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Parameter optimization of nanosecond laser for microdrilling on PVC by Taguchi method

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ABSTRACT

Formation of cavities having maximum aspect ratio (depth-to-width (D/W) ratio) on PVC during laser drilling has several undesirable outcomes with regard to cavity quality. Hence it is essential to select optimum drilling process parameters to maximize aspect ratio and minimize Heat Affected Zone (HAZ) and circularity. This paper presents application of the Taguchi optimization method to obtain cavities possessing maximum aspect ratio influenced by drilling conditions such as wavelength, fluence and frequency. In the present work, the effects of laser processing parameters, including laser fluence, laser frequency and wavelength were investigated in relation to the aspect ratio, HAZ and circularity. Then the optimal values of wavelength, fluence and frequency were determined. According to the result of the confirmation experiment using optimum parameters, it was observed that experimental results were compatible with Taguchi method with 93% rate. The details of experimentation analysis and analysis of variance are presented in this paper.

1. Introduction

Major developments in technology (in all fields such as industry, healthcare, defense and aerospace) have revealed the need to use many different materials. The problems in processing of these materials are largely solved by laser systems, and with parallel to the ongoing studies, the process quality is increasing day by day. Lasers, as a high energy source, are especially being preferred in many areas such as cutting, drilling, welding, surface treatments, marking and coating. Recently, need for lasers have been increased with more usage of micro-sized structure.

Lasers can be used for cutting, drilling and surface treatment with their capability of high energy transfer to the focused point for melting and boiling purposes. Laser systems are being preferred in micro and nano-sized materials (metals, ceramic and polymers) which requires machining with advanced technology [1–7].

For different materials such as metals [8], ceramic [9], and polymers [3,4,6,7,10], different types of lasers (pulsed or continuous) were used with their different parameters [5].

In polymers, especially in thermoplastics, it is difficult to determine the best parameters or best experimental setups for machining the materials due to their poor thermal and physical properties (variable crystallinity and low glassy transition and melting temperatures) compared to metals or ceramics. There are some studies including experimental and theoretical approach to determine best parameters [11–13].

The main problem in laser drilling of materials is to select the most appropriate parameters. Laser beam quality, wavelength, fluence, frequency are important parameters for laser drilling. Effective parameters should be controlled to obtain a good quality laser drilling. Determination of the parameters of laser drilling by classical experimental design methods takes a lot of time and it is costly at the same time. Taguchi method, which decreases number of trials, was used in machining of materials by some researchers to avoid these before mentioned disadvantages [14–18].

To determine optimum conditions for material drilling, Taguchi method has been chosen to design the experiments. This method was used widely in some metals, alloys and polymers. Pan et al. [16] studied on the optimization of Mg alloy thin plate butt welding using Taguchi analytical method. To minimize burr size, best combination values of process parameters were confirmed by Gaitonde et al. [17]. Masmiati and Philip [18] made an attempt to plan the experiments on drilling of some thermoplastic polymers using Taguchi method. El-Taweel and El-Axir [19] made an analysis and optimization of the ball burnishing process through the Taguchi technique.

The goal of this study is to achieve maximum aspect ratio, minimum HAZ and nominal value "1" for circularity for the cavities created on PVC (polyvinylchloride). For the analysis of these experiments, calculated signal-to-noise (S/N) ratios were

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used with the approach of "larger the better" for aspect ratio, "smaller the better" for HAZ and "nominal value is 1" for circularity. Since the process of laser drilling (in particular, UV nanosecond laser drilling) is not optimized, obtaining holes on polymer with high aspect ratio is a significant problem for modern advanced technologies such as microelectronics, micromechanics, aerospace and automotive industry. Therefore confirmation experiment was done for aspect ratio.

2. Design of experiments

2.1. Material and experimental setup

PVC samples with 4.5 mm thickness were cut in 5 mm × 85 mm and used in the experiment after cleaning the surfaces. Cavities are formed on samples by using different parameters of Surelite Continuum Laser, having three harmonics. Pulse energies of laser are 1 J, 450 mJ and 290 mJ, respectively, when wavelengths are laser's fundamental harmonic of 1064 nm, second harmonic of 532 nm and the third harmonic of 355 nm. Spot size is 9.8 mm, pulse duration is 6 ns and pulse repetition rate is 10 Hz. Pulse repetition rate can be extended from 1 Hz to 10 Hz by trigger system. Longitudinal mode of laser beam was determined as TEM_{10} by laser beam profiler (LPB series NEWPORT). Laser focusing system is shown in Fig. 1.

