OPTICAL EMISSION MONITORING FOR DEFOCUSING LASER PERCUSSION DRILLING

Chao-Ching Ho [1], Chih-Mu Chiu[2], Yuan-Jen Chang[2], Jin-Chen Hsu[2] and Chia-Lung Kuo[2]

1 Department of Mechanical Engineering, National Yunlin University of Science and Technology, 123 University Road, Section 3, Douliou, Yunlin, Taiwan, R.O.C., 64002, HoChao@yuntech.edu.tw
2 Department of Mechanical Engineering, National Yunlin University of Science and Technology

Abstract:
This paper presents a novel method for controlling the laser-drilling process for a hole by monitoring induced plasma emission. The variation of light brightness from laser-induced plasma is used as an indicator to control laser percussion drilling. Through on-line plasma emission acquisition and analysis, we obtain the positive association between the increased depth and the optical signal output. A coaxial photodiode is used to estimate the brightness levels of laser-induced plasma. The above constitute an inexpensive and practical on-line feedback system that can be easily implemented in the laser systems. All of the processing work is performed in air under standard atmospheric conditions without gas assist. The acquired signal for drilling could also be used as an input to a focus point process control scheme. Moreover, the technology demonstrates the feasibility to develop an automated laser micromachining system. Experimental results show that drilling efficiency was increased 47% by applying the proposed defocusing laser percussion drilling.

Keywords: Laser micromachining, laser-induced plasma, process monitoring, plasma emission, defocusing laser micromachining.

1. INTRODUCTION

Optimizing the focusing conditions for laser percussion drilling could improve productivity and drilling quality. The position of the focal spot relative to the workpiece surface determines whether the laser beam is converging or diverging. Drilling causes change in focal position, which reduces laser power density and affects drilled-hole quality. An incorrect workpiece standoff or focal position that is due to the defocusing of the laser beam by the increasing depth can be a major cause of process deterioration [1]. As laser percussion drilling become more automated, process monitoring need to be applied to focusing conditions, rather than relying on experience-based control rules.

Previous research has addressed the problems in automatic monitoring of material processing using a laser. Kaebernick *et al*. [2] used a photodiode-based adaptive control system for improving the laser cutting surface quality by controlling the striation frequency.

Fox *et a1.* [1] developed a focus control system for closed-loop control of laser cutting and drilling, which uses the chromatic aberrations of the effector optics. However, the accuracy of the measurement will be reduced when laser drilling with short high-energy pulses.

Stournaras *et al*. [3] used optical signals acquired by off-axial photodiodes that were positioned above the processing zone for real-time monitoring of the diameter and depth of the drilled hole. However, the proposed configuration indicated a weak coefficient of confidence of the output optical signal with machining depth.

Chang and Tu [4] proposed a closed-loop control for ablation depth in femtosecond pulse laser micro-machining by monitoring the brightness of the derived light. The ablation process was recorded by a CCD camera and analyzed frame by frame to obtain the brightness level of the plasma. However, this closed-loop method was not applicable for drilling a deep hole in which the plasma may be blocked by the sidewall of the hole.

Ho *et al*. [5] showed that the cumulative size of the laser-induced plasma correlates with the depth of the hole. However, because of the radial arrangement of the camera, some of the detected plasma signal emitted from a deep hole was blocked by the sidewall of the hole. Therefore, this system is a poor candidate to provide real-time control for laser drilling.

Diego *et al*. [6] attempted to detect the working focus position during laser scribing by monitoring the intensity of plasma emission. A linear correlation between plasma emission intensity and ablated mass per pulse was established.

Our previous work [7] showed that the intensity of the light emitted from the plasma plume correlates with the depth of the drilled hole. In the present work, we used a photodiode to detect the emitted light, and the focus position was adjusted accordingly. This increased quality while reducing process time.

