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Comparative study of mechanical technologies over laser technology for drilling carbon fiber reinforced polymer materials

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More researchers have been worked to increase the quality of the machined composite materials. In this paper, a comparative experimental study of mechanical techniques over the laser techniques has been performed in the drilling process by using the carbon fiber reinforced polymer (CFRP). In order to identify the best process among the mechanical drilling (MD) and laser drilling (LD) technology various analysis methods like normality analysis, control chart analysis, and process capability analysis have been performed. Process capability index analysis for case study 1 and interval plot analysis for case study 2 have been employed to evaluate the best process comparatively. Experiments have been performed in a vertical machining center (VMC) and CO_2 laser. The final results revealed that the MD process is the best technology for drilling CFRP. Therefore, this work has been important for small-scale industries.

Keywords: Mechanical drilling, Laser drilling, Carbide drill, Carbon fiber reinforced polymer, Process capability

1 Introduction

Light weight composite materials are an advanced material group and are shaped by the arrangement of two or more materials in order to get distinctive properties of materials. The CFRP is an extremely strong and light fiber-reinforced polymer which contains carbon fibers and epoxy resin as matrix materials. Applications and development of advanced composite materials are booming in various manufacturing sector such as aerospace sector, structural sector, electronics sector, automobile sector[1]. The CFRP composites having several superior properties such as high strength, lower weight, lower coefficient expansion, higher strength-to-weight, stiffness-to-weight ratios, excellent anti-thermal shock ability, and good vibration absorption[2]. The CFRP is one of the polymer matrix composites that widely performed in various domains like aerospace, electronics, structural industries and automotive due to their outstanding properties such elevated strength to wear ratio, corrosion resistance, and superior wear resistance and high modulus. Machining is an important manufacturing process. Machining is defined as the process of removing material from a workpiece. Tool based machining and energy based machining are important two types of machines. Machining is a most necessary process where tight tolerances on dimensions and surface finishes are required for assembling of components. Normally the available conventional machining processes are turning, milling and drilling, shaping while non-conventional machining is laser machining and abrasive water jet machining. The manufacturing industries are struggling to select the best cutting technology and select the optimum machining process among the various machining process for machining CFRP composites economically. The damages that occur during conventional processing in polymer composites are many such as matrix cracking, fiber pull in/outs, spalling, fuzzing, tool wear, delamination, thermal degradation, high dust generation. This is due to the fact of inherent heterogeneity & anisotropy of materials[3-5].

Minimizing the machining damages becomes pivotal for structural integrity of the part. In order to solve the conventional processing problems, non-conventional machining processes have been developed. Among the non-conventional machining processes, laser beam machining and abrasive water jet machining have received sizeable awareness.

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While abrasive water jet machining has been applied in recent days, the employ of water is difficult. Because the polymer composites are naturally absorbing water and it results in reduced strength of parts. Due to the non-contact nature of the process and the high degree of flexibility, the laser beam machining has sizeable awareness as an alternate option to conventional processes. The necessity of creating micro-hole on carbon-fiber reinforced polymer materials are found in the applications like a printed circuit board, printed wiring board, laptop upper panel, access doors, satellite antenna, bridges, pipes and walkways, panels, wheel chairs and body panels. Therefore, these applications of are components demand the micro-hole drilling process on CFRP plate with accurate dimensions[6]. The diameters of the micro-hole required in CFRP component are less than 1 mm[7,8]. Therefore, Mechanical Drilling (MD) and Laser Drilling (LD) are chosen for this work. The major problems in mechanical drilling are delamination, circularity error, overcut, taper angle[9-16].

The major problems in laser drilling are heat affected zone, kerf width, taper angle[17-21]. Damages caused in MD are due to the improper selection of drilling parameter, tool geometry, and selection of tool material. LD damages are caused by the improper selection of laser mode, assist gas, sample materials, environment, a focusing lens, selection of workpiece material. It is important to identify the causes prior to machining[22]. In order to control the problems in MD and LD and to achieve the desired qualities in the machined micro-holes, it is necessary to know the mechanisms of material removal and kinetics of machining processes.In this work, the process capability of CFRP in the MD process and LD process is studied. Prior to the analysis of process capability, the observed experimental data that the normality test and control chart are checked. In the previous research works, drilling of holes having the size below 0.5 mm in CFRP composite in mechanical drilling and laser drilling processes has never been successfully attempted. Therefore, in this work, the holes of size in CFRP 0.5 mm have been drilled by a mechanical drilling process and the process has been analyzed in different aspects.

