Laser Polishing and Structuring of Metal Alloys
UW-Madison/LasX Team
Laser Polishing and Structuring

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LasX was incorporated in 1998 in St. Paul, MN as a digital converting systems integrator enabling smart manufacturing through proprietary high-speed galvanometric scanner-based laser processing solutions. Solutions available for all industrial wavelengths.

- **2D Pre-Objective Scanning**
  - F-Theta objective lenses offer small spot sizes with minimal angle of incidence variation across the FoV

- **3D Post-Objective Scanning**
  - Rapidly dynamic adaptive focal length varioSCAN unit facilitates larger FoVs and is capable of handling higher laser powers
LasX Industries, Inc.
Laser/scanner control hardware and software

Software and controller developed specifically for coordinating high-speed control of the laser output with the scanner/material position. The controller is designed for several processes:

• Image - laser power of each pixel is adjusted to match the grey scale level at up to 100kHz

• Point and shoot - each individual spot is programmed both in position, down to single micron precision, and pulse period, 33MHz accuracy

• Vector – process speed, frequency and duty cycle are programmed for the vector, power automatically adjusts to compensate for the change in process speed when processing corners and arcs
Laser Polishing and Structuring

Overview

Approach

Polishing

Remelting

Vaporization

Structuring

Outcome

Micro-scale

Meso/Macro-scale

This Talk

Non-metals

Metals
Pulsed Laser Polishing
How does it work?

Two polishing regimes during melting

**Capillary regime** – Smoothing of high spatial frequencies from surface tension & viscosity

- Shorter pulse durations (<2 µs)
- Lower laser fluence (~1 - 2 J/cm²)
- Lower melt depths (~1-2 µm)

*Estimations for Ti6Al4V

Pulsed Laser Polishing
How does it work?

Two polishing regimes during melting

**Thermocapillary regime** – Generation of low spatial frequency features from temperature gradients

- Longer pulse durations (>1 µs)
- Higher laser fluence (~2 - 3 J/cm²)
- Larger melt depths (~3-4 µm)

*Estimations for Ti6Al4V

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Pulsed Laser Polishing

How do we model it? – Capillary Regime

Capillary regime polishing is modeled using Fourier analysis and frequency filtering.

Table 3

<table>
<thead>
<tr>
<th>Material</th>
<th>Unpolished</th>
<th>Polished</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness average, $S_a$ (nm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>191.3</td>
<td>146.8</td>
<td>130.6</td>
</tr>
<tr>
<td>Ti6Al4V</td>
<td>181.2</td>
<td>82.2</td>
<td>89.9</td>
</tr>
<tr>
<td>Al-6061-T6</td>
<td>191.7</td>
<td>130.8</td>
<td>115.0</td>
</tr>
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Root mean square roughness, $S_q$ (nm)

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<tr>
<td>Nickel</td>
<td>252.1</td>
<td>180.3</td>
<td>163.0</td>
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<tr>
<td>Ti6Al4V</td>
<td>238.1</td>
<td>112.0</td>
<td>113.9</td>
</tr>
<tr>
<td>Al-6061-T6</td>
<td>257.5</td>
<td>162.2</td>
<td>150.9</td>
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Fig. 9. (a) Unpolished (measured), (b) polished (measured) and (c) predicted (polished predicted), 3D surface height data of Ti6Al4V.

Pulsed Laser Polishing
How do we model it? – Thermocapillary Regime

Thermocapillary regime polishing is modeled by analytical & empirical relationships to approximate thermocapillary features

Unit cell is generated based on analytical and empirical relationships

Table 3
2-D surface roughness parameters of unpolished, polished and predicted surfaces.

