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On-line depth measurement of micro-scale laser drilled holes

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ON-LINE DEPTH MEASUREMENT

OF MICRO-SCALE LASER

DRILLED HOLES

by

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ABSTRACT

A micron-precision micro-hole depth detection scheme has been developed which utilizes a confocal structure and a photomultiplier tube as a photodetector. This scheme is experimentally confirmed to posses an accuracy of greater than 95% for micro-holes on the order of one-hundred microns in diameter and tens of microns in depth and could be easily be integrated for the control of industrial and research oriented laser micro-machining process.

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1. INTRODUCTION

The advantages of precision laser micro-machining in the industrial, biomedical, electronics, and material processing fields are well known and specific applications requiring the precise control of the process depth have become common. Up to this point no industrially repeatable method has been developed for the real-time monitoring of laser ablation depth in these applications and a variety of methods have been employed to prevent over-processing which typically rely on trial and error methods for efficacy.

In this paper, the development is investigated of a method for the real-time monitoring of laser ablation depth as applied to the prevention of back-wall damage in thru-hole drilling applications in multilayer bulk metallurgical samples where there is a gap and some laser sensitive material behind the hole. Currently, the industry standard approach is the injection of a temporary filler material in the cavity between layers previous to the commencement of the laser machining process. This layer of material acts as a buffer zone to protect the back-wall of the coincident layer. When the process is completed the buffer material is typically removed via a heating and cleaning process. This approach is adequate but leaves much to be desired in terms of process time and resource efficiency.

Many optical distance measuring techniques have been proposed and implemented, some with the nanometer precisions and multi-millimeter depth ranges required in laser micro-hole drilling. Techniques have been proposed which measure the photo-acoustic propagation time of the shock caused by ablation. These can directly measure hole depth utilizing piezoelectric pressure sensors [1,2] or interferometry [3] to measure the time of flight of the shock resulting from laser ablation, either through the air above the workpiece or through the back of the workpiece its self. Direct distance measurement techniques utilizing astigmatic focus control [4,5] or purely interferometric techniques [6-8] have been used to measure the distances required with great accuracy and could be suitable for the task of ablation depth measurement. All of these techniques are of value in their distinct applications but they fall short of the flexibility required when applied to the detection of laser generated micron-scale hole depths in difficult geometries. Photo-acoustic techniques have been applied to the specific ablation depth problem in situations where the time of flight of the acoustic shock wave originating from the pulse can be detected when exiting the material on the back side using piezoelectric [1,2] or interferometric techniques [3], The difficulty here is that one has to either be able to be able to place a sensor or remotely sense the back side of the workpiece. A technique utilizing open piezoelectric acoustic sensors placed above the workpiece has been developed but the characteristics of the acoustic pulse are dependent on the material properties [1] making it less than suitable for industrial situations where differing or non-homogeneous materials are common. Direct interferometric techniques have been used to measure micron and sub-micron level distances in several applications [6-8], but those techniques rely on a high intensity of directly-reflected light to discern the interference fringes. This limitation has been overcome in Optical Coherent Tomography (OCT) [9], but at this juncture the method loses the vision of simplicity and ease of use needed for implementation in an industrial setting. Vibration and misalignment issues also make this method undesirable in industrial settings as well. Optical focus sensing techniques based on focus induced astigmatism have been used measure distances. These techniques have achieved very high resolutions and with modification yield long measurement lengths but are limited to short working distances, making them unsuitable as well. Likewise, for long working distances time-of-flight (TOF) cameras have been used, but at shorter working distances the accuracy of these methods suffers [10]. A confocal structure has been utilized as a distance discriminating probe [11] and using this approach an real-time laser drilled micro-hole depth detection scheme has been developed.