2 Design of Experiments

The function of the Design of Experiments (DoE) requires aware of planning, the prudent layout of the experiments, and analysis of results. Taguchi Orthogonal Approach (OA) has universally accepted and standardized approach for each of this experimental design application. The beneficiary of DoE is used to develop the most affecting process parameter and DoE can radically reduce the ‘n’ number of tests required to meet necessary data. Therefore, the DoE approach has become a more fashionable tool for engineers and researchers. In this case study, the two parameters namely spindle speed and feed rate in MD and the three parameters namely power, cutting velocity and argon pressure in LD were chosen as the controlling factors respectively and each parameter is designed to have four levels denoted by 1, 2, 3 and 4 and are shown in Table 1 and Table 2, respectively.

3 Normality Test, Control Chart and Process Capability

A normality test is used to check whether a sample or any groups of data satisfy normal distribution and it is performed either mathematically or graphically. The most important application of the normality tests is to find the residuals of a linear regressions model. The normality test or probability plot is carried out to evaluate how well the continuous data follows the normal distribution. In this work, Minitab 17 statistical software is used for this purpose. The plot report of AD values and p-values are used to justify whether the observed continuous data are with a 95% confidence interval either follow the normal

Table 1— Mechanical Drilling parameters and their levels.

Control parameters	symbol	Levels			
		1	2	3	4
Spindle speed (V), rpm	V	1000	1500	2000	2500
feed rate (f), mm/rev	f	0.01	0.03	0.06	0.09

Table 2 — Laser Drilling parameters and their levels.

Control parameters	symbol	Levels			
		1	2	3	4
Power (P), W	P	15	30	45	60
Cutting velocity (v), mm/min	v	20	40	60	80
Argon pressure (p), kpa	p	200	300	400	500

distribution or non-normal distribution. The well fit data must have a low AD value (less than one) and high p-value (greater than 0.05).

Quality is the grade to which finished services or products fulfill the requirement of customers. The aims of quality specialist are minimizing defect rates, fabricating the products within design/customer requirement and economical time. Minitab has the broad number of process available to assess quality based on the objective. In a quantitative manner: quality planning tools, process capability, control charts, measurement analysis, and reliability analysis are the methods. In order to study the stability of a process, the control charts are required. Depending upon data type and subgroup size, the control chart is chosen for analysis to find whether the observed data are in control or out of control. There are two types of data such as continuous data (quality characteristics such as surface roughness and hole size) and attribute data (defective item and defects/unit). The I-MR chart was chosen for this study. The reason for choosing the I-MR chart is that the type of data is continuous data and subgroup size is one. The Upper Control Limit (UCL) and Lower Control Limit (LCL) are employed as the control limits for the I-MR charts in Statistical Process Control (SPC). Therefore, the UCL and LCL are calculated from I-MR charts by employing the following expressions.

Control Limit for I Chart:

$$\mathrm{UCL} = \bar{\mathrm{x}} + 3\,\frac{\overline{\mathrm{MR}}}{1.128} \quad \dots (1)$$

$$\mathrm{CL} = \bar{\mathrm{x}} \quad \dots (2)$$

$$\mathrm{LCL} = \bar{\mathrm{x}} - 3\,\frac{\overline{\mathrm{MR}}}{1.128} \quad \dots (3)$$

Control Limit for MR Chart:

$$\mathrm{UCL} = 3.267\overline{\mathrm{MR}} \quad \dots (4)$$

$$\mathrm{CL} = \overline{\mathrm{MR}} \quad \dots (5)$$

$$\mathrm{LCL} = 0 \quad \dots (6)$$

$$\bar{\mathrm{x}} = \frac{\mathrm{x_1} + \mathrm{x_2} + \dots + \mathrm{x_m}}{\mathrm{m}} \quad \dots (7)$$

$$\mathrm{MR} = |\mathrm{x_i} - \mathrm{x_{i-1}}| \quad \dots (8)$$

$$\overline{\mathrm{MR}} = \frac{\mathrm{MR_1} + \mathrm{MR_2} + \dots + \mathrm{MR_m}}{\mathrm{m}} \quad \dots (9)$$

Where, x_i is the measured quality characteristic obtained from the drilling tests.

