Investigation of CO_2 Laser Drilled Micro Holes for Heat Affected Zone and Structural Integrity in CFRP Composites

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Abstract—This paper analyses the CFRP composites upon which laser drilling is performed using Marbach Compact CO2 laser cutting system (2115 DC-020), and their analysis is done through scanning electron microscope (SEM) JOEL JSM-6490 LV. Considering the continuous wave laser instead of the pulsed laser and the selection of the optimum gas pressure of 4bar of the assist gas (Argon) in the laser in this study has resulted in the contribution of least heat affected zones. Optimum parameters of the CO2 laser drilling techniques such as the cutting speed, gas pressure, assist gas, laser type, laser beam power, and frequency are developed. The characteristics of the workpiece such as the material, diameter, and thickness is also considered, and an optimization process is performed to maintain the structural integrity of the composite by reducing the induction of HAZ in the composite, after performing the laser drilling. The SEM images for the various parameter values are developed. The optimization of these parameter values concludes the paper.

Keywords—*CFRP, HAZ, Laser Drilling, SEM, Structural Integrity.*

I. INTRODUCTION

Composite materials are emerging as the materials of the future with enormous applications in various engineering domain, because of its various structural, mechanical and chemical properties. While joining two different composite structures, drilling is one of the essential machining operations required. The conventional drilling poses a large number of problems due to the contact type of machining, such as the damage and cracks in the material, tool wear, mechanical degradation of the material under machining [1]. However, with the laser machining being a non-contact process all these problems are reduced. Machining through laser techniques involves thermal processes and is independent of the hardness and strength of the material, making it a suitable machining method for the non-homogenous material [2]. The high density power beam from the laser is converted to heat upon impact with the work piece. This localized impact zone with extremely high temperatures begins to melt or vaporize, leading to material removal [3], [4]. Laser cutting can be controlled to a high degree of precision with reproducibility by adjusting several parameters to obtain micro-level holes. However, due to the anisotropic nature of the composites the holes get distorted and results in HAZ (heat affected zone) [2]. Grooving experiments [5] using beam power levels from 350W to 650 W at 300 Hz were conducted, which represented HAZ by cross-sectional area, and was given as A=function(const. SQ/F), where A depicted the sectional area of thermal damage, S as the peak power, Q as pulse duty, and F as the traverse speed. It was finally concluded that with the decrease in the traverse speed (F) and the increase in the specific laser energy, the sectional area of HAZ (A) increases, also the HAZ was observed in large quantities when the nitrogen pressure was low. Many research works and experimental studies were carried out which resulted in a numerical model considering the composite to be anisotropic in nature [6], [7]. According to their second research paper they used section area to represent the HAZ and found that HAZ is proportional to the specific laser energy, given by PQ/V. In their third research work [7] they developed a more advanced model which incorporated temperature dependence of thermal conductivity wherein the maximum width of HAZ at T = Tc (char temperature of matrix), was observed instead of the sectional area of HAZ. A mathematical model was developed for grooving-in off the principal material axes, according to which the maximum HAZ was found for grooving perpendicular to the fiber axis and least for parallel grooving. Laser drilling was carried out on APC-2 (PEEK and 61% carbon fiber) composite [1]. The Nd:YAG pulsed laser was used which melted the matrix and volatilized from around the hole. The swelling in the order of 50% was observed around the region of the hole. The swelling of the fiber was studied intensely from the experiments on fiber composites [8] which concluded it to be a factor dependent on the impurities in the carbon fibers. Experiments on the fiber composites with heat treatment resulted in 60% less fiber swelling as compared to the composites not having undergone heat treatment. This is due to the fact that the carbon content in the heat treated materials is increased while the amount of impurities is reduced. When the carbon fiber composites are heated rapidly as in laser drilling the impurities evaporate creating high gas pressure. This high pressure leads to swelling of the fibers within the HAZ which are retained even when the material cools down and returns to normal pressure. Many experiments [9]-[13] were conducted to study the effects of the CFRP laminates upon machining and predicted the various parameters in laser cutting of composite materials such as kerf

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width at the entry and exit, MRR and energy transmitted through the cut kerf. A thermal model [14] was developed for the laser cutting of fibre reinforced plastic composites for the prediction of maximum laser cutting speed. The conclusion drawn was that when vaporization temperature is reached, the material is removed by an instantaneous evaporative process, with the assumption that no melting takes place in HAZ. A numerical method [15] was developed based on the thermal energy equation to predict the HAZ and the shape of the hole, which have been applied on a number of test cases and the results are in good agreement with the experimental data. This method is particularly useful in predicting the HAZ and the shape of the hole during the laser drilling process. The observation of the HAZ area in CFRP material in Laser machining resulted in the fiber swelling of 50 or 60% and fibers near the top are seen to curl up [1]. The laser processing is very challenging [16], as the heat affected zone (HAZ) has been the major obstacle for wide industry applications of laser machining of CFRP composites. The results show that minimum HAZ (about 50 lm) is achievable in machining of CFRP composite by using short pulsed UV laser.

Investigation of the machining-depth [17] which depended on the focus positions and various scanning speed, resulted in formulating the threshold properties of the power density in CFRP processing. It was found that the machining-depths were also increased as the sizes of overlapping areas were increased. The investigation of the results of the CO_2 laser trimming [18] of fiber reinforced plastic (FRP) composites using scanning electron microscope (SEM) analysis revealed that matrix constituent in both composites incurred to elevated cutting temperature which resulted in melting and adhering to the cut surface and have an adverse effect on its quality (Ra of up to ~ 6 μm). Greatest entry kerfs width of 0.5 mm and 0.28 mm was measured for GFRP and CFRP samples respectively using pulsed UV laser. With the carbon fibers sliced into small chunks, the accumulation of the heat in the material is highly favored resulting in HAZ.

