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Real-time depth measurement for micro-holes drilled by lasers

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Abstract

An optical system based on the confocal principle has been developed for real-time precision measurements of the depth of micro-holes during the laser drilling process. The capability of the measuring system is theoretically predicted by the Gaussian lens formula and experimentally validated to achieve a sensitivity of 0.5 μm. A nanosecond laser system was used to drill holes, and the hole depths were measured by the proposed measuring system and by the cut-and-polish method. The differences between these two measurements are found to be 5.0% for hole depths on the order of tens of microns and 11.2% for hundreds of microns. The discrepancies are caused mainly by the roughness of the bottom surface of the hole and by the existence of debris in the hole. This system can be easily implemented in a laser workstation for the fabrication of 3D microstructures.

Keywords: laser hole drilling, hole-depth measurement, confocal technology

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The advantages of precision laser micromachining in the fields of biomedical, electronics and material processing have attracted much interest recently [1–3]. In many laser micromachining processes, it is a common desire to know the amount of the material being removed as a function of time which is required for precision control of the process. For example, in the laser drilling of cooling holes in a turbine airfoil, which is a double-wall structure, if the hole depth can be constantly monitored, the possibility of inner-wall damage can be avoided [4]. However, so far no reliable method has been specifically developed for real-time monitoring of the depth of a micro-hole in laser machining. Instead, other approaches using materials such as wax or ceramic beads to fill up the double-wall gap in the laser drilling of turbine airfoils have been reported to prevent over-processing, which is very costly [4].

There are several optical measuring techniques which provide the capability of high resolution depth measurements, such as optical interferometers [5–7], astigmatic focus control [8, 9], time of flight [10], etc. The optical interferometer can achieve a nano-scale resolution and is suitable for the situation when the depth changes continuously. The astigmatic focus control method has been employed in the CD/DVD pick-up head to achieve the auto-focusing functionality with sub-micron resolution. The working distance is limited by the optical design and is usually in the range of tens of microns. The time-of-flight method is a direct measuring technique

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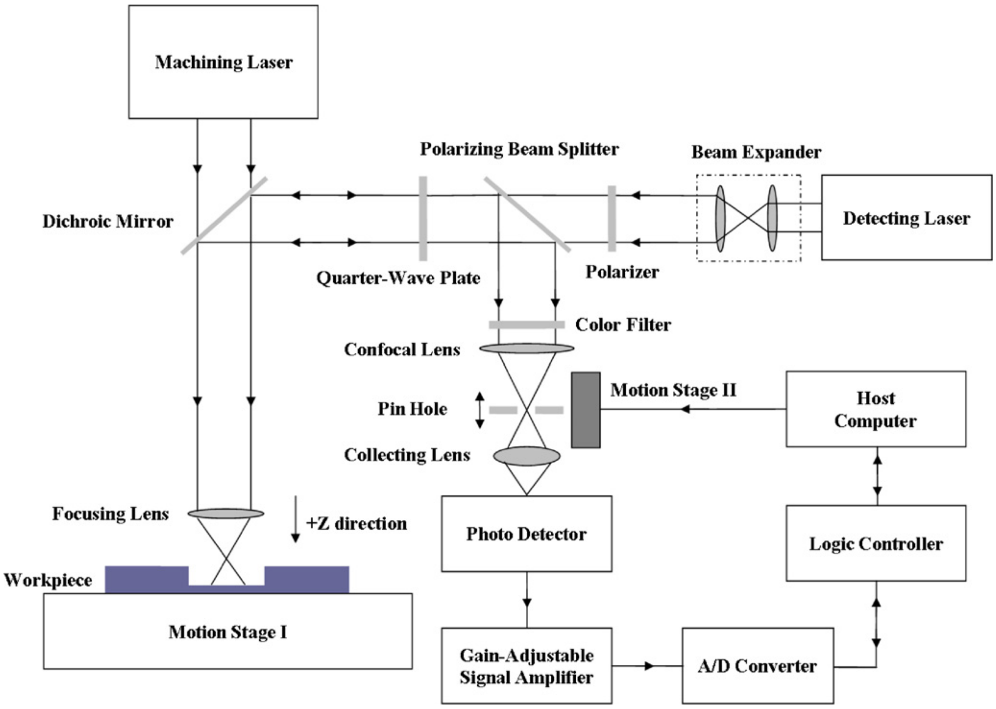

