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High-resolution, high-speed inline optical topography measurement system for laser micro-machining process control

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Abstract

An *in situ* topography measurement system for monitoring and controlling laser micromachining processes is presented in this paper. A frequency-domain low-coherence interferometry (FD-LCI) system is used to generate high-resolution, high-speed topographic data that will enable an automatically adaptive micro-machining process with increased machining precision.

To provide the topographic data directly in machine coordinates, the measurement beam has to be co-axial with the ultra-short pulse machining laser (wavelength 515 nm). A camera sensor-based module was developed to measure offset and angle between both beams, which can be corrected by fine-adjustment of the measurement beam. The reflectivity of the workpiece can vary over a very wide range. To maintain an optimal strength of the interferometry signal while scanning the workpiece surface, the feedback light power from the reference path is adapted with a high-speed beam shutter, such that it always matches the return light levels from the measurement path. Preliminary tests indicate that the FD-OCT system can provide topographic measurement points at varying rates of up to 20 kHz, with a depth measurement range of z_{range} = 1 mm and a depth resolution better than 4 µm.

Topography measurement, laser micro-machining, FD-OCT, FD-LCI, optical coherence tomography, low-coherence interferometry

1 Introduction

Ultrashort-pulse (USP) laser micro-machining offers a flexible method for machining or texturing materials with micrometre accuracy. USP lasers operate at pulse durations ranging from tens of femtoseconds to tens of picoseconds. The resulting non-thermal removal of the material (ablation) avoids detrimental effects such as heat-affected zone, burrs, and material cracks. The laser spot is scanned rapidly across the surface of the workpiece by a galvo based scanner, in combination with a multi-axis motion system to cover larger areas.

One of the applications of USP laser processing is for example micro-milling of hardened steel. While this machining process can be very precise, until now it is an open-loop process. Compared to conventional machining, inaccuracies in the workpiece prior to the machining directly translate to the machined surface. Moreover, the correct laser parameters may not be known exactly for each location, and material differences or contaminations may result in different ablation depths.

The Horizon2020 project "ADALAM" aims at developing an *in situ* topography measurement system for monitoring the ablation process. The topography data of the workpiece will be used to automatically adapt the processing parameters to obtain improved ablation results.

2 Low-coherence interferometry

The topography system integrates a frequency domain low-coherent interferometer (FD-LCI) set-up in the beam path of the micromachining system. The FD-LCI combines a Michelson interferometer with a low coherence (i.e. broadband) laser source. The interfering light returned from the sample and the

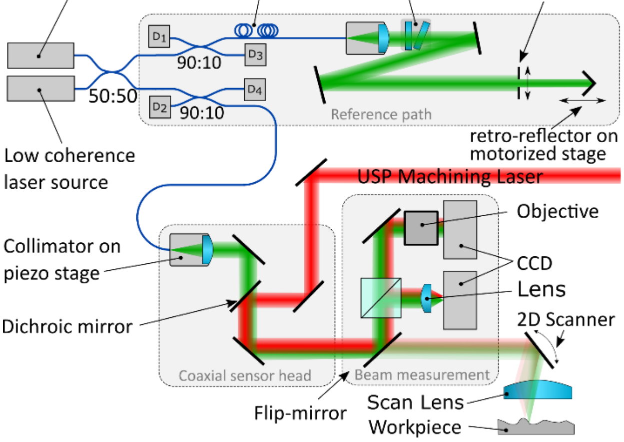

Figure 1. Schematic overview of the measurement system. The measurement beam is indicated in green, the USP beam in red. The two beams are misaligned in this figure.

reference arm is analysed with a spectrometer. The Fourier transform of the spectrum provides the optical path length (OPL) difference between both arms, which corresponds to the local sample height. As opposed to conventional LCI methods, mechanical modulation of the reference arm length is not required.

For a Gaussian light spectrum (centre wavelength λ_0 and FWHM bandwidth $\Delta\lambda$) the theoretical depth resolution δz and range Δz of the measurement system are given (in air) by: [1,2]

$$\delta z = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda} \qquad \text{and} \qquad \Delta z = \frac{N}{4}\frac{\lambda_0^2}{\Delta\lambda}$$

where N is the number of line-camera pixels assumed to define the spectral resolution of the spectrometer.

3 System components

The complete measurement system consists of four main components (see Figure 2); a low coherence broadband laser source, a custom fast spectrometer, an automatically adapting reference path module, and a beam combiner and beam measurement module. For the presented system an NKT SuperK COMPACT supercontinuum laser is filtered to a central wavelength λ_0 of 557 nm, with a spectral bandwidth of 64 nm. This laser has a 2 ns pulsed output at a repetition rate of 20 kHz. The spectrometer is a custom design (Fraunhofer IPT) featuring a high-speed line camera with N=2048 pixels. This combination results in theoretical values of δz = 2.3 µm and a Δz = 2.5 mm.

