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Indirect geometry measurement method for in situ application in laser chemical machining

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Summary:

The optical geometry measurement of submerged micro-surfaces in chaotic fluid environments, e.g. for electric discharge machining (EDM) or laser chemical machining (LCM), is challenging when the specimen feature high aspect ratios and steep surface gradients. To avoid reflection-caused artifacts at steep gradients, fluorescent molecules are added to the fluid, whose fluorescence is detected with a confocal setup. A model-based signal processing enables an indirect measurement in fluid layers > 1 mm and is capable to cope with process-inherent bubbles and surface gradients up to 84°.

Keywords: micro geometry, optical measurement, in situ, fluorescence, signal modeling

Introduction

The laser chemical machining (LCM) process uses an electrolytic fluid and localized heating by a laser to generate a material removal in submerged workpieces. It produces microstructures with high aspect ratios, high surface gradients and small edge radii. In contrast to competing processes such as micro-milling or laser ablation there is no thermal stress induction or tool wear [1]. However, the in situ conditions hinder conventional optical methods of geometry measurement. Interferometric methods such as white light interferometry suffer from measurement deviations caused by thermal gradients and refractive index fluctuations [2]. Confocal microscopy is prone to artifacts caused by the high surface angles and curvatures [3] typically produced with the LCM process. However, an indirect measurement using confocal fluorescence microscopy shows promise for in situ application, since it does not capture the light reflected by the specimen, but the light emitted by a fluorescent liquid covering it. The detected fluorescence signal $S(z)$ can be limited to a small volume around the focal plane of the objective by axial light sectioning produced by confocal microscopy (cf. Fig. 1), where a pinhole, confocal to the objective lens, attenuates light far outside the focal plane. This way, a signal is only detected when the so-called confocal volume intersects the fluorescent fluid. The surface geometry can then be determined by the change of the fluorescence signal produced by pointwise scanning of the confocal detection volume from fluid surface to specimen surface. The method was successfully used on metallic microspheres with high curvatures by coating their surface with a thin fluorescent film < 100 nm [3]. It was shown that a measurement was possible even at angles > 75° from the surface normal with a lateral resolution comparable to conventional confocal microscopy without generation of artifacts. This paper aims to determine the influence of fluid contaminants (e.g. gas bubbles) and high surface angles on the measurement in thick fluid layers.

Model-based indirect measurement method for thick fluid layers

To determine the specimen surface position z_0 with micrometer precision in the thicker fluid layers > 1 mm present in the LCM process, a model-based evaluation of the fluorescence signal $S(z)$ is necessary [4]. The signal model is based on a simplified confocal volume function in the shape of a 3D-Gaussian function. It represents the spatial distribution of the contributions of all infinitesimal volume elements to the total fluorescence signal. The signal function $S(z)$ at position z is obtained by weighting the confocal volume function with a depth dependent absorption term and integrating it over all spatial dimensions [4]. To cope with small deviations due to inclined surfaces, the model was extended by two additional terms, resulting in

$$S(z) = S_0\, e^{\epsilon(z-z_1)} \Bigg[\mathrm{erf}\left(\frac{z-z_0}{2\Xi} + \epsilon\Xi\right) - \mathrm{erf}\left(\frac{z-z_1}{2\Xi} + \epsilon\Xi\right) + K_1 \cdot \left(\mathrm{erf}\left(\frac{z-z_2}{2\xi} + \epsilon\xi\right) - \mathrm{erf}\left(\frac{z-z_1}{2\xi} + \epsilon\xi\right)\right)\Bigg] + K_2 e^{-\frac{(z-z_2)^2}{2\sigma^2}}, \quad (1)$$

with ϵ being the attenuation coefficient, ξ/Ξ confocal volume parameters and S_0, $K_{1,2}$, σ and z_2 weighting parameters. The desired position z_0 (specimen surface) is obtained by using the model function $S(z)$ for a non-linear least-squares approximation of the measured data.