Process control is defined as the ability of the process to keep a state of good statistical control. Prior to process capability evaluation, the obtained experimental data have some quality characteristics such as statistically within control, normally distributed and data independent. Process capability is also defined as the measure of degree that a process achieves specifications. The main purpose of the process capability is to find the variations spread and find the impact of the quality characteristic on both the average and spread. Obtained results are further utilized for new inspection planning, evaluation techniques, and design applications. The following three steps are carryout to find out the process capability of attributes criterion[23]. In this work, hole size at entry (D) and exit (d), delamination factor at entry (F_{dent}) and exit (F_{dext}), taper angle (Ø) and aspect ratio (AR_{MD}) are the attribute in MD whereas kerf width at entry (K_{went}) and exit (K_{wext}), heat affected zone entry (HAZ_{ent}) and exit (HAZ_{ext}), kerf angle (K_a) and aspect ratio (AR_{LD}) are the attributes in LD.

Step 1: Calculation of mean (X): calculation of mean is ascertained for every trial run by using following equation.

$$X = \sum_{i=1}^{N} \frac{x_i}{N} \quad \dots (10)$$

Here, x_i = response parameter value for i^{-th} replicate trial, N = number of replicates.

Step 2: Computation of standard deviation (α): Following equation was used to compute Standard deviation (α).

$$\alpha = \sqrt{\frac{\sum_{i=1}^{N}(x_i - X)^2}{N}} \quad \dots (11)$$

Here,

x_i= Response parameter value for i^{-th} replicates of a distinct trial, X = Mean of the N replicates for the trial.

Step 3: Process capability index (c_{pi}): following equation was used to calculate process capability index (c_{pi}) for each experimental run.

$$C_{pi} = min\left\{\frac{X - LSL}{3\alpha}, \frac{USL - X}{3\alpha}\right\} \quad \dots (12)$$

Here, USL= Upper Specification Limit for individual attributes, LSL = Lower Specification Limit for individual attributes. USL and LSL actually are a destination value. Specification limits are typically provided from outside which depends on production necessities, market pre-requisites. It can be either one-sided or two-sided.

4 Running Experiment

A CFRP composite with 55 percent of carbon fibers reinforcement in a total of 12 layers and having 3 mm thickness along a fiber orientation of 0/90° with epoxy matrix is chosen and it is shown in Fig. 1. This composite was fabricated by autoclave method and was supplied by M/s GALARK Industry. The chemical composition of CFRP plate has been tested by EDX analysis and composition is as follows: 84.12% C, 14.92% O, 0.20% Na, 0.20% Si, 0.28% CI, 0.10% K and 0.21% Ca. Hardness of CFRP is most commonly measured by the shore-D (Durometer) test. The Shore-D hardness number is in range 64 to 88. Tensile strength of CFRP is 1200 MPa and elastic modulus of CFRP is 145000 MPa[6]. The composite was laminated rectangular sheet of dimension 120 × 60 × 3 mm^3. The MD tests were carried out using computer numerical controlled vertical machining center under dry condition as per design (Make: HARDINGE, Model: VMC 800II machine) and specifications are shown in Table 3.