2. OPTICAL ALGORITHM AND DESIGN

The principle of the confocal structure was patented by Marvin Minsky in 1957 [12] with application to fluorescence microscopy. Confocal microscopy utilizes point-illumination and a pinhole in an optically conjugate plane in front of the detector to filter out defocused image information. Only light emanating from within the focal plane is detected allowing the image quality to be far superior to that of wide-field fluorescence images, and the thickness of the focal plane is inversely proportional to the square of the numerical aperture of the objective lens used and is also dependent on the optical properties of the specimen and the ambient index of refraction [13]. The concept presented here applies this confocal structure to the laser ablation depth detection problem. A confocal microscope only receives the signal reflected back from the focal plane of the objective in a specimen and this property of confocal systems is implemented here. It is proven that by scanning the pinhole, a position of maximum signal intensity can be found which corresponds to the depth of the bottom surface of the hole being drilled in the laser machining process.

An implementation of the confocal structure is proposed which uses a secondary laser to illuminate the workpiece. The layout is described as follows and is shown in Figure 1. In this implementation, an illuminating laser emits a beam which is passed through a beam expander and then through a linear polarizer, allowing only the vertically aligned light to pass through. After this, a quarter-wave plate is used to convert the linearly polarized light into circularly polarized light. This circularly polarized light is coupled into the machining laser optical path employing a dichroic mirror, which is chosen depending on the wavelengths of both the machining and the illumination lasers. In this specific implementation, the machining laser was a 355nm frequency-tripled YAG laser (Coherent Avia 355x) and the illumination laser was a 670nm diode laser. A short-pass dichroic mirror with a cut-off wavelength of 460nm was utilized to combine the beams. After combination, the machining laser and the illuminating laser pass through a focusing lens and are focused onto the workpiece. The light from the illumination laser is reflected off of the bottom surface of the ablated area of the workpiece and gathered by the same focusing lens. The quasi-collimated gathered light is then passed back through the dichroic mirror and, taking advantage of the additional 90 degree relative phase shifts induced by the light passing back through the quarter-wave plate, converted into linearly polarized light which is orthogonal to the original polarization. This light is reflected by the polarizing beam splitter to the confocal lens, passing through a narrow-bandwidth filter in order to filter out any background light from the machining laser, and is then focused by the confocal lens, shown in Figure 1.1. The pinhole is moved by a computer controlled linear stage, searching online for the position with the maximum intensity while simultaneously collecting light utilizing a collecting lens, shown in Figure 1.1, which is focused onto a photodetector. The photodetector converts the light signal into an electrical current, and this was amplified via an adjustable gain signal amplifier manufactured in-house which amplifies the signal in order to take advantage of the entire range capability of the employed data acquisition board. The amplified signal was acquired by a custom-designed data acquisition board with a USB 2.0 interface. A host computer and logic controller control the timing of sampling and the movement of the stage through use of software which was developed specifically for the task.

A hurdle was anticipated which had to be overcome, this being the chromatic aberration of the focusing lens due to the wavelength difference between the illuminating and machining laser sources. In the specific implementation tested by the group, the wavelength of the illuminating laser was 670nm and the wavelength of the machining laser was 355nm, inducing a projected difference in focus between the two lasers. The effect of this was somewhat mitigated by the confocal structure in that the light, though arriving defocused, was still reflected from points on the surface of the workpiece and the net effect is an offset in the confocal distance which can be calibrated out of the production system. However, chromatic aberration is still problematic in the fact that the illumination of the bottom surface of the workpiece is decreased as the incoming light is defocused, decreasing the signal to background noise ratio of the system. If the focal distance difference of the focusing lens is known, the focal length difference could be tuned out of the system by tuning the beam expander positioned near the illuminating laser, effectively canceling the effects of chromatic aberration.