2. ANALYSIS AND EXPERIMENTS

A high-speed, silicon photodiode (Hamamatsu, S1223) with an active area of 3.6×3.6 mm^2 was employed coaxially to measure the light emission of the plasma that appeared near the workpiece surface. It had a maximum sensitivity of 960 nm and a response time of 50 ns, which makes it reliable for signal detection. The intensity of the light emitted from the plasma plume formation passed back up through the nozzle, the focusing lens through a focused lens, and two neutral density filters (transmittance 13%) onto the photodiode. An amplifier with a peak detector circuit indicated when light level was maximal. The analog signal from the photodiode was periodically sampled by a digital signal processor (DSP) with a sampling rate of 1 MHz. Fig. 1 shows a schematic of the experimental configuration.

A Q-switched Nd:YAG laser that delivers 200 mJ of radiation energy of the pulse laser in 6 ns at 532 nm was employed. The beam was focused to 12.90 µm, and the focal length was 120 mm. It was focused on the surface of the workpiece, with the workpiece surface normal to the laser beam. The laser was operated at 15 Hz, and induced a plasma that expanded normal to the workpiece surface. The apparatus was set up on an electric discharge machine (Sodick, Model: AQ35L).

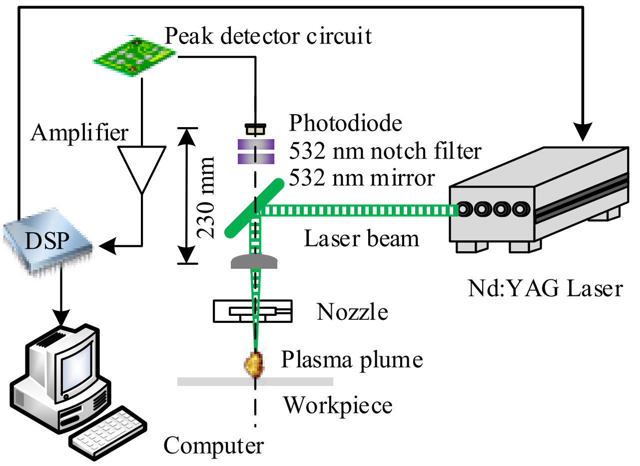

Fig. 1: Configuration for defocusing laser percussion drilling

Table 1: Experimental conditions of on-line depth measurement.

Parameter	Value
Laser source	Nd:YAG
Laser radiation energy per pulse	200 mJ
Laser wavelength	532 nm
Focusing lens	120 mm
Pulse time	6 ns
Pump pulse	80–100 µs
Pulse frequency	15 Hz
Ambient temperature	25 °C
Ambient moisture	66 %

Jiang *et al.* [8] hypothesized that the strength of the laser intensity on the axial direction would be weakened as the defocusing distance increased. Our previous work [7] showed that the penetration depth is in inverse proportion to the peak plasma light emission measured for a given laser pulse number.

The first part of our experiment used 1.0 mm-thick sheets of stainless steel (SUS 304) and an industrial Nd:YAG pulsed laser (Table 1). Fig. 2 shows the drilling depth and the responding voltage of the coaxial photodiode $B_{RES}(N)$ for a given laser pulse number (N). Fig. 3 shows that the incremental drilling depth $D_{INC}(N)$ for different values of N decreased with cumulative hole formation depth $D_{AC}(N)$, in part due to the laser defocusing effect stemming from the thickness of the part.

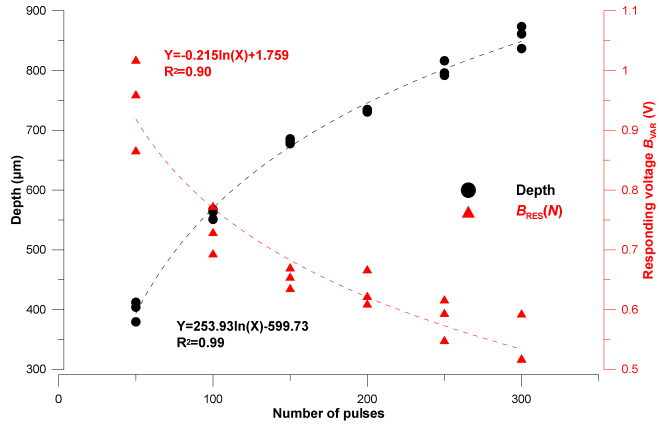

Fig. 2: The drilling depth and the responding voltage of the coaxial photodiode $B_{RES}(N)$ under different values of laser pulse number N