160 Laser pulses with 40 µm spot size have been sent on PVC. Because of increasing depth began to lose linearity after 160 pulses, this pulse number were taken as reference.

2.2. Taguchi method

In a study according to design of experiment for Taguchi method, steps are;

a. Identify the quality characteristics and process parameters to be evaluated.
b. Determine the number of levels for the process parameters and possible interactions between the process parameters.
c. Select the appropriate orthogonal array and assign the process parameters to the orthogonal array.
d. Conduct the experiments based on the arrangement of the orthogonal array.
e. Analyze the experimental results using the signal-to-noise (S/N) ratio and statistical analysis of variance.
f. Select the optimal levels of process parameters.
g. Verify the optimal process parameters through the confirmation experiment [14].

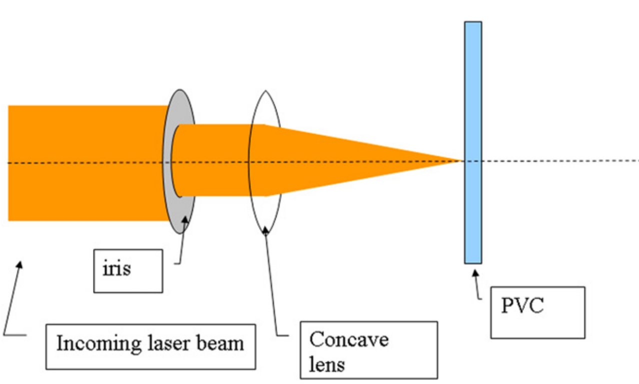

Fig. 1. Laser focusing system.

In an earlier study on polymers, number of pulse, standoff distance gas pressure and nozzle diameter were chosen by Masmiati and Philip [18] as control factors. In our study, the wavelength of laser, frequency (repetition rate) and fluence were chosen as control factors. Three levels of these factors were chosen in the orthogonal array. The fluence of the pulses is varied by changing the energy of one pulse, and the wavelength is varied by using the fundamental, second and the third harmonic of laser. Repetition rate is varied by *Q*-switched Nd-YAG laser system. Therefore it is seen that none of these three factors interact with each other. These factors and levels were given in Table 1. To determine experiment sets Taguchi $L_9(3^3)$ orthogonal array was given in Table 2.

In the signal-to-noise (S/N) ratio, signal refers to real value which is desired and noise refers to undesired factors in measured values. There are three basic categories to determine the best results of experiments: Smaller-the better-characteristic, Larger-the better-characteristic and nominal-the best. All characteristics and formulas used in this study were given below:

(a) Smaller-the better-characteristic (used for HAZ):

$$S/N_i = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_{ij}^2\right] \quad (1)$$

(b) Larger-the better-characteristic (used for aspect ratio):

$$S/N_i = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_{ij}^2}\right] \quad (2)$$

(c) Nominal-the best-characteristic (used for circularity):

$$S/N = -10\log_{10}\left[\frac{1}{n} * \sum_{i=1}^{n} (y_{ij}-m)^2\right] \quad (3)$$

where y_{ij} is measured characteristic from experiments (aspect ratio, circularity and HAZ), n is number of experiments and m is nominal value "1" for Nominal-the best-characteristic.

Parameters with their levels of experiments were given in Table 1.

Table 1
Parameters of experiments and levels.

	1	2	3
Wavelength (nm)	355	532	1064
Fluence (J/cm^2)	8	16	24
Frequency (Hz)	6	8	10

Table 2
Tabulation of levels according to L_9 orthogonal array.

Experiment no	Wavelength (nm)	Fluence (J/cm^2)	Frequency (Hz)
1	355	8	6
2	355	16	8
3	355	24	10
4	532	8	8
5	532	16	10
6	532	24	6
7	1064	8	10
8	1064	16	6
9	1064	24	8