High Intensity Lasers Application to Advanced Materials Processing: Laser Peening and Related Processes

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1. Introduction

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3. Metallic Surfaces Treatment by High Intensity Short Pulse Lasers. Laser Shock Processing
   3.1. Concept and Physical Basis
   3.2. Process Modelling
   3.3. Experimental Implementation
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   3.5. Discussion and Outlook

4. Final Discussion. Application of High Intensity Short Pulse Lasers to other Materials Processing Applications
   4.1. Laser shock microforming (LSμF®)
Phenomenology of Laser-Matter Interaction at Moderately High Intensities ($10^9$-$10^{12}$ W/cm²) Macroscopic Approach

\[ F_c = m_c \frac{\partial \nu}{\partial t} = -\mathbf{E} = -E_c \exp(\imath \omega t) \quad [A.24] \]

\[ \nu(t) = -\frac{\omega}{m_c} \int E(t) dt = -\frac{i}{\omega} \frac{\mathbf{E}(t)}{m_c} \quad [A.25] \]

\[ J(t) = -N e \nu(t) = -\frac{N e^2}{\omega} \mathbf{E}(t) = \sigma E(t) \quad \Rightarrow \quad \sigma(\omega) = -\frac{N e^2}{\omega} \quad [A.26] \]

\[ P = \langle J \cdot \mathbf{E} \rangle = \langle \sigma \mathbf{E} \cdot \mathbf{E} \rangle = \frac{1}{2} \sigma \langle \mathbf{EE}^* \rangle = 0 \quad [A.27] \]

\[ J_c = \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} = (\sigma + i \omega \varepsilon_0) \mathbf{E} = (\sigma + i \omega \varepsilon_0) \mathbf{E} \quad [A.28] \]

\[ \mathbf{J}_c = (\omega \varepsilon_0 - i \frac{N e^2}{\omega m_c}) \mathbf{E} - i \omega \varepsilon_0 (1 - \frac{N e^4}{\omega^2 m_c^2}) \mathbf{E} \quad [A.29] \]

\[ J_c = i \omega \varepsilon_0 \left(1 - \left(\frac{\omega_c}{\omega}\right)^2\right) \mathbf{E} \quad [A.30] \]

\[ \omega_0 = \left(\frac{N e^2}{m_c \varepsilon_0}\right) \quad [A.31] \]

\[ L^2(\omega) = \frac{\omega^2 \varepsilon_0}{\omega_0^2} \left(1 - \frac{\omega}{\omega_0}\right) = \frac{\omega^2 \varepsilon_0}{\omega_0^2} \left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right) \quad [A.32] \]

\[ N_c(\omega) = \frac{m_c \varepsilon_0 \omega^3}{\varepsilon_0^2} \quad [A.33] \]

Phenomenology of Laser-Matter Interaction at Moderately High Intensities (10^9-10^{12} W/cm^2)
Macroscopic approach

Phenomenology of Laser-Matter Interaction at Moderately High Intensities ($10^9$-$10^{12}$ W/cm$^2$) Macroscopic Approach
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Phenomenology of Laser-Matter Interaction at Moderately High Intensities ($10^9$-$10^{12}$ W/cm$^2$) Macroscopic Approach

Nielsen, P.E.: J. Appl. Phys. , 46 (1975), 4501-4505
Phenomenology of Laser-Matter Interaction at Moderately High Intensities (10⁹-10¹² W/cm²) Detailed Physical Approach

LSP Concept

FREE MODE

CONFINED MODE

FREE PLASMA EXPANSION

IMPROVED PRESSURE AND IMPULSION

CENTRO LÁSER
UNIVERSIDAD POLITÉCNICA DE MADRID

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LSP Concept

Permanent Deformation
Damping
Elastic Precursor

AI 2024-T3
$L_0 = 5.4$ GW/cm$^2$

$t = 0$ ns
$t = 50$ ns
$t = 100$ ns
$t = 150$ ns
$t = 200$ ns
$t = 250$ ns

Minimum Residual Stress $S_{min}$ (MPa)

