Efficient metal processing using high average power ultrafast laser

Strasbourg, September 13th, 2017

Motivations

Increasing interest for high throughput surface processing:
Manufacturing tools (molding, embossing, printing)
Texturing or engraving (jewelry, watch, automotive)

Hard to produce:
High quality issues (no HAZ) & accuracy (tiny spot)
Large area to process

Short pulse laser: limited productivity due to uncontrolled melting (10 mm³/min)

Ultrashort pulse laser: promising technology enables to mitigate the thermal load
Scaling up capability?

**How to scale-up the ablation process?**
Increasing average power, fluence, rep. rate, overlap, scanning velocity?

**How to take advantage of new industrial tools?**
Ultrafast laser: up to 100 W & 20 MHz
Beam deflector devices: Galvo & Polygon

The purpose of this study is to identify parameters of influence and process windows for surface ablation with a 100W / 10MHz ultrashort pulse laser combined with galvo or polygon scanners.
Outline

1. Motivations

2. USP ablation mechanism
   i. Kinetic of laser ablation
   ii. Heat accumulation at high fluence & high rep. rate

3. Experimental
   i. Setup & ultrafast laser
   ii. Protocol & sample analysis

4. Results & discussion
   i. Galvo scanner
   ii. Polygon scanner
   iii. How long to remove 1 mm³?

5. Summary
Kinetic of laser ablation | Role of fluence

Ablation depth vs fluence

- **Low fluence**: high quality, low removal rate
- **High fluence**: poor quality, high removal rate

- **0.5 J/cm²**, 200 fs, 200 J/cm²

Parameters: Copper in vacuum, 150 fs, 780nm
Mean depth is measured on 40x40µm²

Optimum in fluence

Specific Removal Rate vs Fluence

- There is an optimal fluence which depends on the pulse duration
- High fluences are less efficient

\[
\frac{\Delta V}{\Delta t} = \frac{e^2}{2} \cdot \frac{\phi}{\phi_{th}}
\]

Heat accumulation induced by high repetition rate

Particles shielding
- Reduces ablation efficiency

Heat accumulation
- Improves ablation efficiency
- but enhances HAZ

Rising rep. rate

High Rep. Rate -> thermal load

- Higher drilling efficiency for shorter pulses
- Heat accumulation overbalances particles shielding at 350-550 kHz
- High rep. rate enhances detrimental side-effects

Influence of heat accumulation on surface morphology

Laser irradiation introduces residual heat into the target. If subsequent pulses are too close in time or distance, the surface temperature raises.

For a critical value between 600° and 800°C on Steel the surface morphology changes.

Smooth & reflective surface
No melting

Bumpy & oxidized surface

Bauer and al., Optics Express, Vol. 23, No. 2 (2015)
Remaining questions?

- Can we take advantage of 100W? How?
  \[ P_{av} = E_{pulse} \times RR \]
  
  - Low fluence only
  - Where is the limit?

- Limitations / process windows with galvo or polygon scanners?

- Correlation between ablation efficiency, multipass capability and surface morphology?

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Laser & Experimental setup

**Laser & Experimental setup**

**Laser**
- **USP**
- **Pulse Picker**
- **Energy controller**
- **Beam expander**
- **Zoom x2**
- **Galvo head**
- **Work piece**

**Energy controller**
- **Scanlab Intelli Scan III-14**
  - **f(θ)100mm**
  - **Spot 30 ± 2µm**
  - **up to 5 m/s**
- **Steel foil AISI316L**
  - **500µm-thick**
  - **on XYZ stages**

**Beam expander**
- **Nextscan LSE170**
  - **f(θ)190mm**
  - **Spot 38 ± 2µm**
  - **up to 100 m/s**

**Laser**
- **Tangor 100 W**
- \(\lambda\) **1030 nm**
- \(\tau\) **<500fs**
- \(v\) **100 kHz to 10 MHz**
- \(M^2\) **1.2**

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Experimental protocol

**Laser Irradiation**

- Laser 500 fs
- f(θ)100mm
- Spot 30 µm
- Steel foil

**Process parameters:**
- Single or multipass (30, 60, 120, 240)
- Velocity: 0.1 to 100 m/s
- Rep. rate: 0.5 to 10 MHz
- Ave. Power: 10 to 100 W

*Lopez et al, ICALEO, M303 (2013)*

**Confocal Microscopy for Topography**

**Scanning Electron Microscopy**
Ablation efficiency

Ablation efficiency is defined by the ratio:

\[ \rho = \frac{E_{\text{th}}}{E_{\text{exp}}} \]

where:

- \( E_{\text{th}} = C_p(T) \Delta T_{\text{Sol-Liq}} + \Delta H_{\text{melt}} + C_p(T) \Delta T_{\text{Liq-Gas}} + \Delta H_{\text{boil}} \)
- \( E_{\text{exp}} = \frac{P_{\text{av}}}{S \cdot V} \)

