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A Feasibility Study of Low-Power Laser Trepanning Drilling of Composite Using Modified DVD Writer

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Abstract: In the present study, laser cutting of cotton fiber composite laminate is experimented using a modified DVD writer drive. A 250 mW diode laser is initially extracted from a DVD writer drive, and then regulated by a custom-made laser driver circuit designed using a Proteus® software. Experimental tests are carried out using multi-pass laser trepanning drilling at different drilling speeds and standoff distances (SODs). The cut quality is evaluated by measuring the extent of both oxide and resolidified resin regions. It was discovered high speed of trepanning drilling and positive SOD significantly improve cutting region quality. Furthermore, positive and negative SODs require relatively high number of passes at different drilling speeds. From SEM micrographs, it is found out that the crack formation and fiber protruding happen in the drilling area due to thermal stresses and matrix vaporization.

Keywords: Laser drilling; laser trepanning; cotton; fiber composite; grey relational analysis; optimization

1. Introduction

Lasers are widely utilized in machining and manufacturing sectors. Their applications include cutting, drilling, engraving, welding, micromachining, soldering (brazing), cladding, hardening, surface treatment, ablating, marking, etc. Therefore, laser has become one of the crucial production tools especially in machining complex geometrical designs, and currently being employed in the biomedical, communication, automotive, and aerospace sectors for reasons of precision, flexibility, and accuracy. The interaction between laser and material includes heating, melting, vaporization, plasma formation, chemical degradation and/or ablation. As the high density of laser beam is focused on the surface of the substrate, a portion of the material is eventually removed [1-5]. The thermal energy absorbed by the substrate may cause melting, evaporation and phase transformations that are normally associated with the threshold laser intensities [6-8]. In particular, laser drilling is one of the best alternatives to perform conventional hole drilling as it produces precision, neat and clean micro-holes size even for hard and brittle materials [9-11]. For instance, lasers have been used for drilling metal (e.g. stainless steel, tungsten), ceramics (e.g. silicon nitride, alumina), glass, etc. with promising results [12-14].

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In general, laser micro drilling of non-metals requires significantly less power than drilling metals of the same thickness [15]. There are many controlling laser parameters such as peak power, pulse width, pulse repetition rate, number of pulses, assist gas pressure, focal plane position (FPP), etc. to obtain the desired hole characteristics. These include circularities of the hole, depth of the hole, entrance and exit diameter of the hole. Nevertheless, the cost of acquiring laser machine is prohibitively expensive and often beyond the budget of many local small and medium-sized enterprises (SMEs).

The ever-increasing and rapidly growing volume of waste electrical and electronic equipment (WEEE) has become a serious threat to the environment in many countries including Malaysia [16]. According to the latest report conducted by the Department of Environment Malaysia, the quantity of e-waste generated in Malaysia had multiplied by about 3.3 times from approximately 40 tons in 2006 to about 134 tons in 2009 [17]. It is projected that personal computers would become the third major contributor of e-waste in 2020 behind mobile phone rechargeable batteries and mobile phones [16]. The e-waste is usually mined for precious metals ranging from copper, iron, gold, silver and aluminum among other elements. Apart from these, very few materials/components are ever recovered and reused, therefore resulting in majority of the e-wastes ending up in landfills. This includes laser diodes which are an integral part of optical disc drives. The primary objective of this study is to investigate the feasibility of a modified DVD writer drive as an inexpensive tool for precision laser micro-drilling of paper laminated composites. In addition, the effect of laser–material interaction on hole characteristic as a function of circularity and heat-affected zone are investigated and measured using optical techniques.

2. Experimental methods and analysis

2.1. Extraction of a laser diode from a DVD writer drive

Our preliminary investigation shows that a 16× DVD writer or higher contain laser diodes that capable of performing drilling. In addition, it is recommended to use a DVD writer from used computers rather than used laptop since the latter has a slimmer build, and extracting the laser diode would require special skills and equipment.