Spot Diameter = 1.5 mm, water jet 2 bar, no paint

625 pulses/cm$^2$
900 pulses/cm$^2$
2500 pulses/cm$^2$
LSP Physical Basis

Solid/Liquid  \( D = C + S u \)

Gas  \( D = u = \left( \frac{(\gamma + 1) P}{2 \rho} \right)^{\frac{1}{2}} \)

LSPSIM

Interface thickness

\[ L(t) = \int_{0}^{t} [u_1(t) + u_2(t)] \, dt \]

Shock wave relation

\[ P = \rho_i D_i u_i \]

Heating phase

\[ I(t) = P(t) \frac{dL(t)}{dt} + \frac{d}{dt} \left[ E_i(t) L(t) \right] \]

\[ P(t) = \frac{2}{3} E_i(t) = \frac{2}{3} \alpha E_i(t) \]
Pressure pulse applied to Al target with water as confining medium

- Constant Intensity Laser pulse \( I_0 = 5 \text{ GW.cm}^{-2}, 10 \text{ ns} \)
- Gaussian Intensity Laser pulse \( I_{\text{max}} = 5 \text{ GW.cm}^{-2}, \text{FWHM} = 10 \text{ ns} \)
LSP Physical Basis

![Graph showing Laser Pulse Intensity and Pressure over time. The graph indicates that $I_0 = 7.18 \times 10^{13}$ W/m$^2$.](image-url)
Maximum transmitted pressure and pressure pulse duration vs. laser intensity; \( \lambda = 532 \text{ nm}, 1064 \text{ nm} \)

Water dielectric breakdown thresholds; $\lambda=1064$ nm

Purified water

Water with impurities
LSP Physical Basis

Al 2024-T3
$I_0 = 5.39 \text{ GW/cm}^2$
LSP Physical Basis

Al 2024-T3
$I_0 = 5.39 \text{ GW/cm}^2$
LSP Physical Basis

Ti6Al4V

Radial stress dynamic analysis

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Ti6Al4V

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

Multiple shocks
dynamic analysis
The SHOCKLAS Calculational System

Process Modelling
Process Modelling

HELIOS

ATBASE Atomic Database

Energy Source Parameters
(Laser, Current, Ext. rad. field)
Target Composition

PROPACEOS Database
- LTE
- Multigroup opacity data
- Equation of state data

SESAME Database
- Equation of state data (LTE)

HELIOS
- 1-D Radiation-Hydrodynamics

Plasma Properties
$T(r,t)$, $\rho(r,t)$, $u(r,t)$, ...

Electron temperature

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HELIOS  Analysis of relative influence of confining material
HELIOS

Analysis of influence of water layer thickness

Process Modelling
Process Modelling

HELIOS

Analysis of plasma for LSP conditions
- 1D Motion: Mass
  Momentum
  Energy
  (Method of characteristics)

- Hydrodynamic/elastic-plastic
  (Von Mises yield criterion)

- Ideal gas/Grüneisen E.O.S.

\[
\begin{align*}
\rho_1 u_1 &= \rho_0 u_0 \\
P_1 + \rho_1 u_1^2 &= P_0 + \rho_0 u_0^2 \\
\varepsilon_1 + \frac{P_1}{\rho_1} + \frac{u_1^2}{2} &= \varepsilon_0 + \frac{P_0}{\rho_0} + \frac{u_0^2}{2}
\end{align*}
\]

\[|\sigma_x - \sigma_y| < -YS\]

\[
\begin{align*}
P &= P_h + \Gamma \rho (W - W_h) \\
W_h &= \frac{P_h \varepsilon}{2\rho_0} \\
P_h &= \frac{\rho_0 C_0^2 \varepsilon}{(1 - S\varepsilon)^2} \\
U_s &= C_0 + S \cdot U_p
\end{align*}
\]