II. Fiber Reinforced Plastic (FRP)

Fiber-reinforced polymers/plastics is a material developed typically for strengthening of reinforced concrete and masonry structure as it has high strength to weight ratio and high corrosion resistance. However, at present, their cost is high. The commonly used fibers are Carbon fibers, Glass fibers and Aramid fibers along with the commonly used resins are polyester, vinyl ester and epoxy. Composite materials can be produced by a range of processes. These processes vary from manual lay-up of reinforcement and hand application of resin to fully automated continuous processes. The Hand lay up being the simplest, oldest and common open molding method, due to its ease of use and flexibility, allows for all types of reinforcement to be utilized and has been adopted in this study for preparing the composite material.

A. Machining on Carbon Fiber Reinforced Plastic

Laser drilling of cylindrical holes generally occurs through melting and vaporization of the work piece material through absorption of energy from a focused laser beam. The energy required to remove material by melting is about 25% of that needed to vaporize the same volume, so a process that removes material by melting is often favoured [19]. For the purpose of material processing such as welding and cutting, carbon-dioxide laser is the best suited laser system due to its operating wavelength range of 9.4 μm-10.6 μm. CO_2 lasers operate in both continuous and pulsed modes at the infrared wavelength of 10.6 μm [20]. Carbon dioxide lasers have the highest-power continuous wave lasers that make them suitable for machining operations on the CFRP composites [21]. The efficiency in terms of the ratio of output power to pump power is 20%.

However, it is not uncommon that laser, as a thermally acting tool, may damage the matrix element in the composite, which reduces the composites mechanical properties. With regards to composite machining, laser beam was relatively less used to cut CFRP and GFRP aiming at improving cutting productivity [22], [23]. The anisotropic properties of composites, lack of plastic deformation, poor thermal conductivity and issues related to the HAZ, charring, and potential delamination are the major complications for industrial applications with laser beam machining of composites [24]. However, numerous reasons make CO_2 lasers attractive for cutting FRP composites due to their good-quality beam combined with high output power. It was also reported that Excimer laser machining of CFRP is achievable with diminutive heat-affected zones (HAZ) of only 5–30 μm, however, the main drawback was the limited laser power which resulted in low cutting rates [28]. Yet for relatively thin laminates of 0.7 mm thick, a maximum cutting speed of only 4.9 mm/min was used [26]. It can be concluded that research on laser cutting of GFRP and CFRP is deemed limited especially using CO_2 laser beam. Additionally, the use of low cutting speeds (which does not meet today's market requirements and expectations) is arguably the focal drawback of laser cutting. Another serious drawback of using the laser drilling process for the CFRP is the damage to the matrix material in micro-level scale (inducing HAZ) which is able to significantly alter the physical characteristics of the material. The heat-affected zone (HAZ) is the area of the base material, either a metal or a thermoplastic, which is not melted and has had its microstructure and properties altered by welding or heat intensive cutting operations. The large differences in material properties of the carbon fiber and the epoxy resin in carbon fiber reinforced plastic (CFRP) composite make laser processing very challenging. It was found that laser parameters such as laser power, repetition rate, work piece temperature determines the extent of HAZ. Therefore, the present study is carried out to investigate the drilling of CFRP composites using CO_2 laser beam in order to provide better understanding of the impact of key process variables on surface quality and productivity when employing relatively higher cutting speeds in addition to identifying the best/preferred levels for process control factors.

From the existing literature the authors' are able to conclude that laser drilling on the CFRP is a promising processing method with high micro-level accuracy to obtain good surface finish, however, the heat produced during the laser drilling is of the major concern as it induces HAZ (Heat Affected Zone) which compromises on the structural integrity of the product [26]. Extensive research is ongoing in the laser machining processes on the CFRP material, but to the best of authors' knowledge limited availability of the resources makes the investigation of the laser machined CFRP material even more challenging. This research work has been taken up due to this challenge and the analyses of the HAZ and the surface finish in terms of its topography and roughness of the laser drilled product using SEM techniques are performed. The objective of this research work is to minimize the damage due to laser drilling in CFRP composite materials using optimization of drilling parameters.

III. Methodology and Experimental Setup

The methodology adopted in this study is as explained as follows: -

1) Hand layup process
2) Laser drill
3) Scanning electron microscope (SEM)

B. Hand Layup Process

The basic hand layup process is used in this study for producing the composite materials. The following elements are successively applied onto the mould surface

- Release agent
- Gel coat
- Liquid thermosetting epoxy resin – LY545
- Reinforcement or hardener – HY045

Several layers were required to obtain the desired product fabric which are positioned manually in the open mold, where resin is poured, brushed, or sprayed over and into the fabric. Entrapped air is removed manually with rollers to complete the laminates structure. Laminates are left to cure under standard room temperatures by using matrix resins. Curing is initiated by a catalyst in the resin system, which hardens the fibre reinforced resin composite without the requirement of the external heat. This operation is repeated for each layer of reinforcement to obtain the desired thickness of the structure.

C. Laser Drilling

The experimental laser drilling process were carried out on a state-of-art Marbach Compact CO_2 laser cutting system (2115 DC-020). The machine is CNC controlled employing high-speed flatbed offering maximum cutting speed of 20,000 mm/min together with maximum cutting power of 2500W. CFRP work piece materials were manually laid up to provide nominally 3mm thick symmetric unidirectional CFRP laminates. The laminates were then cured according to the manufacturers' specifications to give a fiber weight fraction of ~ 65 % and subsequently cut into plates.

The CO_2 laser drilling involves 3 stages for the material removal: (1) melting (2) vaporization (3) chemical degradation which essentially requires the breaking of the chemical bonds. The melting and vaporization of the material is due to the thermal energy gained from the high density laser beam which is focussed on the work piece using lenses as shown in the figure 1 below [25].