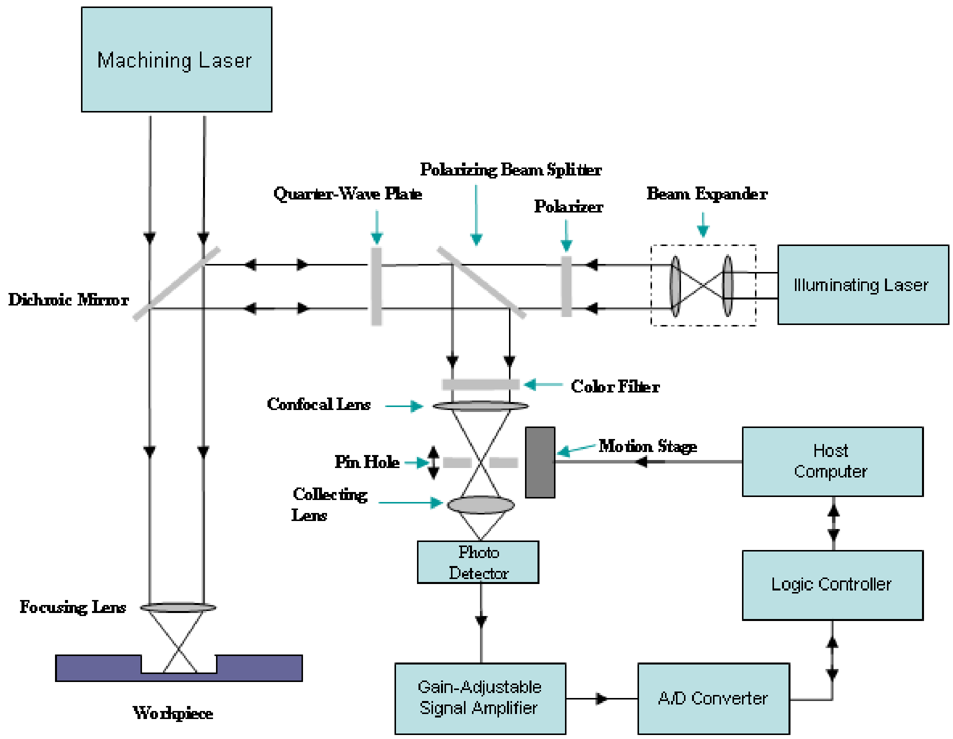


Figure 2.1. Schematic diagram of optical algorithm utilizing an illuminating laser

3. NUMERICAL SIMULATION

From the common form of Gaussian lens equation (1) p, q, and f represent the objective distance, the image distance, and the focal length of a thin lens.

$$\frac{1}{p}+\frac{1}{q}=\frac{1}{f} \tag{1}$$

The focal spot shift corresponding to the depth change of the machined surface of the micro-hole can be calculated by applying (1) for the focusing lens of the machining laser and the confocal lens in the optical setup. For the focusing lens in the machining laser and the confocal lens in the module, the lens equations can be represented in (2) and (3) respectively.

$$\frac{1}{p_1}+\frac{1}{q_1}=\frac{1}{f_1} \tag{2}$$

$$\frac{1}{p_2}+\frac{1}{q_2}=\frac{1}{f_2} \tag{3}$$

Lens 1 is the focusing lens in the laser machining workstation and the lens 2 is the confocal lens in the system. Considering the focusing lens in the workstation, the imaging distance shown in (2) can be expressed as shown in (4).

$$q_1=\frac{f_1 p_1}{p_1 - f_1} \tag{4}$$

The imaging distance q_1 is the position of the image of the object located at S_{o1} as is imaged by lens 1. The image from lens 1 becomes the object of the confocal lens 2. Therefore, (3) can be expressed as shown in (5) by use of the relationship $p_2 = d - q_1$.

$$\frac{1}{d - q_1} + \frac{1}{q_2} = \frac{1}{f_2} \qquad (5)$$

Combining (4) and (5), the confocal focus spot position q_2 can be shown as expressed in (6). Based on this solution, a program was constructed in Matlab to perform an optimization of the parameters shown.

$$q_2 = \left\{ f_2 d - \frac{f_2 f_1 p_1}{[p_1 - f_1]} \right\} / \left\{ d - f_2 - \frac{p_1 f_1}{[p_1 - f_1]} \right\} \qquad (6)$$

Based on (6), the numerical simulation offered the resolution information for optimization of the system's performance. For the setup tested as shown in the effective schematic diagram in Figure 3.1, the focal length of the machining laser focusing lens was constrained at 76.2mm and the focal length of the confocal lens was chosen to be 99.1mm, specified for 532nm light. The distance between the machining laser focusing lens and the confocal lens was measured to be approximately 970mm and a numerical simulation varying the focusing laser object distance was performed in order to establish the theoretical resolution of the system.