*L.M. BARKER, L.M., YOUNG, E.G.:
Johnson-Cook deformation model

\[
\sigma = \left[ A + B \cdot \varepsilon_{eq}^{pl,n} \right] \cdot \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}_{eq}^{pl}}{\dot{\varepsilon}_{0}} \right) \right] \cdot (1 - \theta^m)
\]

\[
\varepsilon_{eq}^{pl} = \int_0^t \dot{\varepsilon}_{eq}^{pl} \, dt
\]

\[
\varepsilon_{eq}^{pl} = \sqrt{\frac{2}{3} \left( \varepsilon_{eq}^{pl} : \varepsilon_{eq}^{pl} \right)}
\]

\[
\theta = \begin{cases} 
0 & T < T_r \\
(T - T_r)/(T_m - T_r) & T_r \leq T \leq T_m \\
1 & T > T_m
\end{cases}
\]

\[T_r = \text{room temperature}\]
\[T_m = \text{melting temperature}\]
Material Properties effects

Graphs showing stress-strain curves for Ti6Al4V and Al2024T3 materials under different conditions.

- Ti6Al4V
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 300 \text{ K}$
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 400 \text{ K}$
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 700 \text{ K}$
  - $\frac{dc}{dt} = 10^3 \text{ s}^{-1}, T = 300 \text{ K}$
  - $\frac{dc}{dt} = 10^6 \text{ s}^{-1}, T = 300 \text{ K}$

- Al2024T3
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 300 \text{ K}$
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 400 \text{ K}$
  - $\frac{dc}{dt} = 1 \text{ s}^{-1}, T = 700 \text{ K}$
  - $\frac{dc}{dt} = 10^3 \text{ s}^{-1}, T = 300 \text{ K}$
  - $\frac{dc}{dt} = 10^6 \text{ s}^{-1}, T = 300 \text{ K}$
Ti6Al4V

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

Multiple shocks
dynamic analysis
Prague, (Czech Republic) 23-28 June 2013

HARDSHOCK-2D Semi-infinite

Ti6Al4V

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

Multiple shocks
dynamic analysis
HARDSHOCK-2D Semi-infinite

Ti6Al4V

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

Multiple shocks dynamic analysis
Process Modelling

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/cm²
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$^2$
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$^2$
### Material Properties effects

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Ti6Al4V</th>
<th>Al2024T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) Density (kg.m(^{-3}))</td>
<td>4.500</td>
<td>2.785</td>
</tr>
<tr>
<td>( \nu ) Poisson’s ratio</td>
<td>0.342</td>
<td>0.330</td>
</tr>
<tr>
<td>( E ) Elastic Modulus (MPa)</td>
<td>110</td>
<td>73.45</td>
</tr>
<tr>
<td>( Y ) Yield strength (GPa)</td>
<td>1.345</td>
<td>0.330</td>
</tr>
<tr>
<td>HEL Hugoniot Elastic Limit (GPa)</td>
<td>2.8</td>
<td>0.65</td>
</tr>
<tr>
<td>( T_m ) Melting temperature (K)</td>
<td>1878</td>
<td>775</td>
</tr>
<tr>
<td>Deformation model A (MPa)</td>
<td>862</td>
<td>265</td>
</tr>
<tr>
<td>Deformation model B (MPa)</td>
<td>331</td>
<td>426</td>
</tr>
<tr>
<td>Deformation model C</td>
<td>0.012</td>
<td>0.015</td>
</tr>
<tr>
<td>Deformation model m</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Deformation model n</td>
<td>0.34</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Process Modelling

HARDSHOCK-3D (full scope)

**Al2024T3**

Residual Stress $\sigma_x$ (Pa)  
(at middle xz plane)

Laser Nd:YAG ($\lambda=1064$ nm)  
Effective Energy 1 J, 0.5 J and 0.2 J  
FWHM 10 ns  
Spot radius = 0.75 mm  
Spot overlapping 900 pulses/cm$^2$  
$\alpha=0.15$
Process Modelling

HARDSHOCK-3D (full scope)