Energy required to bring 1 mm\(^3\) from solid to gas with calculation based on thermo dynamical laws

\( E_{\text{th}} \) is given by Shomate equation,

http://webbook.nist.gov/chemistry/name-ser.html

\[ \rho = 1 \quad \text{Ideal process: all energy is used for ablation} \]
\[ \rho < 1 \quad \text{Real process: part of energy is lost (heating, shielding, scattering)} \]
High fluence induces high throughput but low efficiency.
Specific Removal Rate decreases with increasing pulse duration.
Ablation efficiency versus fluence

Heat accumulation enhances ablation efficiency above 2 J/cm²
BUT introduces detrimental thermal effects

Data 2017
Data 2015

Galvo 1m/s

Depth 40 µm
53 mm³/min
Eff. 0.75
Groove collapses due to melting

Depth 14 µm
15 mm³/min
Eff. 0.42
Burr (10µm)

Depth 1.2 µm
1.6 mm³/min
Eff. 0.23
Smooth
Multipass processing capability with Galvo

Average Power 9 W

- 2 MHz 5 m/s 0.6 J/cm² Overlap 92.7%
- 10 MHz 5 m/s 0.13 J/cm² Overlap 98.3%
- 0.5 MHz 5 m/s 2.6 J/cm² Overlap 66.7%

Ablation efficiency [a.u.]

Number of passes

500 fs 5 m/s
Multipass processing capability with Galvo

### Average Power 9 W
- 2MHz 5m/s 0.6J/cm² Overlap 92.7%
- 10MHz 5m/s 0.13J/cm² Overlap 98.3%
- 0.5MHz 5m/s 2.6J/cm² Overlap 66.7%

### Average Power 45 W
- 2MHz 5m/s 3.2J/cm² Overlap 92.7%
- 10MHz 5m/s 0.6J/cm² Overlap 98.3%
- 0.5MHz 5m/s 12.7J/cm² Overlap 66.7%

**500fs 5m/s**

- **9 W**
- **45 W**

**40 µm**

**45 W**

No multipass capability at 45 W & 90 W
## Multipass processing capability with Galvo

### Average Power 9 W
- 2MHz 5m/s 0.6J/cm² Overlap 92.7%
- 10MHz 5m/s 0.13J/cm² Overlap 98.3%
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### Average Power 45 W
- 2MHz 5m/s 3.2J/cm² Overlap 92.7%
- 10MHz 5m/s 0.6J/cm² Overlap 98.3%
- 0.5MHz 5/µs 12.7J/cm² Overlap 66.7%

### Average Power 90 W
- 2MHz 5m/s 6.1J/cm² Overlap 92.7%
- 10MHz 5m/s 1.2J/cm² Overlap 98.3%
- 0.5MHz 5/µs 25J/cm² Overlap 66.7%

**No multipass capability at 45 W & 90 W**
# 2D multipass processing / Cavity

**Cavity**
- Dimensions 2.5 x 1 mm²
- Pulse-to-pulse pitch 1 µm
- Line-to-line pitch 1 µm

**Single Line**
- Dimensions 2.5 mm
- Pulse-to-pulse pitch 1 µm

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<td>10</td>
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<td></td>
<td>Similar etch rate measured for single line and cavity</td>
</tr>
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</table>

500fs 2MHz 2m/s pitch 1µm overlap 96.7%

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### Cavity

Dimensions 2.5 x 1 mm²  
Pulse-to-pulse pitch 1 µm  
Line-to-line pitch 1 µm

### Single Line

Dimensions 2.5 x 1 mm²  
Pulse-to-pulse pitch 1 µm  
Line-to-line pitch 1 µm

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Similar etch rate measured for single line and cavity

500fs 2MHz 2m/s pitch 1µm overlap 96.7%  
Ra 0.5 µm  
Ra 6 µm
Influence of scanning velocity at 10 MHz

- **5 m/s**: Acceptable quality, Eff. 0.237
- **4 m/s**: Burrs appear, Eff. 0.192
- **3 m/s**: Melting flow appears, Eff. 0.222
- **2 m/s**: Groove starts to collapse

- **0.1 m/s**: Overthickness
- **0.25 m/s**: Melting pool fills the groove
- **0.5 m/s**: Acceptable quality, Eff. 0.237
- **1 m/s**: Overthickness

**500fs 10MHz 50W 0.3J/cm²**
Influence of scanning velocity at 10 MHz

- Thermal load rises while decreasing velocity
- We need higher scanning velocity & lower overlap

\[ 500\text{fs} \ 10\text{MHz} \ 50\text{W} \ 0.3\text{J/cm}^2 \]

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Ablation efficiency versus fluence

Polygon 25m/s (30 passes)

