Laser Based Manufacturing in Micro-Processing and Energy

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Content

- Material ablation with Short and Ultrashort Laser Pulses

- High Power Cavity Dumped Disk Laser
  - Principle and Technology
  - Application for Solar Cells and Turbine Plates

- Ultrashort Disk Lasers
  - Regan Disk Amplifier
  - Applications: Micro Processing and Precision Drilling

- Summary
Material ablation with Short and Ultrashort Laser Pulses
# The optimum machining process

<table>
<thead>
<tr>
<th>Main effect</th>
<th>Heating</th>
<th>Melting</th>
<th>Melting and vaporization</th>
<th>Vaporization</th>
<th>Vaporization and ionization</th>
<th>Sublimation and direct dissociation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density starting from</td>
<td>30 W / mm²</td>
<td>1 kW / mm²</td>
<td>10 kW / mm²</td>
<td>1 MW / mm²</td>
<td>10 MW / mm²</td>
<td>10 GW / mm²</td>
</tr>
<tr>
<td>Interaction time</td>
<td>s</td>
<td>ms</td>
<td>ms</td>
<td>ms</td>
<td>ns</td>
<td>ps</td>
</tr>
<tr>
<td>Process examples</td>
<td>Hardening, soldering</td>
<td>Heat conduction welding</td>
<td>Deep penetration welding, cutting</td>
<td>Drilling</td>
<td>Ablation, engraving</td>
<td>Structuring</td>
</tr>
</tbody>
</table>

Power density and interaction time determine how much energy is delivered to the workpiece and what the resulting effects will be. Shown here: metals.
Efficiency of the ablation process

- Ablation threshold decreasing with pulse duration
- Ablation rate per pulse increases with pulse energy
- Higher efficiency
  - shorter pulse duration
  - increased pulse energy
  - increased frequency

\( A H = 0.1 \text{ J/cm}^2 \)

Higher average power
High Power Cavity Dumped Disk Laser
- Disk Technology
- Cavity Dumping
- Applications
Scalability of Laser Output Power

A certain laser power can be extracted per unit of area

\[ P_L \sim D_p^2 \]
Scaling by Disk Coupling to 20 kW CW

Output
20 kW

- 4 disks: 20.0 kW
- 2 disks: 10.7 kW
- 1 disk: 5.5 kW

Pump Current (a.u.)
Pulsmode Q-switching

Characteristics:
- Loss modulation
- Beam quality and pulse duration are correlated

Pulsmode Cavity Dumping

Characteristics:
- Modulation of OC
- No correlation BPP and pulse duration
- Pulse is formed by EO-Switch
Modes of Operation: Q-Switching

Coupled Pulse Formation and Output Coupling

Pulse duration \( \Rightarrow 100 \text{ ns} - \mu\text{s} \)
Modes of Operation: Cavity Dumping

- **Output Coupling**
- **Loss**
- **Power inside Resonator**
- **Output Power**

**Pulse duration**

\[10 \text{ ns} - \mu\text{s}\]
Cavity-dumping Scheme

- photodiode triggers timing of output coupling
- stable even at high repetition rates
- short pulses even at long resonators $\Rightarrow$ good beam quality
Highest throughput with short pulses
– Cavity-dumping enables short pulses –

Pulse duration: 30ns
Energy stability: RMS < 5%
**Highest throughput with short pulses**
**fiber delivered ns Disk Laser -**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>TruMicro 7050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>1030</td>
</tr>
<tr>
<td>Average power</td>
<td>W</td>
<td>750</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>ns</td>
<td>30</td>
</tr>
<tr>
<td>Max. pulse energy</td>
<td>mJ</td>
<td>80</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>kHz</td>
<td>5 – 100</td>
</tr>
<tr>
<td>Fiber Core diameter</td>
<td>µm</td>
<td>400* - 800</td>
</tr>
</tbody>
</table>

*special configuration allows smaller fiber core diameter*
Concept SHG

Green-emitting nanosecond disk laser

Cavity with disk

Pockels cell

Polarizer

Crystal
Cavity dumped nanosecond Disk Laser

Lab results:

- Ave. power: 700 W @ 515 nm
- Pulse energy: 12 mJ
- Pulse duration: 300 - 600 ns
- Fiber delivered: 4 mm mrad

C. Stolzenburg: Photonics West 2010
Optical solutions from TRUMPF

Laser Light Cable (LLK): Delivery fiber with different core geometry
Fiber shape: Round or square

Processing optics: Scanner or fixed
Productivity

25 cm²/s  +50%  37.5 cm²/s  +5%  39.2 cm²/s  +57%
Edge Deletion of Thin Film Solar Cells

- Laser deletion through Glass Plate

- Transmission > 77 %
  (Note: uncoated glass-plate: T = 92 %)

- Surface Resistivity > 100 MΩ

→ High power short pulse laser required
Laser Edge Deletion through Glass-Plate

Aim: Replacement of sand blasting due to environmental aspects
Requirements: High removal rates
Result: Optical transparent and electrical isolated edge
PV: Laser Edge Deletion – TruMicro 7050

- Removal rates increased by quadratic fibers
- Ablation rate up to 50 cm²/s – through glass
- High transmission through delaminated area
- Insulating resistance > 100 MΩ
Drilling of turbine blades

Two parameters which influence the efficiency:
- High temperatures lead to high efficiency
- Cooling air is branched off the compression stage; more air leads to lower efficiency

Requirements for cooling holes:
- Cooling of blades and vanes.
- Holes have to be small with an optimized geometry and preferably only at hot spots

→ Shaped holes
Drilling of cooling holes in turbine blades

Application:
- Hole drilling in bare metals using the TruMicro 7050

Result:
- 90 and 45 degree hole drilling in bare metals.
- The holes have very little taper and minimal HAZ and recast.
- The holes are being drilled in less than 1 second.

Source: CCAT, ICALEO 2010
Shaped holes - laser ablation

Application: Ablation
- Ablation (shaping) process done with Scanner (here about ~ 80 passes)
- Max. recast layer: < 50µm
- Roughness: $R_a < 10µm$
Ultrashort Disk Lasers
- Regan Disk Amplifier
- Applications
Motivation – Why shorter than short?

- Precise micro-processing without burr or melt formation
- Cold micro-processing
Influence of Pulse Duration on Quality

Quality

Pulse Duration

melt debris

precision

nonlinear effects

10 ns 1 ns 100 ps 10 ps 1 ps 100 fs
Scaling the average power of ps lasers

- Rod-type amplifiers:
  - Limited in average power due to thermal effects

- Disk technology
  - High peak power, but big beam diameter in active medium
    - Moderate intensity

- Advantages:
  - High surface to volume ratio
  - Superior heat management
  - High average powers with good beam quality
  - No nonlinear effects

\[ P_L \sim D_p^2 \]
Obtaining ps-Pulses

ps (and fs) Oscillators:
- Tens of MHz Repetition Rate (given by resonator length)
- Pulse selection to lower Repetition Rate

- Pulse Energies in nJ scale
- Amplification needed (5 orders of magnitude)
External Modulator

Features:
- Variable energy (proportional to external analog input or programmed internally)
- Pulses triggerable, (e.g. every 2nd pulse)

Advantages:
- No first pulse issues! (precisely controlled energy for every pulse)
- No variation of output beam properties (focus position, diameter, $M^2$) with power!
TruMicro 5050 – Power and Pulse Duration

- **Average Power:** >50 W (max. 65 W)
- **Optical Efficiency:** 50%
- **Pulse Duration:** 6 ps (sech^2 Fit)
- **Spectral Width:** 1 nm (FWHM)
- **>300µJ @ Repetition Rate:** 200 kHz
Application Set-up

- Processing Methods:
  - Scanner
  - Fixed Optics

- Beam quality on workpiece (i.e. f160 F-Theta-Lens):
# TruMicro Series 5000 compact (~1000x600mm²)