Al2024T3

![Graph of residual stress vs depth for Al2024-T3 with different energy levels: E = 0.2 J, E = 0.5 J, E = 1 J.](image)
HARDSHOCK-3D (full scope)

Ti6Al4V

Residual Stress $\sigma_x$ (Pa)
(at middle xz plane)

Laser Nd:YAG ($\lambda=1064$ nm)
- Effective Energy 1 J, 0.5 J and 0.2 J
- FWHM 10 ns
- Spot radius = 0.75 mm
- Spot overlapping 900 pulses/cm$^2$

$\alpha = 0.15$
Process Modelling

HARDSHOCK-3D (full scope)

Ti6Al4V

![Graph showing residual stress vs depth for Ti-6Al-4V with different energies E = 0.2 J, 0.5 J, and 1 J using the Johnson-Cook model.](image)

- Residual stress $\sigma_x$ (GPa) vs depth (mm)
- Graph for Ti-6Al-4V with Johnson-Cook model for different energies.
HARDSHOCK-3D (Materials comparison)

Ti6Al4V

Al2024T3
Process Modelling

Evaluation of relative effects of thermal and mechanical waves on shocked material

Water / Aluminium
Nd:YAG (1064 nm),
$\tau = 9 \text{ ns}$
$F = 84 \text{ J/cm}^2$
$R = 1.5 \text{ mm}$
Process Modelling

Evaluation of relative effects of thermal and mechanical waves on shocked material

Water / Aluminium; Nd:YAG (1064 nm),
τ = 9 ns, F = 84 J/cm², radius = 1.5 mm
Evaluation of the residual stress and deformation obtained by application of adjacent pulses covering an extended surface

Laser Nd:YAG ($\lambda=532$ nm)
- Energy 200 mJ
- FWHM 8 ns
- Spot radius = 0.4 mm
Material: Ac304 20%CW
Spot overlapping:
3500 pulses/cm$^2$

**SIMULATION**
LSPSIM
$\alpha=0.2$ (experimental)
+
HARDSHOCK 3D /ABAQUS
Experimental Implementation

![Diagram of experimental implementation setup]

- Laser pulse
- X, Y driving mechanism
- Water supply
- Test piece
- Mirror
- Lens
- Window
- Positioning system
- Laser
- Target
- Water jet

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Q-SWITCHED Nd:YAG LASER

\[
\begin{align*}
\lambda &= 1064 \text{ nm}; \ E = 2.5 \text{ J/pulse} \\
\lambda &= 532 \text{ nm}; \ E = 1.4 \text{ J/pulse}
\end{align*}
\]

\[\tau = 10 \text{ ns}; \ f = 10 \text{ Hz}\]
Experimental Implementation

Experimental Implementation
CONCEPTUAL INTERRELATED DIAGNOSTICS SYSTEM

## Summary of correlated experimental observations and simulation results defined for plasma monitoring and process design

<table>
<thead>
<tr>
<th>PLASMA EXPLORED CHARACTERISTICS</th>
<th>EXPERIMENTAL OBSERVATION NEEDED</th>
<th>MATCHING SIMULATION RESULTS</th>
</tr>
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<tbody>
<tr>
<td>Average plasma ionization energy in interaction region</td>
<td>Line Spectroscopy (Integrated spectrum energy)</td>
<td>HYDRA ionization model results</td>
</tr>
<tr>
<td>Average plasma density and temperature in interaction region</td>
<td>Line Spectroscopy (collisional line broadening)</td>
<td>HYDRA hydrodynamic simulation</td>
</tr>
<tr>
<td>Space resolved plasma density</td>
<td>Shadowgraphy + Schlieren photography</td>
<td>HYDRA hydrodynamic simulation</td>
</tr>
<tr>
<td>Shock wave generation and plasma expansion speed</td>
<td>Shadowgraphy + Schlieren photography</td>
<td>HYDRA (short times) + LSP$^2$IM free surface evolution simulation</td>
</tr>
<tr>
<td>Breakdown in confining medium</td>
<td>Line spectroscopy</td>
<td>Dielectric breakdown evaluation module in LSP$^2$IM</td>
</tr>
</tbody>
</table>
DIRECT IMAGING - HYDRODYNAMIC ANALYSIS