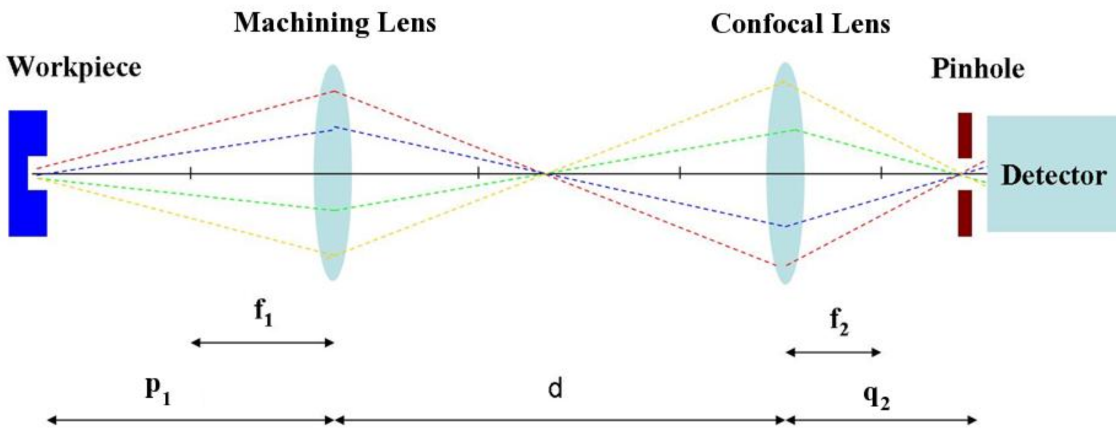


Figure 3.1. Illustration of simplified confocal depth detection system critical parameters

The results of the simulation are presented in Figure 3.2. As the object distance of the focusing lens shifted throughout 1mm of travel, the intensity peak in the confocal setup was shown to shift 2mm, yielding a lateral sensitivity ratio of 2:1 over 1mm of travel. The linear resolution of the motion stage which was used to position the pinhole is 1 micron which indicates a theoretical resolution of a half of a micron for the specific system presented here. Some degradation in the resolution of the system was expected due to electrical noise and imperfect optical alignment.

