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On line sensing of ultrafast laser microdrilling processes by optical feedback interferometry

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Abstract

The instantaneous measurement of both ablation front displacement and removal rate during ultrafast laser microdrilling is demonstrated by on line sensing technique based on optical feedback interferometry in both unipolar and bipolar semiconductor laser. The dependence of laser ablation dynamics on pulse duration, energy density and working pressure has been investigated, thus allowing a significant advancement of the basic understanding of the ultrafast laser-material interactions. Moreover, the detection system results high-sensitive, compact, and easily integrable in most industrial workstations, enabling the development of real-time control to improve ablation efficiency and quality of laser micro-machining processes.

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Keywords: optical sensing and control; ultrafast laser material processing; ablation rate dynamics; optical feedback interferometry

1. Introduction

Recently, it has remarkably increased the push to device miniaturization and the need to carry out, with extreme precision, a countless number of industrial applications as for example drilling, cutting and surface

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processing, whose dimensioning are not greater than tens of micron with tolerances lower than few microns. In this context, the field of laser technologies for micro-processing and material treatment has established as one of the more effective in many strategic sectors, such as automotive, mechatronics, aeronautical, photovoltaic, biomedical, etc [1, 2]. Nonetheless, the increasing use of last-generation laser sources with excellent performance at repetition frequencies up to MHz and pulse energies sufficient to ablate a large variety of soft and hard materials, has concurrently required an intensive research effort aiming to the development of innovative sensing techniques capable to spatial and time-dependent characterization of the laser micromachining process.

Post-process offline analysis of laser ablated structures and damage morphology have been extensively explored to understand the physical mechanisms controlling the laser ablation process and adjust the process technology in order to improve the achievable precision [3]. Invasive inspections of the borehole geometry have tentatively contributed to infer the formation and the time-evolution of deep laser ablated structures [4]. Nonetheless, to characterize high aspect-ratio micro-machined structures more reliable detection techniques are required, and the physical interactions between intense light beam and bulk materials need diagnostic tools capable of real-time response to be fully described and unambiguously interpreted. The direct investigation of crucial parameters such as the penetration depth and the removal rate all along the process time is therefore of paramount importance to identify different ablation phases along with providing additional insight into the ablation dynamics.

In semiconductors, real-time imaging of the hole shape evolution during laser drilling of high aspect-ratio holes has been reported, employing trans-illumination of the sample perpendicularly to the drilling direction [5]. This technique enabled direct and high resolution investigation of the temporal evolution of the drilling process studying the influence of pulse duration, from the ns- to the fs-regime, on the hole morphology [6]. This approach can only be adopted for materials transparent to the illumination wavelength but cannot be employed for metals.

Webster *et al.* [7] employed spectral-domain optical coherence tomography for in-situ imaging of morphology changes during and between percussion drilling pulses with a hole depth resolution of 14 μm. Also, inline coherent imaging allowed in-situ micron-scale depth measurements of laser keyhole welding and laser drilling processes at kHz rates [8].

Real-time depth measuring system using a confocal imaging technique integrated into the laser machining workstation has been also demonstrated [9]. The detection system was capable to return the signal expected by a certain penetration depth with a resolution of about 0.5 μm, although the scanning speed and accuracy of the confocal motion stage might intrinsically cut-off the performance of the technique

Here, we investigate the ultrafast laser ablation of metals in the high energy pulse regime, by implementing in-situ a detection system based on optical feedback interferometry in both bipolar and unipolar semiconductor laser [10, 11]. This inherently coherent optical sensor is capable to instantaneously measure the ablation front displacement, allowing on line monitoring of the penetration depth and the ablation rate all through the laser-matter interaction. Its noninvasiveness and real-time response are crucial to accurately assess the influence of laser fluence, pulse duration and working pressure on the ablation dynamics. Furthermore, the detection system results high-sensitive, compact, and easily integrable in most industrial workstations, enabling the development of on-line control to improve the ablation efficiency and the quality of laser micro-machining processes.

