G Model
PRE-6253; No. of Pages 9
ARTICLE IN PRESS
Precision Engineering xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Precision Engineering
journal homepage: www.elsevier.com/locate/precision

Laser percussion drilling of highly reflective metals with external interdigital electrodes

Chao-Ching Ho*, Guan-Ru Tseng, Yuan-Jen Chang, Jin-Chen Hsu, Chia-Lung Kuo

Department of Mechanical Engineering, National Yunlin University of Science and Technology, No. 123, Sec. 3, University Road, Douliou, Yunlin 64002, Taiwan

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 1 May 2015
Accepted 19 June 2015
Available online xxx

Keywords:
Electrical field
Reflective surface
Micromachining
Laser drilling
Laser percussion drilling
Laser-induced plasma
Interdigital electrodes

ABSTRACT

In this study, a novel interdigital electrode was employed during the laser percussion drilling of highly reflective materials. The main advantage of using interdigital electrodes is one-sided access for removing the charged particles in the plasma plume. Another benefit is the acceleration effect on the particles, which increases the drilling performance. Different configurations of interdigital electrodes were proposed and investigated in this work to provide a simple, low-cost method for expelling the laser-induced plasma plume generated during the laser percussion drilling process. Electrical fields with different electrode configurations applied to the charged particles carrying the ions were also simulated in this work. The results show that vaporized debris is expelled by applying an electrical field, and hence the penetration depth can be maximally increased by 84.9% through an optimal electrode configuration. Although the electrical field strength and drilling efficiency of interdigital electrodes show an underperformance compared with the plane electrodes, the lifetime of interdigital electrodes outperforms that of the plane electrodes owing to a less-scattered particle deposition.

1. Introduction

Laser percussion drilling, a non-contact machining process, has attracted strong interest from the industry owing to its wide range of industrial applications, smaller beam spot size, high operating speeds, great flexibility, accuracy, and capability to process various materials, including metals, glasses, and ceramics. However, difficulties are encountered in applications that use highly reflective target surfaces (e.g., aluminum), which reflect the optical energy and dramatically reduce the processing efficiency [1]. The specific heat of Al 5052 (0.88 J/g °C) is higher than that of other metals such as Au (0.129 J/g °C) and Cu (0.385 J/g °C). Thus, the machining efficiency for Al 5052 is deteriorated [2], thereby lengthening the drilling time and increasing the process cost and decreasing the yield.

Several solutions to overcome this issue have been proposed. Thawari et al. [3] used a high-power pulsed Nd:YAG laser to provide sufficient energy to penetrate a highly reflective surface without reducing the yield of the process, but the efficiency remains low. Gu et al. [4] reported that lasers with a shorter wavelength improve the absorption by the reflective material, thereby providing a higher cutting speed. Zhu et al. [5] utilized an ultra-fast pulsed laser, such as a femto-second laser, to provide a high cutting speed without the effect of reflectivity from the surfaces. All of these methods require expensive short-pulsed laser equipment, thereby increasing the machining cost.

External electrical fields have been developed for status monitoring based on the detection of phenomena from laser interactions with the materials during the ablation process. A simple and low-cost monitoring method was provided using plasma detection with an external electrical field [6]. Different electrode configurations were proposed to determine the optimal detection of the hole penetration [7]. Our previous works [8] suggested the possibility of a new interlaced finger-like electrode design, i.e., an interdigital electrode, to increase the signal level and detection sensitivity of laser-induced plasma. Meanwhile, the same setup was utilized to determine the focal position of the laser processing. An interdigital electrode also plays a vital role in material removal in a vaporized state during the drilling process because the charged particles in the plasma plume are attracted to the electrodes. The aim of this paper is to explore the dual benefits (i.e., sensing and machining) and capability of this novel interdigital design.

Studies on the use of electrical field techniques for laser machining have been reported [9–13]. In Refs. [9,10], the feasibility of using an electrical field as a plasma control tool to assist the laser welding by a CO_2 laser and provide a better machining performance

* Corresponding author. Tel.: +886 5 534 2601; fax: +886 5 531 2062.
E-mail address: HoChao@yuntech.edu.tw (C.-C. Ho).

http://dx.doi.org/10.1016/j.precisioneng.2015.06.008
0141-6359/

Please cite this article in press as: Ho C-C, et al. Laser percussion drilling of highly reflective metals with external interdigital electrodes. Precis Eng (2015), http://dx.doi.org/10.1016/j.precisioneng.2015.06.008

was explored. In Ref. [11], electrostatic fields and laser-induced discharges used to enhance both the debris removal and the ablation rate during the ultra-short pulse laser drilling of copper were evaluated. The results show that the debris was expelled over a much greater distance by applying an electrical field. However, the different configurations of the electrodes and a quantitative analysis of the penetration depth have not been investigated. In Ref. [12], an external electrical field was employed during femto-second laser micromachining. It was found that the strength of the applied external electrical field has a significant effect on preventing the particles from re-depositing on the machined silicon wafer surface because the charged ions in the plasma plume are drawn to the electrodes. Our previous works [13] have shown that vaporized debris is expelled by the applied electrical field of the plate electrodes, and when an optimal configuration is applied, the penetration depth can be increased by up to 91.1%.

In this paper, the effects of the electrical field produced by interdigital electrodes, and the influence of different electrode configurations on laser percussion drilling, are explored. An electrical field simulation was conducted to determine the field strength of the different electrode configurations. The penetration depth and inlet diameter were measured and examined.