In this research, a DVD writer made by LG was removed from an old PC. Careful steps should be taken to take out a laser diode from the DVD writer drive (see Fig. 1a). It is contained inside a DVD holder in the laser carriage assembly as shown in Fig. 1b.

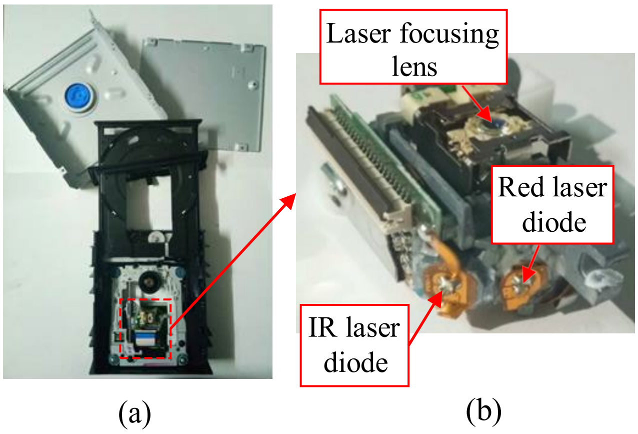

Fig. 1 - a) The DVD writer drive; b) Laser carriage assembly

2.2. Design of a laser driver circuit

A driver circuit is needed to regulate the voltage and current going to the laser diode. Excessive amount of current can cause the laser diode to explode and moderate amount of current will only have enough power to turn on the laser diode. Therefore, the laser driver circuit must be able to supply sufficient range of current and voltage required to operate the laser diode. The basic circuit driver essentially requires one unit three-terminal adjustable regulator, resistors, capacitors, diode, potentiometer, switch, and DC voltage source.

Proteus® design suite software is used to design the circuit. In this software, the functionality of the driver circuit can be first tested through simulation. By changing and adjusting the value of each component in the circuit, the output for the voltage and current can be set to obtain the desired wattage and power rating of the laser diode. As there are no laser diode component in the Proteus software, it was replaced with a LED to complete the circuit and to act as an indicator that the circuit is supplied and running. A voltmeter and an ammeter are added into the circuit to view the voltage and current output during simulation. Since the laser diode extracted from the DVD driver requires current around 0.2 to 0.8 A, the simulation results shows that the circuit has more than enough power rating to supply and run the laser diode. Fig. 2 shows circuit simulation of the laser driver. A better representation of the entire driver circuit is shown in Fig. 3.