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Experimental Implementation

DIRECT IMAGING - HYDRODYNAMIC ANALYSIS

Experimental Implementation

IMAGING TECHNIQUES – SHADOWGRAPHY

OSCILLOSCOPE
BEAM CONTROL

CALORIMETER
PHOTODIODE

LASER

LASER
CONTROL

BEAM
SPLITTER

PULSE
GENERATOR

ICCD

PLASMA

FLASH
Experimental Implementation

IMAGING TECHNIQUES – SHADOWGRAPHY

Experimental Implementation

IMAGING TECHNIQUES – SHADOWGRAPHY

Experimental Implementation

IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY
Experimental Implementation

**Imaging Techniques – Schlieren / Interferometry**

Experimental Implementation

EMISSION SPECTROSCOPY

Stark Broadening

Electron density $n_e$

$\Delta \lambda_{1/2} = 2w \frac{n_e}{10^{16}}$

Relative Line Intensity

Temperature

$$\ln \left( \frac{\lambda_{mn} I_{mn}}{g_m A_{mn}} \right) = \ln \left( \frac{N(T_{ex})}{U(T_{ex})} \right) - \frac{E_m}{kT_{ex}}$$
Spectroscopic system calibrated in wavelength with Hg lamp and in intensity with Deuterium lamp
Electron density determination via Stark effect of Al II line at 2816,2 nm:

**Experimental Implementation**

<table>
<thead>
<tr>
<th>Distance from target</th>
<th>2 µs</th>
<th>3 µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>20.4 (10^{16}) cm(^{-3})</td>
<td>2.4 (10^{16}) cm(^{-3})</td>
</tr>
<tr>
<td>6 mm</td>
<td>17.2 (10^{16}) cm(^{-3})</td>
<td>2.0 (10^{16}) cm(^{-3})</td>
</tr>
</tbody>
</table>
Electron temperature determination through Boltzmann plot of relative intensities of Mg II lines at 279.5528 nm, 280.2704 nm, 292.8633 nm and 293.6509 nm:

Preliminary electron temperature distributions in the range of 1.0-1.5 eV (i.e. ≈ 11 600 - 17 400 K) were found close to the target 2-3 μs after laser shut-down.
Experimental Results at CLUPM

Material: Al2024 T3
Pulses: \( \varnothing = 1.5 \text{ mm}; \tau = 10 \text{ ns}; f = 10 \text{ Hz}; \)
\[ E = 1 \text{ J/pulse}; I = 1.41 \text{ GW/cm}^2 \]
Swept Area: 15x15 mm\(^2\); 2500 pulses/cm\(^2\)
Experimental Results at CLUPM

- **Al 2024 T3**
  - 900 pulses/cm²

- **AISI 304**
  - 2500 pulses/cm²

- **Ti6Al4V**
  - 5000 pulses/cm²
Experimental Results at CLUPM
Experimental Results at CLUPM

$$\text{Equivalent Overlapping} \equiv \text{EOD} = \frac{N^o \text{ of pulses}}{\text{Total treated surface}} = \frac{x \ y}{\Delta x \ \Delta y} \frac{\Delta x}{\Delta s} \frac{\Delta y}{xy} \frac{1}{d^2}$$

$$\text{Equivalent Energy} \equiv \text{EED} = \frac{N^o \text{ of pulses} \cdot \text{Pulse Energy}}{\text{Total treated surface}} = \frac{x \ y}{\Delta x \ \Delta y} \frac{\Delta x}{\Delta s} \ E \ = \frac{x \ y}{xy} \ E \ = \frac{E}{d^2}$$

$$\text{Equivalent local overlapping factor} \equiv \text{ELOF} = \frac{N^o \text{ of pulses} \cdot \text{Pulse Area}}{\text{Total treated surface}} = \frac{\pi \ \phi^2}{4 \ d^2} = \frac{\pi \left( \frac{\phi}{d} \right)^2}{4}$$
Experimental Results at CLUPM