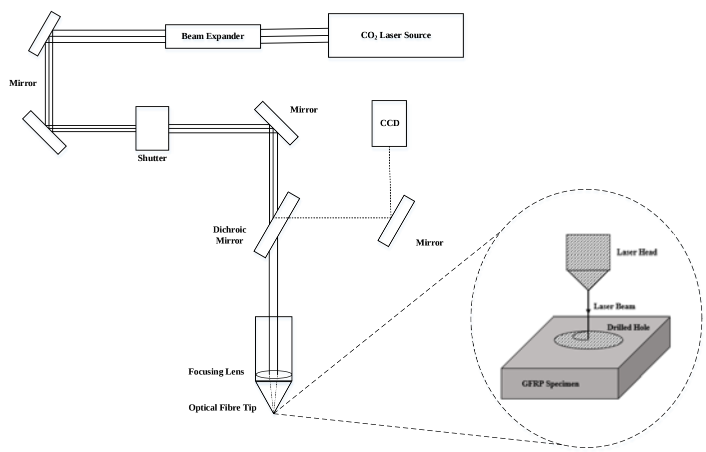


Fig. 1 Schematic Diagram of CO_2 Laser Drilling

The CO_2 laser drilling was performed with the various process parameters at different values and their contribution to the extent of the induction of HAZ was studied. The process variables in the laser drilling were varied with the cutting speeds of 1000 mm/min, 1250 mm/min, 1500 mm/min, and 1750 mm/min, frequency as 200 Hz, 400 Hz, and 600 Hz, power beam of the laser from 2250 W to a maximum of 2500 W. The gas pressure of the drilling system was studied at three different pressures of 3 bar, 4 bar and 5 bar. The continuous and pulsed laser type were adopted to find the best suited for laser drilling. The characteristics of the workpiece such as the material, diameter, and thickness were also varied correspondingly to observe the influence on the induction of the HAZ in the composite material and to analyse the surface finish as well. Shown below in figure 2 is the laser drilling in progress.

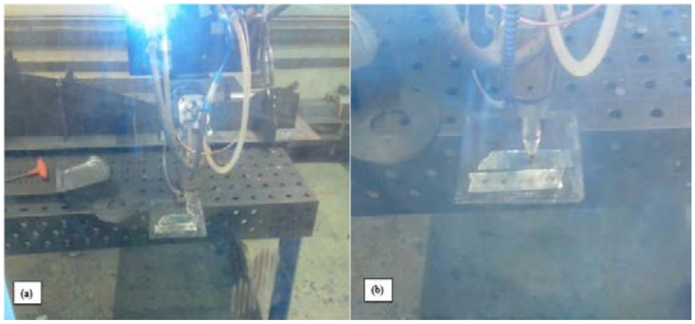


Fig. 2 Laser drilling in progress

CFRP with layer thickness of 1000µm were used for laser processing. The laminate ply was composed of unidirectional fibres in 00 orientation in which all fibers are aligned in parallel direction and within the plane, and 900 orientation in which the fibres are perpendicular to the axis but lies within the same plane. The 00 unidirectional orientation provides higher bending strength, while the 900 orientation makes it flexible. Thus, the cross ply laminate used has the orientation of the laminates as 00/900/900/00 and a resin that hardens them as such. The resulting cross laminate ply was then used for the laser drilling experiment, which was of the thickness of the order of 3 – 4 mm. The speed on the surface of the material was kept constant while scanning the surface with the laser beam. The constant distance between the laser focus and the surface was maintained for the uniform heat transfer to the material to enhance the uniform material removal rate throughout the surface region in consideration. The focus positions of laser beam on the CFRP surface is of the utmost importance while considering the rate of transfer of heat to the work piece. It was observed that by varying the distance between the laser focus and the surface, a higher or lower rate of heat transfer to the surface could be achieved which resulted in poor material removal and hence a decrease in the drilling efficiency. The CFRP surface was taken as the reference and was defined as the origin. The positive sign indicated the focus of the laser beam on the inside of the CFRP surface, whereas the negative sign represented the focus to be located above the surface. The transfer of heat from the laser beam to the material surface is predominantly depended on the focus of the laser beam with respect to the reference surface [27].

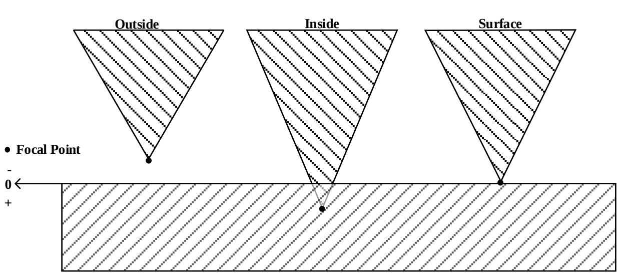


Fig. 3 Positioning of the focal point

D. Scanning Electron Microscope

The SEM analysis is used to produce the various signals that contains the information about the sample's surface topography and composition that ascertain the influence of the process parameters [27]. The production of the image to analyse the surface morphology of the laser drilled holes is done by the combination of the electron beam which is scanned in a raster scan pattern with the beam's position and the detected signal. The SEM used for the analysis of the laser drilled holes is the JOEL JSM-6490 LV. The SEM was able to capture essential regions of swelling around the drilled hole, indicating the induction of the HAZ due to laser drilling. SEM analysis is particularly helpful to detect the regions of deviations from circularity and the degree of taper in the drilled holes to obtain near-cylindrical nature [29].

IV. Results and Discussion

To obtain a finely drilled hole in the CFRP work piece, many parameters were identified and their corresponding contributions to obtaining the hole with the least value of induced HAZ, were observed, as shown in the following fish-bone diagram: -

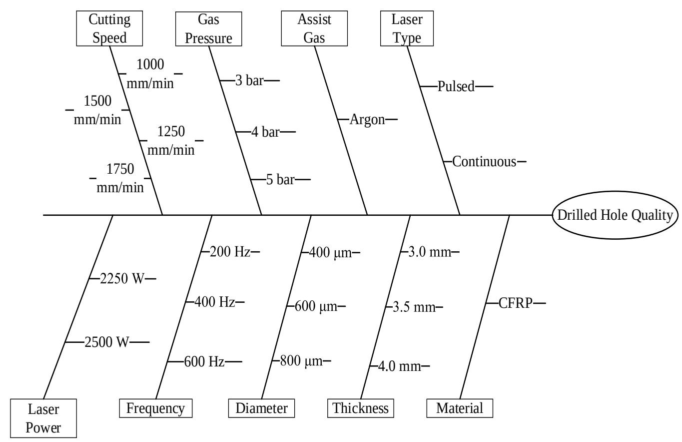


Fig. 4 Fishbone Diagram of experimental parameters for obtaining better quality of drilled holes

The figure 5 shown below depicts the SEM laser drilled hole in composite structure showing matrix volatilization inducing fiber swelling, and damage. When the carbon fiber composites are heated rapidly as in laser drilling the impurities evaporate, creating regions of high gas pressure. This high pressure leads to swelling of the fibers within the HAZ which are retained even when the material cools down and returns to the normal state of pressure. Laser delivers high power-density beam which upon impact with the work piece is converted into heat. As the impact zone is very small, very high temperature capable of melting or volatilizing the material can be attained, which leads to material removal. Residues and micro cracks are normally observed as a result of the thermal process. The high amount of heat transfer is because of the focusing capability of the laser drilling system, which results in material removal through vaporization. The degree of HAZ induced mainly depends on the laser parameters employed and also to some extent on the material being drilled and their thicknesses [23] [24]. The induced HAZ in and around the drilled hole effects the structural integrity of the material in terms of the damage to the surface, and the deterioration of the fiber material within.

