Understanding and Optimization of ultra-short pulse laser ablation of technical ceramics based on experimental data

Maria Friedrich

WOST 2019 – Weimarer Optimierungs- und Stochastiktage
Laser processing of glass and ceramics

Joining
Polishing
Cutting
Marking
Structuring

High thermal influence
High resolution / precision

CO₂ laser
Solid state laser
Fiber laser
USP laser

Maria Friedrich
June 7, WOST 2019
Outline

1. Experimental Approach
2. Design of Experiments
3. Sensitivity Analysis
4. Industrial Applications

Maria Friedrich
June 7, WOST 2019
1. Experimental Approach

- **CO\textsubscript{2} laser**
  - $\lambda = 10.6\,\mu\text{m}$
  - Thermally affected process
  - Melting of material

- **Solid state laser**
  - $\lambda = 1064\,\text{nm}$
  - Redeposited material, cracks
  - OR: material transparent

- **Fiber laser**
  - $\lambda = 1064\,\text{nm}$
  - Non-linear absorption
  - Thermal conduction negligible
  - Precise material removal

- **USP laser**
  - $\lambda = 1064\,\text{nm}$, $\tau_p < 10\,\text{ps}$

Maria Friedrich
June 7, WOST 2019
1. Experimental Approach

Multitude of process parameters ...

- Roughness
- Properties
- ...

- Process
- Laser
- USP ablation
- Scanner
- Optics

- Strategy
- Atmosphere
- ...

- Wavelength
- Pulse duration
- Pulse energy
- Repetition rate
- ...

- Marking speed
- Line distance
- Pulse overlap
- Number of layers
- ...

- Beam profile
- Focus diameter
- Divergence
- ...

... results in various surface qualities
1. Experimental Approach

Multi-dimensional parameter space

→ Value ranges are unevenly distributed

- Wavelength: 1064 nm, 532 nm, 355 nm
- Pulse duration: 230 fs – 10 ps
- Repetition rate: < 1 MHz
- Max. power: 25 W

### Process Parameters

**Power $P$ [W]**

<table>
<thead>
<tr>
<th></th>
<th>IR</th>
<th>VIS</th>
<th>UV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>12</td>
<td>6</td>
</tr>
</tbody>
</table>

**Fluence (Energy density) $F$ [J/cm²]**

<table>
<thead>
<tr>
<th></th>
<th>IR</th>
<th>VIS</th>
<th>UV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>35</td>
<td>30</td>
</tr>
</tbody>
</table>

**Pulse Overlap $O_h$ [%]**

<table>
<thead>
<tr>
<th></th>
<th>IR</th>
<th>VIS</th>
<th>UV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>-10</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>
1. Experimental Approach

Multi-dimensional parameter space

→ Sensitivity analysis, meta model, optimization
→ Identification of main parameters and non-linear effects

**DoE**
- Latin Hypercube Sampling

**Experiments**
- USP ablation of alumina (Al$_2$O$_3$)

**Measurement**
- Roughness, Ablation depth

**Analysis**
- Sensitivity analysis based on MOP

Maria Friedrich
June 7, WOST 2019
2. Design of Experiments

**DoE 1.0**

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

**INPUTS**

- Wavelength: $\lambda = 355 / 532 / 1064$ nm
- Focal length: $f = 40 / 100 / 250$ mm
- Focus diameter: $d_f = 11 \ldots 110$ µm
- Number of Designs: 100

- Experimental Design according to native parameters
  - Power $P$
  - Line distance $a_L$
  - Pulse distance $a_P$

**DoE 3.0**

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

**INPUTS**

- Wavelength: $\lambda = 532$ nm = const.
- Focal length: $f = 100$ mm = const.
- Focus diameter: $d_f = 14$ µm = const.
- Number of Designs: 50

- Experimental Design according to derived parameters
  - Fluence $F$
  - Vertical pulse overlap $O_v$
  - Horizontal pulse overlap $O_h$
2. Design of Experiments

DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

Avoidance of input correlations
2. Design of Experiments

DoE 1.0
- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

\[ \text{INPUT : } F \text{ vs. INPUT : } N, \text{ (linear) } r = 0.104 \]

\[ \rightarrow \text{Asymmetric distribution, even of independent parameters} \]

DoE 3.0
- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

\[ \text{INPUT : } F \text{ vs. INPUT : } N, \text{ (linear) } r = 0.001 \]

\[ \rightarrow \text{Symmetrical distribution of all parameters} \]
2. Design of Experiments

DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

→ Good roughness model due to large value range ($Ra = 0.4 \ldots 3.8 \, \mu m$)

DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

→ Weak roughness model ($Ra = 0.5 \ldots 1.1 \, \mu m$)
→ Good models for depth-related parameters
2. Design of Experiments

DoE 1.0
- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

→ Good roughness model due to large value range ($Ra = 0.4 \ldots 3.8 \, \mu m$)

DoE 3.0
- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

→ Weak roughness model ($Ra = 0.5 \ldots 1.1 \, \mu m$)
→ Good models for depth-related parameters
3. Sensitivity Analysis

- Ablation rate increases with power
- Line distance and pulse distance interact
  → High values: high speed
  → Small values: high material removal

\[
\text{Al}_2\text{O}_3:
\]

- \( r_{min} \approx 0 \text{ mm}^3/\text{min} \)
- \( r_{max} = 7.8 \text{ mm}^3/\text{min} \)

Line distance:

- \( a_L = 15 \mu\text{m} \)
- \( a_L = 4.4 \mu\text{m} \)
- \( a_L = 1 \mu\text{m} \)
3. Sensitivity Analysis

- In general: roughness increases with fluence
- Optimal pulse overlap depends on fluence
- With increasing fluence: minimum shifts to smaller values

$\text{Al}_2\text{O}_3$:

$Ra_{\text{min}} = 0.42 \, \mu m$

$Ra_{\text{max}} = 3.8 \, \mu m$
3. Sensitivity Analysis

- Transfer of DoE 3.0 to other materials (LTCC, AlN, Porcelain)
- Use of “Space filling Latin Hypercube Sampling”

- Similar materials can be combined to one model
- Model quality stays the same
4. Industrial Applications

- Microsystems technology: fabrication of precise cavities in Al₂O₃ / LTCC for the positioning of microchips:
  - Profile depth: 800 µm
  - Bottom: 5 x 5 mm²
  - Flank angle: 30°

- High-value consumer goods: manufacturing of individual design structures in porcelain: Example: “Zugspitze” (ΔX = 25 mm, ΔZ = 2,1 mm)

Stack of 100 layers ➔ Ablation of negative volume ➔ 3D freeform profile
Summary

- optiSLang can be used to create physically meaningful metamodels based on experimental data
- The further development of the DoE (symmetrical parameter space, restriction to a few parameters) increased the model quality
- For a comprehensive understanding of the process, all models should be considered
  - DoE 1.0: Knowledge about whole parameter space
  - DoE 3.0: Comparison of different materials
- Native and derived parameters must be considered separately, but both provide important insights
  - Native parameters: depth-related outputs, focus diameter
  - Derived parameters: roughness-related outputs
- General question: What knowledge would you like to achieve?
  - Reduce the experimental design to provide additional insights!
The project „ProFunK“ has been supported by the free state of Thuringia (2015 VF0021). A cofinancing was carried out by the Europäischer Fonds für regionale Entwicklung (EFRE). This support is gratefully acknowledged.