Optics & Laser Technology 69 (2015) 23–33

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Influence of nanofillers on the quality of CO_2 laser drilling in vinylester/glass using Orthogonal Array Experiments and Grey Relational Analysis

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ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form
26 November 2014
Accepted 3 December 2014
Available online 27 December 2014

Keywords:
Nanofiller
Laser drilling
HAZ

ABSTRACT

This paper presents the influence of nanofillers on the CO_2 laser drilling of vinylester/glass based on L_9 Orthogonal Array Experiments and Grey Relational Analysis. Three nanofillers such as nickel nanopowder, carbon black and Closite 15-A were studied. Multiple responses such as Damage Width, Surface Damage Width and Taper Angle were optimised using the Grey–Taguchi method for laser power, cutting speed, air pressure and nanofiller content. Heat affected zone along with char due to the complete burning of the matrix was largest and caving through the depth of the hole was observed in vinylester/glass. Nickel nanopowder effectively reduced the heat affected zone and improved the quality of the hole due to the absence of char. Closite 15-A reduced the surface damage and the char was thicker and distributed as globules. Carbon black caused greater surface damage at the entry of the hole due to the burning of the fibres and very thin char covered the fibres through the length of the hole. Regression models were developed to predict the laser drilling responses.

1. Introduction

Fibre Reinforced Plastics (FRP) are widely used as structural materials in aerospace, space, marine, automotive, electronics and other applications because of their superior specific strength and stiffness. Glass Fibre Reinforced Plastics (GFRP) are used for printed wiring boards in electronic industry. Laser drilling is particularly useful for high-aspect ratio microdrilling applications where conventional drilling is not applicable or less efficient. Laser drilling rates as high as 100 holes/sec are achieved in production environment by coordinating the workpiece motions with pulse period of pulsed laser source. Trepanned laser drilling is a method used to remove cylindrical core or circular disc from a substrate. Trepanning is a standard technique for large holes, e.g. 500 micron holes in turbine blades. It can increase the quality of hole, reduce taper and barrelling or the local increase of hole diameter compared to percussion. Other advantages of trepanning include consistency and ability to drill shaped holes. CO_2 and Nd:YAG lasers are commonly used for trepanning.

There is a vast range of temperature at which the materials melt (soften or decompose). Laser beam has a certain power and thus has a defined heat input into the material. However, because of differential properties of fibre and matrix, they react very differently to the thermal input. In general, energy needed for the vaporisation of the fibres is greater than that of the matrix. When a CO_2 laser is employed to cut the composites, a large volume of resin is vaporised in the process which causes delamination and matrix recession. A possible limitation of laser cutting is Heat Affected Zone (HAZ) which results from matrix recession, decomposition and delamination. Matrix recession occurs when matrix and fibres are removed at different rates owing to their different thermophysical properties [1]. Although considerable amount of work has been done on laser cutting of composite materials the results are so scattered that it is very hard to realise the present status of the laser cutting of polymer composites in general and thermoset polymer composites.

Many parameters influence quality of cut in laser machining of polymer composites [2–6]. They are laser power [3,4,7,8], frequency, scanning speed [7,9], and pulse repetition rate [2,5] which influence HAZ, kerf width and Taper Angle. Mathew et al. [2] reported that HAZ is affected by pulse repetition rate and gas pressure in laser cutting of Carbon Fibre Reinforcement Plastics (CFRP). Goeke and Emmelmann [3] proposed that HAZ and cutting kerf reduce with higher feed rate due to decrease in energy per unit length. Al-Sulaiman et al. [4] reported that kerf width increased with laser power based on scale law analysis and sideways burning and edge irregularities were minimised by using Nitrogen gas which reduced the oxidation reactions taking place in the cutting section. Ayoma et al. [5] reported that pulse repetition rate and the material property influenced the hole quality in CO_2 and Nd:YAG laser drilling GFRP printed wiring boards.

Yung et al. [6] observed that HAZ is reduced by reducing pulse energy and increasing the repetition rate in laser drilling of GFRP

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http://dx.doi.org/10.1016/j.optlastec.2014.12.002
0030-3992/

used for Printed Circuit Board (PCB). Al-Sulaiman et al. [8] proposed that assisting gas pressure and laser power influence significantly the laser cutting of Kevlar. Li et al. [9] investigated the laser parameters for cutting Quad Flat No-lead (QFN) packages by Taguchi's matrix method using a Diode Pumped Solid State Laser System (DPSSL). The authors observed that 95.47% of laser cutting quality was contributed by three control factors, namely, frequency (51.83%), cutting speed (23.16%) and driving current (20.48%). Hirogaki et al. [10] employed 100 W CO_2 laser for drilling blind holes in Aramid and glass/epoxy laminates used for PCBs and reported that HAZ was dependent on the irradiation time.

