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Near-process Indirect Surface Geometry and Temperature Measurement for Laser Chemical Machining (LCM)

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Summary:

Laser chemical machining (LCM) is intentionally limited in its removal rate to avoid disturbing boiling bubbles in the process fluid. To overcome this limitation, an enhanced material removal model is required based on surface geometry and temperature in-process data. For this purpose, fluorescence measurements and confocal microscopy are combined to enable in-process experiments in LCM environment. Derived from fluorescence effects, the geometry and surface temperature are indirectly determined under LCM-equivalent conditions such as thick fluid layers and gas bubbles in the beam path.

Keywords: Geometry measurement, in-process measurement, signal modeling, laser chemical machining, confocal fluorescence microscopy

Introduction

Compared to 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 speed is significantly lower since the process energy, or removal rate respectively, supplied by a focused laser is severely limited to avoid the creation of disturbing boiling bubbles in the process fluid when the induced surface temperature reaches the boiling point. The influence of boiling bubbles on the material removal rate can be reduced by adjustments of the laser beam and fluid properties (e.g. beam shape or fluid viscosity). However, to achieve an increased removal rate while maintaining removal quality, the current understanding of removal mechanisms must be fundamentally expanded. In this context, comprehensive LCM process modeling that incorporates the boiling bubble influence is only possible through in-process measurements of the surface geometry, the surface temperature, and the boiling bubbles in the removal zone. With the complex fluid environment, the gas bubbles occurring during removal, and the measurement requirements for the manufactured cavities, no suitable in-process measurement technique exists for the cavity geometry or the process-relevant surface temperature. Due to various aspects, conventional optical geometry measurement methods are unsuitable for a near-process application in the LCM environment. Refractive index variations in the process fluid prevent the use of interferometric methods and steep edge angles produce unavoidable artifacts due to unwanted reflections in measurements using confocal microscopy [3]. In contrast, an indirect geometry measurement using confocal fluorescence microscopy is not subject to these interferences. The method has already been successfully applied close to the process in manufacturing environments with fluid layers as thin as 120 µm [4] and in situ in fluid layers several millimeters thick [5]. However, no near-process application of the indirect measurement approach has been performed in the LCM process environment to date. Thus, it is of fundamental interest to investigate whether removal geometry and temperature can in principle be measured in the LCM process environment with thick fluid layers, interfering gas bubbles, or particles in the beam path.

Measurement principle

The indirect measurement technique is based on a conventional confocal fluorescence microscope with a model-based evaluation of the fluorescence signal to measure the micro-geometry and temperature in the mm-thick fluid layers present in LCM [5]. In contrast to conventional methods, which use the light scattered from the surface, the indirect principle determines the fluid boundary layer to the workpiece by detecting the fluorescence light emitted by the fluid, from which the geometry and temperature of the workpiece are inferred. Since light is detected even at angles > 75° to the surface normal, samples with steep edges can also be measured [2]. The detection of the fluorescence signal is limited to a confocal volume around the focal plane of the objective. If the confocal volume moves in $\boldsymbol{z}$-direction through the fluid, a characteristic fluorescence signal $\boldsymbol{S}$ is generated, which can be modeled as follows:

$$S(x,y,z) = S_0 \cdot \left(\mathrm{erf}\left(\frac{z - z_0(x,y)}{2\Xi} + \epsilon\Xi\right) - \mathrm{erf}\left(\frac{z - z_1}{2\Xi} + \epsilon\Xi\right)\right) \cdot \mathrm{e}^{\epsilon(z-z_1)} \quad (1)$$

Here, $\boldsymbol{S_0} = \boldsymbol{f}(\boldsymbol{T}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}), \boldsymbol{\epsilon})$ represents a parameter of the total fluorescence intensity that is dependent on the temperature and the concentration dependent absorption parameter $\boldsymbol{\epsilon}$ while Ξ describes the properties of the confocal volume, and $\boldsymbol{z_1}$ the position of the fluid surface. From the pointwise measured fluorescence signal $\boldsymbol{S}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$, eq. (1) the surface geometry $\boldsymbol{z_0}(\boldsymbol{x},\boldsymbol{y})$ and temperature distribution $\boldsymbol{T}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})$ is determined by a least squares approximation.

Results

The result of an indirect in-situ geometry measurement under LCM-equivalent environmental conditions, i.e. gas bubbles generated during material removal contaminating the fluid, is shown in Fig. 1a. It turns out that the presence of gas bubbles in the fluid directly above the measured object, does not hinder the determination of a surface position but leads to an increased measurement uncertainty that correlates with the gas bubble density. The model-based evaluation of the indirect measurement of the fluorescence intensity signal enables the indirect measurement approach to compensate for the signal noise resulting from the presence of interfering gas bubbles in the beam path by considering the total signal data in the least squares optimization. As a result, the indirect geometry measurement approach is shown to cope with realistic process conditions such as contaminated fluids while also enabling measurements of steep surface geometries and in thick fluid layers, as required for use in the LCM environment. In order to demonstrate the capabilities of the indirect measurement approach with regard to near-surface temperature measurements, a metal foil submerged in a fluorescent solution is heated on the bottom side by a gaussian laser profile. At the same time, the fluorescence intensity on the top side of the foil surface is measured confocally at a constant distance close to the surface. The lateral temperature profile resulting from the temperature-dependent fluorescence signal is shown in Fig. 1b. While this intensity-based measurement required calibration to yield quantitative results, it highlights the potential for simultaneous temperature and geometry measurements when the temperature is considered in the fluorescence signal model (see eq. 1).

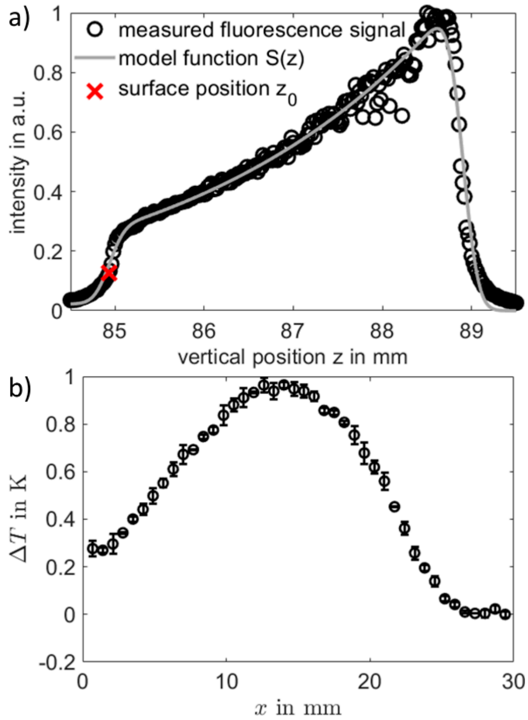

Fig. 1: a) Fluorescence signal and surface position z_0 resulting from model-based evaluation in a fluid contaminated with gas bubbles. b) Temperature profile on the top side of a submerged metal foil heated on the bottom side by a laser, measured via fluorescence.

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