Prior to drilling, a micro-tool holder, ER32 collect with drill was held in main spindle drive of VMC setup shown in Fig. 2. In order to conduct experiments, the laminate was fastened to the rigid fixture which was mounted on the worktable. Equal spacing was maintained between successive drilled holes in the plate. The standard solid carbide twist drills of 0.5 mm diameter with constant point angle 130 degrees, helix angle 30 degrees and number of flutes 2 were used for the experimental work and overall photograph of the used drill bit with a magnified view of the drill tip region shown in Fig. 3. After drilling, the hole size at entry and exit, delamination factor (F_d) at entry and exit, taper angle (Ø) and aspect ratio (AR_{MD}) were measured using anon contact video measuring system (VMS) and it is shown in Fig. 4. The LD tests were carried out using computer numerical controlled 1640W CW CO_2 laser drilling machine (Make: Rofinsinar, Model: OEM 65 iX). The specification is shown in Table 4. The CO_2 laser setup is shown in Fig. 5. Equal spacing was maintained between successive drilled holes in the plate. The spot diameter of 0.5 mm diameters were used for the experimental work. The heat affected

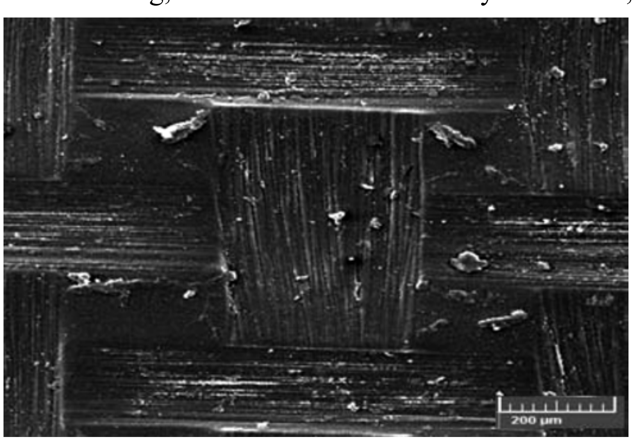

Fig. 1— Image of CFRP composite laminated plate.

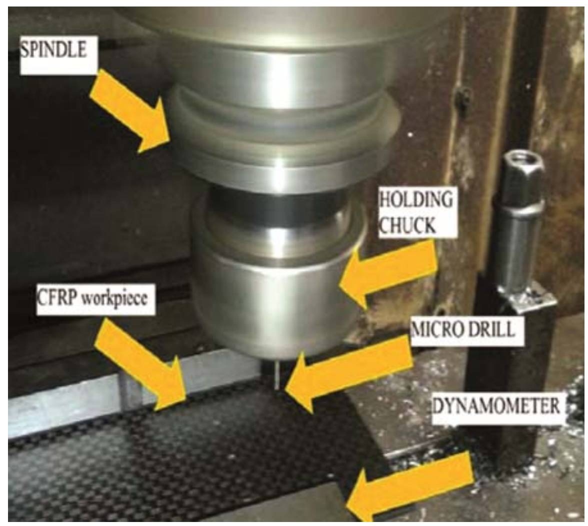

Fig. 2 — Photograph of VMC.

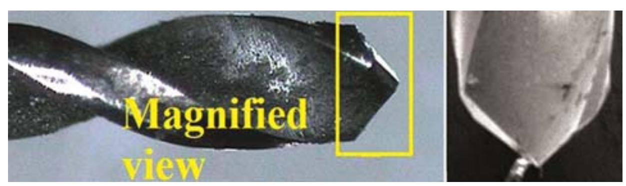

Fig. 3 — Solid carbide drill with 0.5 mm diameter.

Fig. 4 — Setup of video measurement system.

Table 3 — Specifications of the VMC.

Type of machine	Vertical machine center
Brand	HARDING
Model	VMC-800 II
Control	Fanuc series 18-M
Maximum Speed	12000 rpm
Travel length	500 x 800 x 500 mm
Table size	920 x 510 mm

Table 4 — Specifications of the CO_2 laser.

Parameters	Specification
Operating mode	CW
Wavelength	10.6 µm
Peak Laser output power	1640W
Pulse Width/Frequency	2-400µs/0-130KHz
Spot size at focus	0.5 mm
Beam quality M^2	1.7
Assist gas	argon
Stand-off	1.5 mm
Focus position	surface
Maximum power	650 W