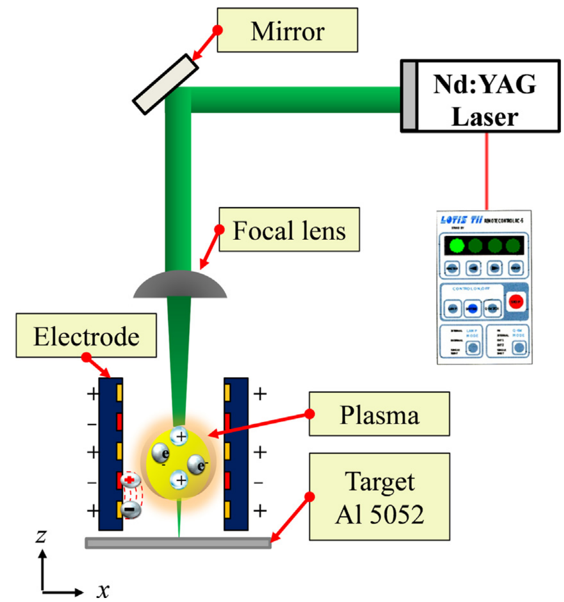

Fig. 1. Mechanism of interdigital electrodes and one-sided access to attract vaporized plasma.

2. Electrical field simulation

A laser-induced plasma plume is produced during the laser percussion drilling process [14]. A high-energy plasma plume is composed of charged particles (electrons and ions), and when a laser-induced plasma plume is generated between two metallic charged electrodes, and the separation distance between the two electrodes is close to the width of the plasma plume, the charged particles reach the electrodes. An electrical field has an accelerating effect on the particles: a charged particle experiences an electrical force that is directly proportional to both the charge of the particle and the applied voltage, and inversely proportional to the distance between the two electrodes [12]. Moreover, a strong electrical field draws charged particles in the plasma. Simulations were carried out to explore the features of an electrical field produced by interdigital electrodes.

2.1. Features of interdigital electrodes

The operational principle of interdigital electrodes is the same as that of parallel-plane electrodes. The interdigital electrodes are arranged in a coplanar manner, and the positive and negative electrodes are arranged in the shape of an interlocking brush. An electrical field is created between the positive and negative electrodes. One side of each electrode is grounded, and a voltage source is applied to the other side. Therefore, the interdigital electrodes form a strong electrical field between the two adjacent electrodes, as shown in Fig. 1. As Fig. 2 illustrates, the copper pattern on the interdigital electrodes was 100-μm thick with a line width of 100 μm and a line spacing of 200 μm. To understand how the electrical field of the plate electrodes is distributed, a finite-element simulation was conducted using COMSOL software. Initially, a mesh model was constructed to simulate the distribution of electrical field lines, the simulation results of which are shown in Fig. 3. It was observed that the maximum electrical field occurred at the edge of the electrode line. It appears that the partial enlargement at the edges of the interdigital electrodes generates a strong electrical field, which enhances the lateral force moving the charged particles. Radially outward streamlines of the electrical field circulate around the electrode lines. The charged particles traversing the circulated electrical field undergo a vector force, resulting in a curved path. Therefore, the main advantage of interdigital electrode structures is the one-sided access to the charged particles. Single-sided access can penetrate the produced plasma plume with a fringing electrical field effect. Therefore, when the plasma produced by a laser is sputtered substantially, the charged particles in the plasma plume are forced outward by the external electrical field. Once the charged ions and electrons reach the interdigital electrodes during the laser percussion drilling, they are accelerated by the interaction of the electrical field. In addition to the sensing applications described in our previous work [8], fringing electrical fields were used to generate mechanical forces, especially in assisting with the laser percussion drilling. Owing to the fringing electrical field effect, the maximum electrical field strength produced by the interdigital electrodes is 2.7×10^6 V/m greater than

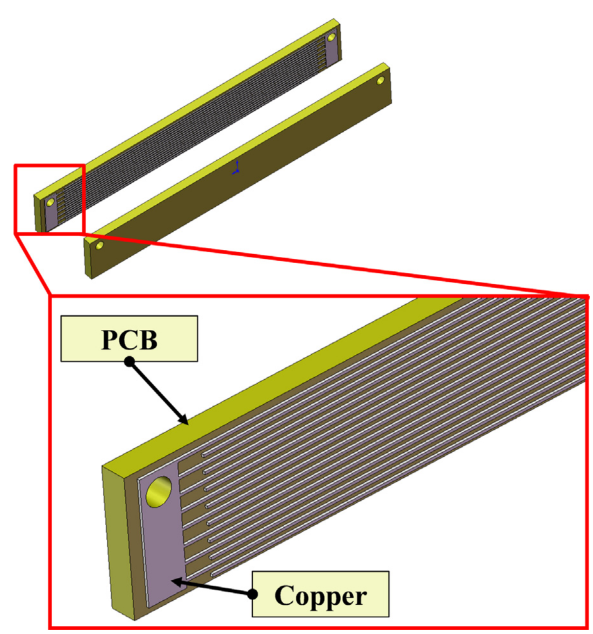

Fig. 2. Layout of the parallel interdigital electrodes. The copper pattern was produced on a PCB board using photolithography. An electrical field was formed between two electrodes at a 200-μm pitch.