Sensor based adaptive laser micromachining using ultrashort pulse lasers for zero-failure manufacturing

Fraunhofer Institute for Production Technology, Aachen

M. Sc. Guilherme Mallmann
Prof. Dr.-Ing. Robert Schmitt

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Outline

1 Process monitoring in laser material processing - brief overview
   Process monitoring, challenge

2 High-precision optical inline measurement technology for distance measurement
   Solution concept, measuring principle, applications

3 Laser process monitoring with Inline distance measurement technology
   Machine integration, automatic parameterization and control processes

4 Outlook / Summary
Process monitoring in laser material processing

Brief overview

- Laser processes are dependent on machine, workpiece and environmental related parameters
- … which influence the process stability and product quality
- Particularly in the manufacturing of precision components is the process window, i.e. the range of allowable parameter variations, extremely tight.
- For this reason, process monitoring and its consequent control are essential in laser micro machining

State of the art on Process monitoring and control:

- Data acquisition
  - Acoustic and electromagnetic process emission (e.g. Pyrometer, Photodiode, 2D cameras)
  - In situ capacitive, confocal chromatic and triangulation sensors
- Monitoring or control variables
  - Direct monitoring of the focal position, removal depth or melting bath (diameter, temperature, etc.)
  - Shape of lasered component (e.g., weld seam’s shape and position)

Process monitoring in laser material processing
Current challenges in laser material processing

- **Time-consuming determination of process parameters**
  - Machining results are dependent on material, laser, surface properties, optical beam path, environment-related factors

- **Characterization of the actual component shape and position**
  - Form deviations resulting from previous process steps can lead to process failures (e.g. removal deviations)
  - Deviation of the component position due to clamping variations can lead to process failures (e.g. removal deviations)

- **Process control**
  - No feedback of current laser machined depth
  - Strong material and process dependency of methods for process monitoring and control (High calibration and modeling effort)
  - Monitoring and control of laser processes with new materials (e.g. composites, plastics) are very limited

- **Quality control**
  - Workpiece inspection after the processing
  - Increased risk of rejects at the end of the value chain
  - Insufficient vertical or lateral accuracy of current measurement techniques
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4. Outlook / Summary
Laser process monitoring using inline distance measurement
High precision optical inline distance measurement

Objective
- Monitoring and optimization of laser structuring processes
- Integration of an in-process measurement technique for performing a feedback control of laser structuring processes

Principle
- Modular measurement technology based on low coherence interferometry
- Measurement system integrated in the machine’s laser beam optical path
- Feedback of the measured data to the process control

Results
- Automatic optimization of process parameters
- Improvement of process quality
- Enhancement of process automation
Laser process monitoring using inline distance measurement

Measurement principle (reflective surface)

Approach with reflective materials

- Measuring principle: low coherence interferometry
- Vertical height information is obtained in the spectrum of the interferogram generated
- Fourier transform of this spectrum provides distance-dependent peak
- Measurement systems able to be implemented with different wavelengths (from 450 to 2300 nm) and therefore of being integrated in different laser system configurations

Intensity distribution of the spectrometer

Source: Brezinski, M., [Optical coherence tomography – Principles and Applications]

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Laser process monitoring using inline distance measurement

Measurement principle (part transparent materials)

Approach part transparent materials

- Measuring principle: low coherence interferometry (Optical coherence tomography)
- Vertical height information is obtained in the spectrum of the interferogram generated
- Fourier transform of this spectrum provides distance-dependent peak
- Measurement systems able to be implemented with different wavelengths (from 450 to 2300 nm) and therefore of being integrated in different laser system configurations

Source: Brezinski, M., [Optical coherence tomography – Principles and Applications]
Laser process monitoring using inline distance measurement

Technical possibilities

Before machining
- Characterization of the workpiece’s position and topography for machine aligning as well as adjustment of the machining strategy / CNC code
- Automatic process initialization (laser parameter setting)

During the machining
- Inline measurement of ablation depth
- Detection of process deviations and control
- Inline monitoring the focus position
- Early identification and correction of manufacturing defects

After the machining
- Quality assurance directly in the machine (using machine coordinates)
Laser process monitoring using inline distance measurement

Application possibilities

Material independence

- Inline measurement system / process monitoring can be used with:
  - Metals
  - Glass
  - Plastics
  - Fiber-reinforced composites (CFRP, GFRP)
  - Multilayer systems (OLEDs, solar cells)
  - Ceramics

Integrability

- Evaluation system adjustable on the machine configuration (laser wavelength scanning optics, solid optics) and thus flexibly integrated and applicable
- Integrable with continuous wave (CW), short-pulse / ultra-short pulsed laser systems
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Laser process monitoring using inline distance measurement
High precision inline metrology for the Laser micro processing