<table>
<thead>
<tr>
<th></th>
<th>TruMicro 5050</th>
<th>TruMicro 5250</th>
<th>TruMicro 5350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Average Power</td>
<td>50 W</td>
<td>30 W</td>
<td>10 W</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1030 nm</td>
<td>515 nm</td>
<td>343 nm</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>&lt; 10 ps</td>
<td>&lt; 10 ps</td>
<td>&lt; 10 ps</td>
</tr>
<tr>
<td>Max. Pulse Energy</td>
<td>250 µJ</td>
<td>150 µJ</td>
<td>50 µJ</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>200-800 kHz</td>
<td>200-800 kHz</td>
<td>200-800 kHz</td>
</tr>
<tr>
<td>Beam Quality</td>
<td>$M^2 &lt; 1.3$</td>
<td>$M^2 &lt; 1.3$</td>
<td>$M^2 &lt; 1.3$</td>
</tr>
</tbody>
</table>
TruMicro 5050 - Stability

- Guaranteed Power stability < 1.5% for ambient temperatures of 20 – 30 °C

- Guaranteed Energy Stability: < 2% (RMS)
Patterning for Thin Film Solar Cells

- P1: Patterning of front contact (TCO) through the Glass (IR)
- P2: Patterning of absorber through the Glass + TCO (green)
- P3: Patterning of back contact and absorber through the Glass + TCO (green)

Connection of Cells on a Module
PV: Thin Film Ablation

Laser patterning of thin CIGS

- Advantages:
  - Burr free
  - Melt free
  - No delamination
  - High speed (> 0.5 m/s)

- Application: P2 step for CIGS cell connection
**PV: Thin Film Ablation**

Laser patterning of thin TCO on CIGS

- **Advantages:**
  - Burr free
  - Melt free
  - No delamination
  - High speed (> 1.2 m/s)

- **Application:** P3 step for CIGS cell connection
PV: Thin Film Ablation

Laser patterning of thin films on Silicon

Direct patterning of SiO/SiN layers

- Thickness of layers: 100 nm

- Single shot ablation

- Selective removal without affecting base material (Silicon)

- Application: Cell connection for Silicon Solar Cells, low-k dielectric grooving
Automotive: Drilling with high Aspect Ratio

Helical Drilling of Stainless Steel

- No melt or debris
- No Heat Affected Zone
- Free selection of taper (positive, negative or zero)
- Diameters: 50 to 100 µm
- Material thickness: up to 1.5 mm
- Applications: Injectors
Aerospace: Drilling with high Aspect Ratio

Helical Drilling of Titanium

- No melt or debris
- No Heat Affected Zone
- Free selection of taper (positive, negative or zero)
- Diameters: 50 to 100 µm
- Material thickness: up to 2 mm
- Applications: cooling holes for turbine blades
Drilling of Green Ceramic Foils

Drilling on the fly (percussion)

Diameter < 100 µm

Drilling rate: > 800-1000 holes/sec

Negligible melting of Mylar tape on backside
Cutting Semiconductors

Silicon Wafer Dicing

- Small cutting kerf (< 20 μm)
- Low HAZ
- High quality of cutting edge
- High productivity due to high average power
Stent Cutting with TruMicro Series 5000

- Highest quality cutting process
  - Negligible burr formation
  - Negligible HAZ

- Materials (e.g.):
  - CrCo
  - Nitinol
  - Polymers
  - Absorbable Materials

- Reduction of scrap at the beginning of the process chain
- Saving of expensive materials
- Saving of expensive finishing processes
Cutting of Nitinol
Cutting of Polymers
Summary
Absorption rate (at 20 °C)

Absorption in %

Absorption in %

Wavelength in µm

UV

IR
Parameters

- Wavelength
- Peak power
- Pulse length
- Beam quality

High frequency or cw mode
⇒ ave. power

...stability...
...from pulse to pulse.
...beam quality

feasibility

economical

Repeatability
Application demands

Remote cutting and ablation

- Pulses short enough to vaporize material
  - q-switching, cavity dumped or modelocking

- Scanner for fast beam steering
  - High beam quality

- Stability from Pulse to pulse
  - Reliability of the process
And now I’m looking forward to your questions!

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