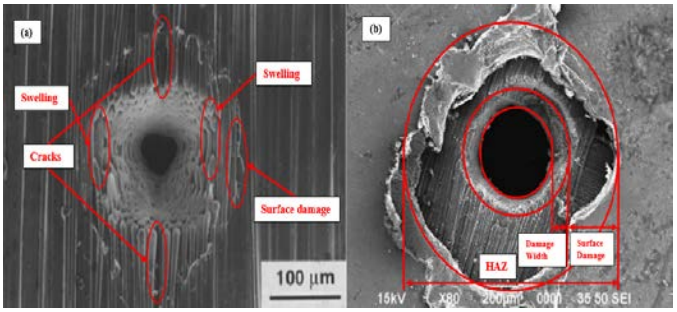
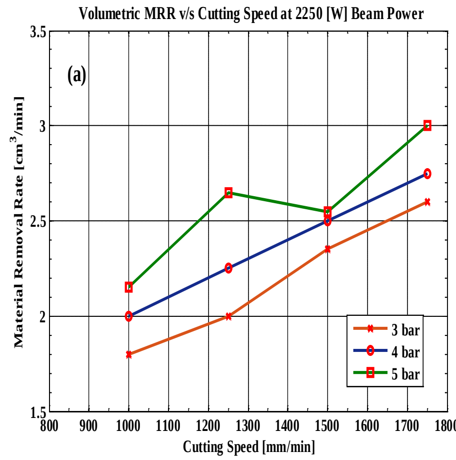


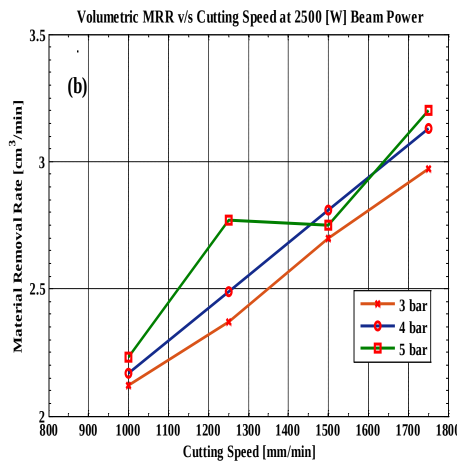
Fig. 5 SEM images of a laser drilled hole indicating the fiber swelling and the damaged areas

The parameters as observed from the fish-bone diagram in figure 4, is analyzed during the laser drilling and their corresponding contribution to the induction of HAZ and the resulting damage is identified in the SEM images as shown in figure 11 later.

The volumetric material removal rate (cm3/min) as a function of the cutting speed (mm/min) of the CO_2 laser system has been plotted in the figure 6 as shown below, at the two laser beam power of 2250 W and maximum power 2500 W. It is clear from the plot that with the increase in the cutting speed, the higher amount of material will be removed from the work piece, thus increasing the rate of drilling. With the gas pressure at 4 bar, the material removal rate increases steadily with the corresponding increase in the cutting speed from 1000 mm/min to 1750 mm/min. Whereas, with the 3 bar gas pressure the material removal rate is relatively lower and the induced HAZ is higher because of the lower pressure leading to larger deposition area, and with the 5bar gas pressure the rate of material removal fluctuates, with the corresponding increase in the cutting speed from 1000 mm/min to 1750 mm/min. At 1500 mm/min the material removal rate decreases significantly for a gas pressure of 5 bar, which is due to the fluctuations caused because of the higher gas pressure than required. At maximum beam power of 2500W, the 4bar gas pressure is more efficient in removing the material than the 5bar gas pressure, as the high beam power and high gas pressure results in over excitation of the laser source, and a slight fluctuation is observed. Thus, for a steady increase with respect to the rate of machining the gas pressure at 4bar and a maximum laser beam power of 2500W was found to be the optimum as the machining time was reduced due to higher rate of material removal.



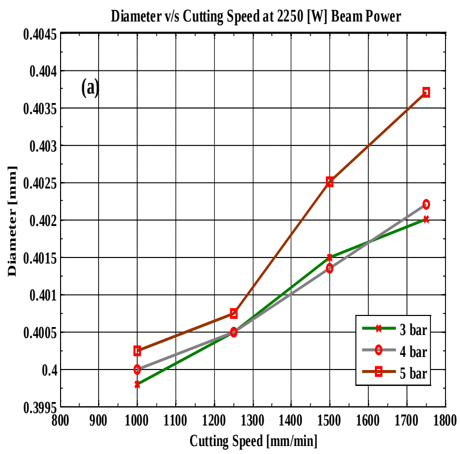
(a) At 2250 [W] Beam Power



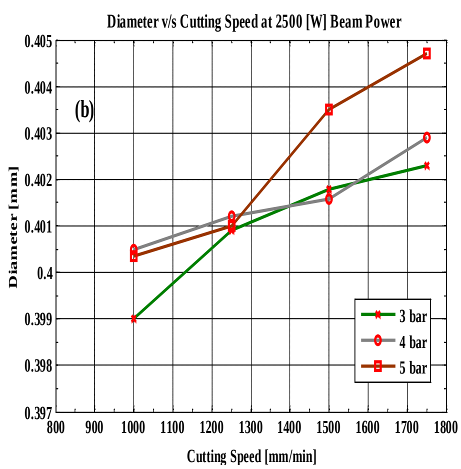
(b) At 2500 [W] Beam Power

Fig 6 Volumetric material removal rate (cm3/min) as a function of the cutting speed (mm/min) at various beam powers