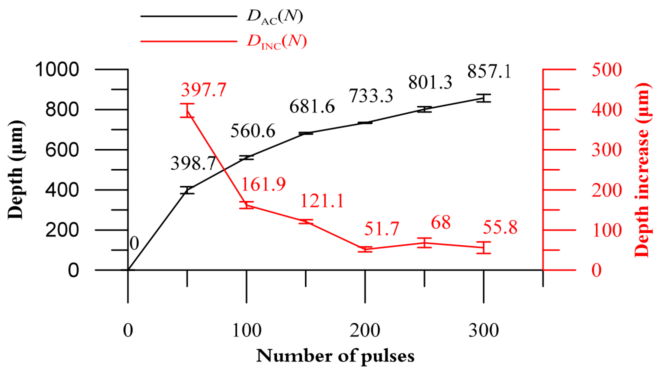

Fig. 3: Incremental drilling depth $D_{INC}(N)$ and cumulative hole formation depth $D_{AC}(N)$ for different values of N

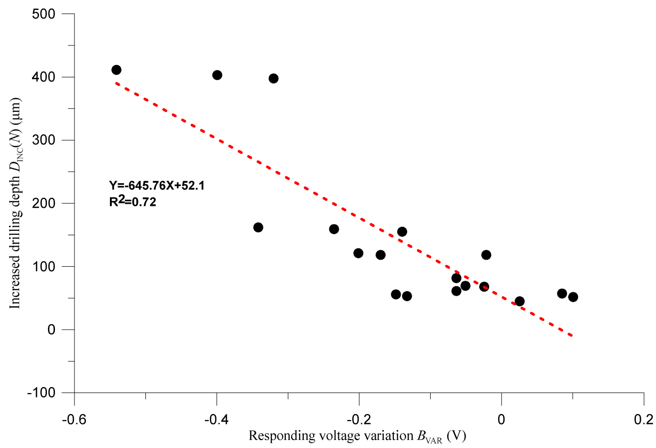

Fig. 4: Correlation between increased drilling depth $D_{INC}(N)$ and responding voltage variation $B_{VAR}(N)$ of the coaxial photodiode

2.1 Correlation between Variation of Plasma Brightness and Increased Depth

When the laser strikes the workpiece surface repeatedly at the same spot, the workpiece is heated, which effects drilling, and the laser intensity on the bottom surface of the drilled cavity is reduced. As a result, plasma size reduces as focus position is more distant from the material surface [9], and its brightness also declines [7]. Hence, the brightness variation of the derived light from the plasma can be used as an indicator to control laser percussion drilling. Fig. 4 shows a correlation between the increased drilling depth $D_{INC}(N)$ and the responding voltage variation $B_{VAR}(N)$ of the coaxial photodiode due to induced plasma emission under different values of laser pulse number (N). A linear relationship exists with a linear regression coefficient of 0.72.

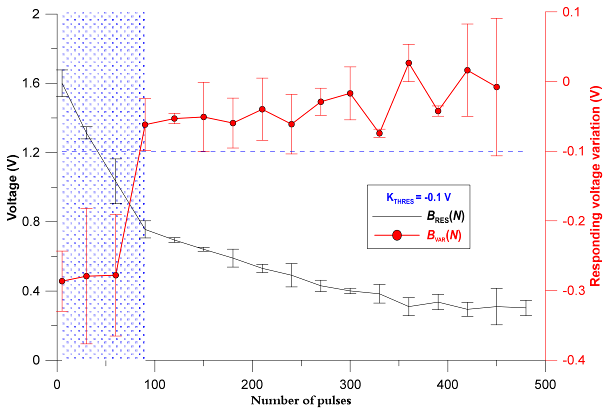

Fig. 5: After initial laser percussion drilling at laser pulse number 100 at the drilled depth 400 μm, $B_{RES}(N)$ declines slowly as the result of $B_{VAR}(N)$ exceeding a threshold K_{RE}

