Real-Time Depth Monitoring of Galvo-telecentric Laser Machining by Inline Coherent Imaging

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Abstract: We achieve in situ, micron-scale tracking of laser machining through a galvo-telecentric beam delivery system using coherent imaging. We collect both high speed intrapulse and interpulse morphology changes as well as overall sweep-to-sweep depth penetration.

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1. Introduction

One of the most widely employed delivery methods for laser machining is through the use of scanning galvanometer mirrors (galvos) and a telecentric lens since it requires no movement of the laser source or workpiece. Due to a lack of accurate and real-time depth monitoring method, laser processing has serious constraints: 1) it is difficult to study parameter dependence (assist gas, laser power, scanning speed, etc) because post-cut analysis simply studies accumulated effects rather than directly resolving transient processes [1, 2]; 2) without a real time feedback control method, high machining precision requires sophisticated characterization of material properties

Inline coherent imaging (ICI) has been demonstrated as a powerful tool for *in situ* monitoring of laser penetration into materials [3, 4]. ICI is a frequency-domain coherent imaging technique which offers high imaging speeds, high signal-to-noise and high dynamic range ($>$ 60 dB), all without requiring a moving reference arm similar to the medical imaging modality spectral-domain optical coherence tomography [5]. ICI combines the sample arm of the Michelson interferometer of OCT "inline" with a machining laser beam and simultaneously resolves backscatter from multiple depths along the laser processing beam path. In ICI, the coincidence of the machining and the imaging foci is of critical importance and, due to complicated nature of the telecentric lens, it is still a question whether ICI can be used in scanning delivery systems. In this work we integrate ICI into the laser processing system and, to the best of our knowledge, this is the first successful demonstration of ICI monitoring of cutting and welding with scanning optics.

2. Experiment

Our ICI system includes a broadband 830 ± 12.5 nm superluminescent diode light source, a single-mode-fiber 50:50 Michelson interferometer, and a 312 kHz (maximum) line-rate IR spectrometer. The axial resolution is 18 μm in air (dispersion limited), though single interfaces can be located more precisely as demonstrated below.

The machining beam is a 100 W, 1064 nm industrial CW Yb:fiber laser. The machining beam and imaging beam are combined together before a scanning mirror which is placed at the entrance pupil of a telecentric lens (Thorlabs. LSM05-BB). The beam is scanned between -5 mm and +5 mm on the focal plane. Both the machining beam and the imaging beam have a waist of 31 μm FWHM which coincide with each other at the center of the scan range. At $\pm$5 mm the measured separation between the waists is 11 μm, with the imaging beam closer to the center.

The sample of stainless steel is located at the focal plane. During the machining process, the machining laser is modulated by 20 ms period, 50% duty cycle pulses, corresponding to an average power of about 50 W. The focal point moves at 15 mm/s, corresponding to 667 ms per sweep. For the studies discussed here, ICI imaging operates at a line rate of 1.6 kHz, but higher etch /faster scan rates can be accommodated easily with imaging line rates up to 312 KHz. SD-OCT data are processed and displayed as an M-mode (reflectance versus time and depth) using homodyne filtering and noise-floor equalization.

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3. Results

Fig 1 shows an M-mode comprised of a small fraction of A-lines to show real time morphology change during and between laser pulses. In this regime of thermal cutting, the machining laser creates a vapour channel (depth $\sim 25\ \mu$m) which pushes melt out of the target keyhole. After the pulse, some of this melt flows back in while the imaging beam is scanned forward. Sample surface is tracked by digital imaging processing (*k*-NN method, Fig 1 - green line).

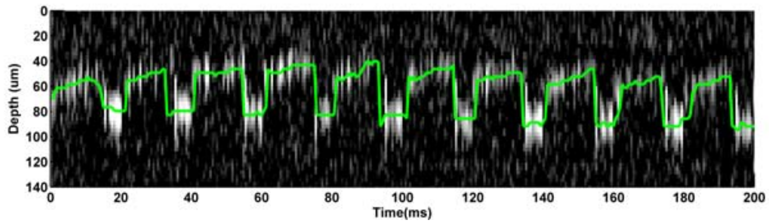

Fig. 1. Vapour channel formation (during pulse) and refilling (between pulses) during laser processing. The bottom of the work pieces is tracked (green line).

The overall removal rate of material can be extracted from the ICI results as shown in Fig. 2. Using ICI, it is possible to distinguish variations that occur during the machining process. For example, at -3.7 mm and -1.9 mm, the amount of material removed is relatively small and at 4 mm, a pit develops from sweep 18 to sweep 36. Using ICI, we are able to track the impact of material imperfections that accumulates over many sweeps. This offers the potential real-time correction of the ablation depth even with a process that exhibits a high degree of intrinsic variability.

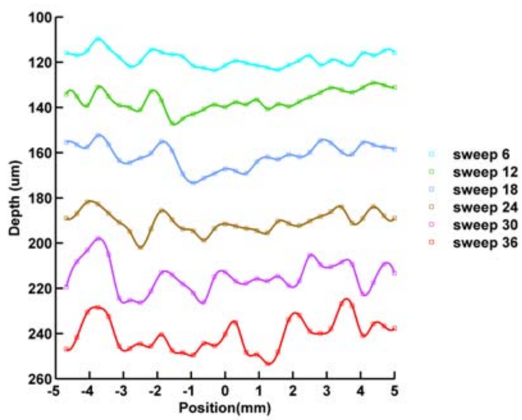

Fig. 2. Overall depth change of 6 representative sweeps. At -3.7 mm and -1.9 mm, the amount of material removed is relatively small and at 4 mm, a pit develops from sweep 18 to sweep 36. Solid curves are meant as a guide to the eye.

With this method, high-speed raster scanned laser engraving, welding and cutting of a variety of materials such as metal, ceramics, wood and even textiles can be studied. This technology shows the capacity of rapid, direct and quantifiable process monitoring in galvo-telecentric laser machining system. Future work includes understanding the interaction mechanism and its parameter dependence, and real-time depth control and ablation depth correction.

References

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