The diameter (mm) of the holes drilled as a function of the cutting speed (mm/min) is plotted as shown in the figure 7 below, at the two laser beam power of 2250W and maximum power 2500W. The diameter of the hole to be drilled was 0.4mm. It is observed that with the increase in the cutting speed, the diameter of the hole initially increases gradually, and then steadily. This is due to the fact that, with the high heat transfer rate and at higher cutting speed, the rate of material removal increases resulting in the increased diameter of the hole. The maximum gas pressure of 5bar resulted in a similar fluctuations in the diameter of the drilled hole which was low at lower cutting speeds and drastically increased at greater cutting speeds. The drilled hole with the most accuracy to the true value is obtained at 4bar pressure and 2250W laser beam power and lower cutting speeds, which is the optimum parameter for drilling the hole with the most accurate dimensions. The increase in the diameter of the hole was 0.55% with the optimum parameters, as a result of the increase in the cutting speed, which results in the induction of the HAZ in the material. This is in agreement with the prediction that HAZ around the holes cause swelling of about 0.50% in diameter [1]. The circularity of the hole was compromised as a result of the increased hole diameter which is a function of the cutting speed, which is studied in detail using the SEM images.



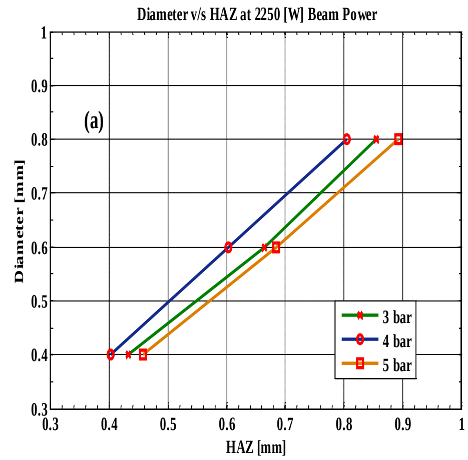
(a) At 2250 [W] Beam Power



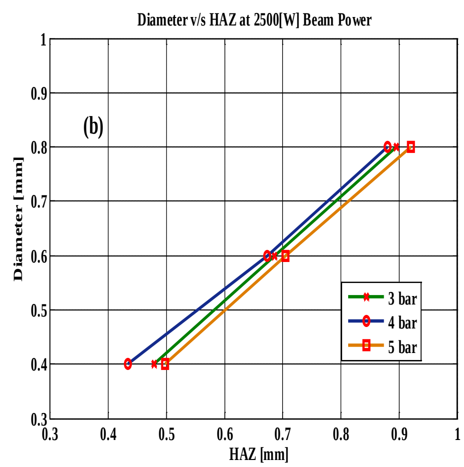
(b) At 2500 [W] Beam Power

Fig. 7 Diameter (mm) of the drilled hole varying with the cutting speed (mm/min) at various beam powers

The diameter of the hole to be drilled has a significant effect on the heat affected zone as is visible from the figure 8 shown below. As the hole diameter to be drilled is increased, more material has to be removed by transferring heat and vaporizing them which results in the localized overheated zones that alters the physical characteristics of the material and results in the formation of HAZ. Figure 8 shown below is a plot of the diameter of the drilled hole with respect to the induced HAZ in the material, at the two laser beam power of 2250W and maximum power 2500W. Initially, the HAZ increases steadily with the increase in the hole diameter which however changes at higher hole diameters as is visible from the steeper slope. It is clear from the figure below, that with the increase in the diameter of the hole, the induced HAZ increases more steeply for the higher beam power of 2500W as compared to the beam power of 2250W, which is due to the fact that with the higher beam power, the induced HAZ gets saturated to higher values. Therefore, the optimum parameter to obtaining the least induced HAZ is with 4bar gas pressure and laser beam power of 2250W.



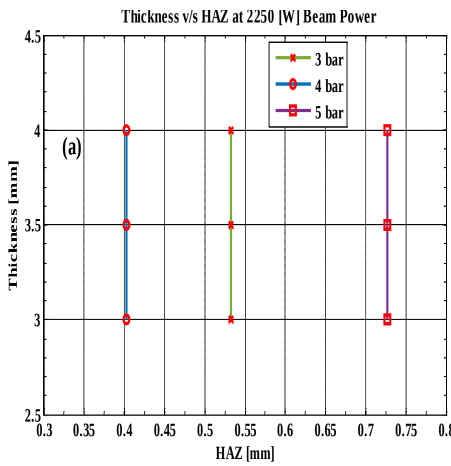
(a) At 2250 [W] Beam Power



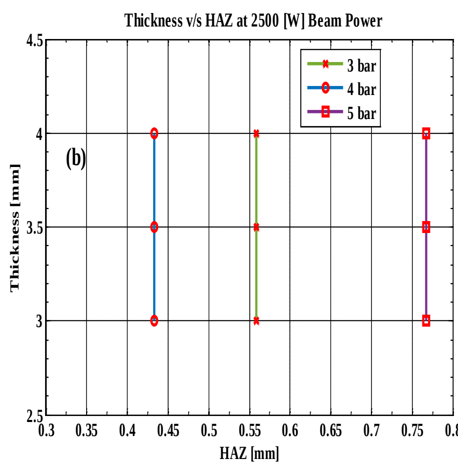
(b) At 2500 [W] Beam Power

Fig. 8 Heat Affected Zone with respect to the hole diameter at various beam powers

Keeping the diameter of the hole to be drilled at a constant value of 0.4mm, the following graphs as shown in figure 9 is obtained, which shows the relationship between the thickness and the HAZ developed in the material at the two laser beam power of 2250W and maximum power 2500W. The graph explains that for a constant hole diameter of 0.4mm which is drilled over 3 different thickness levels, the amount of HAZ induced remains constant. Thus, the optimum parameter to reduce the HAZ as much as possible is with the 4bar gas pressure with the beam power of 2250W.