Ablation efficiency increases with fluence up to 3 J/cm² (70W at 2MHz) WITH a good processing quality

500fs 2MHz 25m/s pitch 12.5µm overlap 67.1%

Depth 2.3 µm 3.6 mm³/min
Eff. 0.07
Smooth
No melting

Depth 16 µm 3.1 mm³/min
Eff. 0.6
Smooth
No melting
Multipass processing capability with Polygon

- Multipass capability is proven up to 70 W with polygon
- Ablation efficiency & processing quality depend on Rep. Rate

500fs 70W

- 10MHz 100m/s 0.6J/cm² Overlap 74%
- 10MHz 25m/s 0.6J/cm² Overlap 67%
- 2MHz 25m/s 3J/cm² Overlap 67%

Depth 16 µm
Depth 42 µm

240 passes
Influence of repetition rate
same fluence, same velocity

<table>
<thead>
<tr>
<th>Rep. Rate</th>
<th>2 MHz</th>
<th>4 MHz</th>
<th>8 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Power [W]</td>
<td>17.3</td>
<td>34.5</td>
<td>70</td>
</tr>
<tr>
<td>Fluence [J/cm²]</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Overlap [%]</td>
<td>67</td>
<td>84</td>
<td>92</td>
</tr>
<tr>
<td>Nb passes</td>
<td>120</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Dose [J/mm] single pass</td>
<td>0.0007</td>
<td>0.0014</td>
<td>0.0027</td>
</tr>
<tr>
<td>Cumulative Dose [J/mm] multi pass</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Ablated volume [µm³/pls]</td>
<td>3</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Ablation Efficiency [a.u.]</td>
<td>0.02</td>
<td>0.08</td>
<td>0.12</td>
</tr>
</tbody>
</table>

- Increasing rep. rate enhances ablation efficiency due to heat accumulation BUT leads to a bumpy surface as well
Influence of repetition rate
same fluence, same overlap

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<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Nb passes</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Pulse-to-pulse delay [µs]</td>
<td>0.5</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Dose [J/mm] single pass</td>
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</tr>
<tr>
<td>Ablated volume [µm³/pls]</td>
<td>3</td>
<td>7</td>
<td>17</td>
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<tr>
<td>Ablation Efficiency [a.u.]</td>
<td>0.02</td>
<td>0.06</td>
<td>0.15</td>
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</table>

- Increasing the velocity and rep. rate in the same ratio enables us to maintain a good processing quality
- Each pulse is more efficiency due to the offset temperature
- Overlap seems to be the key parameter
Optimal overlap at 70W?

Scanning Velocity (m/s)

Pulse to pulse delay (µs)

- 10 MHz 100m/s, Overlap 74%
- 8 MHz 100m/s, Overlap 67%
- 10 MHz 50m/s, Overlap 87%
- 8 MHz 50m/s, Overlap 84%
- 8 MHz 25m/s, Overlap 92%
- 4 MHz 25m/s, Overlap 93%
- 2 MHz 25m/s, Overlap 67%

HAZ

no HAZ

Efficient metal processing using high average power ultrafast laser
### How long to remove 1mm³ of Steel?

<table>
<thead>
<tr>
<th></th>
<th><strong>Galvo scanner</strong></th>
<th><strong>Polygon scanner</strong></th>
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</thead>
<tbody>
<tr>
<td>Rep. Rate (MHz)</td>
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<td>8</td>
</tr>
<tr>
<td>Fluence (J/cm²)</td>
<td>2.6</td>
<td>0.75</td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>Overlap (%)</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Efficiency (a.u.)</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>Removal Rate (mm³/min)</td>
<td>2.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Time (s)</td>
<td>24</td>
<td>6.3</td>
</tr>
</tbody>
</table>

500fs

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Summary

• **Galvo scanner (up to 5 m/s):**
  - High ablation efficiency: 0.36 at 9W (w/o burr, bumpy surface)
  - Low ablation ablation efficiency: 0.18 at 3W (smooth, melt-free)
  - Multipass processing: up to 9 W, drastic drop for higher $P_{av}$

• **Polygon scanner (up to 100 m/s):**
  - Lower ablation efficiency: 0.18 at 70W (smooth, melt-free)
  - Up-scaling has been demonstrated up to 70 W with 67% overlap
  - Pulse to pulse delay is not a limiting factor up to 8 MHz but we expect a detrimental effect for higher rep. rate
  - Multipass processing: up to 70W, may be more
  - Best results 6 s/mm$^3$

• **Stainless Steel** is very sensitive to parameters such as fluence, velocity, rep. rate. We expect different behavior with other metals

• All these results do not take into account the **max. utilization rate** of galvo scanner (50 to 100%) and polygon scanners (50 to 70%) that reduce the time window actually dedicated to the process
Acknowledgements

Thank you for your kind attention

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