Laser Shock Microforming of Thin Metal Sheets with Q-Switched ns Lasers

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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

Residual Stress
- Tensile
- Neutral
- Compressive

Initial beam shape

Final beam shape

Bending angle produced by Bending Moment

Net bending angle

Bending angle produced by Shock Wave

β₁

α

β₂

Laser

d

4th International Conference on Laser Peening and Related Phenomena
May 6th-10th 2013
ETS de Ingenieros Industriales. Universidad Politécnica de Madrid, Spain
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
\[ I(t) = P(t) \left( \frac{dL(t)}{dt} + \frac{d[E_i(t)L(t)]}{dt} \right) \]
\[ P(t) = \frac{2}{3} E_i(t) = \frac{2}{3} \alpha E_i(t) \]

Shock wave relation
\[ P = \rho_i D_i u_i \]

Solid/Liquid
\[ D = C + S u \]

Gas
\[ D = u \left( \frac{(\gamma + 1) P}{2 \rho} \right)^{1/2} \]
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>
</tr>
</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/m(^3)]</td>
<td>7896</td>
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<tr>
<td>Melting Temperature: Tm [K]</td>
<td>1811</td>
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<tr>
<td>Test Temperature: T0 [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>
<td></td>
</tr>
<tr>
<td>A [MPa]</td>
<td>350</td>
</tr>
<tr>
<td>B [MPa]</td>
<td>275</td>
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<tr>
<td>C</td>
<td>0.022</td>
</tr>
<tr>
<td>n</td>
<td>0.36</td>
</tr>
<tr>
<td>m</td>
<td>1</td>
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<tr>
<td>(T_r) [K]</td>
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<td>(\dot{\varepsilon}_0) [s(^{-1})]</td>
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LSPSIM PARAMETERS

<table>
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<tr>
<th>Property</th>
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<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>
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

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<tbody>
<tr>
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<td>variable</td>
</tr>
<tr>
<td>Pulse length [ns]</td>
<td>9.4</td>
</tr>
<tr>
<td>Spot Radius [μm]</td>
<td>175</td>
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</table>

<table>
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<th>Material Model</th>
<th>SS304</th>
</tr>
</thead>
<tbody>
<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>

#### Graphs

- **Left Graph:**
  - **Z coordinate (μm)** vs. **Distance from base $d$ (mm)**
  - Lines represent different pulse energies: 0.033 J, 0.048 J, 0.062 J, 0.105 J.

- **Right Graph:**
  - **Bending Angle (mrad)** vs. **Pulse Energy (J)**
  - Lines represent different values: $\beta_s$, $|\beta_b| = -\beta_b$, $\alpha$.

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**CENTRO LÁSER**
**UNIVERSIDAD POLITÉCNICA DE MADRID**
### 3. NUMERICAL SIMULATION RESULTS

Spot Center Distance Parametrization

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<tr>
<th>Nd:YAG Laser [nm]</th>
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<td>Confining medium</td>
<td>Air</td>
</tr>
<tr>
<td>Interaction parameter α</td>
<td>0.2</td>
</tr>
<tr>
<td>Spot center distance [µm]</td>
<td>variable</td>
</tr>
</tbody>
</table>

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**Graphs:**

- **Graph 1:** Plot showing the spot center distance from base as a function of distance from base d (mm).
  - Legend: 0.0 mm, 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, 0.8 mm.
  - Z coordinate (µm) on the y-axis.
  - Distance from base d (mm) on the x-axis.

- **Graph 2:** Plot showing the net bending angle (mrad) as a function of spot center distance from base d (mm).
  - X-axis: Spot center distance from base d (mm).
4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

ML-100 LASER WORKSTATION

<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>TEM00 (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>

- 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
4. EXPERIMENTAL SETUP. SAMPLE PREPARATION

SEM IMAGES OF LASER CUT SHEET

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

Thickness: 50 μm
4. EXPERIMENTAL SETUP. SAMPLE IRRADIATION

<table>
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<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Nd:YAG Laser Wavelength [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Energy per pulse [J]</td>
<td>1.651</td>
</tr>
<tr>
<td>Laser Pulse length FWHM [ns]</td>
<td>9</td>
</tr>
<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>

**Diagram:**
- Fast Camera
- Sample
- Mirror
- Mask
- Focussing lens
- Test piece
5. EXPERIMENTAL RESULTS. INFLUENCE OF SPOT CENTER DISTANCE

SEM IMAGES

CONFOCAL MICROSCOPY

![SEM Image 1](image1.png)

![SEM Image 2](image2.png)

![Confocal Microscopy Image](image3.png)

![Graph](graph.png)
5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

**SEM IMAGES**

**CONFOCAL MICROSCOPY**

![SEM Images](image1.png)

![Confocal Microscopy](image2.png)

![Graph](image3.png)
5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

25 pulses

No pulses

25 pulses

No pulses
5. EXPERIMENTAL RESULTS. INFLUENCE OF NUMBER OF PULSES

Steel AISI 304, Thickness = 50 μm

Net Bending Angle (mrad)

Number of pulses

0 5 10 15 20 25
0 5 10 15 20 25 30 35
5. EXPERIMENTAL RESULTS. LAST RESULTS

1 pulse

4 pulses
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 very much for your attention!
ACKNOWLEDGEMENTS

Work partly supported by Spanish MEC Projects PSE020400-2006-1 and CIT0205002005-11

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Residual Stresses produced by Shock Wave

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Final beam shape

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Bending angle produced by Shock Wave

Net bending angle