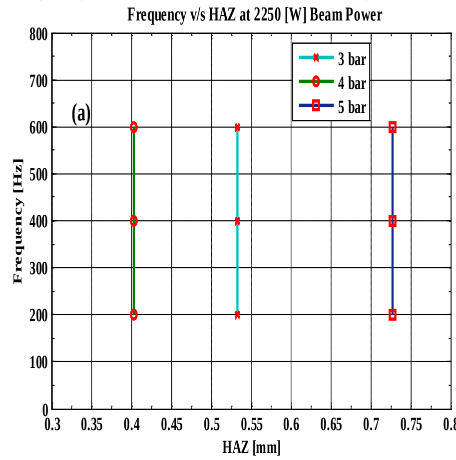
(a) At 2250 [W] Beam Power



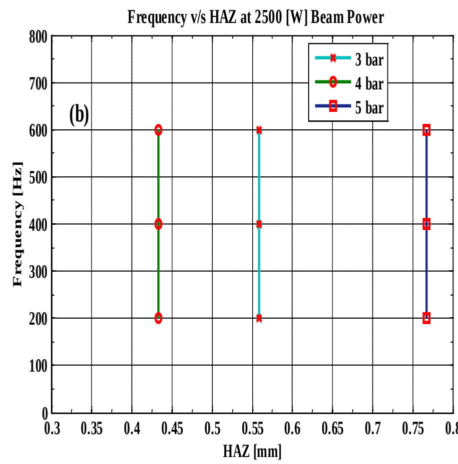
(b) At 2500 [W] Beam Power

Fig. 9 Heat Affected Zone with respect to the thickness at various beam power

The graph shown in figure 10 below is plotted between Frequency (Hz) of the laser cutting system and the amount of HAZ (mm) induced in the material at two laser beam power of 2250W and 2500W, keeping the diameter of the hole to be drilled at a constant value of 0.4mm. It is observed that for a continuous wave (CW) laser the HAZ is independent of the frequency of the laser cutting system, and remains constant throughout for the varying frequency. This is because, the variation in the frequency does not vary the rate of heat transfer to the materials. With the constant rate of heat transfer the HAZ remains constant. However, for the pulsed laser, the pulse frequency has effect on the induction of the HAZ in the material. The higher the pulse frequency, the lower the time available for the re-deposition of the material around the periphery of the drilled hole upon cooling, and the lesser will be the HAZ induced in and around the drilled hole. Better results in terms of lower induced HAZ and damage width were obtained with the continuous wave laser, and is therefore optimum. The parameters for reducing the HAZ with the CW laser is with gas pressure of 4bar and beam power of 2250W.



(a) At 2250 [W] Beam Power



(b) At 2500 [W] Beam Power

Fig. 10 Heat Affected Zone with respect to the frequency at various beam power

The HAZ as observed from the SEM is tabulated in the table 1 below along with the varying parameters of thickness, diameter hole and the cutting frequency. It was observed that the HAZ increases proportionally by almost 0.54% for 0.4mm, 0.6mm and 0.8mm diameter hole. The pulse duration (in pulsed laser) played a significant role in the induction of HAZ, as it leads to re-deposition around the drilled hole resulting in fiber swelling and in eventually inducing HAZ in and around the drilled hole. However, the variations in the HAZ inductions were high, and were proving to be unstable. However, the assist gas pressure variations were highly effective in reducing the HAZ to a minimum in the CW laser. The assist gas used was Argon as it is an inert gas with strong emissions in the visible blue green and weaker lines in the ultra violet and infra-red and is suitable for commercial applications.

Table I. - Heat Affected Zone Values obtained after laser drilling

Sr. No.	Thickness (mm)	Diameter of Hole (mm)	Frequency (Hz)	Assist gas	HAZ (mm)
1	3.0	0.4	200	Ar	0.4022
2	3.5	0.4	200	Ar	0.4022
3	4.0	0.4	200	Ar	0.4022
4	3.0	0.6	200	Ar	0.6033
5	3.5	0.6	200	Ar	0.6033
6	4.0	0.6	200	Ar	0.6033
7	3.0	0.8	200	Ar	0.8044
8	3.5	0.8	200	Ar	0.8044
9	4.0	0.8	200	Ar	0.8044
10	3.0	0.4	400	Ar	0.4022
11	3.5	0.4	400	Ar	0.4022
12	4.0	0.4	400	Ar	0.4022
13	3.0	0.6	400	Ar	0.6033
14	3.5	0.6	400	Ar	0.6033
15	4.0	0.6	400	Ar	0.6033
16	3.0	0.8	400	Ar	0.8044
17	3.5	0.8	400	Ar	0.8044
18	4.0	0.8	400	Ar	0.8044