Figure 1. Schematic diagram of the micro-hole depth measuring system.

which resolves the time delay between the reflected lights from the reference light and from the target. Limited by the bandwidth of the electronics, the resolution of the time of flight is in the range of tens of microns. In general, in laser micromachining the depth of micro-hole ranges from tens of microns to several hundreds of microns and the depth of material being removed by one laser pulse can be a few microns. Optical interferometers and the astigmatic focus method are not suitable for the case when a few microns of material are removed per laser pulse due to the intrinsic drawbacks of loss-tracking when a big jump occurs in depth between two laser pulses. Also, the possible vibration of the sample to be drilled and the signal distortion due to the rough surface at the bottom of the hole challenge the optical interferometer method. The concept of the time-of-flight technique is suitable for drilling due to its simple structure but the resolution of tens of microns is not enough for precision micro-hole drilling. Besides the aforementioned pure optical approaches, the photoacoustic effect generated by laser pulses has been widely employed in biomedical imaging applications due to its 3D imaging capability, deep penetration depth and high spatial resolution [11, 12]. This technique has also been employed in the field of laser material processing to monitor the drilling depth. The shock-wave propagation caused by the laser pulse–material interaction can be directly measured utilizing piezoelectric pressure sensors [13] or interferometers [14]. The measurement of shock-wave propagation, either in the air above the workpiece or at the back of the workpiece (which may not always be possible), has been achieved. As the characteristics of acoustic wave are material property dependent, it is less suitable for industrial applications where different or non-homogeneous materials are common. All of these techniques are of value in their distinct applications, but they are not suitable for the depth measurement of laser-drilled micro-holes.

In this work, based on the confocal principle, an optical measuring system is developed which is integrated with the laser machining workstation for real time monitoring the depth of the micro-hole drilled by lasers.

2. Optical design

The confocal principle is commonly used in fluorescence imaging for biomedical applications to improve the spatial resolution [15]. Based on this principle, an optical measuring system was developed and integrated into the laser machining workstation, which consists of a diode-pumped solid-state Q-switch nanosecond laser (Avia 355X, Coherent), a computer-controlled four-axis motion stage (Aeroteck) with a resolution of 1 μm and a side-view imaging system to monitor the machining process. The central wavelength, pulse duration, maximum average power and maximum repetition rate of the nanosecond laser are, respectively, 355 nm, 30 ns, 10 W and 300 kHz.

The schematic diagram of the measuring system is shown in figure 1. In this implementation, a continuous wave diode laser with an output power of 2 mW and a wavelength of 670 nm is used as a detecting laser. The detecting laser beam is expanded to 3 mm diameter by a 3× beam expander (Thorlabs) and then passes through a linear polarizer to allow only the p-wave (E-field parallel to the drawing) to pass. After this, a quarter-wave plate (QWP), aligned with the optical axis, which is 45° relative to the polarization direction, is used to convert the linearly polarized light into circularly polarized light. This circularly polarized light is coupled into the same optical path of the machining laser by employing a

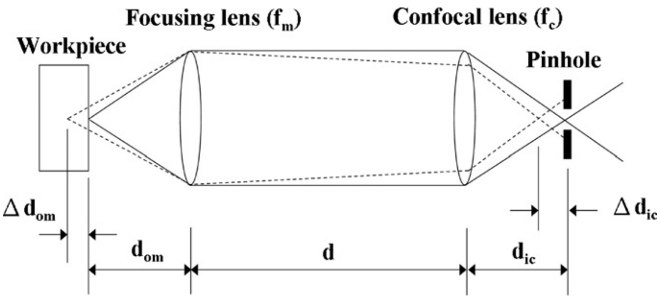

Figure 2. Simplified scheme of the system.

