Parametric analysis of hole circularity for laser percussion drilling of carbon fibre reinforced plastic using Nd: YAG laser

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Abstract. Holes of diameter less than 1 mm have wide application of manufacturing sector. Laser beam can be conveniently used for creation of such hole in different materials. The Carbon Fiber Reinforced Composite (CFRP) is quickly replacing the conventional materials in most of the engineering applications. Therefore, a detailed parametric study to analyse the influence of factors like laser current, laser interaction time, pressure of assist gas, workpiece thickness and incidence angle on the geometrical accuracy of hole in terms of hole circularity at top (HCT) has been explored by changing the individual contributing factors. Small holes (< 1mm) have been fabricated with Nd: YAG laser of millisecond pulse duration in CFRP workpiece of thickness 1mm, 3mm, and 5 mm. It was observed that hole circularity at top surface is highest for zero angle of incidence. The increase of laser current, interaction time, and pressure of assist gas increases the HCT when the laser direction is normal to the workpiece whereas it shows a decline trend when the angle of incidence is 10° and 20°. The increase of workpiece thickness reduces the HCT irrespective of angle of incidence.

Keywords: Statistical modelling; parametric analysis; hole circularity; Nd: YAG laser, Laser percussion drilling

1. Introduction
Composites find wide usage in the aviation, wind and automotive sectors owing to their high specific strength, high thermal stability and improved wear resistance properties. The synergetic combination of matrix and reinforcement yields high fracture strength. Fiber-reinforced polymer (FRP) are composites made of a high-strength fiber like carbon, aramid, glass etc. and a thermoset polymer i.e., vinyl ester, polyester, epoxy. FRPs are good structural material due to their high specific strength and ease of application [1]. Drilling is one of the indispensable parts of the manufacturing industry. Due to anisotropy and inhomogeneity, drilling of composite materials by conventional methods produces several defects like burr formation, fiber pull-outs, thermal destruction, fiber fracture and delamination etc which deteriorates the hole quality [2]. Laser beam machining is rapidly substituting the other traditional and non-traditional machining methods available for creating holes of diameter smaller than 1 mm in variety of materials. In laser machining photon energy is transported to the target material to remove the material through melting and vaporization [3]. Any material that absorbs laser energy is suitable for drilling while mechanical drilling chooses suitable tools and materials that produce a high depth to diameter ratio for the drilling mechanism [4].
Fig 1. Causes and impact diagram for laser drilling

Fig 1 shows cause and effect diagram to form hole formation by laser drilling techniques. Holes can be created in work piece using single pulse, multiple pulse at single point (percussion), through laser cutting in single pass (trepanning) and laser cutting in multiple pass (helical drilling). Percussion drilling (PD) is a static drilling technique in which successive laser pulses strike the same spot to create hole cavity. Trepan drilling is basically used for producing large diameter hole by removing a cylindrical core from the material. Helical drilling split the process into multiple number of ablation steps [5]. Helical and trepan drilling are respectively single pass and multi pass hole generating technique normally used for producing large diameter hole. Solid state Nd: YAG lasers are normally used for PD due to its short wavelength and high peak power [6]. The wide acceptability of CFRP in various engineering applications will arise the need for inclined holes in near future. Since laser beam is the machine tool of future therefore its viability to create inclined hole in CFRP will further enhance the utility of CFRP. The probability of creating circular hole in workpiece is maximum when the laser is normal to the interacting surface and with the increase of angle of incidence, the circularity gets reduced. The benefit of inclined drilling is to decrease hole diameter and increase the density of the hole [6]. Machining of CFRP is more difficult compared to conventional materials due to its inhomogeneity and contrasting nature of the constituent element i.e., epoxy and carbon fibre. For example, the resin approximately decomposes at 500°C while the carbon fibres get vaporize at 3300°C [7]. Laser drilling (LD) of CFRP generates defect like charring, delamination and matrix recession which can destroy the circularity of the laser fabricated hole. Since circularity controls the primary function of hole therefore in-depth analysis of the effect of the laser input parameters, workpiece thickness and incidence angle on hole circularity will help us to improve one of the important dimensional of hole quality i.e., circularity. Sincedrilling starts with the interaction of laser at the top surface therefore the hole circularity at the top has been evaluated here. Several authors have probed the effect of process variables on various aspects of hole quality through modelling and optimization. Few numerical and analytical studies have also been performed to get in-depth knowledge of the LD process.