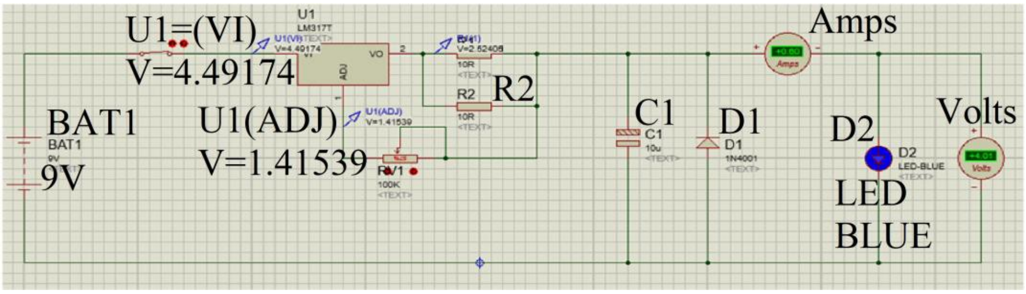

Fig. 2 - Simulation of Laser Driver Circuit

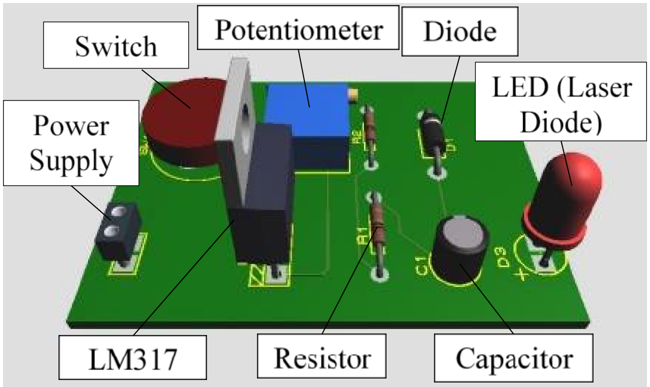

Fig. 3 - Design of laser driver circuit

2.3. Fabricating and testing of the laser driver circuit

Before inserting the component into the circuit, all the components must be inspected with a multimeter to check its their polarity and condition. The testing must be done based on the characteristic stated in the datasheet of the respective component. The components testing is done with a digital multimeter as it is fast and reliable. The easiest component to check is the resistor in which the measured resistance does not rely on polarity. In testing the diode, the probes polarity must follow the positive indicator mark on the diode. The display of the multimeter will show a value which represents a minimum voltage that could be conducted through the diode. A buzzing sound can be heard from the multimeter if the diode is faulty.

After all components have been tested as fully-functional, they are soldered onto a PCB as shown in Fig. 4. A continuity test is done on the circuit to avoid unwanted contact between components and copper in the circuit. Once the circuit energized, voltages input and output from the voltage regulator are checked with a multimeter to measure whether the voltage output is correct and to test the similarity between the actual output with the simulation output result. The output of the driver circuit is tuned to match the laser power rating by adjusting the power supply input voltage and the current output. The entire laser diode and its driver are then placed inside an aluminum casing.

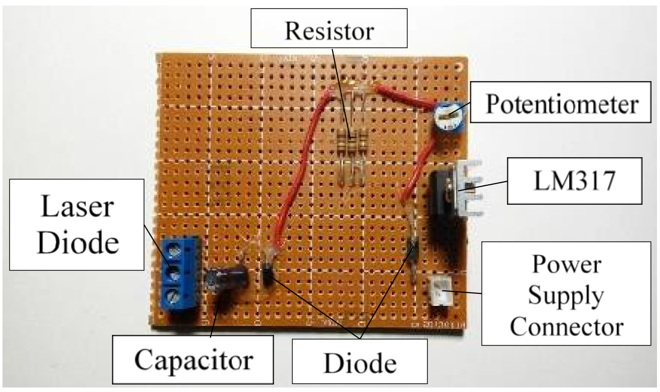

Fig. 4 - Laser driver circuit

2.4. Material characterization and experimental setup

A cotton laminated composite with modified phenolic resin of 0.4 mm thickness was used as a workpiece material. Table 1 shows some selected thermo-mechanical properties of the composite.

Table 1 - Thermo-mechanical properties of the composite

Material properties	Value
Density	1.36 g/cm³
Thermal Conductivity	0.37 W/m°K
Maximum Operating Temperature	+120 °C
Impact Strength	8.6 kJ/m²
Cross Breaking Strength	150 MPa

The composite sheet was drilled using a red laser with maximum power of 250 mW and wavelength of 650 nm. Due to limitation of the electronic circuit, the maximum achievable power output of the laser is 224 mW. Fig. 5 shows measurement of laser power using laser power meter (LaserBee AX) with display resolution in 1 mW increment to 3100 mW.

