $\alpha = 0.15$
- Overlapping = 900/cm$^2$
Laser Nd:YAG ($\lambda=1064$ nm)
- Effective Energy 1 J
- FWHM 10 ns
- Spot radius = 0.75 mm

Material: Al2024-T3
Spot overlapping 900 pulses/cm²
$\alpha=0.15$

Residual Stress $\sigma_x$ (Pa)
Laser Nd:YAG ($\lambda=1064$ nm)
- Effective Energy 1 J
- FWHM 10 ns
- Spot radius = 0.75 mm

Material: Al2024-T3

Spot overlapping 900 pulses/cm²
$\alpha = 0.15$
Laser Nd:YAG (λ=1064 nm)
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Material: Ti-6Al-4V

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Residual Stress $\sigma_x$ (Pa)
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- Effective Energy 1 J
- FWHM 10 ns
- Spot radius = 0.75 mm

Material: Ti-6Al-4V

Spot overlapping 900 pulses/cm²
α = 0.15
PROCESS EXPERIMENTAL SETUP

YAG LASER OSCILLATOR

X, Y DRIVING MECHANISM

WATER SUPPLY

TEST PIECE

LASER PULSE

MIRROR

LENS

WINDOW
Q-SWITCHED Nd:YAG LASER

\[
\begin{align*}
\lambda &= 1064 \, \text{nm}; \quad E = 2,5 \, \text{J/pulse} \\
\lambda &= 532 \, \text{nm}; \quad E = 1,4 \, \text{J/pulse}
\end{align*}
\]

\[\tau = 10 \, \text{ns}; \quad f = 10 \, \text{Hz}\]
PROCESS EXPERIMENTAL SETUP

LSP TREATMENT PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength (nm)</td>
<td>1064</td>
</tr>
<tr>
<td>Q-switched Nd:YAG</td>
<td></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 VALIDATION. DIAGNOSIS SETUP

DIRECT IMAGING - HYDRODYNAMIC ANALYSIS

$1 \text{ mm}$

$t = 10 \text{ ns}$
$25 \text{ ns}$
$50 \text{ ns}$
$100 \text{ ns}$
$200 \text{ ns}$
EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY
EXPERIMENTAL PROCEDURE
EXPERIMENTAL PROCEDURE

Table 1: 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>
EXPERIMENTAL RESULTS

Material: Al2024 T3

Pulses: $\varnothing=1.5$ mm; $\tau=10$ ns; $f=10$ Hz; $E=1$ J/pulse; $I=1.41$ GW/cm²

Swept Area: 15x15 mm²; 2500 pulses/cm²
### EXPERIMENTAL RESULTS

#### Reported Analysis

<table>
<thead>
<tr>
<th>Material</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" alt="Sample Image" /></td>
<td><img src="image2" alt="Sample Image" /></td>
</tr>
<tr>
<td>1600 pulses/cm²</td>
<td><img src="image3" alt="Sample Image" /></td>
<td><img src="image4" alt="Sample Image" /></td>
</tr>
<tr>
<td>2500 pulses/cm²</td>
<td><img src="image5" alt="Sample Image" /></td>
<td><img src="image6" alt="Sample Image" /></td>
</tr>
<tr>
<td>5000 pulses/cm²</td>
<td><img src="image7" alt="Sample Image" /></td>
<td><img src="image8" alt="Sample 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>
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
EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

<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>9.98</td>
<td>3.62</td>
<td>3.87</td>
<td>3.87</td>
</tr>
<tr>
<td>&lt;Δz&gt;</td>
<td>----</td>
<td>2.81</td>
<td>7.40</td>
<td>5.80</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Microscopic material compactation: Ti6Al4V

900 pulses/cm²

2500 pulses/cm²

5000 pulses/cm²
EXPERIMENTAL RESULTS

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)

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

![Graphs showing residual stresses for Al2024-T351 and Ti6Al4V.](image)
Residual Stresses (According to ASTM E837-08)

**Al2024-T351**

- $S_{\text{max}}$ in Al2024-T351 for different irradiation intensities
- $S_{\text{min}}$ in Al2024-T351 for different irradiation intensities
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V

$S_{\text{max}}$ in Ti6Al4V for different irradiation intensities

$S_{\text{min}}$ in Al2024-T351 for different irradiation intensities
EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening

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

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities
DISCUSSION AND OUTLOOK

- 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.
7. DISCUSSION AND OUTLOOK

LASER PLASMA INTERACTION
EXPERIMENTAL CHARACTERIZATION
OF MATERIAL PROPERTIES

LASER PLASMA INTERACTION
SIMULATION AND DIAGNOSIS

NUMERICAL SIMULATION
OF SOLID BEHAVIOUR

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LSP: An Emerging Sustainability Supporting Technology