2. Experimental

Figure 1 shows the schematic layout of the experimental setup.

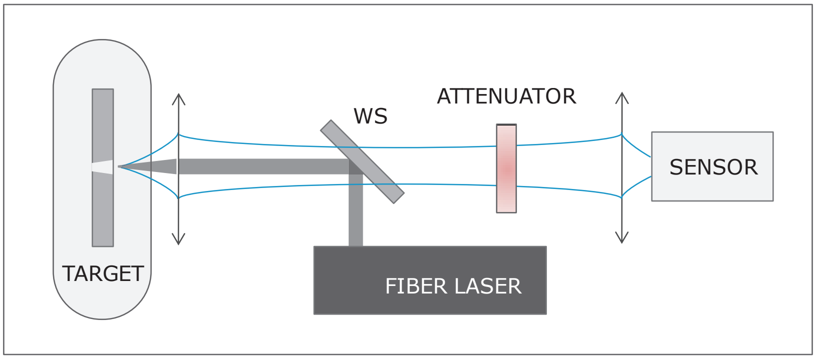

Fig. 1. Schematic layout of the experimental setup

The source used for the ablation is a prototype ytterbium-doped fiber laser amplifier delivering 120-ps pulses at the wavelength of 1064 nm. The maximum average power is 10 W at 110 kHz repetition rate, corresponding to a maximum pulse energy of 90 μJ. A wavelength separator (WS) was used to coaxially align the fiber laser beam with that of the sensing laser used in the self-mixing interferometer [10, 11]. A variable attenuator allows to adjust the fraction of light back-reflected at the bottom surface of the drilled hole into the optical cavity of the laser interferometer. This feedback radiation coherently interferes with the optical field inside the cavity of the sensing laser and eventually modulates its optical power by characteristic sawtooth-like fringes (i.e. self-mixing interferometry), corresponding to a change of the external optical path by multiples of half the emission wavelength.

The performance of the ablation sensor using a commercial laser diode (LD) and a quantum cascade laser (QCL) are compared. Particularly, quantum cascade lasers are bandgap-engineered semiconductor sources well suited for applications as process control [11, 12], chemical sensing [13], spectroscopy [14] and imaging [15], in which the laser source is used to simultaneously generate and detect the radiation in the self-mixing configuration. Also, their continuous performance improvement (i.e. fast response, wavelength selectivity, high output power, etc.) coupled with an inherent sensitivity to external optical feedback are highly attractive for the diagnostic of ultrafast laser ablation processes, since a large variety of QCL systems emitting in the mid-IR to THz spectral region, can be employed to further extend the intrinsic detection range of such a sensing application.

3. Results and Discussion

Figure 2a shows a representative time resolved evolution of the ablation process in air as a function of the fiber laser fluence when the fiber laser beam is focused onto the surface of a 50 μm thick stainless steel target. The instantaneous penetration depth is measured by the LD-based ablation sensor during the percussion drilling of the metallic plate.

