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Self-mixing interferometry as a diagnostics tool for plasma characteristics in laser microdrilling

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ABSTRACT

In this work, self-mixing interferometry (SMI) was used to monitor the optical path difference induced by the ablation plasma and plume. The paper develops the analytical relationships to explain the fringe appearance in the SMI during laser microdrilling. The monitoring principle was tested under a large experimental campaign of laser microdrilling on TiAlN ceramic coating with a low-ns green fibre laser. Key process parameters namely pulse energy, number and repetition rate were varied. The effect of side gas on the SMI signal characteristic was analysed. Laser induced breakdown spectroscopy (LIBS) was used to identify the plasma temperature and electron number density. The SMI signals were correlated to the plume size and its evolution as a function of process parameters, as well as electron number density estimated by spectroscopy. In addition to proving the validity of the proposed new method, the results show insights to the micromachining of the ceramic material with low ns pulses.

1. Introduction

Lasers are playing a key role in industrial manufacturing as key enabling technologies for precision manufacturing. Micro material processing and marking applications cover 1.28 billion USD revenue worldwide, corresponding to the 41% of the total revenues of laser processing market [1]. Pulsed lasers are fundamental tools for industrial micromachining applications. Nanosecond pulsed lasers are cost effective solutions being widely employed in marking, cutting, drilling and texturing operations. Ultra-fast pulsed lasers operating at ps to fs pulse durations provide superior machining quality and have become much more reliable and affordable in the last few years. With increased reliability of the lasers and reduced costs, more machine tool manufacturers are moving towards adapting these technologies in integrated systems and lasers are expanding their market beyond the original equipment manufacturers' realm. The importance of integrated monitoring equipment is already apparent and will raise as the need for quality assurance increases in time. On the other hand, laser micromachining relies on the complex ablation phenomenon occurring in a very restricted spatial and temporal window.

Several works are available in literature regarding the observation and monitoring of laser ablation dynamics. The used methods vary and are mainly based on mechanical [2], acoustic [3,4] and optical [5–22] principals. Only a few of these methods can be readily adapted as online industrial process monitoring means. The optical methods provide the flexibility of using either the optical emission of the process or a probe light for the monitoring task. A large amount of literature deals with the optical emission of laser ablation for fundamental studies concerning single pulsed laser material interaction [5]. These works study the evolution of plasma temperature and electron number density as a function of position and time. Using a probe light, plasma, shock wave and plume propagation can be also observed. Using methods such as pump-probe [6], schielleren [7], shadowography [8–10], or digital holography [11–13], researches have indicated critical phenomenon and time instances in single pulsed ablation. However, almost all laser micromachining applications consist of a train of pulses with a certain overlap in space and time. Hence, plasma characteristics, shock wave propagation, plume and material ejection vary according to how the pulse train is applied on the material surface. Moreover, the proposed methods require complex optical arrangements and are not easy for implementing on an industrial machine tool. An industrial monitoring tool is expected to be non-intrusive on the machine tool and should preferably use the existing optical chain. From this point use of photodiodes for observing process emission stands out as an appealing option [14]. However, the choice of monitoring wavelength bandwidth is dependant on used material.

In the meantime, interferometric methods have emerged for direct monitoring of the ablated region geometry. In particular, ablation depth

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monitoring by Fourier domain optical coherence tomography (FT-OCT) [15,16] and self-mixing interferometry (SMI) [17–19] have been demonstrated. A certain stability issue regarding the SMI depth measurements was found, since ablation depth measurements could be possible only in the presence of a side gas [19]. The stability issue concerned the change of SMI signal behaviour, and was attributed to the local variations of the refractive index caused by the ablation plasma and plume [20]. From another point of view, the SMI can be used to interact with the ablation plasma and plume as used as a novel monitoring technique. SMI is easy to implement in existing optical chains of the machining equipment. The information regarding plasma characteristics can be used to ensure the micromachining quality, since plasma and particle shielding as well as heat accumulation are known to reduce machining quality and efficiency [21,22].

Accordingly, this work investigates the use of SMI as a potential monitoring device for ablation plasma characteristics in laser micro-drilling. In particular, the SMI measurements are correlated to the plasma characteristics measured via laser induced breakdown spectroscopy. The work initially describes the theory behind the monitoring principle. The SMI signal characteristics under different process conditions are analysed in order to confirm feasibility of the monitoring principle. In a large experimental campaign, laser percussion drilling on TiAlN ceramic coating was carried out. SMI signals were acquired as well the emission spectra. The hole depths were measured with focus variation microscopy, optical path change was calculated from the SMI signals and plasma temperature and electron number density were estimated from the emission spectra. The results show the feasibility of the proposed method as well as providing insights to the physical phenomenon occurring during the microdrilling process.