One of the recent approaches to improve quality of LASER drilling in FRP is dispersing nanofillers [7,11,12] of superior thermal conductivity and coefficient of thermal expansion for modifying the thermal properties of the laminates. Nagesh et al. [7] investigated the effect of carbon black on HAZ and Taper Angle in laser drilling of vinylester/glass and reported that both HAZ and Taper Angle significantly reduced with the addition of carbon black. Dosser et al. [11] investigated Nd:YAG solid state laser to micromachine carbon nanocomposites and reported that addition of carbon black increased the material removal rate and hence the quality of drilling. Winco et al. [12] studied laser drilling performance of blind vias in epoxy/aluminium nitride (AlN) composites using Nd:YAG laser and observed that there was no residue at the surface of the entrance of the blind vias. The authors reported that addition of AlN increased the thermal conductivity and CTE of the material and hence reduced the HAZ. The Grey–Taguchi method is finding importance for optimising multiple parameters as evidenced by its application for Electric Discharge Machining by Muthu et al. [13], Chen et al. [14] and Choudhury et al. [15] for laser machining.

Review of the literature [2–15] indicates that differential heat transfer characteristics of resin and fibre are a major concern for reducing the damage caused due to laser machining of polymer composites. In this direction the recent approach of dispersing nanofillers in polymer composites for improving the thermal properties has yielded promising results. However, further efforts are needed to substantiate these improvements by conducting parametric studies of laser cutting with the use of thermally superior nanofillers. Also, most of the previous works related to hole drilling used percussion drilling with intense laser burst, where the hole size was the size of the beam, causing greater damage to the material. Thus, trepanning was adopted in the present research mainly to reduce the damage. Nanofillers, of varied thermal properties, such as nickel nanopowder, carbon black and Closite 15-A were used to investigate their effect on the quality of laser cut holes in vinylester/glass laminates. Multi-objective response optimisation was achieved using Grey Relational Analysis. Regression models were used for predicting damage zone and Taper Angle for the parametric combinations of laser drilling.

2. Experimental

2.1. Laser drilling of polymer nanocomposites

The specimens used in the experiments were fabricated with 3 mm thickness by the wet hand lay-up process using fibre to resin ratio of 65:35 wt%. Thermal conductivity [16–19] of resin, FRP with and without nanofillers are presented in Table 1. BISPHENOL based vinylester which has very good chemical resistance is highly preferred for marine structural applications. E-glass (2D plan woven mat 0°/90°) of 360 gsm (Vetrotex India) was selected because of its low cost, high strength and chemical resistance. Nanofiller was dispersed in vinylester using a high speed tip ultrasonicator of frequency 37 kHz and co-rotating twin screw extruder. The extrusion parameters (100 rpm, 5 °C) were based on our previous experiments [20].

A laser system consisting of peak power 1600 W CW Rofin Sinar CO_2 laser and three axes CNC controlled table with work volume $1.5 \times 2.5 \times 1\ m^3$ (Fig. 1a) was used for drilling of the nanocomposite laminates. The output beam had a TEM_{00} (Gaussian) energy distribution, and the spot diameter was 200 μm. Compressed N_2 was used as a shield gas for removing the burnt material from the cut zone and at the same time to protect the lens from smoke emitted due to vaporisation of the material. Nitrogen also enables effective

Table 1
Thermal conductivity of resin, FRP with and without nanofiller.

Nanofiller (Supplier) with average particle size and thermal conductivity	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)					
	Nanofiller (wt%)/vinylester			Nanofiller (wt%)/vinylester/glass		
	0	2	4	0	2	4
Nickel nanopowder (Sisco Research Lab. Pvt. Ltd.), 20 nm and 158 $W\ m^{-1}\ K^{-1}$	0.19	1.303	1.428	0.879	1.269	1.312
Carbon black (Phillips Carbon Black Ltd., Grade N220), 20–30 nm and 100 $W\ m^{-1}\ K^{-1}$	0.19	1.293	1.405	0.879	1.265	1.304
Nanoclay- Closite 15-A (Southern Clay Products), 150 nm and 0.25 $W\ m^{-1}\ K^{-1}$	0.19	1.169	1.149	0.879	1.22	1.214

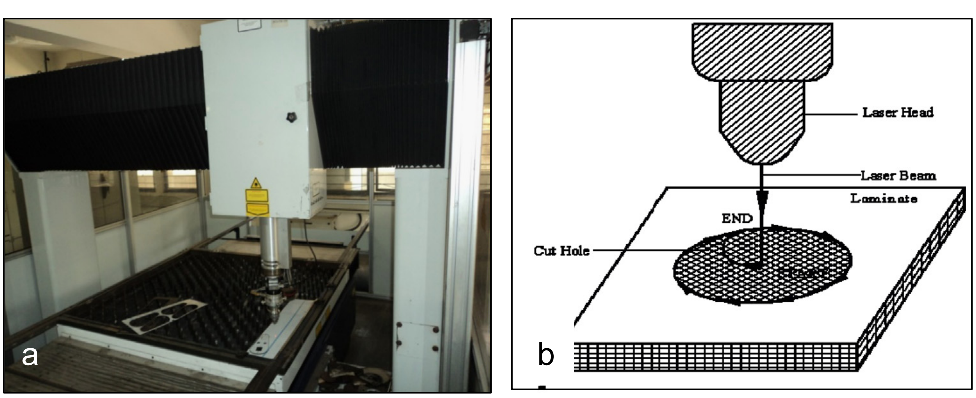

Fig. 1. (a) 1600 W CO_2 Laser beam machine, and (b) Trepanning drilling profile.