The spectrometer adapts the exposure time automatically to the amount of incident light, with a minimum exposure time of 50 µs. The short exposure time requires the exposure of the line camera to be synchronized with the laser pulse output.

3.1 Automatically adapting reference path module

The reference path returns light that has travelled a fixed OPL, which can be adjusted with a motorized stage. To maintain an optimal interference signal [3] while scanning a sample surface with strongly varying reflectance, the light power returned by the reference path is adapted continuously with high speed.

Rapid adaption of the reflectivity is achieved by attenuating the beam using a specially designed shutter in the open-beam section of the reference arm. In each arm, a portion of the in-going and returned light is tapped off with a 90:10 fiber-optic splitter and measured by a pair of photodetectors (D_1 to D_4 in Figure 1). The reference arm shutter opening is controlled in real-time to minimize the difference between the detected light power ratios D_1/D_3 and D_2/D_4, which results in a continuous matching of the sample reflectivity at a rate of about 400 Hz.

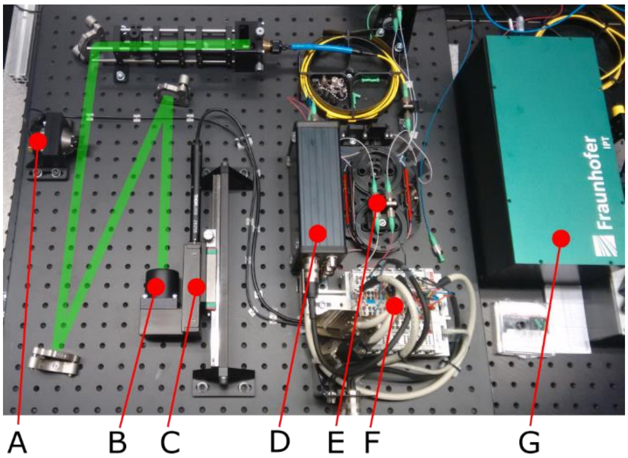

Figure 2. Photo of the reference path and spectrometer. A: High speed shutter, B: Retro-reflecting mirror, C: Motorized OPL stage, D: Photodetectors, E: Fiber splitters, F: Digital I/O, G: Spectrometer.

3.2 Beam combiner and beam measurement module

In the beam combiner module, a dichroic mirror with a narrow spectral transition is used to overlap the measurement beam with the USP machining beam (see Figure 1). To enable alignment with the USP beam the fiber collimator emitting the measurement beam is mounted on a 4-axis piezo motor stage. To ensure focusing on the same spot on the work piece, the tip/tilt angle between both beams has to be less than 50 µrad. For alignment, a motorized flip-mirror deflects the beams towards the beam measurement module (see Figure 1). Using two camera sensors, the lateral position of each beam is measured with a precision of 5 µm and the tip/tilt angle with a precision of 10 µrad.

4 Results

The system has been tested using a lab-setup that mimics the actual measurement beam path in the USP laser machining system. The lateral resolution is about 40 µm, which is mainly determined by the spot size on the sample and the 2D galvo scanner hardware. The axial (depth) resolution and stability is better than 4 µm. A measurement range of 1 mm is achieved. Figure 3 shows test results obtained with a USP machined samples (Lightmotif BV, Enschede, The Netherlands).

The maximum speed of a surface measurement scan is strongly dependent on the amount of reflected light. For very low-reflectance areas such as machined pockets, about 500 points per second are achieved, whereas for highly reflective areas up to 20000 points per seconds can be measured.

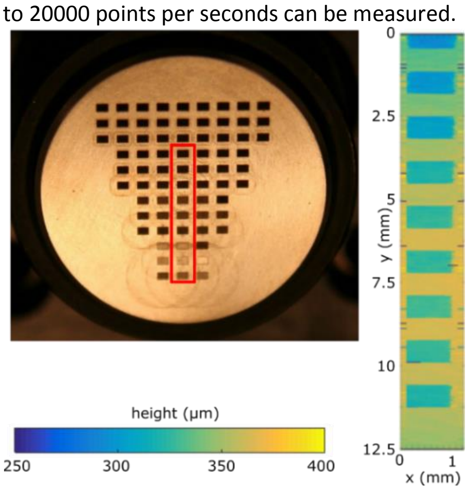

Figure 3. Test sample with USP machined pockets with increasing roughness from bottom to top. Colour-coded height map: The apparent gradual depth change over the measured area (red rectangle) is caused by an uncorrected OPL change due to the moving scanner mirrors.

5 Conclusion

Within the ADALAM project, a complete inline topography measurement system has been developed and tested. A high resolution and high speed in-line depth measurement is achieved using FD-LCI. The setup is currently being integrated in the USP machining workstation at the company Lightmotif, where further characterization will take place. This inline topography system will then be used for testing adaptive laser micro-machining for a range of applications.

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