2. Theory

SMI method has been previously employed in laser microdrilling for ablation depth monitoring, where plasma related phenomenon occur contemporarily. The feasibility of monitoring plasma characteristics instead of the ablation depth progression should be demonstrated theoretically and experimentally. Therefore, in the following, the SMI working principle for plasma monitoring purpose is explained. Spectroscopy is also employed in the present work in order to correlate the plasma characteristics measured by a more conventional system to SMI signals. Hence, the basic theory for laser induced breakdown spectroscopy (LIBS) is also explained.

2.1. Working principle of self-mixing interferometry

Conventional interferometry technique used for displacement measurement (Michelson interferometry) uses a reference and a measurement arm. Moreover, the displacement direction is ambiguous. SMI exploits interference occurring in the laser cavity due to back-reflected light. Conventionally, laser diodes (LD) are employed to construct self-mixing interferometers. The photodiodes (PD) for monitoring output power attached to the back of the laser diode is used to measure the power fluctuations due to the interference. In a SMI configuration, the power back reflected from a remote target enters the cavity after being attenuated in the external cavity. The reflected laser field is phase shifted depending on the distance of the reflecting body [23,24]. In SMI, the back reflected field E_r, adds to the lasing field E_l, modulating its amplitude and frequency. The interferometric phase can be retrieved from the change of the optical power, measured by the monitor photodiode. The periodic function of the interferometric phase, hence the signal shape depends on the feedback parameter (C). When operating in moderate feedback regime ($1 < C < 4.6$), the signal shows saw-tooth shape, as a fringe is formed at each passage of half-wavelength ($\lambda/2$). Moreover, due to the signal asymmetry, the displacement direction is sensed along with amplitude. The displacement (Δp) can be calculated by counting the number of fringes (n_{frg}):

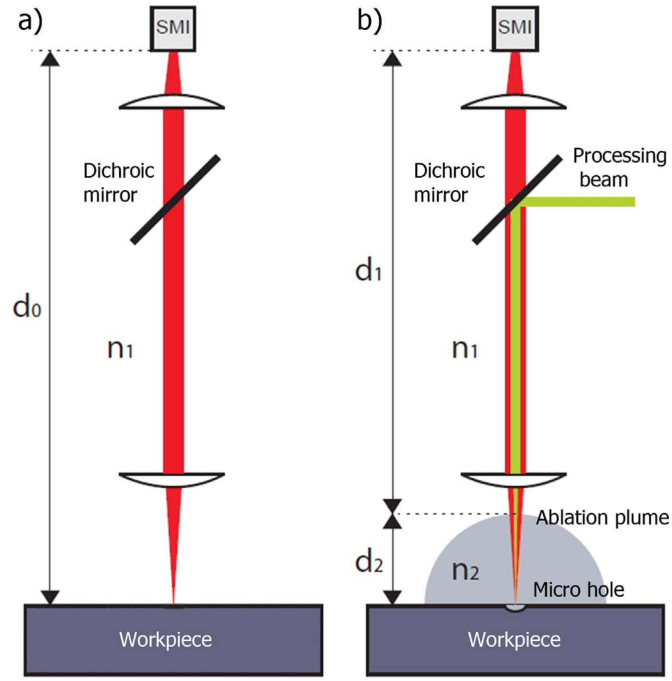

Fig. 1. Schematic representation of the optical path change induced by the ablation plume during laser microdrilling.

$$\Delta p = n_{frg} \cdot \lambda/2 \quad (1)$$

As a matter of fact, the displacement sensed by an interferometer is the result of the change in the optical path (p). The optical path change can be induced by a change of distance (d) as well as a change in refractive index of the media (n). Thus, SMI can be used to measure the change in refractive index too [25]. As schematically represented in Fig. 1, ablation process generates ablation plume. The plume consists of a plasma core, expanding wavefront and ejected material. All these factors contribute to the change in the refractive index on the material surface, in the proximity to the ablation process. For a stationary target the initial optical path (p_O) can be expressed as:

$$p_0 = d_0 n_1 \quad (2)$$

where d_O is the distance between the interferometer and the target, and n_1 is the refractive index of the surrounding media. If the refractive index changes locally due to perturbations in the surrounding media, the optical path (p_1) is equal to:

$$p_1 = d_1 n_1 + d_2 n_2 \quad (3)$$

with

$$d_0 = d_1 + d_2 \quad (4)$$

where d_1 is the distance between the interferometer and the perturbed zone, d_2 is the length of the perturbed zone and n_2 is its refractive index. In this work, the perturbed zone corresponds to the ablation plume. Accordingly, the optical path difference between the two instances (Δp) can be calculated as:

$$\Delta p = p_1 - p_0 = d_1 n_1 + d_2 n_2 - d_0 n_1 \quad (5)$$

hence,

$$\Delta p = d_2 \Delta n \quad (6)$$

where Δn is the change in the refractive index. Eq. (6) holds in the case of a stationary target. Therefore, the SMI should not measure the vibrations due to the ablation process. Additionally, both d_2 and Δn are time dependant, which are held constant in this analytical expression. Previous studies showed that ablation depth measurements with SMI in the absence of a side gas jet was not feasible [19]. Therefore, in the