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/cm(^2))</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 at CLUPM

Residual Stresses (According to ASTM E837-08)
Experimental Results at CLUPM

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 at CLUPM

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 at CLUPM

## Experimental Results at CLUPM

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Details</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>

![Images of experiments with 900 and 1600 pulses/cm²]
Experimental Results at CLUPM

Residual Stresses:

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

Graphs showing residual stresses (MPa) vs. depth (mm) for different conditions.
Experimental Results at CLUPM

Short pulse (Q-switched, ns) commercial table top lasers provide a practical solution for the experimental implementation of LSP Processes.

The need for a practical capability of LSP process control in practical applications has led to the development of comprehensive theoretical/computational models for the predictive assessment of the complex phenomenology involved.

High intensity laser-plasma interaction has revealed itself as a critical point for a proper process understanding and predictive assessment of LSP processes.

The developed calculational model (SHOCKLAS) allows a systematic study of LSP processes starting from laser-plasma interaction. The integrated laser-plasma analysis routine, based in realistic material EOSs, provides a unique capability for process parametrization.

Additionally, the development of the appropriate experimental diagnosis facilities and the connection of numerical simulation to experimental material characterization results enable a fundamental and reliable process understanding capability in view of process industrial implementation.
Discussion and Outlook

EXPERIMENTAL CHARACTERIZATION OF MATERIAL PROPERTIES

LASER PLASMA INTERACTION SIMULATION AND DIAGNOSIS

NUMERICAL SIMULATION OF SOLID BEHAVIOUR
Laser Shock Microforming of Thin Metal Sheets with Q-Switched ns Lasers

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Laser Shock Microforming of Thin Metal Sheets with ns Lasers

OUTLINE:

• Introduction
• Physical Principles. Simulation Model
• Simulation Results
• Experimental Setup. Sample Preparation
• Experimental Results
• Discussion and Outlook
1. INTRODUCTION

- The increasing demands in MEMS fabrication are leading to new requirements in production technology. Especially the packaging and assembly require high accuracy in positioning and high reproducibility in combination with low production costs.

- Conventional assembly technology and mechanical adjustment methods are time consuming and expensive. Each component of the system has to be positioned and fixed. Also adjustment of the parts after joining requires additional mechanical devices that need to be accessible after joining.

- Accurate positioning of smallest components represents an up-to-date key assignment in micro-manufacturing. It has proven to be more time and cost efficient to initially assemble the components with widened tolerances before precisely micro-adjusting them in a second step.

- As mounted micro components are typically difficult to access and highly sensitive to mechanical forces and impacts, contact-free laser adjustment processes offer a great potential for accurate manipulation of micro devices.
1. INTRODUCTION (Cont.)

- Long relaxation-time thermal fields developed in continuous or long-pulse laser forming of metal thin sheets are responsible for the introduction of constraint residual stresses in component assembly processes.
  - Changes in the materials microstructure could cause changes in density and volume and create stresses
  - Chemical reactions of the irradiated surface, e.g. oxidation could take place and lead to stressed surface layers

- The use of ns laser pulses inducing predominantly mechanical deformation stresses provides the capability for a suitable parameter matching in laser bending of MEMS components.

- Theoretical interaction regime description, computational process simulation results and preliminary experimental results and practical issues are presented in this work.
2. PHYSICAL PRINCIPLES
2. PHYSICAL PRINCIPLES

- Residual Stresses produced by Bending Moment
- Residual Stresses produced by Shock Wave

- Tensile
- Neutral
- Compressive

- Bending angle produced by Bending Moment
- Bending angle produced by Shock Wave
- Net bending angle

Final beam shape

Initial beam shape

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2. NUMERICAL SIMULATION. MODEL DESCRIPTION

PRESSURE PULSE MODEL

LSPSIM

Interface thickness

\[ L(t) = \int_0^t [u_1(t) + u_2(t)] \, dt \]