Before machining
- Acquisition of the workpiece topography for machine alignment
- Automatic process initialization (laser parameter setting)

During machining
- Inline measurement of removal depth
- Detection of process deviations and control
- In-line monitoring of the focal position
- Early identification and correction of manufacturing defects

After machining
- Quality assurance directly in the machine
High precision inline metrology for the Laser micro processing
First generation system – IR Laser applications

Measurement system
- Measurement wavelength range: 1017 nm ± 50 nm
- Measurement range: 1.3 mm
- Measuring system repeatability: 200 nm (Standard deviation)
- Measuring frequency: max. 2kHz

Prototype – Laser micro machining
- Nano second pulsed fiber laser (central wavelength: 1064 nm)
- Scanning System (analog based)
- Telecentric F-theta objective with focal distance of 80 mm
- Measurement area: 30 mm x 30 mm
- Beam coupling: Edge Filter
System characterization

Z Accuracy

Accuracy validation with a Piezo linear stage (1 µm step size)

<table>
<thead>
<tr>
<th>Range</th>
<th>Mean value</th>
<th>Step</th>
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<tbody>
<tr>
<td>Range 1</td>
<td>0.9454 mm</td>
<td>1.0333 µm</td>
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<tr>
<td>Range 2</td>
<td>0.9444 mm</td>
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</table>

<table>
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<tr>
<th>Range</th>
<th>Mean value</th>
<th>Std.Dev.</th>
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System characterization

Z Accuracy

Accuracy validation with a Piezo linear stage (2 µm step size)

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System characterization

Z Accuracy

Accuracy validation with a Piezo linear stage (5 µm step size)

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<td>Step</td>
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<td>Mittelwert</td>
<td>0.9452 mm</td>
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<tr>
<td>Std.Dev.</td>
<td>0.0422 µm</td>
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</tbody>
</table>
System characterization
Measurement range and Linearity

- Step standard for the evaluation of the measurement range
  - Measurement values in millimeters
  - Scanning area of 6.5 mm x 2 mm

- The deviation between the developed and a reference measurement system is of a maximum of 9.053 μm, which represents 0.79% of the measurement range
High precision inline metrology for the Laser micro processing
Measurement of laser structured surfaces

Measurement of laser structured surface: textile structure
High precision inline metrology for the Laser micro processing

Measurement of laser structured surfaces

Measurement of laser structured surface: leather structure
High precision inline metrology for the Laser micro processing
Second generation system – IR Laser applications

Measurement system
- Measurement wavelength range: 980 nm ± 50 nm
- Measurement range: 4.9 mm
- Measuring system repeatability: 200 nm (Standard deviation)
- Measuring frequency: max. 10kHz
- Optimized telecentric F-theta for perfect laser and measurement beam coaxiality as well as spot and focal match
High precision inline metrology for the Laser micro processing
Second generation system – IR Laser applications – First integration
High precision inline metrology for Laser micro processing

First generation system – Green laser applications (Work in Progress)

Measurement system

- Measurement wavelength range: 557nm ± 31 nm
- Measurement range: 2,5 mm
- Measuring system repeatability: 200 nm (Standard deviation)
- Measuring frequency: max. 10kHz

- Optimized telecentric F-theta for perfect laser and measurement beam coaxiality as well as spot and focal match
High precision inline metrology for the Laser micro processing
Test and validation

- Lightmotif OP2
  - 5-axis laser micromachining system
  - Picosecond pulsed laser
  - High accuracy galvo-scanner (digital based)
  - Air bearing direct-drive stages, sub micrometer repeatability
  - 600 x 600 mm
  - 300 kg load
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4. Outlook / Summary
Summary

- Current challenges in laser material processing involving process monitoring
  - Time-consuming determination of process parameters
  - Characterization of the actual component shape and position
  - Process control based on feedback of the current laser machined depth
  - Strong material and process dependency of methods for process monitoring and control (High calibration and modeling effort)
  - Inline quality control

- High-precision optical inline measurement technology for distance measurement
  - Measuring principle: low coherence interferometry
  - Vertical height information is obtained directly in axis
  - Measurement systems able to be implemented with different wavelengths (from 450 to 2300 nm) and therefore of being integrated in different laser system configurations

- Laser process monitoring with Inline distance measurement technology
  - Measurement system for IR-Range
    - Measurement wavelength range: 980 nm ± 50 nm
    - Measurement range: 4,9 mm
  - Measurement system for Green-Range
    - Measurement wavelength range: 557nm ± 31 nm
    - Measurement range: 2,5 mm
  - Measuring system repeatability: 200 nm (Standard deviation)
  - Measuring frequency: max. 10kHz