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<td>181</td>
<td>99</td>
<td>102</td>
</tr>
<tr>
<td>57 tool steel</td>
<td>248</td>
<td>139</td>
<td>158</td>
</tr>
<tr>
<td>Root mean square roughness, $S_r$ (nm)</td>
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<td></td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>415</td>
<td>192</td>
<td>192</td>
</tr>
<tr>
<td>57 tool steel</td>
<td>493</td>
<td>241</td>
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Pulsed Laser Polishing
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Pulsed Laser Polishing
Multi-pass polishing and edge features

Improve surface finish with multiple pass polishing

Edge features become dulled by laser polishing


Pulsed Laser Polishing
Microstructures

Martensitic lathes following a single laser pulse on S7 tool steel

Crystalline structure suppression after laser polishing with two different laser settings on Fe-B-Si alloy


Richter, B., Morrow, J.D, Cantwell, P.R., Pfefferkorn, F.E., In-Preperation, “Re-vitrification of glass-forming Fe-B-Si alloy with pulsed laser remelting”

Transmission Electron Microscopy

Proprietary Images That Cannot Be Published
Pulsed Laser Polishing
Metals Applications

Molds and dies

Laser polished glass bottle mold

Biomedical devices

Manually polished vs. Laser Polished Heart Pump Component

*Uses CW Laser Polishing


Roughness reduced up to 4.2% of original (Sa 13.06 µm to 0.55 µm)

*Results for CW Laser Polishing

Additive manufacturing

Pulsed Laser Polishing

Process Setup

Image Based Processing
To achieve the desired polishing results the proper pulse spacing and power need to be determined and set using the process speed, pixel frequency, line spacing and power.

- Process speed and pixel frequency determine pulse spacing
- Line spacing is the step over distance for each pass
- Power is the maximum duty cycle (laser on time) for a pixel. For laser on black, a pixel grey scale value of 0 would be assigned this value and all other pixel values would be scaled from this value

Vector Based Processing
Pulse spacing and power are set for the entire vector using process speed, frequency and power.

- Process speed and frequency determine pulse spacing
- Power is the duty cycle (laser on time) for each pulse period during processing of the vector
Pulsed Laser Structuring
How does it work?

Higher pulse fluence (e.g., pulse duration, power) causes increased flow...

... variation of local flow causes periodic surface topography

Pulsed Laser Structuring
How does it work?

Surface 1

Surface 2

Pulsed Laser Structuring
How does it work?

A laser pulse hits the surface

High Fluence

Low Fluence

Pulsed Laser Structuring

How does it work?

The surface begins to heat up and melt

High Fluence

Low Fluence

Pulsed Laser Structuring
How does it work?

The surface begins to heat up and melt

Pulsed Laser Structuring
How does it work?

High Fluence

The surface begins to heat up and melt

Low Fluence

Pulsed Laser Structuring
How does it work?

High Fluence

The surface begins to heat up and melt

Low Fluence

Pulsed Laser Structuring
How does it work?

High Fluence
Circulation occurs in the melt pool from temperature gradients

Low Fluence

Pulsed Laser Structuring
How does it work?

As the material freezes, an induced feature is created.

The size of the induced feature is related to the fluence of the laser pulse.

**Pulsed Laser Structuring**

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Pulsed Laser Structuring

How does it work?

By varying each laser pulse

Different size surface features can be generated

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Pulsed Laser Structuring
How does it work?

If the pulses are close enough together, the induced features appear as waviness.
Pulsed Laser Structuring
How does it work?

Features grow larger in height with progressive passes (same laser parameters)

100-µm-wavelength sinusoidal feature, created with 30-µm-diameter melt pool

Pulsed Laser Structuring
How do we implement control?

Grayscale image
Intensity values 0 – 255
Black (0) = laser OFF
Minimum gray (1) = minimum pulse duration, $t_p$
White (255) = maximum pulse duration, $t_p$

Linear scan path (unidirectional) for all structure patterns

Each pixel corresponds to a laser pulse

Pulsed Laser Structuring
Meso-scale structures on friction stir tool (H13 tool steel)

Pulsed Laser Structuring
Micro-scale structures on Ti6Al4V surface

University of Wisconsin-Madison crest surrounded by annular region with sinusoidal structure

Funding

The current understanding of pulsed laser polishing and structuring, development of the technology, and training of manufacturing engineering students has been supported by

- U.S. National Science Foundation
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- University of Wisconsin-Madison