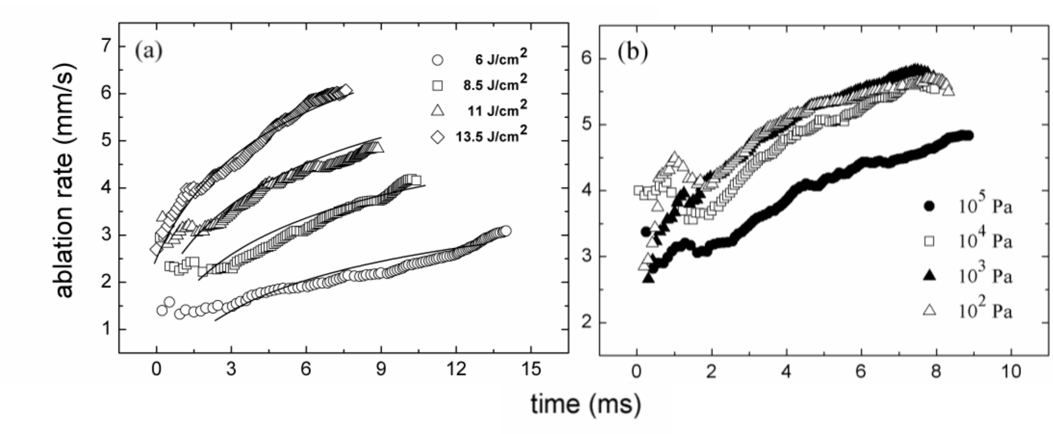

Fig. 2. Dependence of laser ablation efficiency and material removal on (a) pulse fluence and (b) working pressure. The theoretical data (lines) based on the Hertz-Knudsen law [16] well reproduce the experimental results.

A clear evidence of the ablation onset is provided. Furthermore, several stages of the drilling process and fluctuations of the ablation rate can be distinguished in the depth. The theoretical curves (lines in Fig. 2a) are calculated using the generalized Hertz-Knudsen formula and well fit the experimental results [16]. The detection system describes faster dynamics for percussion drilling at higher energy density pulses, revealing the route to minimizing the breakthrough time and enhancing the efficiency of material removal. Also, similar experiments were performed in vacuum, as shown in Fig. 2b, to investigate the ambient pressure influence on the removal rate. We demonstrated that the ablation efficiency can be enhanced when the pressure is reduced with respect to the atmospheric pressure for a given laser fluence, reaching an upper limit despite of high-vacuum conditions.

Furthermore, this sensing technique was proven successful for monitoring the ablation front displacement during microdrilling of 50 μm-thick metal targets with different thermal properties, i.e. using off-the-shelf stainless steel and aluminum plates, without requiring any sample preparation.

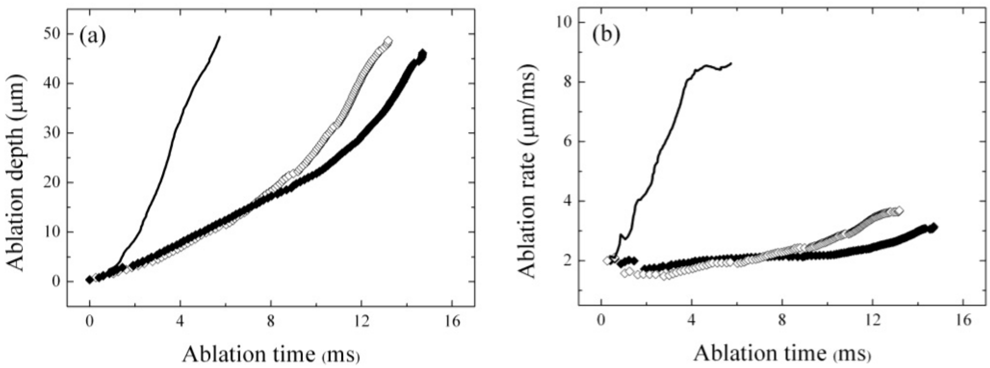

Fig. 3. Time-dependence of (a) the ablation front depth and (b) the ablation removal rate, during drilling of carbon steel (full diamonds), stainless steel (open diamonds) and aluminum (line) plates, respectively. The machining pulse fluence ~ 5.3 J/cm^2.