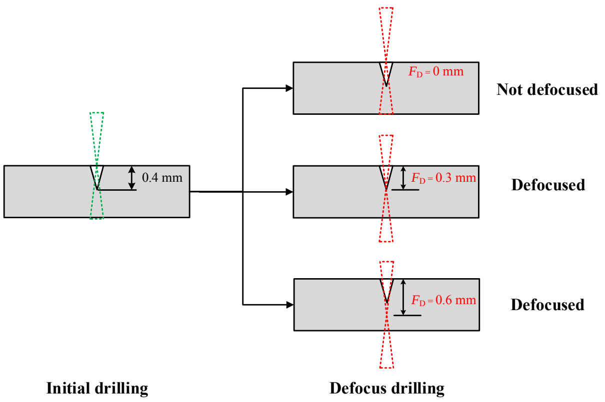

Fig. 6: The defocusing experiment of increasing the defocusing distance F_D under fixed laser pulse power

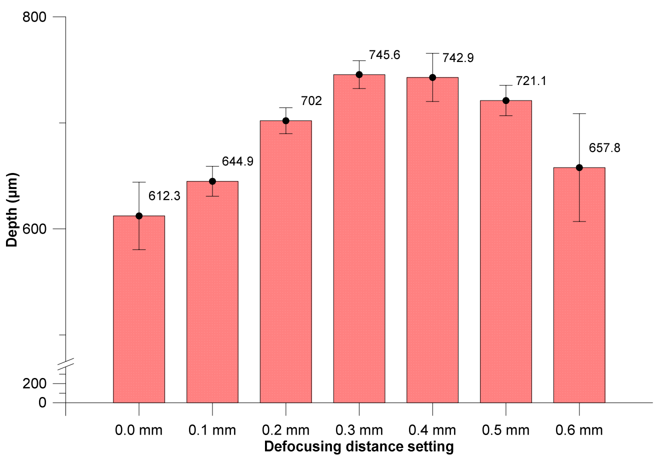

Fig. 7: The increased depth obtained under different defocusing distance settings

2.2 Relationship between the Increased Depth and the Defocusing Distance

From the previous sections, the increased depth can be correlated with a signal variation from the photodiode. The defocusing experiment was then employed to find the relationship between the increased depth and defocusing distance during drilling. The only changing parameter is the defocusing position. Fig. 5 shows that after initial laser percussion drilling, the responding voltage of the coaxial photodiode $B_{RES}(N)$ at laser pulse number 100 declines slowly as the result of the responding voltage variation $B_{VAR}(N)$ being increased beyond -0.1. The marked region on the curve in the left image shows the responding voltage variation $B_{VAR}(N)$, which falls below the setting threshold K_{RES} (i.e., -0.1) as the drilled workpiece surface is more distant from the focus position. The increment in the brightness of the plasma indicates the reduction in the drilled depth. Fig. 6 shows that the initial 100 pulse number is focused on the surface of the target, at which time the laser drilled depth is 400 μm. The defocusing drilling depth on the target surface can be investigated by increasing the defocusing distance F_D under fixed laser pulse power. The threshold value K_{RES} is a good indicator to judge the progress of drilling. Since the brightness of the derived light is dominated by the defocusing, K_{RES} can be used as the criterion to perform defocusing drilling by adjusting the focal position during the process. Fig. 7 shows the result of the defocusing experiment under fixed laser pulse power with additional 200 pulse numbers applied to measure the depth increment under different defocusing settings. The diagram shows that when defocus position in the range between 0.1 mm and 0.6 mm, the defocusing strategy has a positive effect on the average drilling depth. This information can be used to monitor the brightness variation signal of the plasma $B_{VAR}(N)$ to control feedback drilling. The maximum increased depths at defocusing distance setting are F_D = 0.3 mm and F_D = 0.4 mm.