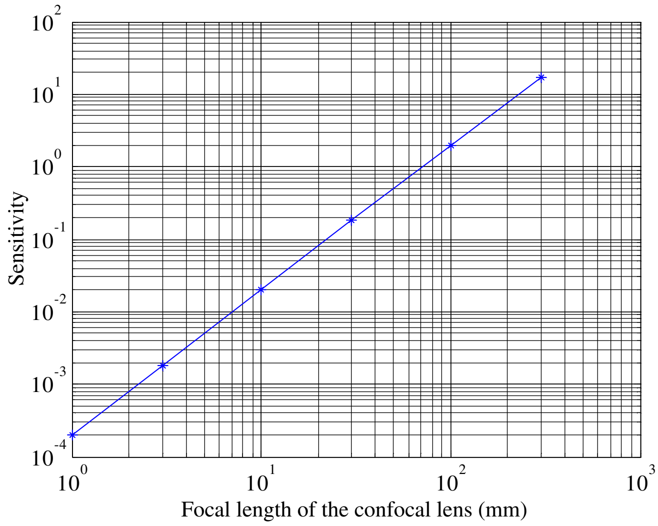

Figure 3. Simulation results of the system resolution for different focal lengths of the confocal lens.

dichroic mirror, which depends on the wavelengths of both the machining and the detecting lasers. As the wavelengths of the machining laser and the detecting laser are 355 nm and 670 nm, respectively, a short-pass dichroic mirror (Chroma) with a cut-off wavelength of 460 nm is utilized to combine the two beams. After combination, both the machining laser and the detecting laser pass through a focusing lens and are focused onto the workpiece. During the hole drilling process, the signal lights from both the machining laser and the detecting laser, reflected from the bottom surface of the hole, are gathered by the same focusing lens. These quasi-collimated lights then pass back through the dichroic mirror which again separates the machining laser light and the detecting laser light. The reflected detecting laser light, after passing through the QWP, will have an additional 90° relative phase shift and be converted into linearly polarized light whose polarization is orthogonal to the original polarization (i.e. s-wave). This signal light is reflected by the polarizing beam splitter, passes through a narrow-bandwidth color filter in order to filter out possible background light from the machining laser and then is focused by the confocal lens. The pinhole is moved by a computer-controlled linear stage (Newport), searching online for the position at which the maximum light intensity passes through the pinhole. The light passing through the pinhole is collected by a collecting lens which is then focused onto a photomultiplier tube (PMT) (Hamamatsu). The current-signal output from the PMT is converted to voltage-signal and is amplified to fit the dynamic range of the data acquisition system. Controlled by the self-implemented software, the amplified signal is then recorded at different pinhole positions by a lab-integrated data acquisition system. Finally, the data sets of laser intensity versus pinhole position are analyzed.

In the optical design, the selection of the confocal lens is significant because it directly affects the sensitivity of the measuring system and the subsequent pinhole selection. The schematic diagram of a confocal system is simplified as shown in figure 2. The Gaussian lens formula is expressed as

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f_L}, \quad (1)$$

where d_o is the distance between the object and the lens, d_i is the distance between the image and the lens and f_L is the focal length of the lens. In this system, the image of the object formed by the focusing lens becomes the object of the confocal lens. Therefore, the distance between the image and the confocal lens, d_{ic}, is derived as

$$d_{ic} = \left[f_c d - \frac{f_c f_m d_{om}}{(d_{om} - f_m)} \right] \Bigg/ \left[d - f_c - \frac{d_{om} f_m}{(d_{om} - f_m)} \right]. \quad (2)$$

The parameters in equation (2) are given in figure 2. The preliminary simulation was performed based on equation (2) to predict the sensitivity of the system in different focal lengths (f) of the confocal lens. The f of the focusing lens used in the laser workstation is 76.2 mm (3 inch). The distance between the focusing lens and the confocal lens, d, was measured to be around 970 mm, which is limited by the layout of the hardware and could not be arbitrarily adjusted. The sensitivity of the system, S, is defined as