Heating phase

\[ I(t) = P(t) \frac{dL(t)}{dt} + \frac{d[E_i(t) L(t)]}{dt} \]

\[ P(t) = \frac{2}{3} E_i(t) = \frac{2}{3} \alpha E_i(t) \]

Shock wave relation

\[ P = \rho_i D_i u_i \]

Solid/Liquid \hspace{1cm} D = C + Su \]

Gas \hspace{1cm} D = u \left( \frac{(\gamma+1) P}{2 \rho} \right)^{1/2}
2. NUMERICAL SIMULATION. MODEL DESCRIPTION

FEM MODEL – STRESS-STRAIN ANALYSIS

GEOMETRY AND DIMENSIONS

PLASTIC STRAIN

MIN. PRINCIPAL

MAX. PRINCIPAL

STRESS DISTRIBUTION

S11

S22
2. NUMERICAL SIMULATION. MODEL DESCRIPTION

### MATERIAL PROPERTIES (AISI 304)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Target</td>
<td>AISI 304</td>
</tr>
<tr>
<td>Young’s Modulus: $E$ [GPa]</td>
<td>193</td>
</tr>
<tr>
<td>Poisson’s Coefficient: $\nu$</td>
<td>0.25</td>
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<tr>
<td>Density: $\rho$ [kg/m³]</td>
<td>7896</td>
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<tr>
<td>Melting Temperature: $T_m$ [K]</td>
<td>1811</td>
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<td>Test Temperature: $T_0$ [K]</td>
<td>300</td>
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<tr>
<td>Inelastic Heat Fraction: $X$</td>
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<tr>
<td>Johnson-Cook parameters</td>
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</tr>
<tr>
<td>$A$ [MPa]</td>
<td>350</td>
</tr>
<tr>
<td>$B$ [MPa]</td>
<td>275</td>
</tr>
<tr>
<td>$C$</td>
<td>0.022</td>
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<tr>
<td>$n$</td>
<td>0.36</td>
</tr>
<tr>
<td>$m$</td>
<td>1</td>
</tr>
<tr>
<td>$T_r$ [K]</td>
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</tr>
<tr>
<td>$\dot{\varepsilon}_0$ [s⁻¹]</td>
<td>1</td>
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</table>

### LSFSIM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG Laser [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Energy per pulse [mJ]</td>
<td>33 - 150</td>
</tr>
<tr>
<td>Pulse length [ns]</td>
<td>9.4</td>
</tr>
<tr>
<td>Spot Radius [$\mu$m]</td>
<td>175</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Air</td>
</tr>
<tr>
<td>Interaction parameter $\alpha$</td>
<td>0.2</td>
</tr>
</tbody>
</table>

---

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3. NUMERICAL SIMULATION RESULTS

SHOCKLAS EXPLICIT – VON MISES EVOLUTION
3. NUMERICAL SIMULATION RESULTS

SHOCKLAS EXPLICIT – STRESS (S11) EVOLUTION
3. NUMERICAL SIMULATION RESULTS

SHOCKLAS STANDARD – STRESS (S11) EQUILIBRATION
3. NUMERICAL SIMULATION RESULTS

Pulse Energy Parametrization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG Laser [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Energy per pulse [mJ]</td>
<td>variable</td>
</tr>
<tr>
<td>Pulse length [ns]</td>
<td>9.4</td>
</tr>
<tr>
<td>Spot Radius [μm]</td>
<td>175</td>
</tr>
<tr>
<td>Material Model</td>
<td>SS304</td>
</tr>
<tr>
<td>Confining medium</td>
<td>Air</td>
</tr>
<tr>
<td>Interaction parameter $\alpha$</td>
<td>0.2</td>
</tr>
<tr>
<td>Spot center distance [μm]</td>
<td>150</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between pulse energy and Z coordinate](image1)

![Graph showing the relationship between pulse energy and bending angle](image2)
3. NUMERICAL SIMULATION RESULTS