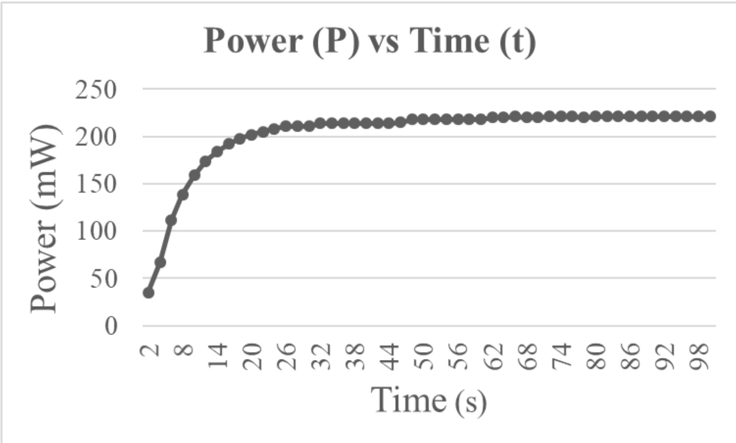

Fig. 5 - Power output over time

2.5. Process variables

The input laser processing parameters like standoff distance (SOD) and drilling speed were selected as process variables in order to determine the passes needed to obtain through hole. The selected value of parameters is non-structured. Multi-pass method was done due to restricted laser power of the laser diode itself which is 250 mW. Apart from that, multi-pass method was employed to control burning rate of cotton laminated plastic which can easily burn due to lack of assist gas. The position of focused laser beam is on top of the workpiece (focal length, Fig. 6a). By moving the lens upper and lower, the standoff distance changes which influences the beam spot sizes (Fig. 6b & 6c).

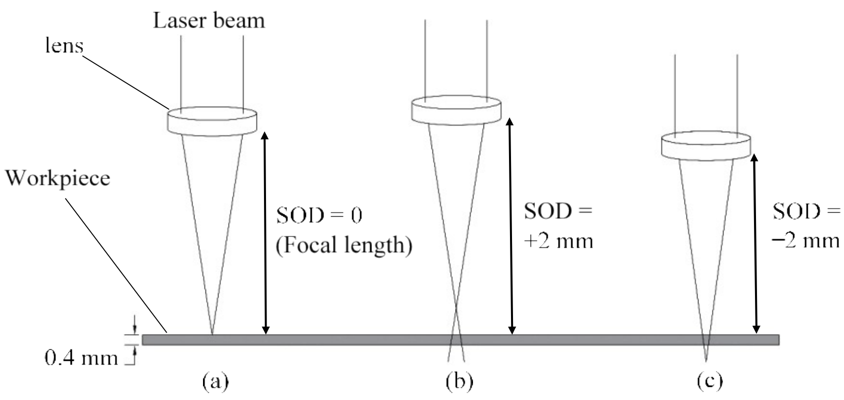

Fig. 6 - Position of standoff distance (SOD)

Heat affected zone (HAZ) can be considered as a region created resulting from laser drilling. Measurement of HAZ is important as it often causes unforeseen damage, creep and thermal fatigue. As shown in Fig. 7, HAZ can be divided into two dissimilar sections namely, oxide section and burnt resin section. Three measurements were taken to obtain the mean values of burnt resin section and oxide layer.

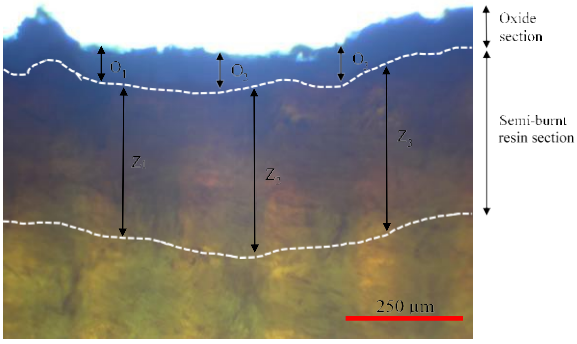

Fig. 7 - Oxide section and semi-burnt resin section measurement

The desired hole diameter was set at 5 mm. Hole diameter for each laser drilled holes is measured to determine the accuracy of the drilled hole with the assumption that the laser gantry is perfectly aligned. The hole dimension was measured from top to bottom and left to right (see Fig. 8) using an optical microscope (MD500, AmScope) with resolutions of 0.57 for 4x objectives. A scanning electron microscope (SEM) (TM3030, HITACHI) was also used for obtaining micrographs of the cut section.

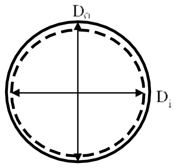

Fig. 8 - Hole measurement

$$D = (D_o+D_i)/2 \quad (1)$$

where D is diameter, D_o is outer diameter and D_i is inner diameter.