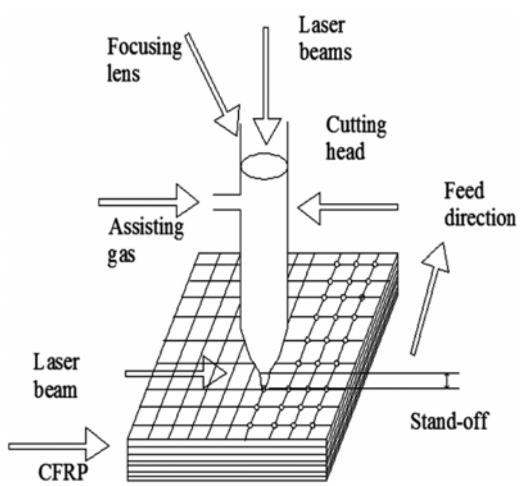

Fig. 5 — Schematic experimental setup of CO_2 laser.

zone (HAZ), Kerf width (K_W), kerf angle (K_a) and aspect ratio (AR_{LD}) were measured using a non contact video measuring system (VMS). Three trials were taken for each set of parameters and the average values of responses were taken for further analysis.

5 Mechanical Drilling and Laser Drilling Calculation

The delamination factor (F_d) was calculated using the formula given below

$$F_d = D_{max}/D \quad \dots (13)$$

where, D_{max} is maximum damaged diameter and D is drill diameter.

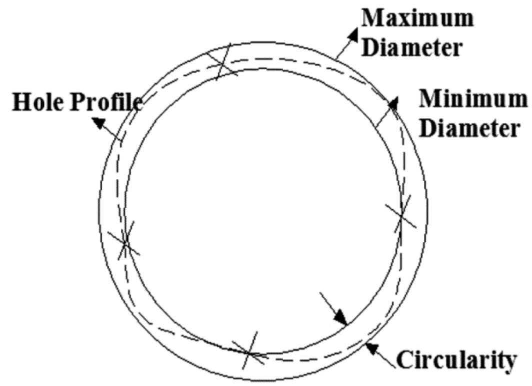

Fig. 6 — Schematic representation of circularity error.

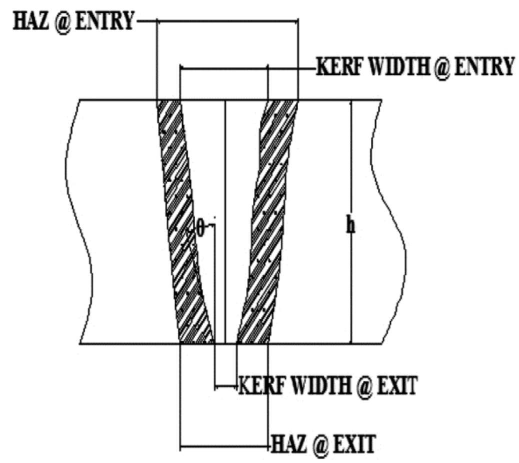

Fig. 7 — Geometry of the laser cut.

The circularity error (C) was also calculated using the formula given below and schematic representation was shown in Fig. 6 and geometry of laser cut is shown in Fig. 7.

$$C = (D_{max} - D_{min})/2 \quad \dots (14)$$

The taper angle (Ø) was calculated using the formula given below

$$Ø = tan^{-1}(D - d)/2t \quad \dots (15)$$

Where, D is mean entrance diameter, d is mean exit diameter and t is thickness of sample.

6 Results and Discussion

Composite materials applied in aerospace and structural applications were machined at Shri Angalamman industry, Thuvagudi in MD and Nano marker, Srirangam in LD. The aim was to find the best process among the two in one through microscopic analysis. Sixteen experiments were performed out using CFRP. Tests were conducted as per the design of experiment using MINITAB version 17. After performing MD and LD test, the computer aided video measurement system was used to take the photo shot of machined hole. From the MD photo shot Fig. 8 and Fig. 9, the hole size at entry, hole size at exit, maximum damaged surface diameter were measured whereas from the LD photo shot Fig. 10 and Fig. 11, the heat affected zone at entry and the heat affected zone at exit and kerf width were measured. The MD and LD experimental values are shown in Table 5 and Table 6, respectively.

The guideline procedures are followed to evaluate the process capability.