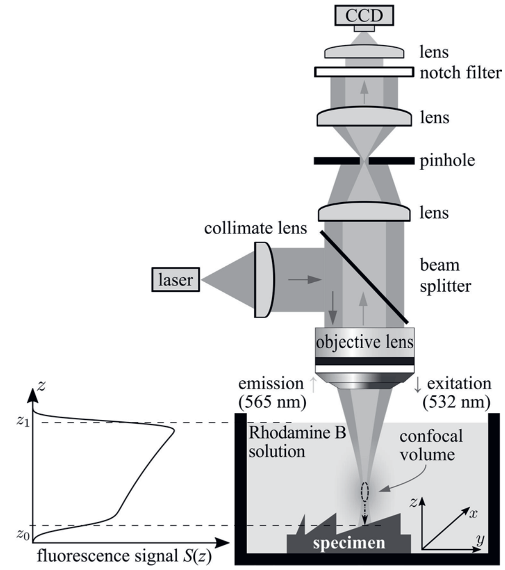

Fig. 1. Principle of confocal microscopy based indirect measurement. The specimen surface position z_0 is obtained from the fluorescence signal $S(z)$.

Results

To determine the influence of the inclination on the indirect measurement, three different inclinations were measured. The fluorescence intensity signals for three points on the 65° inclined surface of the submerged specimen, as well as the model functions approximated with Eq. (1) are shown in Fig. 2a). The resulting surface positions z_0 are marked as black circles. The measurement was performed on three different surface inclinations 35°, 65° and 85°. The surface positions z_0 for one line in y-direction on each surface are shown in Fig. 2b) respectively. The deviations from a linear fit of the measurements were shown to be of equal magnitude as those of the reference measurement with conventional confocal microscopy. In contrast to the reference measurements however, no artifacts were observed with the indirect measurement on the 85° surface. To determine the influence of the LCM process environment on the measurement, bubbles were created by chemical reaction of phosphoric acid and a non-passivating specimen material, see Fig. 2c). The measurements with bubbles in the optical path are shown in Fig. 2d). The fluorescence signal is shown to exhibit increased noise, dependent on bubble density. However, the model-based signal evaluation enables the determination of the surface position z_0 even under the influence of increased signal noise. In conclusion, the indirect geometry measurement method is suitable for the in situ application in thick and contaminated fluid layers similar to the LCM or EDM process environments and enables measurements even on highly inclined surfaces up to 84.3°.

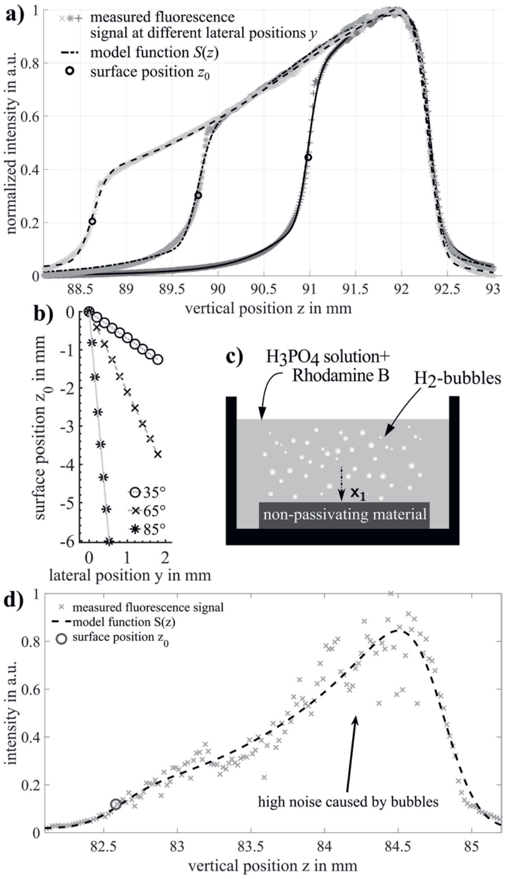

Fig. 2. a) Signal and model fit for three y-positions on a 65° inclined surface. b) Surface position for different inclinations (with linear fit). c) Setup to generate gas bubbles induced by chemical reactions d) Signal at position x_1 with bubbles in optical path.

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