There is a steady increase in the HAZ with the increase in the diameter of the hole in the CFRP material, and fluctuations were observed with the various gas pressures of the laser system as observed from the graphs shown earlier. Figure 11 shown below is the SEM images obtained for the laser drilled holes depicting the variation of the HAZ and the physical damage with respect to the variation in the diameter of the hole and the gas pressure of the laser system. The other optimum parameters of laser beam power of 2250W, cutting speed of 1000 mm/min was used to obtain the SEM image in figure 11. The diameter of the laser drilled holes vary as 0.4mm, 0.6mm and 0.8mm, and the gas pressure of the laser system varies as 3.0bar, 4.0bar, 5.0 bar for each of the diameter size. For the figures 11(a), 11(b), 11(c) with the hole diameter remaining as 0.4 mm and the gas pressure of the laser system varies as 3.0 bar, 4.0 bar, 5.0 bar, it is noted that the HAZ varies as 0.432 mm, 0.402 mm, 0.457 mm respectively. The least amount of HAZ induced at 4 bar pressure is 12.03% lower, and 6.94% lower than the HAZ induced with the maximum gas pressure of 5 bar, and minimum gas pressure of 3 bar respectively. The maximum gas pressure caused burring on the underside of the cut (cracks seen on the periphery of the hole) whereas the minimum gas pressure resulted in the deterioration of the surface finish. The gas pressure of the laser drilling system is responsible for the damage width and the corresponding induction of HAZ. For the figure 11 (d), 11 (e), and 11 (f) with the hole diameter remaining 0.6 mm and the gas pressure of the laser system varies as 3.0 bar, 4.0 bar, 5.0 bar, it is noted that the HAZ varies as 0.663 mm, 0.603 mm, 0.684 mm respectively. The least amount of HAZ induced at 4 bar pressure is 11.84% lower, and 9.04% lower than the HAZ induced with the maximum gas pressure of 5 bar, and minimum gas pressure of 3 bar respectively. With the increase in the diameter of the hole from 0.4 mm to 0.6 mm, a steady rise in the HAZ is observed correspondingly. For the figures 11(g), 11(h), 11(i) with the hole diameter remaining as 0.8 mm and the gas pressure of the laser system varies as 3.0 bar, 4.0 bar, 5.0 bar, it is noted that the HAZ varies as 0.854 mm, 0.804 mm, 0.893 mm respectively. The least amount of HAZ induced at 4 bar pressure is 9.96% lower, and 5.85% lower than the HAZ induced with the maximum gas pressure of 5 bar, and minimum gas pressure of 3 bar respectively. Therefore, from the values observed above, the least amount of HAZ is induced for the 4 bar pressure with the least diameter of the hole to be drilled (0.4 mm). Therefore for the optimum 4 bar gas pressure, the corresponding HAZ induced in the material has increased tremendously by 50% from the hole with the diameter from 0.4 mm to 0.8mm and 33.3% from the hole with the diameter of 0.4mm to 0.6mm, and 25% from the hole with the diameter of 0.6mm to 0.8mm. With the increase in the diameter of the hole the HAZ increases steadily as shown in the graphs earlier and the resultant surface has induced cracks because of the swollen fiber due to increased heat transfer.

From theses SEM images it is clear that with the variation in the gas pressure of the laser from minimum to maximum, the surface damage and the cracks are induced respectively and an optimum value of the gas pressure results in the reduced damage width and correspondingly lower induction of HAZ in the material. With the increase in the diameter of the hole, the HAZ induced is increased to such an extent that, it compromised the structural integrity of the material by deteriorating the fibers. The surface cracks were visible which suggested an induction of the thermal stresses which were locally distributed in and around the periphery of the drilled hole [28], and resulted in the overall compromised structure.

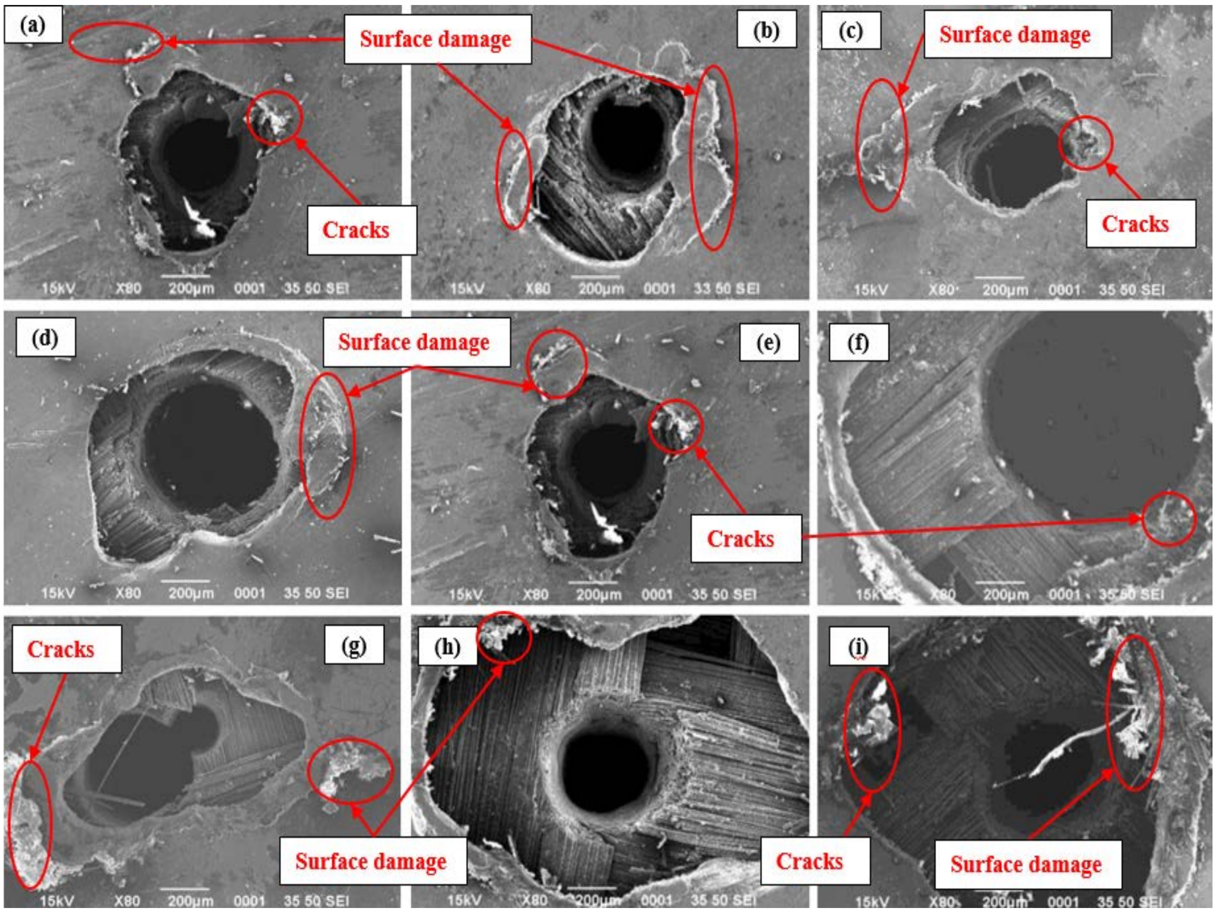


Fig. 11 (a-i) SEM images of laser drilled holes of diameter 0.4 mm, 0.6 mm and 0.8 mm with varying thickness of 3.0 mm, 3.5 mm, 4.0 mm

