In-situ assessment of laser-chemically machined surfaces by means of an indirect optical measurement approach and scanning confocal fluorescence microscopy

Claudia Niehaves[1,*], *Yasmine* Bouraoui[2], *Tim* Radel[2], *Andreas* Tausendfreund[1], and *Andreas* Fischer[1]

[1]University of Bremen, Bremen Institute for Metrology, Automation & Quality Science, Linzer Str. 13, 28359 Bremen, Germany
[2]BIAS - Bremer Institut fuer angewandte Strahltechnik, Klagenfurter Str. 5, 28359 Bremen, Germany

Abstract. The manufacturing rate of laser-chemical machining (LCM) is limited to avoid disruptive boiling bubbles in the process fluid. Adjustments to e.g. the laser beam or the fluid properties can increase the removal rate. However, the existing understanding of the surface removal mechanisms is insufficient to ensure the removal quality under these conditions. Thus, near-process measurements of the surface geometry and the surface temperature are required for an improved process modeling. Due to the complex process environment, no suitable in-process measurement technique for the geometry or surface temperature exists so far. This contribution presents an indirect geometry measurement approach based on scanning confocal fluorescence microscopy that is integrated into the LCM plant. As a result, it is shown that the approx. $200\,\mu$m deep micro-geometry of laser-chemically processed surfaces can be indirectly measured *in-situ*, i.e. inside the LCM system. The realized setup is designed in such a way that in future it will be additionally possible to measure the temperature by means of the fluorescence life-time.

1 Introduction

In comparison to traditional micro-manufacturing techniques like micro-milling, laser-chemical machining (LCM) is a gentle metal-removal technique that achieves higher dimensional accuracy at acute edge angles and small edge radii [1]. However, its manufacturing rate is significantly lower because the process energy applied to the component surface by means of a focused laser, and thus the removal rate, is severely limited in order to avoid disruptive boiling bubbles in the process fluid. The influence of boiling bubbles on the material removal rate can be reduced by different adjustments of the laser beam and fluid properties (e.g. beam shape or fluid viscosity). However, to achieve an increase in removal rate while maintaining removal quality, the current understanding of surface removal mechanisms must be fundamentally expanded. In this context, comprehensive LCM process modeling that considers the boiling bubble influence is only possible by means of in-process measurements of the surface geometry and the surface temperature in the removal region. However, due to the complex fluid process environment, the gas bubbles occurring during the material removal, and the measurement requirements for the manufactured cavities, there is no suitable in-process measurement technique for the removal geometry or the process-relevant surface temperature [2]. Conventional optical geometry measurement methods are unsuitable for near-process applications due to various aspects. For example, refractive index variations in the chaotic fluid environment prevent the use of interferometric methods, while steep edge angles produce unavoidable artifacts due to unwanted reflections in measurements using confocal microscopy [3]. In contrast, an indirect measurement of the removal geometry using confocal fluorescence microscopy is not subject to these impairments. The method has already been successfully applied close to the process in manufacturing environments with fluid layers as thin as $120\,\mu$m [4] and in fluid layers several millimeters thick [5] and with reactant gas bubbles in the path [5]. However, to date, no near-process application of the indirect measurement approach has been performed in the LCM process environment. Therefore, it has to be elucidated if the removal geometry can be measured indirectly inside the LCM system by means of a fast surface scan. In addition, it is important to ensure that the realized setup of the confocal fluorescence microscope can also be used to measure the near-surface temperature, in order to develop an extended understanding of the process.

2 Measurement approach

The indirect geometry measurement technique is based on confocal fluorescence microscopy with a model-based evaluation of the fluorescence signal to measure the microstructures in the mm-thick fluid layer present in laser-chemical machining [7]. In contrast to conventional methods, which use the light scattered from the surface for geometry measurement, the indirect measurement principle

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[*] e-mail: c.niehaves@bimaq.de

determines the fluid boundary layer to the workpiece by detecting the fluorescence light emitted by the fluid, from which the geometry of the workpiece is inferred. The confocal optical system used, consisting of pinhole, lens and objective (see Figure 1), limits the detection of the fluorescence signal to a confocal volume around the focal plane of the objective. When this volume is moved in z-direction through the fluid, a characteristic fluorescence signal $S(z)$ is generated, which can be modeled as follows:

$$S(z) = \left(\mathrm{erf}\left(\frac{z - z_0}{2\Xi} + \epsilon\Xi\right) - \mathrm{erf}\left(\frac{z - z_1}{2\Xi} + \epsilon\Xi\right)\right) e^{\epsilon(z - z_1)}, \quad (1)$$

