EPJ Web of Conferences **266**, 10011 (2022)
EOSAM 2022
https://doi.org/10.1051/epjconf/202226610011

Near-process indirect surface characterization of laser-chemically produced removal contours

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Abstract. The manufacturing rate of laser chemical machining (LCM) is currently restricted to avoid disruptive boiling bubbles in the process fluid. An increase necessitates adjustments to the laser beam or fluid properties. However, the current understanding of the surface removal mechanisms is insufficient to achieve a consistent removal quality under these conditions. For an improved process modeling, in-process measurements of the surface geometry, the surface temperature and the boiling bubbles are required. Due to the complex process environment, no suitable in-process measurement technique for the geometry or surface temperature exists. This contribution presents an indirect geometry measurement approach based on confocal fluorescence microscopy that offers the potential for near-process application in the LCM process environment. As a result, the micro-geometry of different surfaces is shown to be indirectly measurable under LCM-equivalent process conditions such as thick fluid layers or gas bubbles in the beam path. Furthermore, a combined fluorescence-based measurement of geometry and temperature is proposed.

1 Introduction

Compared to conventional micro-manufacturing processes such as micro-milling, laser chemical machining (LCM) 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, the surface temperature and the boiling bubbles 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 µm [6] and in-situ in fluid layers several millimeters thick [7]. 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 under the LCM process conditions such as thick fluid layers and gas bubbles or particles in the beam path. In addition, it is important to investigate whether the near-surface temperature can also be measured by means of fluorescence, in order to be able 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 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. Since light is detected even at angles > 75° to the surface normal [4], samples with steep edges can also be

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measured [5]. The confocal optical system used, consisting of pinhole, lens and objective (see Fig. 1a), 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:

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

Here, the normalized intensity is shown 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. From the pointwise measured fluorescence signal, this model function can be used to determine the surface position z_0 by using a least-squares approximation. If the measurement is repeated for several lateral surface positions (x, y), the surface geometry $z_0(x, y)$ is obtained. Additionally, the fluid temperature can be measured, since the fluorescence intensity and also the life-time are both temperature-dependent.

3 Measurement results

The results of the indirect in-situ geometry measurements under LCM-equivalent environmental conditions, such as gas bubbles present in the fluid generated during material removal, are shown in Fig. 1. It turns out that the model-based evaluation of the indirect measurement of the fluorescence signal enables indirect measurements even in the presence of interfering gas bubbles in the beam path, see Fig. 1b. Thus, even when gas bubbles are present in the fluid directly above the measured object, a surface position can be determined whose uncertainty correlates with the gas bubble density. Further measurements demonstrate the robustness of the measurement approach towards different practical geometries of both step geometries (Fig. 1c) and surfaces with different surface inclinations (Fig. 1d). As a result, the indirect geometry measurement technique allows the determination of relevant geometric parameters, such as step heights, of micro-objects immersed in fluid layers several millimeters deep. Even 85°-inclined surfaces, comparable to the flanks of laser-chemically manufactured cavities, can be measured indirectly. In contrast to conventional reflection-based confocal microscopy, no undesirably high measurement deviations occur in the regions of greatest slope. Thus, the indirect geometry measurement approach is shown to cope with realistic process conditions such as thick fluid layers, steep surface geometries and contaminated fluids by employing a model-based signal processing approach to determine the desired surface position.

Additionally, first investigations show that due to the temperature dependence of the fluorescence signal, spatially resolved measurements of a constant spatial surface temperature distribution are also possible, provided that the confocal volume is moved over the surface at a constant distance. This highlights the potential for simultaneous measurement of temperature and geometry when temperature is considered in a holistic modeling of the fluorescence signal.

Financial support was received from the Deutsche Forschungsgemeinschaft (DFG), project number 451385285.

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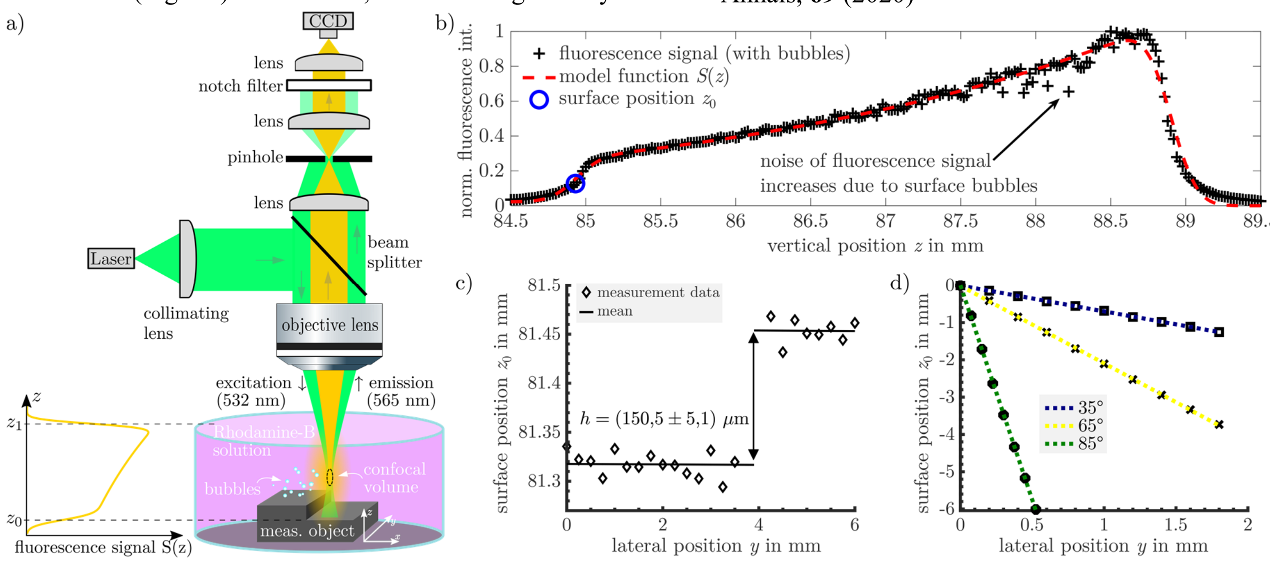

Fig. 1. Indirect geometry measurement : a) Schematic of the measuring system ; b) Fluorescence intensity in the presence of gas bubbles in the beam path ; c) Measurement results of a step and d) of differently inclined surfaces.