$$S = \frac{\Delta d_{ic}}{\Delta d_{om}} \quad (3)$$

where Δd_{om} is the change of the hole depth during the drilling process and Δd_{ic} is the corresponding shift of the pinhole location at which the maximum laser intensity occurs. The sensitivity, S, is a function of f_c when other parameters such as f_m and d are given. Figure 3 shows the sensitivity estimation based on equation (2) and the foregoing parameters. In the simulation, the lenses were assumed to be aberration-free and very thin, and the range of the hole depth was 1 mm. From the simulation results, the theoretical sensitivity is improved from 2×10^{-4} to 17.2657 when the f of the confocal lens increases from 1 mm to 300 mm. In this design, a confocal lens with 100 mm f is employed and the corresponding sensitivity is 1.995 which is sufficient for micro-hole drilling applications. As the resolution of the motion stage, which is used to scan the pinhole, is 1 μm, the resolution of the measuring system could achieve about 0.5 μm (i.e. 1 μm ÷ 1.995). For the 100 mm focal length and 670 nm wavelength of the detecting laser, the theoretical focal spot (diameter of the Airy disk) is 6.488 μm, assuming the signal is collimated and covering the entire confocal lens. Considering the aberration effect and the numerical aperture (NA) of the signal that might be smaller

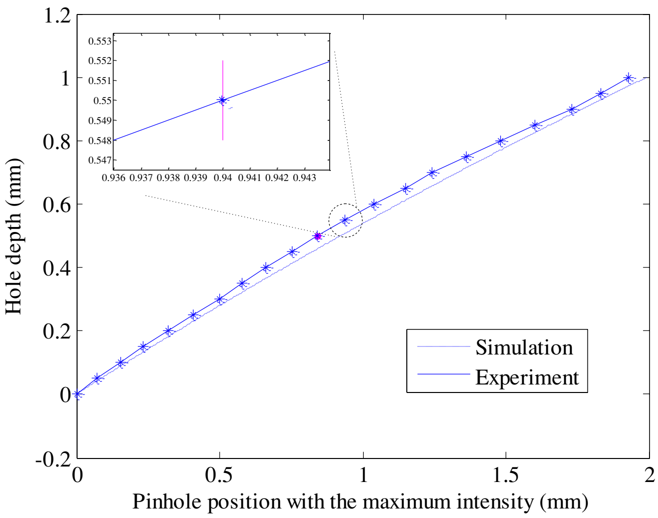

Figure 4. Experimental results and theoretical predictions of the sensitivity for the system with a confocal lens of 100 mm focal length.

(which would increase the focal spot size), a 10 μm diameter pinhole was selected in this work. The full width at half maximum (FWHM) of the profile in the plot of laser intensity versus pinhole position was calculated to be 0.7624 mm for the 10 μm pinhole.

3. Experiment and discussion

A polished silicon wafer was used as a high reflectivity workpiece to investigate the optical tracking ability of the measuring system. The wafer was fixed on the top of the motion stage I and positioned right at the focal plane of the focusing lens which was verified by the side-view imaging system. The motion stage I was set to move downward from $z = 0$ (focal plane) to $z = 1$ mm with 50 μm increments, which simulates the change of hole depth during the drilling process. At each z-location, the corresponding pinhole location at which the maximum laser intensity occurs was determined by moving the motion stage II. Figure 4 shows the experimental results (solid line) are close to the theoretical predictions (dashed line). The differences are mainly caused by the aberration of the lenses and the measuring error of the distance between the focusing lens and the confocal lens. The average sensitivity was calculated to be 1.981, which is close to the theoretical value of 1.995. Note each data point in the figure is the average of five measurements, and the average standard deviation of each data point is about 4.04 μm (see the insert of figure 4).