Sezer et.al. [1] investigated the HAZ and Recast layer thickness for Nd: YAG laser percussion drilling at different incidence angle. Nimionic 263 used as a workpiece with 2.5mm thickness. Laser power, pulse width and oxygen as an assist gas were used a process variable to find Recast layer
thickness and HAZ. A 3D numerical simulation technique is used to analyse the data. The obtained result indicate that HAZ & recast layer were thicker for small incidence angle. Wider HAZ were obtained at the front and trailing edge of the hole at the opening and exit side of the drilled hole. Parametric analysis for LD of Nimonic 263 at 30° incidence angle was investigated by Sezer et.al. [2]. Effect of pulse width, laser power, pulse frequency on delamination and melt flow ejection were analysed for thermal barrier coated superalloy. Shin et.al [4] investigated the delamination and melt flow ejection during Nd-YAG LD of IN 718 alloy using technique of helical drilling technique at incidence of 30°. The effect of input process parameters like laser power, focal position, speed and assist gas pressure on hole diameter at inlet and exit, recast layer thickness were analysed. Results show that high laser power at lower speed and fixed focal position produced cooling holes more rapidly. Yao et.al [5] develop a mathematical model to analyse the effect of plume ejection angle during Nd: YAG LD of 0.779 μm thick Graphite substrate. The inclination angle used for drilling are 0°, 10°, 20°, 30°, 40° 50°, 60° degree from normal plane. Laser power and inclination angle were used as a process variable while drilling depth and plume ejection angle were the response variable. Authors found that without shielding gas, plume ejection is normal to the surface of the workpiece and it do not depend on the incidence angle. Ashkenasi et.al [8] investigate symmetric mass distribution in glass plate during fibre LD in trepanning mode. Displacement in focus, rotational speed was taken as a process variable at 3-5° incidence angle. Authors found that nanosecond (ns) and picosecond (ps) laser pulses were very effective for trepanning drilling. Romoli et. al. [7] investigated the application laser induced periodically surface structure (LIPSS) techniques to find hole diameter and recast layer thickness using fibre laser. Stainless steel of thickness 350 μm were used as a workpiece material. Wavelength, pulse duration, spot diameter, pulse energy, pulse frequency, rotational frequency was used as a process variable in femtosecond mode of fibre laser at 0°,3°,4.5° degree inclination angle.

The above literature survey reveals that even though several efforts have been done to investigate the effect of laser and non-laser input parameters on various aspects of hole quality but parametric examination to explore the explicit effect of individual parameters on dimensional accuracy of hole has not been attempted. Therefore, one-parameter- at- a-time (OPAT) analysis has been undertaken here to understand the independent effect of laser peak power, pulse width, assist gas pressure, thickness of workpiece and angle of incidence on HCT. Solid state pulsed Nd: YAG laser with millisecond pulse duration were used to drill inclined holes of small size (< 1 mm diameter) in CFRP of different thickness. This procedure is repeated for all factor until to complete the experiment. It requires m(n-1) +1 experimental trials where m is a factor having n levels. The method gives approximations of the main conditional effects of each experimental factor [12].

2. Materials and Methods

Fabrication of CFRP composite

The CFRP workpiece in the form of laminated plates were prepared from bidirectional high strength carbon fiber. The fiber thickness of CFRP is 200 gsm per piece. It was prepared by hand layup process with a fiber volume of 60 percent and remaining reinforcement material. The matrix material used as an epoxy Lapox L-12 mixed with hardener (K-6) at room temperature. Both the epoxy and hardener were supplied by Atul Ltd, Atul, Valsad, Gujarat (India). The entrapped air was expelled by proper rolling and carbon fibers and epoxy were serially fed into the mould to obtain workpiece of desired thickness. The produced hybrid composite has a dimension of 200mm x 200mm with thicknesses of 1,3 and 5 mm. The working thickness of the CFRP composite samples was determined by the optical Vernier caliper with a least count of 0.001 mm and the flatness of the manufactured sample was tested by dial indicator.
Methodology

The complete experiment comprises of three stages, in the beginning CFRP composite was fabricated. In the next stage, the composites were machined using a laser beam machining system. Finally, diameter of the drilled holes was measured to determine the HCT.