2.3 Defocusing Laser Percussion Drilling

In the previous sections, the responding voltage variation $B_{VAR}(N)$ of the induced plasma was treated as the indicator to adjust the focal position. The derived light signal can be used as the indicator to adjust the defocus position according to the brightness variation of the induced plasma.

Fig. 8 shows the experimental results in which the black line is the result of the focus fixed drilling, while the rest of data depict change in defocusing under fixed laser pulse power. The initial focal position was just on the surface. When the responding voltage variation B_{VAR} exceeded the threshold K_{RES}, the defocus distance F_D moved to 0.3 mm and then again to 0.4 mm according to the feedback of the brightness deviation induced by the plasma plume. Three tests were carried out to confirm the reproducibility of the control process. Fig. 9 depicts the total final pulse numbers for focus-fixed drilling and defocusing drilling. Drilling efficiency was increased more than 47% by applying proposed defocusing laser percussion drilling than with no focus control.

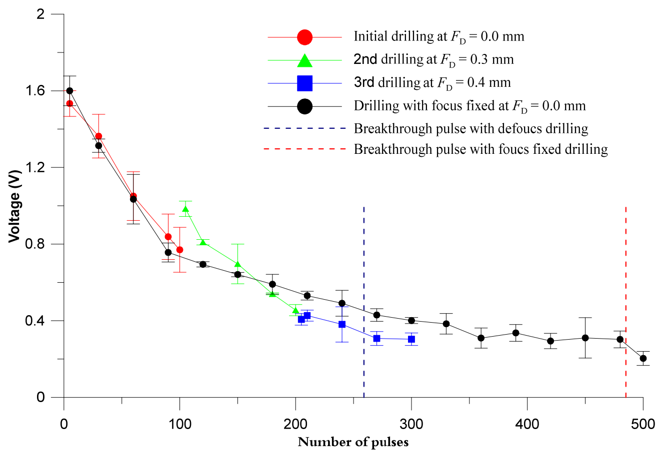

Fig. 8: Experimental results of focus fixed drilling and defocusing laser percussion drilling

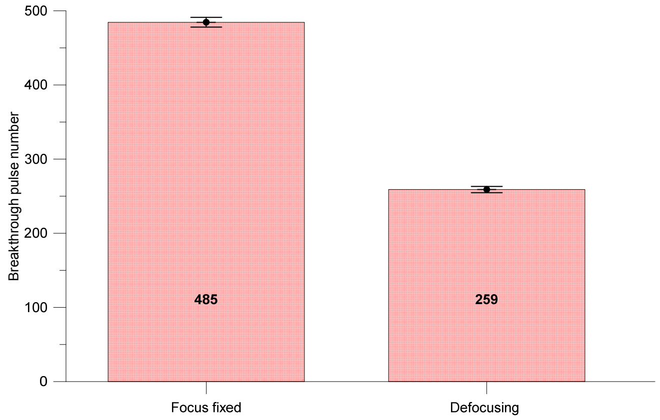

Fig. 9: Comparison of breakthrough pulse numbers between defocusing laser percussion drilling and no focus control

3. CONCLUSIONS

The paper demonstrates a strategy for monitoring and control of focus position during laser percussion drilling. It showed that a coaxial photodiode is capable of measuring deviation of plasma emission on-line, which provides the basic feedback for the improvement of drilling depth through defocus position control.

The increment of the brightness variation induced by plasma is associated with a decrease in drilling depth. The feasibility and improved efficiency of 47% with respect to focus fixed drilling for this defocusing feedback laser percussion drilling method was demonstrated.

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