3. Results and Discussion

It is noted that cotton laminated plastic is a translucent for the red laser with wavelength of 650 nm to initiate the drilling process. Therefore, no laser-material was observed at this wavelength even though the laser was set to maximum power of 224 mW. To increase material's absorptivity, a thin layer of black paint was applied on the surface of the material sheet using a black marker. In the preliminary experiment, the highest drilling speed that can be achieved is 24 mm/min. Table 2 shows the responses of laser drilling for 0.4 mm cotton laminated plastic sheet. As shown in Fig. 9, there is significant HAZ and oxide layer formation along the drilling holes.

Table 2 - Laser drilling results of cotton laminated plastic sheet

No	Standoff distance (mm)	Speed (mm/min)	No. of passes	Ablation depth per passes (µm)	Burnt resin section (µm)	Oxide Section (µm)
1	-2	4	7	57.14	654.9	117.8
2	-2	14	8	50.00	482.8	116.7
3	-2	24	9	44.44	450.0	102.8
4	0	4	5	80.00	475.5	120.3
5	0	14	6	66.67	395.3	117.4
6	0	24	7	57.14	358.5	108.3
7	+2	4	7	57.14	366.9	120.3
8	+2	14	8	50.00	345.7	116.7
9	+2	24	9	44.44	331.1	111.6

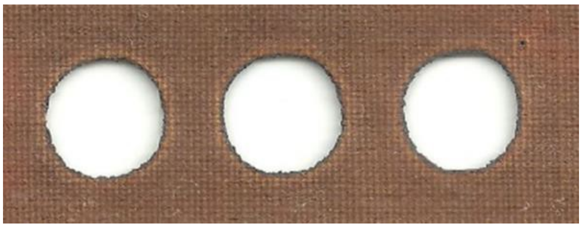

Fig. 9 - Sample holes drilled by diode laser

3.1. Effect of multi-pass technique

As shown in Fig. 10, it is discovered that at zero SOD the lowest number of passes is required for all drilling speeds as compared to positive and negative SODs. This is due to at zero SOD there is the highest focused beam that contribute highest energy and intensity which makes it capable to ablate faster. It is known that SOD affects beam spot size on the sample surface (refer Fig. 6), then influences the surface power density, which will affect HAZ, hole taper and drilling efficiency [18]. Hence, a larger spot means a thinner depth of penetration is required if the whole volume is to be evaporated with the energy supplied [19]. Also noticed that by the increase of drilling speed, the number of passes required to drill the hole increases. the reason is the increment of drilling speed decreases the exposure time of laser beam and material surface and due to cooling effect, the temperature is reduced in inner layers. It leads to less penetration of laser beam and reduction of material removal from the top and bottom surface of the composite.