In Fig. 3a and Fig. 3b are shown the representative ablation characteristics measured by the interferometric technique on targets of carbon steel (full diamonds), stainless steel (open diamonds) and aluminum (line), respectively. The removal rate per pulse was monitored during microhole drilling by percussion technique at a laser fluence of ~ 5.3 J/cm^2, enough to drill through the metallic targets. In all cases, the ablation rates could be described by a monotonically increasing function, although the evolution of the laser drilling inside the capillary featured peculiar time-dependence of the ablation front in Fig. 3a and the removal rate in Fig. 3b, respectively. In particular, the heat transfer mechanism near the ablation zone was heavily affected by the thermal response of the materials to the incident pulses. The thermal conductivity in stainless steel [κ(@273 K) ~ 15 W/mK], results three times lower than carbon steel [κ(@273 K) ~ 52 W/mK], which may explain a faster removal dynamics in the former case. Indeed, the ultrashort pulse laser energy transfer to the bulk material generated heat, which would reside longer into the irradiate volume of metals with a lower thermal conductivity. Furthermore, the local temperature rapidly increased by focusing the incident radiation, yielding to a more effective pulse-to-pulse accumulation mechanism in stainless steel, where the thermal ablation regime was reached faster and the removal rate was higher than carbon steel. The curves relative to the steel targets in Fig. 3 also show how the ablation front displacement proceeded with the same rate in the thermally gentle regime, which elapsed after the first 10-15 μm hole depth, independently from the thermal properties of the material. A bifurcation of the plotted data occurred for deeper penetrations, due to the fact that the thermal ablation regime is achieved more rapidly in the case of stainless steel, thus leading to a sudden increase of the removal rate at the same ablating fluence. Incidentally, by increasing the laser fluence, the overall ablation rate heightens up for both materials and the bifurcation took place earlier in the process.

However, the thermal conductivity of aluminum [κ(@273 K) ~ 236 W/mK] is one order of magnitude higher than stainless steel [κ(@273 K) ~ 15 W/mK], then we would have expected a lower ablation rate in aluminum (see line curves in Fig. 3). Nevertheless, we did observe a faster removal on the aluminum target, mainly at the beginning of the process. There, the vaporization thermodynamics is known to be also affected by the material boiling temperature, which is lower in aluminum ($T_{vap} \approx 2767$ K) than stainless steel ($T_{vap} \approx 3144$ K), thus leading to an earlier ablation onset under the same incident fluence. Furthermore, in Fig. 3b an ablation rate of about 9 μm/ms could be revealed during the drilling breakthrough time of the aluminium, more than four times higher than in steel targets.

Finally, experimental values of the ablation front displacement as fast as 17 μm/ms, resulting in ablation rates ≈ 160 nm/pulse, could be measured at the maximum average power available with the fiber laser by implementing a QCL-based sensing technique which monitored the voltage modulations at the QCL terminals caused by the ablation dynamics in Aluminium plates (not shown in Fig. 3). It is worth noting that this value is close to the maximum ablation rate measurable using a probe beam of a laser diode emitting in the near-IR range, since this interferometric sensing approach is unable to return a sawtooth-like signal for ablation rate higher than half the fringe period, i.e. one fourth of the laser probe wavelength. Therefore, the intrinsic detection limit that may be achieved by as designed QCL-based sensors is limited only by the emission wavelength of the quantum cascade laser itself, thus a large variety of QCL systems whose emission goes down to THz spectral region can be similarly employed to extend the application range of this sensing system to even faster ablation processes.

4. Conclusions

In conclusion, we have developed a new sensing technique based on optical feedback interferometry in both laser diode and quantum cascade lasers for in-situ detection of high ablation rate during laser-material process. A detailed description of the working principle of this non-invasive diagnostic system was given and it should in principle be applicable to the wide variety of opaque and transparent materials, which are typically used for industrial applications. We demonstrated the capability to measure in real-time the instantaneous ablation rate as a function of the target physical properties in order to study fast dynamics in laser-induced surface ablation. Furthermore, we investigated the dependence of laser ablation dynamics on pulse duration, energy density and working pressure, paving the way to further understanding the ablation mechanisms towards a full control on the process parameters. Finally, it is worth noting that under specific configuration, the laser system for ablation monitoring was additionally capable to return a real-time correction of target displacement and/or vibration during the machining process [17].

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