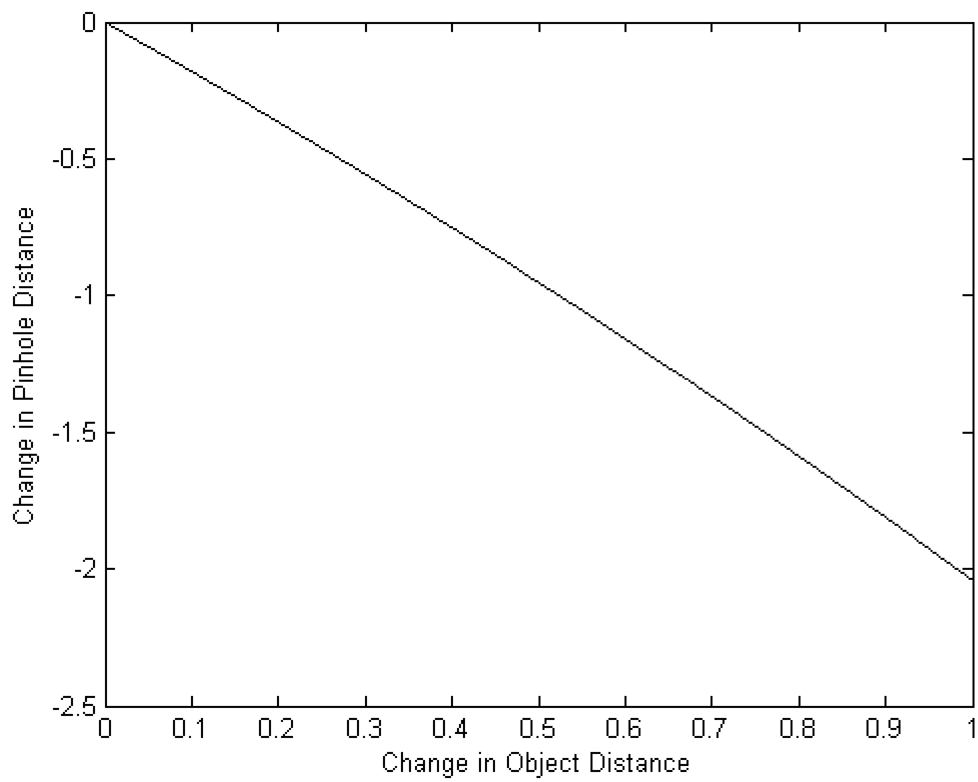
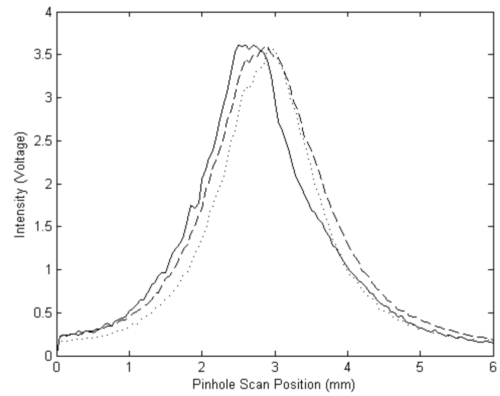


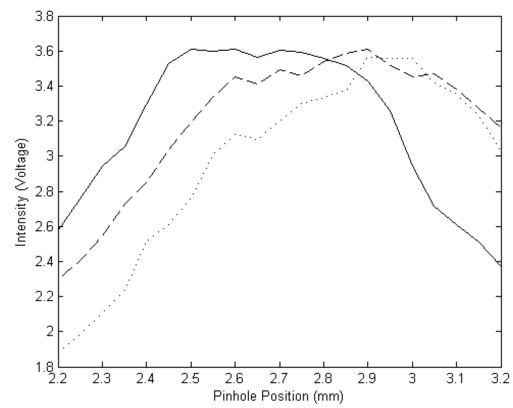
Figure 3.2. Simulation result at parameters f_1: 76.2mm, f_2: 100mm, d: 970mm showing a lateral sensitivity gain of 2:1 over 1mm of travel