The drilling experiments using the aforementioned laser machining system were conducted to demonstrate the capability of the measuring system. A small piece of stainless steel with 1 mm thickness was prepared and affixed to the motion stage I. Initially, before drilling, the pinhole was swept through its travel to get the reference laser intensity as a function of the pinhole position, as shown in figure 5(*a*). Then, the workpiece was percussion drilled for 100 and 1000 pulses by focusing the machining laser with pulse energy of 220 μJ and repetition rate of 50 Hz onto the workpiece. The pinhole was then scanned over a range at a scanning speed of 25 mm s^{-1}, and a data set (laser intensity versus pinhole position) was collected at different pinhole positions. Note the proposed measuring system can perform real-time measurements of laser intensity versus pinhole position at any specified number of laser pulses, including at every laser pulse. However, in this study, in order to compare the measuring depth with the depth obtained by the cut-and-polish method, only 100 and 1000 pulses were selected for measuring the laser intensity versus pinhole position. The experiment was repeated ten times for each case, and the averaged results were obtained, which are also shown in figure 5(*a*) for 100 and 1000 pulses. Note in order to clearly show the profile in figure 5(*a*) for the hole drilled by 1000 pulses, the curve is magnified by a factor of 2. It is seen that the FWHM of the reference profile is about 0.7 mm which agrees well with the previous simulation result, 0.7624 mm. As expected, the maximum reflected laser intensity decreases as the hole depth increases. As shown in figure 5(*a*) for the case of 100 pulses, the maximum laser intensity drops to around 50% as compared to the reference profile, but the peak intensity can still be clearly identified. For the hole drilled by 1000 pulses, the reflected laser intensity significantly decreases

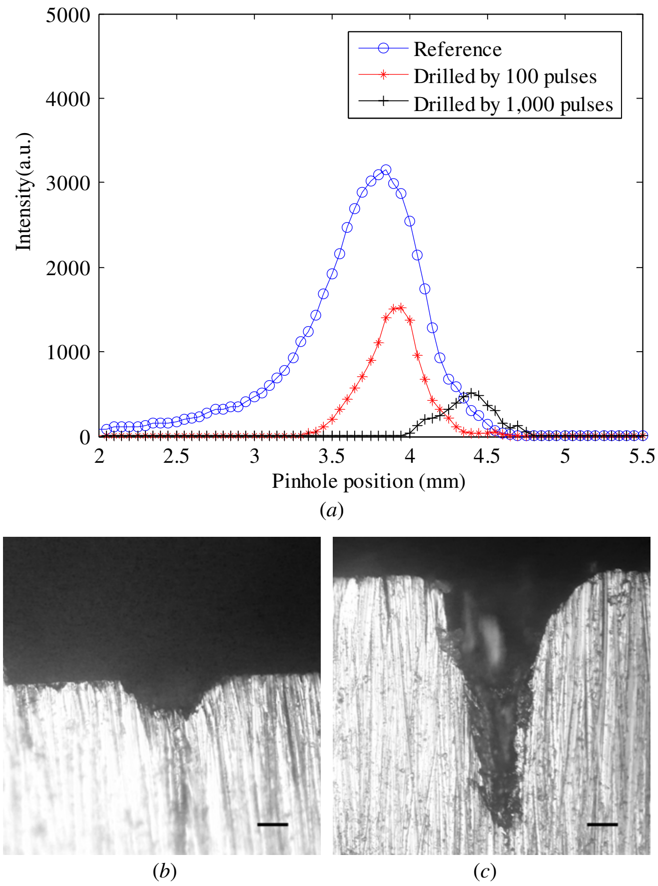

Figure 5. Experimental results, (*a*) position-intensity spectra of the reference, after 100 pulses of drilling, and after 1000 pulses of drilling (2×), (*b*) cross-sectional image of the hole drilled by 100 pulses, (*c*) cross-sectional image of the hole drilled by 1000 pulses. The scale bar is 50 μm.

Table 1. Summary of the experimental results.

	Real-time measurement (μm)		Cut-and-polish measurement (μm)		
Drilled pulses	Hole depth	Standard deviation	Hole depth	Standard deviation	Measurement difference (%)
100	61.3	0.8	58.4	0.8	5.0
1000	347.1	2.8	390.8	3.1	11.2

and its profile is also distorted because of the scattering light from the rough bottom surface of the drilled hole. The data sets were analyzed, and the maximum intensity position shifts were found to be 92.1 μm and 575.2 μm, respectively, for the 100 and 1000 pulses drilled holes, which corresponded to a hole depth of 61.3 μm and 347.1 μm, respectively. The standard deviation for the 100 and 1000 pulses was, respectively, 0.8 μm and 2.8 μm.