Spot Center Distance Parametrization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Nd:YAG Laser [nm]</td>
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<tr>
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<tr>
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<td>Confining medium</td>
<td>Air</td>
</tr>
<tr>
<td>Interaction parameter $\alpha$</td>
<td>0.2</td>
</tr>
<tr>
<td>Spot center distance [μm]</td>
<td>variable</td>
</tr>
</tbody>
</table>

![Graph showing spot center distance from base vs. Z coordinate (μm) and Net Bending Angle (mrad)]
4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

ML-100 LASER WORKSTATION

- Dual Excimer/DPSS Laser processing
- Multiaxis (6) System
- Work volume: 120*100*50 mm
- XY accuracy: 1 μm
- Global positioning accuracy: 40 μm
- CCD direct vision (x 500)

AISI 304
1000 x 200 x 50 μm

---

<table>
<thead>
<tr>
<th>Laser media</th>
<th>Excimer (KrF)</th>
<th>DPSS 3ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>248</td>
<td>355</td>
</tr>
<tr>
<td>Pulse duration (ns)</td>
<td>3–7 ns</td>
<td>&lt;12 ns (at 50 kHz)</td>
</tr>
<tr>
<td>Beam shape/mode</td>
<td>Rectangular (3.5 × 6 mm)</td>
<td>TEM₀₀₀ (M² &lt; 1.3)</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>0–300 Hz</td>
<td>15–300 kHz</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>0.3–5 (at 300 Hz)</td>
<td>5 W (at 50 kHz)</td>
</tr>
</tbody>
</table>
4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

SEM IMAGES OF LASER CUT SHEET

CONFOCAL IMAGES OF LASER CUT SHEET
4. EXPERIMENTAL SETUP. SAMPLER PREPARATION

Thickness: 50 \mu m
4. EXPERIMENTAL SETUP. SAMPLE IRRADIATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Nd:YAG Laser Wavelength [nm]</td>
<td>1064</td>
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<td>Energy per pulse [J]</td>
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<tr>
<td>Laser Pulse length FWHM [ns]</td>
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<tr>
<td>Laser Beam radius [mm]</td>
<td>14</td>
</tr>
<tr>
<td>Confining layer</td>
<td>Air</td>
</tr>
<tr>
<td>Thin sheet material</td>
<td>AISI 304</td>
</tr>
<tr>
<td>Thin sheet thickness [µm]</td>
<td>50</td>
</tr>
</tbody>
</table>

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23-28 June 2013  
CENTRO LÁSER  
UNIVERSIDAD POLITÉCNICA DE MADRID
5. EXPERIMENTAL RESULTS. INFLUENCE OF SPOT CENTER DISTANCE

SEM IMAGES

CONFOCAL MICROSCOPY
5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

SEM IMAGES

CONFOCAL MICROSCOPY

Z Coordinate (µm)

X Coordinate (mm)
5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

- 25 pulses
- No pulses

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5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

Steel AISI 304, Thickness = 50 μm

Net Bending Angle (mrad)

Number of pulses
5. EXPERIMENTAL RESULTS. LAST RESULTS

1 pulse

4 pulses

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23-28 June 2013
5. EXPERIMENTAL RESULTS. LAST RESULTS
5. EXPERIMENTAL RESULTS. LAST RESULTS

5 pulses

5 pulses in two arms
The suitability laser micro-bending of thin metal strips by means of ns pulsed lasers with average power in the range of several Watt has been experimentally demonstrated.

Numerical simulation of the process has shown as critical parameters:
- Pulse energy
- Spot center distance relative to pinned end

Simulations of single-end pinned targets show the presence of two bending components.
- Overall angular displacement from beam clamping
- Local bending at beam incidence position

According to the authors’ experience, the use of ns laser pulses is expected to provide a really suitable parameter matching for the laser bending of an important range of MEMS sheet components.

On the basis of the developed experience, the laser microforming and adjustment stresses release of arbitrary geometry components can be envisaged.
Thank you for your attention!
The LSP Team at CLUPM

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The UPM Laser Centre (CLUPM)