4. EXPERIMENTAL METHOD AND RESULTS

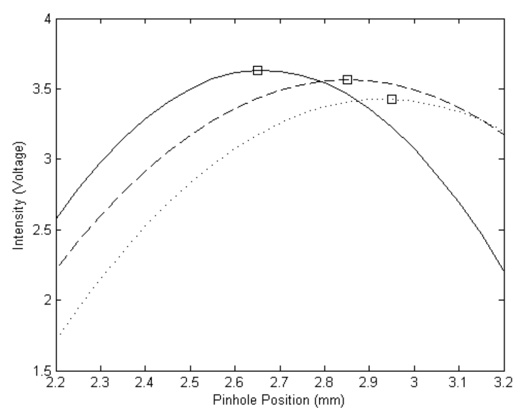
The optical system was configured to utilize an illumination laser as outlined and parameters were chosen as discussed in the numerical simulation section. A 10μm pinhole was utilized for the confocal element and a confocal lens with a focal length of 100mm and a suitable collecting lens were chosen to focus the light which passed through the pinhole onto a light sensitive cell used as a photodetector. The packaged optical system, data acquisition circuit, and controlling software were thoroughly tested to quantify the performance of the proposed system. A polished piece of steel was first affixed on a four axis precision motion stage in the laser workstation as a sample workpiece and the vertical stage was scanned through a portion of its range to simulate the moving machined bottom surface of a drilled hole. The acquired data is presented in Figure 4.1. The solid, dashed, and dotted lines in Figure 4.1 are the scan data at the vertical positions 5.859mm, 5.705mm and 5.488mm reported on the vertical stage. These experimental results confirm that as indicated by the theoretical and numerical studies, the confocal mechanism for micron-precision hole depth detection effectively tracked the change in relative distance of the workpiece. It was noted that even far from the focal plane of the machining laser focusing lens, the sensitivity of the confocal mechanism, though changing a miniscule amount with depth, could essentially be considered a constant for typical micro-machining depth differentials. The raw data was plotted and reviewed as shown in Figure 4.1a and Figure 4.1b, and a 2^{nd} order least squares regression curve fitting algorithm was applied as shown in Figure 4.1c in order to filter out higher spatial-frequency noise caused by the uneven surface of the workpiece.



(a)



(b)



(c)

Figure 4.1. Data produced by scanning a simulated hole bottom. Separate series are delineated by dotted and dashed lines. (a) Full sweep raw data. (b) Partial sweep raw data. (c) Partial sweep regression-fitted data. Squares represent pinhole positions of maximum intensity

The micro-hole depth detection scheme was the tested by machining a hole in an alloy workpiece as data was taken. As this was being done, it was discovered that the reflected light from the bottom surface of the hole was too weak to be detected while preserving a suitable signal to noise ratio by the photodiode being used as the photodetector. Because of this, the detector was changed from a photodiode to a photomultiplier tube (PMT). The PMT can provide a higher sensitivity and is gain adjustable via varying the control voltage and with its use a signal could be readily obtained for the alloy workpiece.

After the detector was changed, a silicon wafer was used as a mirror to investigate the optical tracking ability of the system. The silicon wafer was positioned and measured at different points along the z axis to collect data confirming the numerical simulation of the measuring system. The sample was measured at a different vertical position at 50 micron differentials from z=0 to z=1mm. The results are shown in Figure 4.2. From these results, the ratio of the peak shift to measured depth was approximately 2:1, again confirming the theoretically reported lateral position gain between the workpiece and the position of maximum intensity of the pinhole. Of note is the observation that as the workpiece is moved away from the focus of the focusing lens the signal decreases in intensity and the signal to noise ratio is decreased.