The resulting optimum parameters from the experimental study has been shown in the fish-bone diagram in figure 12 below: -

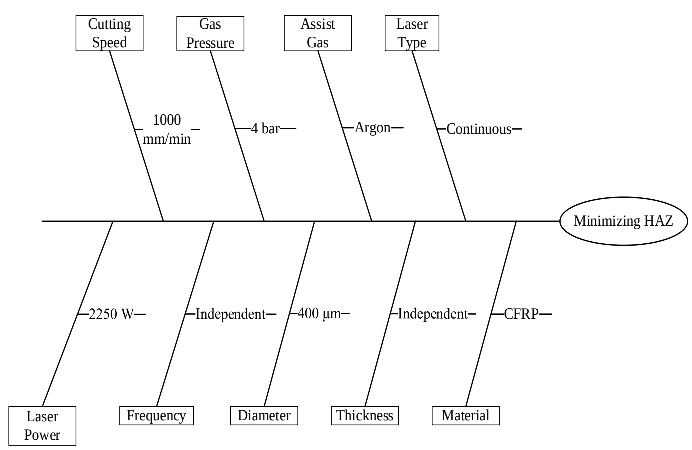


Fig. 12 Fish-bone diagram of the results of the experimental parameters for minimizing HAZ

The optimum parameters in terms of the gas pressure and diameter for the induction of the HAZ as observed from the fish bone has been plotted in the surface plot as shown in the figure 13 below: -

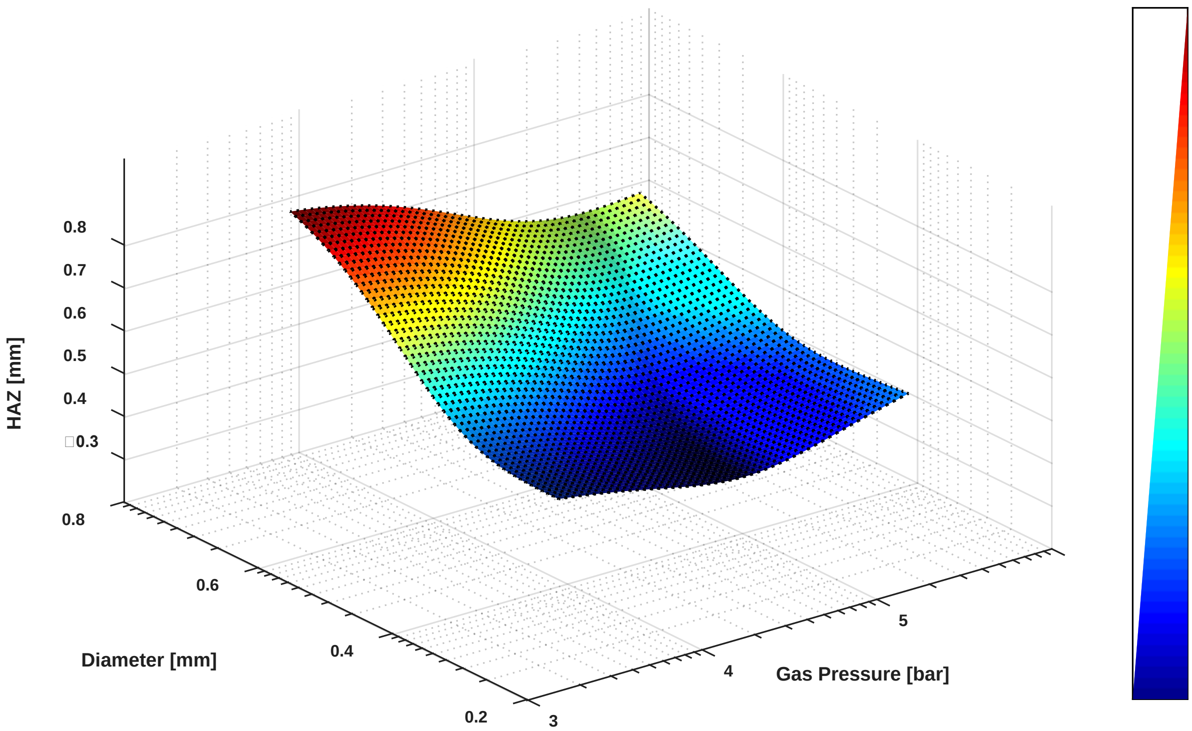


Fig. 13 Surface Diagram of the Optimum Parameters in the induction of HAZ

From the figure 13, it can be concluded that the optimum parameters for the induction of HAZ (as low as possible) is at 4 bar gas pressure, 0.4 mm diameter, and the corresponding HAZ was obtained as 0.4022 mm.

V. Conclusions

1. The extent of HAZ induced in the CFRP due to laser drilling depends on a range of laser parameters such as specific laser energy, laser power, repetition rate, work piece temperature. The use of pulsed lasers instead of the continuous wave laser emissions were resulting in a significant amount of fluctuations in terms of the induced HAZ whereas with the continuous laser, the frequency remained independent in contributing to the induction of HAZ and therefore was considered optimum. Though, the heat accumulation with the short pulsed laser is reduced by almost half in contrast to the continuous laser [25], the use of optimum gas pressure of the assist gas in the continuous laser suitably reduced the amount of HAZ induced in the work piece.
2. HAZ is directly dependent on the diameter of the drilled hole and the cutting speed whereas it is independent of the cutting frequency of the laser beam and the thickness of the material. The larger the diameter of the hole to be drilled, the more the induction of the HAZ, similarly, the larger the cutting speed the more the HAZ was observed.
3. HAZ is found to be minimum at the cutting speed of 1000 mm/min, with the continuous wave (CW) laser, gas pressure of the laser at 4 bar and the laser beam power at 2250 W and the diameter of the work piece to be 0.4 mm.
4. The gas pressure of the laser drilling system is responsible for the damage width and the corresponding induction of HAZ, and a pressure of 4bar of the assist gas was observed to be optimum for this study.

From the SEM analysis it is observed that the selection of the suitable parameters as well as proper bonding of the layers will result in a good finished micro hole and less material removal due to the thermal effect created by the laser [21].

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