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Ultrafast z-scanning for high-efficiency micro-machining

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Abstract

The growing demand for micro-machined elements in scientific research and industry has created a need for high-efficiency laser micro- machining. A laser's machining efficiency is highly sensitive to the relative locations of the beam and surface. Real-time control for beam delivery is time consuming and financially prohibitive for practical applications. Here, we propose an economical solution for high-efficiency micro-machining by combining rapid scanning of focal positions with rapid laser-firing.

Keywords: high efficiency micro-machining ; ultrafast z-scanner; TAG lens

1. Introduction

Laser micro-machining is increasingly essential to modern science and technology; among other applications, it is frequently used in medicine, research and electronic industry (Malinauskas et al., 2016). The growing demand for lab-on-chip devices, medical micro-elements and micro-electronic devices necessitate the development of high-efficiency machining techniques (Shiu et al., 2008, Saga et al., 2010, Gu et al., 2004, Brazzle et al., 1999) To achieve various processing requirements such as a high resolution of the micro-machined product, one must often use optical elements to focus the laser beam to a highly-localized energy source. This focal positioning is a critical determinant of overall machining efficiency. Thus, accelerating the speed at which one can adjust the focus position with respect to the material surface becomes a major challenge for improving material processing efficiency.

Ideally, the highly-focused beam should be focused on the surface throughout the material removal

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process, but this requires knowledge of the real-time surface location as well as a fast focusing method. While some have attempted to acquire real-time surface location information to increase machining efficiency, the complexity and inflexibility of the resulting machining system has drastically reduced its potential for practical use (Duocastella and Arnold, 2012). Aside from the difficulty of real-time surface monitoring, most controlled also suffer from low response rates compared to the repetition rate of the laser. (Bechtold et al., 2015). Here we demonstrate a new method of increasing micro-machining efficiency by combining high frequency laser firing events with an ultra-fast z-scanner. This creates an axial distribution of the focused beam that allows the pulses to be sent to different surface locations of the material without real-time monitoring.

The experimental setup consists of a Nd:YVO4 laser (Coherent Inc., 355 nm, 15 ns pulse duration) guided through the TAG lens (TAG Optics Inc.) and focused onto the substrate, a silicon wafer in our case, using an ultraviolet microscope objective (5x, N.A. 0.13). The TAG lens is an ultrafast vari-focal device for which lens power ($\frac{1}{f_T}$, where f_T is the focal length of TAG lens) varies sinusoidally, and in this case the oscillation frequency is set to 140 KHz (Mermillod-Bondin et al., 2008). This results in an oscillation in a variable focus position after the objective, indicated as the scanning range. We simulate the scanning range in Zemax (Zemax LLC.) for different lens powers, which can be seen in Table 1. (Chen et al., 2017)

Table 1. The scanning range is simulated in Zemax at different operating lens powers.

TAG lens power (1/m)	Scanning range (mm)
0.45	2.92
0.61	3.93
0.76	4.97
0.91	6.04
1.02	7.19
1.21	8.37

We machine a 200 µm × 200 µm square hole on silicon with and without the TAG lens, shown in figure 1. We measure the exit hole area of the square holes and normalize them with the designed area, noting that a value of one indicates ideal performance. The quantitative results are shown in figure 2. In figure 2, we can see that the machining process is about 80% complete with lens power 0.91, 1.06 and 1.21 (1/m) by two passes. The machining process is complete with lens power 0.45 to 1.21 (1/m) with 3 passes, whereas the machining process is only half complete without TAG lens. That is to say, the machining efficiency is doubled with the assistance of an ultrafast z-scanner. These results are particularly exciting for industrial applications where high-efficiency micro-machining is needed for mass production. The setup is comparatively simple and flexible compared to most real-time control systems. Therefore, the system demonstrated in this paper provides a practical solution to high-efficiency micro-machining.

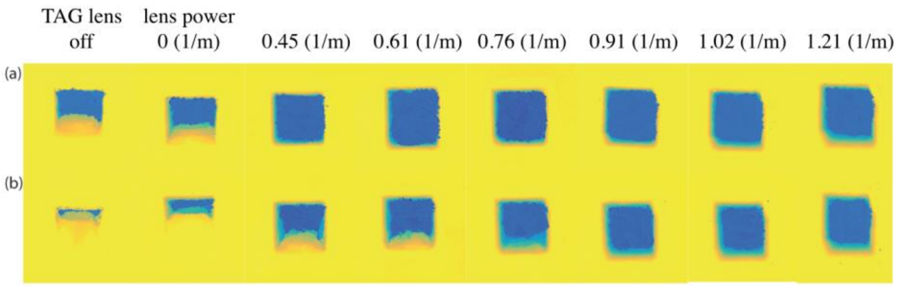

Fig. 1. The image of the square holes machined by (a) 3 passes and (b) 2 passes with different TAG lens powers.

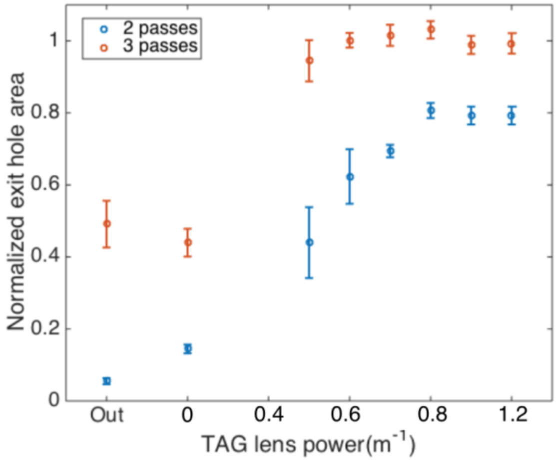

Fig. 2. The normalized exit hole area of the machined hole with different TAG lens powers.

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