After the samples were drilled and the depths were measured, they were cut and polished to obtain the cross-sectional images of the drilled holes using a calibrated optical metallurgical microscope. Figures 5(*b*) and (*c*), respectively, represent the typical cross-sectional images of the holes drilled by 100 and 1000 pulses. The experiment was repeated ten times and the average depths of the hole for 100 pulses and 1000 pulses were found to be 58.4 μm and 390.8 μm, respectively, with the standard deviation of 0.8 μm and 3.1 μm. When compared with 61.3 μm and 347.1 μm measured by the detection system, the differences were 5.0% and 11.2%, respectively, for 100 and 1000 pulses. These experimental results are summarized in table 1. For the case of shallow holes whose depths were in the range of tens of microns, the discrepancy is mainly caused by the roughness of the bottom surface of the drilled hole. However, for a deeper hole, hundreds of microns, a greater discrepancy occurs. In the cutting and polishing process, some debris was observed in the hole which may cause measuring error because the signals may possibly be reflected from the debris rather than from the bottom surface of the drilled hole. In our setup, the pressure of the blowing air was 20 psi. Blowing air with high pressure to remove the debris during the laser hole drilling may be helpful to remove the debris which will improve the measuring accuracy. Furthermore, a laser with a flat-top beam profile may improve the surface flatness at the bottom of the hole. Unlike the conventional machining methods (e.g., milling) in which the depth-of-cut can be pre-determined and controlled, in laser machining the material removal depth strongly depends on the conditions of the laser and the material to be processed. Generally, for a 3D object, if its solid model can be generated by CAD software, the 3D microstructure can be accurately fabricated by, for example, a CNC machine. However, this is not true for laser machining because the material removal depth per laser pulse is unknown in advance. Hence, a real-time depth measuring capability is required in the laser machining system to monitor the material removal depth by each laser pulse. This proposed measuring system, if coupled with a feedback control technique, can achieve the desired 3D microstructure by laser machining.

The possible limitations of the proposed measuring system include (1) the repetition rate and the material removal depth per pulse of the machining laser and (2) the moving speed and accuracy of the motion stage II. The relation of the scanning speed of motion stage II and the conditions of the machining laser system is illustrated by the following equation:

$$V/S \geqslant R \times M \quad (4)$$

where V is the maximum scanning speed of motion stage II, S is the sensitivity defined in equation (3), R is the repetition rate of the machining laser and M is the material removal depth per pulse of the machining laser. In the setup of this study, the sensitivity is close to 2 and the maximum scanning speed of motion stage II is 25 mm s^{-1}. Hence, theoretically this setup can handle the material removal depth up to 0.25 mm/pulse at a 50 Hz repetition rate. If the scanning speed is limited, the decrease of S is another way to increase the repetition rate at the same material removal depth, but the sensitivity of the measuring system will decrease (i.e. smaller S). For machining lasers with repetition rates of hundreds of kHz, the speed of motion stage II must be fast enough to move the pinhole and measure the laser intensity in a time frame between two pulses. Also, the motion stage II must be accurate enough if the laser removal depth per pulse is just a few microns. For hole drilling lasers that are being used in the aerospace industry (<10 Hz and a few hundreds of microns being removed by a pulse) for drilling gas turbine blades, the proposed measuring system has been proved to be successful.

4. Conclusions

Based on the confocal principle, an optical measuring system has been developed which is capable of real-time precision measurements of the depth of micro-holes during laser drilling. Both theoretical and experimental studies have been conducted, and it was found that the measuring system can achieve a sensitivity of 0.5 μm. A discrepancy between the measuring system and the cut-and-polish experiments is found to be 5.0% for hole depths on the order of tens of microns and 11.2% for hundreds of microns. This precision is adequate for real-time depth measurements during the laser micro-hole drilling process and robust enough for industrial applications. The developed method is general and applicable to most laser machining systems with the proper selection of optics that is dependent on the wavelength of the laser. The measuring system can also be implemented in a laser workstation for machining 3D microstructures.

Acknowledgments

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