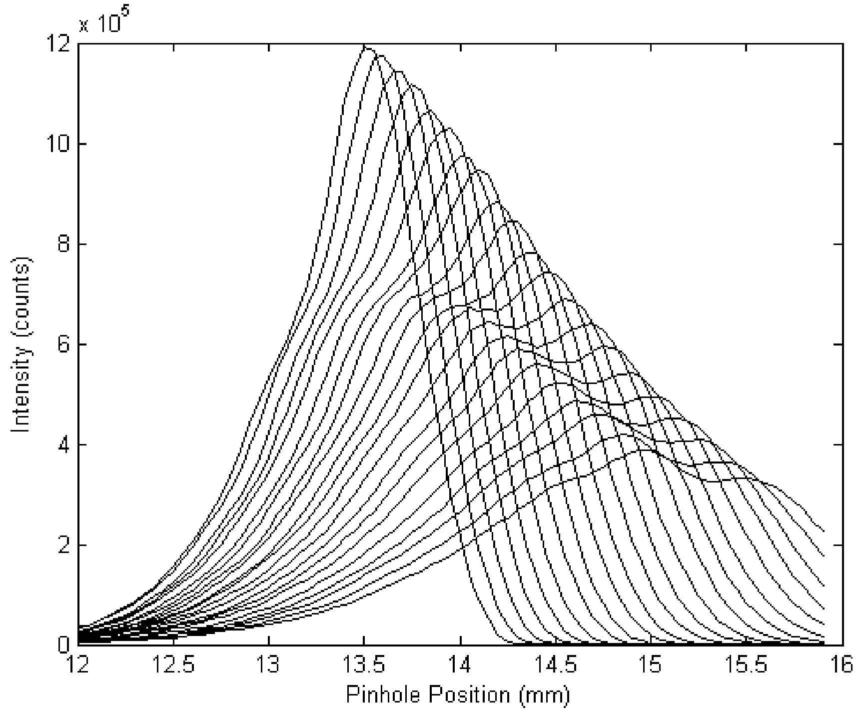
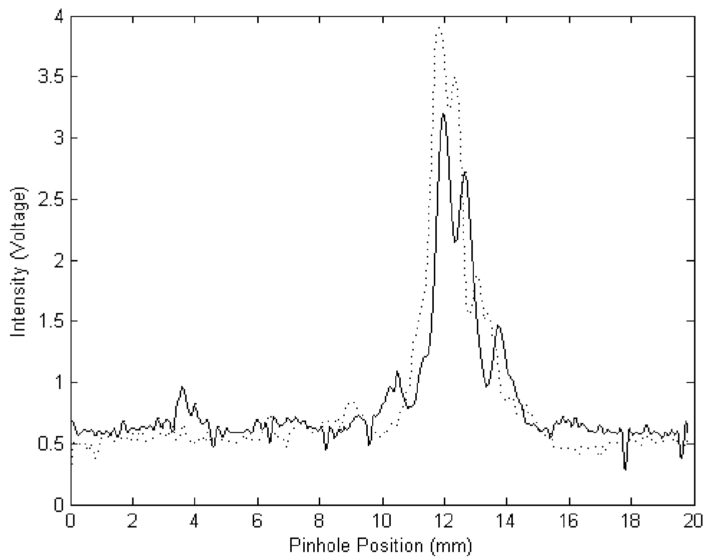
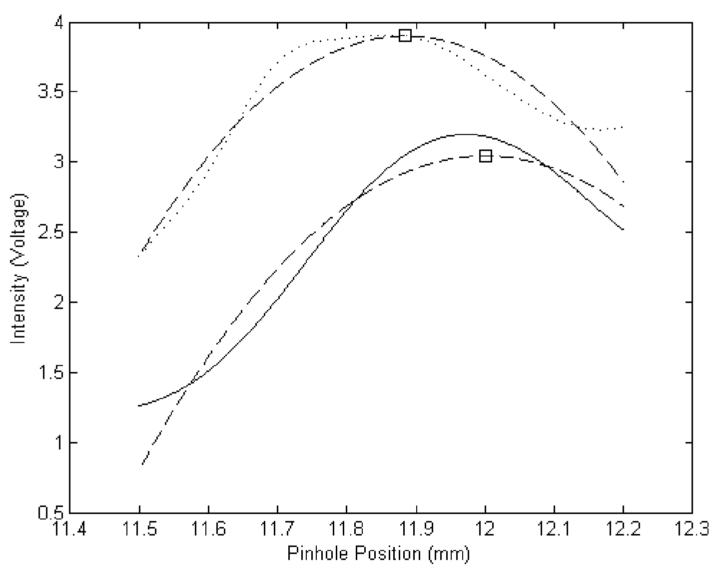


Figure 4.2. Data accrued confirming the theoretical simulation for the laser ablation depth detection system