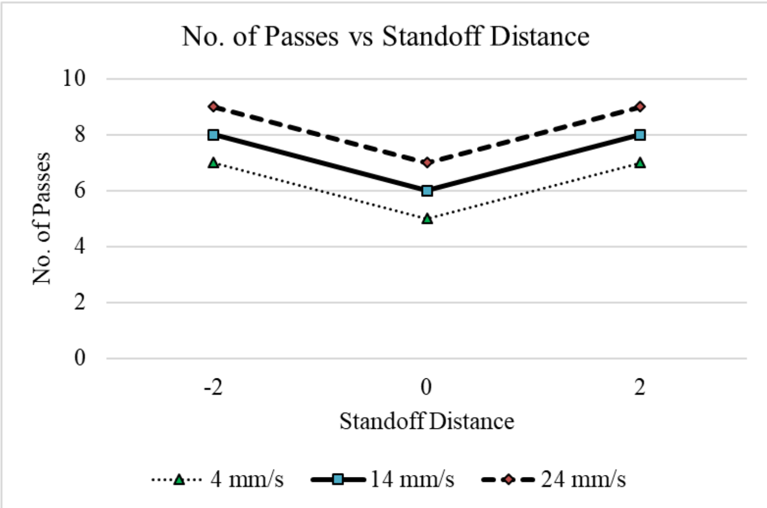

Fig. 10 - Passes vs standoff distance

3.2. Heat Affected Zone (HAZ)

Fig. 11 and Fig. 12 depict the effect of drilling speed and SOD on HAZ. As it was discussed before, HAZ comprises two dissimilar areas, oxide section and burnt resin section. From Fig. 11, it is found out at negative SOD, the oxide section possesses minimum dimension compare to others. Furthermore, higher cutting speed produces minimum oxide layer thickness. It is evident that the cutting speed of 24 mm/min produced smaller thickness compared to 4 mm/min. The reason of this phenomenon can be investigated in less interaction time between laser and the surface of the material. This results in less heat accumulation and burning of the cutting edge.

On the contrary, as shown in Fig. 12, negative standoff distance also contributes to larger burnt resin section width. Refer to Fig. 6, larger area is influenced by the laser beam at negative SOD. It should be noted the size of the beam spot would vary proportionally by moving the condenser lens closer or farther from the top surface of the material. For positive standoff distance, the lowest burnt resin section width is observed. Additionally, at lower drilling speed, longer time is needed to drill the hole which leads to the specimen to be exposed to the high temperature. Therefore, the burnt resin section becomes wider.

3.3. Hole diameter accuracy

Hole diameter was measured to make sure the accuracy of roundness and diameter of the holes. From the result as shown in Fig. 13, it is found out the most accurate to 5 mm diameter hole occurs at the speed of 24 mm/min and positive standoff distance. This is due to increasing the drilling speed and positive standoff distance contribute to acquire lesser HAZ (refer to Figs. 11 & 12) which makes the drilled hole diameter exceedingly closer to actual desired diameter.

