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Characterization of hole circularity and heat affected zone in pulsed CO_2 laser drilling of alumina ceramics

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ABSTRACT

Circularity of drilled hole at the entry and exit, heat affected zone and taper are important attributes which influence the quality of a drilled hole in laser drilling. This paper examines the effect of laser parameters on the quality of drilled holes in Alumina ceramics which are widely used in microelectronic devices, based on orthogonal array experimentation and response surface methodology. Both entrance and exit circularities were significantly influenced by hole diameter and laser power. Heat affected zone was influenced by frequency. Taper was also significantly influenced by laser power. Response surface model predicted nominal entrance circularity at 2.5 kHz, 240 W, 2.5 mm/s, 1 mm hole, exit circularity and taper at 7.5 kHz, 240 W, 4.5 mm/s, and 1 mm hole. The model predicted lowest heat affected zone at 7.5 kHz, 240 W, 2.5 mm/s, and 1 mm. Multiobjective optimization achieved using both response surface model and gray relational analysis indicated that all the four quality parameters are optimized at 7.5 kHz, 240 W, 3.85 mm/s and 1 mm.

1. Introduction

Laser drilling is an inexpensive and controllable alternative to CNC, punching, wire EDM, broaching or other popular destructive hole drilling methods. The use of laser drilling in manufacturing industry can be attributed to high accuracy, repeatability and reproducibility in a short period of time with minimum wastage [1]. It is widely applied in drilling of printed circuit boards, chemical vapor deposited diamond, microelectronic packaging and super luminescent diodes [2–7].

Alumina of 99% purity is one of the most widely used ceramic substrates in ballistic tiles and for thin film circuits in electronic switching systems. Laser drilling is a preferred method in drilling alumina due to its unique properties such as non-contacting nature, absence of mechanical cutting force and tool wear, flexibility and high machining rate [8]. CO_2 laser has excellent reliability characteristics, high average beam power, better efficiency and good beam quality [9]. The laser drilled hole quality is mainly judged by circularity, taper and extent of heat affected zone [10].

Most of the researchers have adopted Nd:YAG laser to drill various metals, alloys and ceramics. Kacar et al. [11] investigated 10 mm thick 99% alumina ceramic plates using 600 W Nd:YAG percussion laser drilling. Effects of laser parameters such as peak power, pulse energy and pulse duration were examined on average hole diameter. The authors reported that there was no variation of entrance hole diameter with respect to pulse duration and peak power whereas exit hole diameter of the craters showed linear variation with respect to these parameters. Hanon et al. [12] investigated the effects of laser parameters such as peak power, pulse duration, focal position and repetition rate on the alumina ceramic plaques of 5 mm and 10.5 mm thickness using 600 W Nd:YAG laser. The authors identified three different layers namely a thin layer, a resolidified material inside the hole and a recast layer at the entrance region of the hole. The crater depth increased with the number of pulses due to insufficient recoil pressure inside the cavity. Yinghou et al. [13] investigated the effects of laser parameters such as peak power, pulse laser power and pulse repetition rate on spatter deposition and hole diameter by drilling 4.4 mm thick alumina ceramic (95%) using 3.5 kW CO_2 laser. The authors reported that the spatter deposition and hole diameter increased with increase in peak power and the size and temperature of the melt front significantly affected both spatter and hole formation. The authors observed that HAZ was incorporated with three zones namely recast layer, over grown grains zone and partial melting zone.

Ng and Li [14] assessed the effects of laser peak power and pulse width on the repeatability of hole geometry in terms of percentage

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standard deviation in percussion drilling of 2 mm thick stainless steel sheets using 400 W Nd:YAG laser. The authors observed that the increase in interaction time between liquid melt and material resulted in higher degree of erosion. Better repeatability was achieved when higher peak power and smaller pulse width were used thereby a cause of hole geometry variation was identified. Ng and Li [15] investigated the influence of laser peak power, pulse width and melt ejection process on the repeatability of holes in terms of circularity and percentage standard deviation by drilling in 2 mm thick mild steel sheets using 400 W Nd:YAG laser. The authors observed greater spatter thickness for longer pulse width and lower peak power. Mutlu et al. [16] investigated the influence of laser wavelength and operation pressure on the crater depth and diameter in drilling 0.8 mm alumina ceramic plates using Nd:YAG pulsed laser. The crater depth and diameter increased non-linearly with laser power because of the plasma shielding effect. Both wavelength and ambient pressures showed the same characteristics.