![Fabrication of CFRP composite](image1)

![Laser drilling of CFRP composite](image2)

![Inclined hole measurement methodology](image3)

**Figure 2.** Flow chart of CFRP composite

3. Experimental Details

Laser drilling were carried out on CFRP of three different thicknesses i.e., 1, 3 and 5 mm using 250-watt Nd: YAG laser of pulsed mode. All the experiments were conducted at RRCAT Indore. During the experiment compressed air were used as an assist gas. Three repetitions of each experiment were carried out to minimize the error and the mean value of these three readings were considered as the final observation. In OPAT approach, only one variable is changed at a time and all other factors are kept constant throughout the test run. This approach unveils the influence of the selected variable on output performance characteristics [12]. Pilots experiments were conducted to determine the levels of input process parameters so that through hole can be obtained for all the thickness.

| Machining Parameter | Unit | Symbol | Level-1 | Level-2 | Level-3 |
|---------------------|------|--------|---------|---------|---------|
| Pulse Current       | ampere | A      | 200     | 220     | 240     |
| Pulse Width         | ms    | P_w   | 2       | 4       | 6       |
| Gas pressure        | kg/cm² | G_p  | 4       | 6       | 8       |
| Thickness           | mm    | T_i   | 1       | 3       | 5       |
| Incidence angle     | degree | θ     | 0       | 10      | 20      |

**Table 1.** Input process parameter range

Measurement of hole circularity

HCT as defined in Eq. (1) represents the extent of geometrical accuracy of the drill hole. Higher value of this ratio indicates good circularity of the drilled hole [10]. It also represents the divergence with respect to ideal circular hole. In this work, the hole-circularity was measured using the Leica MC170.
HD Optical Measurement Microscope (OMM) at 10 x magnification. The diagram and real description of the diameter calculation are seen in Figs. 3 (a-b).

Figure 3. Diameters measurement system (a) Normal representation (b) Authentic measurement. It is defined by the ratio of \( D_{\text{min}} \) to \( D_{\text{max}} \), calculated by using Eq. (1).

\[
HCT = \frac{D_{\text{min}}}{D_{\text{max}}}
\]  

(1)

4. Results and discussion

Methodology (based on pilot theory)
After specifying the levels of input parameters through pilot experiment, 54 micro holes were fabricated in 12 sets for experiment. The individual influence of five input parameters i.e., pulse current, pulse width, air pressure, workpiece thickness and angle of incidence on HCT has been analysed and discussed in the subsequent section.

Effect of pulse current on HCT
Fig. 4 depicts variation of HCT with current at different incidence angle at constant pulse width and assist gas pressure. It is observed that the hole circularity of CFRP at zero-degree angle of incidence increases with current. The variation of HCT is gradual till 250 A but after it increases at very high rate. The HCT at 10\(^\circ\) and 20\(^\circ\) angle of incidence shows a reverse trend and after gradual decrease from 200 A to 220 A, it begins to decrease significantly with the increase of current. It is also observed from the Fig. 4 that highest circularity is obtained when the angle of incidence is zero degree. Since the pulse width and assist gas pressure remain unchanged, the energy per pulse and total power increases with the rise in peak current. The heat diffused into the workpiece depends mostly on the laser peak power. Due to the strong thermal diffusion of CFRP, the heat is quickly dissipated, reducing the thermal gradient. When drilling in parallel to the fibre orientation weak hole circularity created with maximum HAZ produced, but in perpendicular direction the fibre orientation correct hole formation with minimal HAZ [11].
Effect of pulse width HCT