An example experiment was designed to showcase the capability of the system. After the alignment of the optics was checked, a small piece of alloy was cut and prepared, then affixed to the four axis stage. The pinhole was swept through its travel and the data shown as the solid line in Figure 6a was taken. After this, the alloy workpiece was percussion drilled for 20 seconds by focusing a 355nm YAG frequency tripled ns pulsed laser with pulse energy of 220μJ and a repetition rate 60 kHz onto the workpiece. The pinhole was then scanned over the entirety of its range of travel and data was collected in the same fashion as before. This data is shown in Figure 6a as the solid line. Since higher spatial frequency components exist in the signal, a 2^{nd} order least squares regression was fitted around the peaks in the data shown in Figure 4.3a to mitigate the effects of those components, as shown in Figure 4.3b. The solid line is the data collected before machining and the dotted line is the data collected after percussion drilling the workpiece for 20 seconds, whereas the dashed lines are the least squares regression for the data series. After applying the least squares regression and identifying the maximum of the regression curve, the maximum intensity position shift reported was 110μm, corresponding to a hole depth of 55μm assuming a constant lateral position gain ratio of 2:1 as indicated by the numerical simulation.



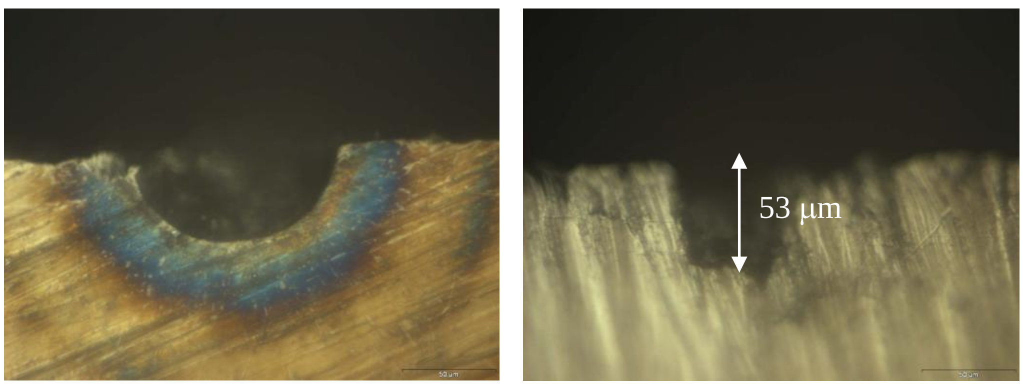
(a)



(b)

Figure 4.3. Data measured for the alloy material. The solid line represents the data before and the dotted line the data after percussion drilling for 20 seconds. Squares represent positions of maximum intensity. (a) Raw data. (b) 2nd order regression-fitted data in the region of the peak signal.

After the sample was drilled and measured using the depth detection probe, it was cut and polished to obtain a cross-section of the hole, and that cross-section was measured using a calibrated optical metallurgical microscope in order to obtain the true depth of the hole. Figure 4.4a and Figure 4.4b are the top view and the cross-sectional image of the prepared hole. From the cross-section image, the hole depth at the center of the hole was shown to be 53μm which when compared to the 55μm reported using the depth detection probe, yields an error of 3.6% in the measurement of the depth of the hole. It is postulated that this minor error emanates primarily from the large-scale variation in depth of the bottom surface of the hole and could be accounted for in future work by demonstrating how the hole surface quality and shape effect the signal returned by the optical algorithm.



(a) (b)

Figure 4.4. Images of the drilled hole confirming depth. (a) Top view; (b) Cross-section view

5. CONCLUSION

The theoretical and experimental considerations of a study pertaining to the development of a purely optical real-time laser ablation depth detection methodology were investigated and such a methodology was developed based on a confocal structure, achieving a precision of less than a micron and showing an error of less than 5% for holes on the order of 100μm in depth and diameter. This precision and accuracy is more than adequate for real time machining depth monitoring and back-wall breakthrough detection during laser micro-hole drilling processes and robust enough for use in industrial and research applications. The developed method is general and applicable to any laser machining system though the specific optical hardware is dependent on the wavelength of the lasers and the process implemented. A reliable control process could easily be implemented for automatic control of machining depth eliminating the need for expensive back-wall protection and for highly skilled and experienced operators in applications sensitive to the required depth of hole.

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