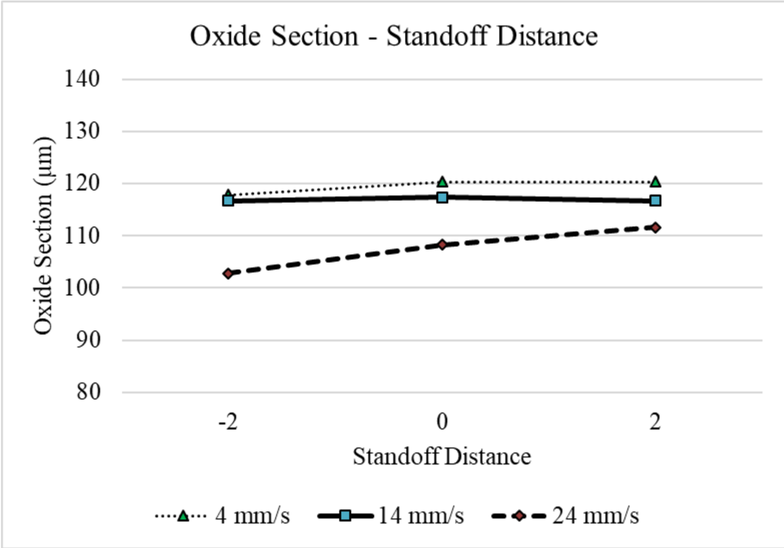

Fig. 11 - Effect of SOD and drilling speed on oxide section

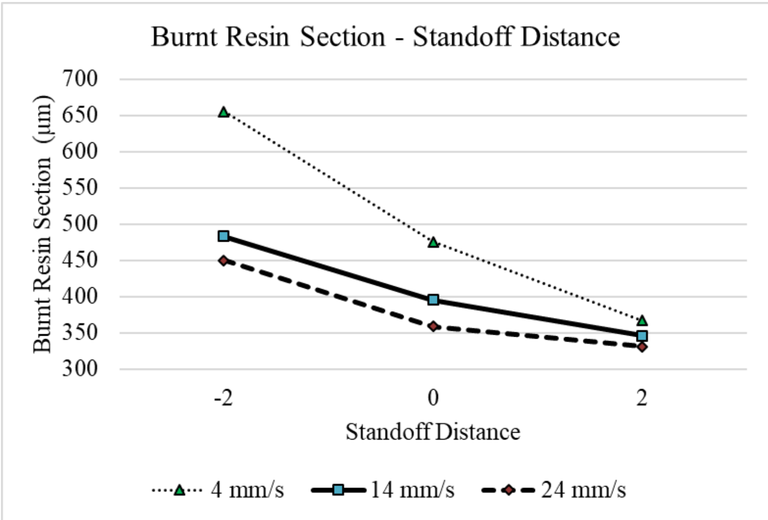

Fig. 12 - Effect of SOD and drilling speed on burnt resin section

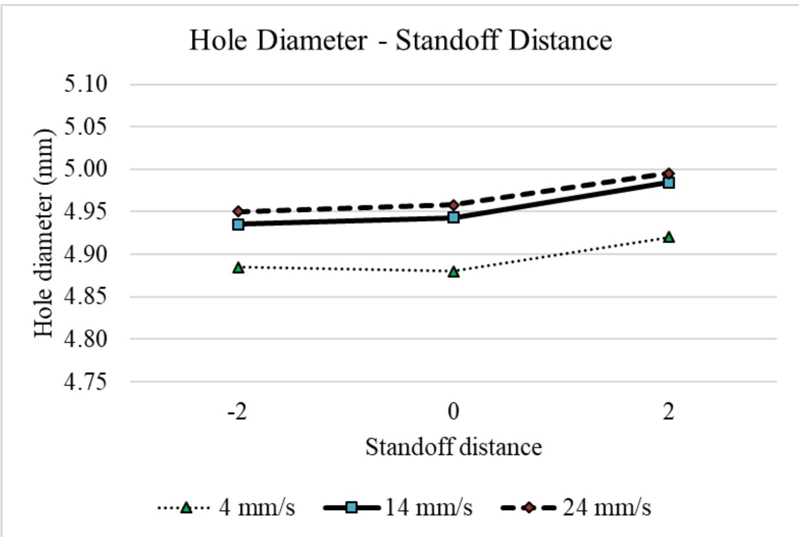

Fig. 13 - Effect of SOD and drilling speed on hole diameter

4. Micro-structure micrographs

Fig. 14 shows the microstructure image of cut section for composite with laser processed of high drilling speed, positive SOD and high number of beam passes. Protruding fibers occur due to the polymeric matrix vaporization in agreement with the results discovered in [20]. The protruding fibers length increases by decreasing drilling speed. It is noted that fiber pullout in multi-pass laser beam is more evident than single pass. Furthermore, it is observed that some cracks appear in the region of cutting. This is due to the accumulation of heat of the focused laser beam which results in melting and vaporizing of phenolic resin in the surrounding region of the cutting and increases the thermal strain and thermal stress of fibers.

As shown in Fig. 15, bubbles morphology presented in cutting region, is due to the melting of plastic resin and it undergoes expansion corresponding to input heat energy. On the contrary, by moving the laser source, HAZ appears in the region of cutting. Hence, resin due to having less melting temperature, starts burning which results in different color from other parts and strength loss of fibers in this region. The results are in agreement with [21, 22].