where Ξ represents a parameter describing the properties of the confocal volume, ϵ the absorption coefficient of the fluid, and z_0 and z_1 the respective positions of the measurand fluid interface (measurand surface) and the fluid-air interface, respectively. From the pointwise measured fluorescence signal, this model function can be employed to determine the surface position z_0 by using a least-squares approximation. By utilizing a scanning galvo-mirror the measurement is repeated for several lateral surface positions (x, y) and the surface geometry $z_0(x, y)$ is obtained. Additionally, the fluid temperature can be measured, since the fluorescence life-time is temperature-dependent.

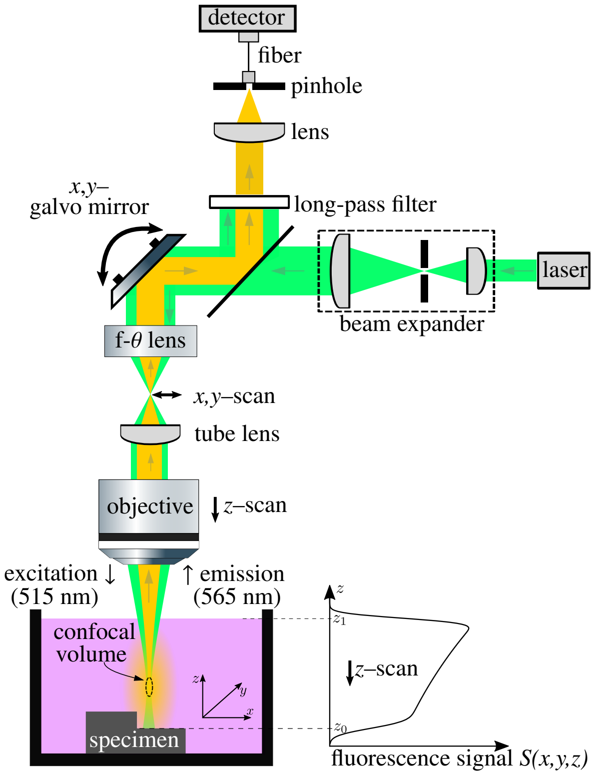

Figure 1. Indirect geometry measurement: Schematic of the experimental setup.

3 Measurement results

An exemplary in-situ surface measurement $z_0(x, y)$ of a laser-chemically produced cavity is presented in Figure 2, showing for the first time the 3D geometry measurement capability by the introduced indirect measurement approach. The depicted LCM-sample has a sinusoidal structure resulting from a laser power modulation [7], which is clearly visible in the obtained measurement results. The cavity has a depth of $200\,\mu$m, superimposed with sinusoidal amplitudes of less than $10\,\mu$m depth. Some artifacts at highly inclined surfaces show up, compared with reference measurements, which might be attributed to phenomena occurring at surfaces not taken into account by our evaluation model like reflections of the surface or an oblique intersection between the surface and the confocal volume. These artifacts can be taken into account as an additional factor in the model function.

The presented results highlight the potential of the indirect measurement approach as an area-based in-situ monitoring tool for the LCM-process. Further studies and an extension of the evaluation model are planned to specify the resolution limit and the measurement uncertainty of the model-based indirect geometry measurement technique. By changing the detector, our setup can also assess the temperature, which offers the possiblity of a combined measurement of temperature and geometry in the LCM process environment.

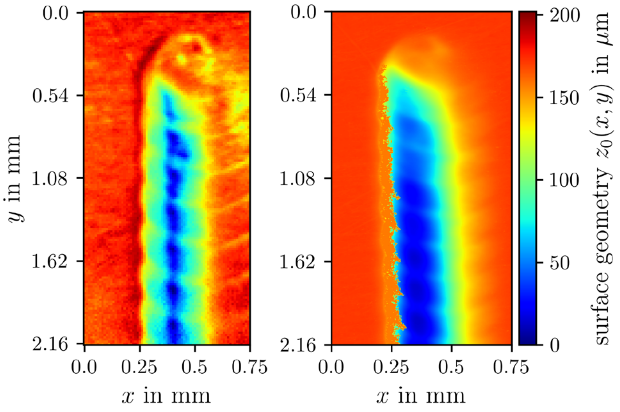

Figure 2. Left: In-situ geometry measurement of a LCM cavity. Right: Ex-situ reference measurement of the same structure by a white-light interferometer. The results match each other qualitatively.

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