Since laser drilling is associated with several parameters development of a physical model becomes complicated and hence researchers have developed statistical models for taper [10,17–21], circularity [1,20,23] and HAZ [21,17] to analyze parameters such as laser peak power, laser power, pulse width, pulse frequency, focus plane position, number of pulses and assist gas pressure. But, no comprehensive research has been reported in the area of multi-objective optimization of the identified responses in laser drilling of alumina ceramic using gray relation analysis and response surface methodology. Circularity at the hole exit is an equally important quality parameter which is scarcely addressed so far. The aim of this research was to investigate the effects of laser parameters on the quality of drilled holes including circularity at the exit based on Taguchi's Orthogonal Array technique. The laser parameters and responses were correlated using Response Surface Methodology (RSM). The laser parameters for optimizing the multiple responses were obtained using gray relational analysis. Laser drilling experiments were carried out using 300 W CO_2 laser and 2 mm thick alumina ceramic plates. Pulse frequency, laser power, scanning speed and diameter of the hole as the main factors and taper angle, circularity at entrance and exit and heat affected zone as responses were studied. Experimental HAZ and taper were validated using analytical models. The quality of drilled holes was examined using SEM.

2. Experimental

2.1. Laser drilling using orthogonal array technique

A 300 W CO_2 Rofin laser was used to assess the quality of drilled holes in 2 mm thick alumina (99%) plates the properties of which are presented in Table 1. The technical specifications of laser system are as shown in Table 2. Pulsed laser trepanning technique was used, in which the laser beam movement relative to the part causes to cut a contour out of the plate. In this study, the experimental plan had four controllable variables, namely pulse frequency, laser power, scanning speed and hole diameter. Based on the preliminary experiments, the range of pulse frequency, laser power, scanning speed and hole diameter were selected as 2.5–7.5 kHz, 150–240 W, 2–4 mm/s and 1–2 mm respectively. When laser drilling was attempted on alumina ceramic plates by employing laser parameters greater than 240 W laser power, 7.5 kHz pulse frequency and 4 mm/s scanning speed, the specimens cracked due to their lower thermal shock resistance. Similarly, laser drilling attempted by employing laser parameters less than 150 W laser power, 2.5 kHz pulse frequency and 2 mm/s scanning speed, through hole drilling was not possible due to insufficient laser energy for the drilling. Thus, the parameters were selected between these higher and lower limits for the investigation. The diameter of the hole to be drilled was varied using WELDMARK software interfaced with the laser system. The laser power was varied in terms of duty cycle. L_9 (3^4) Orthogonal Array experimental layout selected for the research is shown in Table 3. Four replicates were used to ensure repeatability of the responses. The experimental responses along with their mean and standard deviation are presented in Table 4.

Table 1
Properties of alumina ceramic used for drilling.

Density (g/cm^3)	3.89–3.96
Thermal expansion coefficient (10^{-6} J/K)	6.4–8.2
Thermal conductivity (W/mK)	30.4
Young's modulus (GPa)	330–400
Poisson's ratio	0.26–0.24
Hardness (HV1.0)	1300–1700

Table 2
Technical specifications of laser system.

Suppliers	M/S Suresh Indu Laser Pvt. Ltd., Pune
Machine model	RofinSinar SC × 30 sealed slab 300 WE CO_2 laser
Wavelength	10.6 μm
Maximum field size	300 mm × 300 mm
Spot diameter	370 μm
Working distance	480 mm
Resolution	<6 μm
Beam type	TEM00
Peak power	750 W
Mode of operation	Continuous and pulsed mode

Table 3
L_9 Orthogonal array experimental layout.

Expt. no.	Experimental factors			
	Frequency, Fr (kHz)	Laser power, L_p (W)	Scanning speed, Scp (mm/s)	Hole diameter, D (mm)
1	2.5	150	2.5	1
2	2.5	230	3.5	1.5
3	2.5	240	4.5	2
4	5	150	3.5	2
5	5	230	4.5	1
6	5	240	2.5	1.5
7	7.5	150	4.5	1.5
8	7.5	230	2.5	2
9	7.5	240	3.5	1

2.2. Scheme for measuring the responses

The circularity of the hole at the entry and the exit was determined by using Eqs. (1) and (2) respectively as

$$C_{\text{ent}} = \frac{D_{\min}}{D_{\max}} \tag{1}$$

$$C_{\text{ext}} = \frac{d_{\min}}{d_{\max}} \tag{2}$$

where $D_{\min}$ and $D_{\max}$ as shown in Fig. 1a are the minimum and maximum diameters at the entrance of the hole respectively. Similarly, $d_{\min}$ and $d_{\max}$ are the minimum and maximum diameters at the exit of the hole respectively.

The thickness of the heat affected zone (Fig. 1b) was measured using digital image analysis by employing a 10 Mega pixel camera,