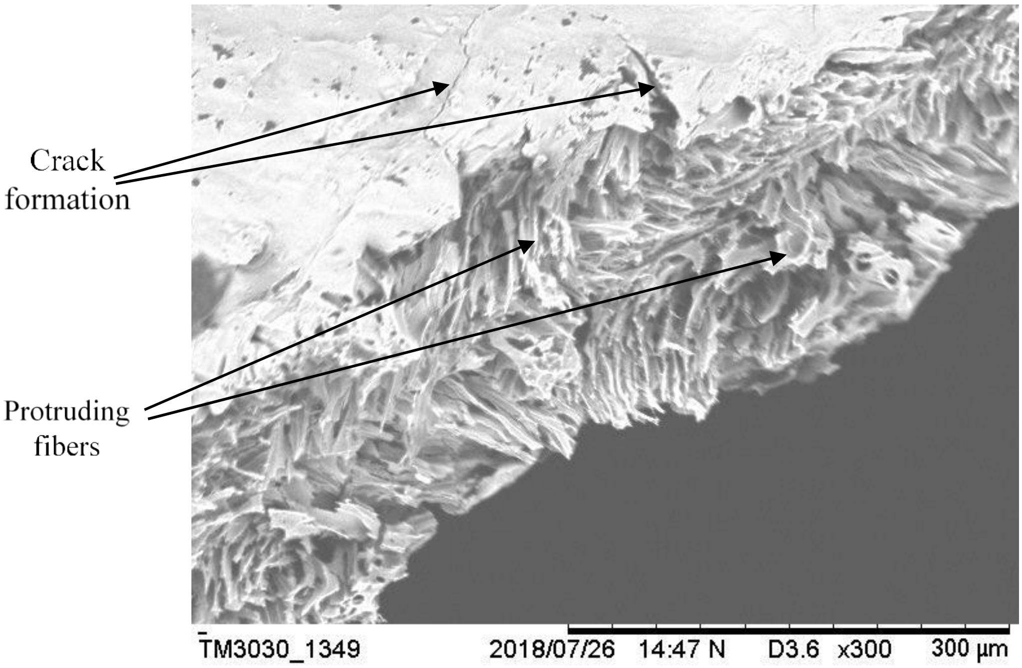

Fig. 14 - The formation of cracks and protruding fibers

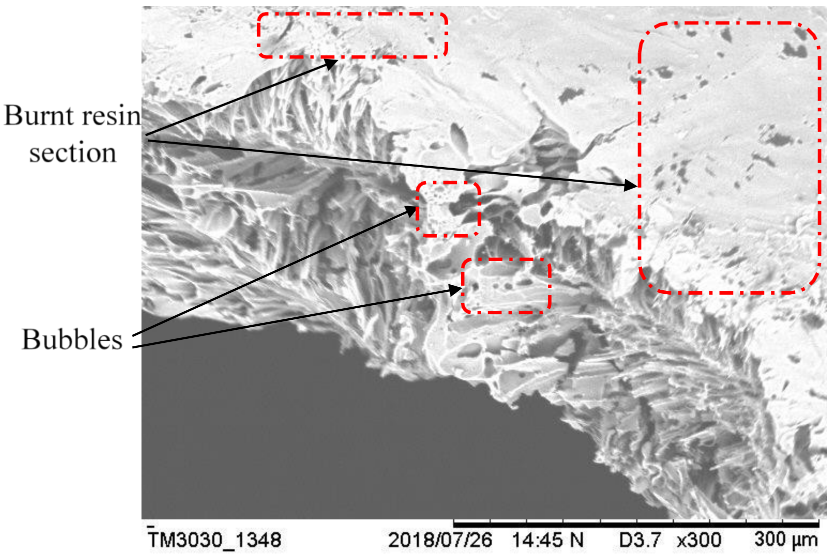

Fig. 15 - Burnt resin section and the presence of bubbles at cutting edge

5. Conclusion

In this paper, a low power laser trepanning drilling of cotton fiber composites was studied. The influence of number of laser passes, scanning speed and standoff distance (SOD) on material removal rate, cross-sectional heat-affected zone extension and hole diameter have been investigated. Results show increasing the drilling speed corresponding to positive SOD using multi-pass technique results in lower HAZ. Furthermore, the accurate dimeter of the circle can be achieved at higher speeds. In contrast, micro-structure micrographs show that cracks appeared in the area of cutting which is due to the residual thermal stress by laser heat accumulation. Additionally, protruding fibers were observed once the composite matrix vaporized. In comparison with the conventional mechanical drilling technique, the hole characteristics of 0.4 mm thick composite are found to have better qualities (i.e., absence of delamination) due to its non-contact method. It is recommended that an improved laser circuit driver should be designed and tested to ensure consistency in power output over longer period of use.

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