When the increases of pulse width at constant pressure, peak current and thickness of material, the energy content of each pulse increases. Fig. 5 elucidates that at the beginning the HCT increases with the rise of pulse width due to higher variation between the diameter of the hole. The laser pulse is used to assess the extent of thermal penetration and the pulse energy supplied to the workpiece. Increased thermal diffusivity and conductivity of CFRP composite with temperature ensures that most of the heat is discharged and a large number of laser pulses are needed to create the melt. At zero incidence angle when the laser beam is perpendicular to the workpiece, the increase of pulse width increases the HCT because higher heat content helps to evaporate the molten material in a better way. When the drilling is performed at incidence angle other than zero the HCT decreases very gradually with increase of pulse width. Fig.5 also shows that the influence of the pulse width adjustment at its lower stage is very small and that the pulse rises of 50 per cent from 2 ms to 6 ms is marginally raised by just 10 per cent of the circularity of the hole.
Figure 5. Change of HCT with pulse duration at fixed input parameter i.e., \( T_i = 3 \text{mm}, A = 250 \text{ ampere}, G_p = 6 \text{ kg/cm}^2 \).

Effect of gas pressure on HCT
The increase in gas pressure at fixed value of pulse width, current and thickness resulted in the increase of HCT as shown in Fig 6. High value of assist gas pressure improves the drilling rate and the consistency of the holes due better removal of molten epoxy and carbon fibre.

Figure 6. Change of HCT with Gas pressure at fixed input parameter i.e., \( T_i = 3 \text{mm}, A = 250 \text{ ampere}, P_w = 4 \text{ms} \).
As the angle of incidence increases, the HCT begin to decrease with the gas pressure as shown in Fig 6. It can also be observed from the figure that the reduction of HCT at 10° angle of incidence is lower compared to 20°.

**Effect of workpiece thickness on HCT**

CFRP of thickness 1 mm, 3 mm and 5 mm were considered in this experiment. As shown in Fig 7, when thickness of workpiece increases the circularity reduces for all angle of incidence including zero. The figure also reveals that when the thickness is 1 mm the effect of increasing the angle of incidence is more prominent compared to higher thickness. For zero-degree angle of incidence, the increase of thickness reduces the HCT more significantly. The HCT varies from 0.65 to 0.46 at 10-degree inclination while at 20-degree inclination HCT varies from 0.43 to 0.35 for 5 mm thickness. The maximum and minimum variation of circularity in the range of 0.77 to 0.47 at zero-degree inclination.

![Graph showing variation of HCT with thickness](image)

**Figure 7.** Variation of HCT with thickness at fixed input parameter i.e., \( G_p = 6 \text{ kg/cm}^2, A = 250 \text{ ampere}, P_w = 4 \text{ ms} \).

**5. Conclusions**

In this experimental analysis the individual influence of laser and non-laser input process variables on geometrical correctness in terms of circularity of laser fabricated hole in CFRP has been explored. Holes were generated on 1 mm, 3 mm and 5 mm thick workpiece of CFRP using millisecond pulse duration Nd: YAG laser. Effect of pulse current, pulse width, workpiece thickness, gas pressure and angle of incidence on HCT during laser percussion drilling of CFRP has been elaborated. The following conclusions can be drawn out based on the findings of the experimental analysis.

i. Solid state pulsed Nd: YAG laser of millisecond pulse duration can be used for the processing of small diameter holes (< 1 mm) in inhomogeneous and anisotropic materials such as CFRP of different thickness.

ii. The effect of changing the angle of inclination at lower current (200 A) on HCT is significantly smaller compared to higher current. At zero-degree angle of incidence the HCT increases with current whereas for higher angle of incidence HCT decreases with rise of current.
iii. The hole circularity increases with rise of pulse width at zero angle of incidence. The increase of pulse width from 2 ms to 6 ms at zero-degree angle of incidence increases the HCT from 0.65 radian to 0.8 radian. The corresponding decrease of taper for 10° and 20° angle of incidence are respectively 30% and 44.4%.

iv. Laser beam normal to workpiece surface increase the HCT with gas pressure but laser drilling at 10° and 20°-degree angle of incidence reduces the HCT with the rise of gas pressure.

v. The increase of thickness always reduces the HCT during laser drilling of CFRP irrespective of angle of incidence. The extent of variation of HCT with the change of angle of incidence is larger for small thickness and it get reduced with the increase of thickness.

vi. The experiment reveals that percussion drilling technique can create hole in the CFRP and GFRP sheet of above thickness till 20° degree angle of incidence. Below this range better hole circularity achieve with minimum taper formation.

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