1. Checking the type of data is given for process capability analysis (*e.g.* continuous data or attribute data).
2. Checking the normality of process by normal probability plot.
3. Selecting the control chart depends on data type and examine whether the process in control or out of control (e.g. I-MR chart, X bar-R chart, X bar- S chart, P chart, U chart).
4. Calculating the process capability.

To effectively estimate the process capability and to consistently predict the process capability in the future, the quality characteristics must have the properties such as stable, normal.

6.1 Normality analysis

The statistical assumption of the null hypothesis following as the data distribution law was normal and alternative hypothesis: the data distribution law was non-normal. The normality test for hole size at entry and exit, delamination factor at entry and exit, taper angle and aspect ratio in MD while kerf width at entry and exit, heat affected zone entry and exit, kerf angle and aspect ratio in LD were with 95% confidence interval. The experimental data are presented in Fig. 12 and it closely presents the straight line. In all the cases of probability plot, an obtained value from Anderson-Darling test value and p-value were

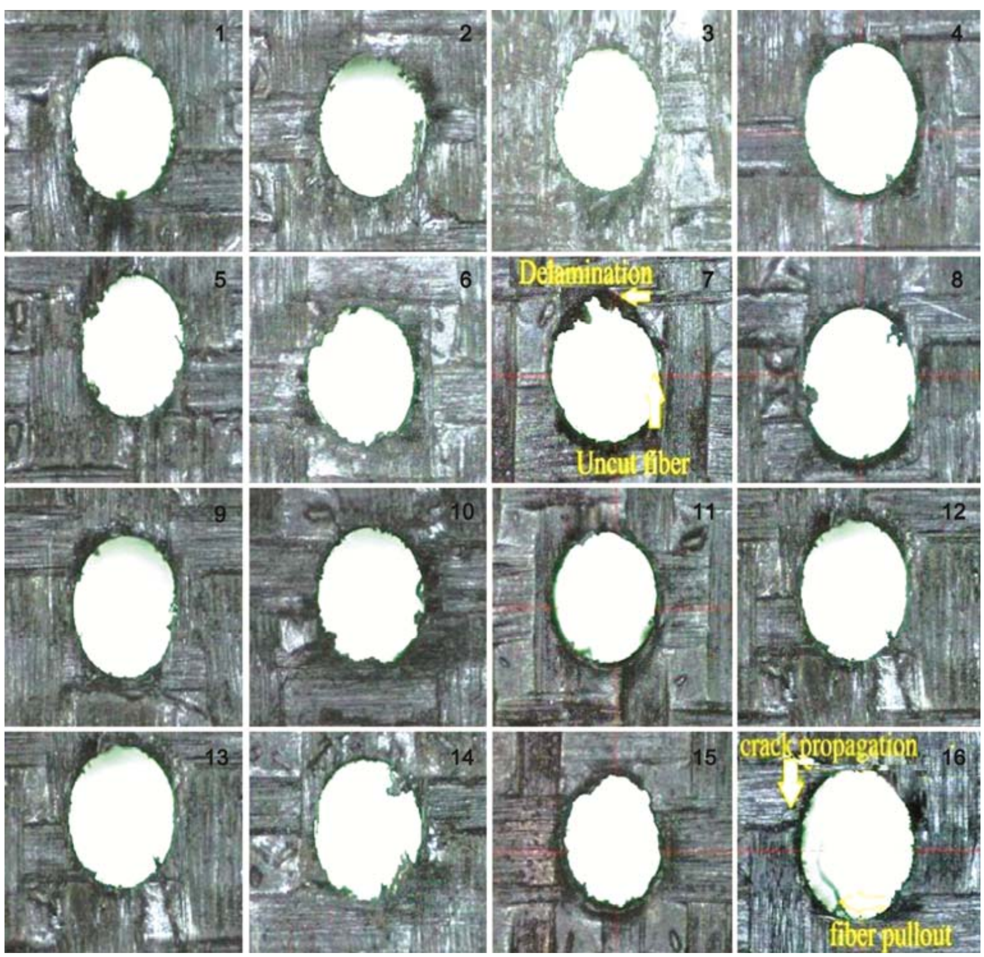

Fig. 8 — Machined hole at the entry side in MD.

Fig. 9 — Machined hole at the exit side in MD.

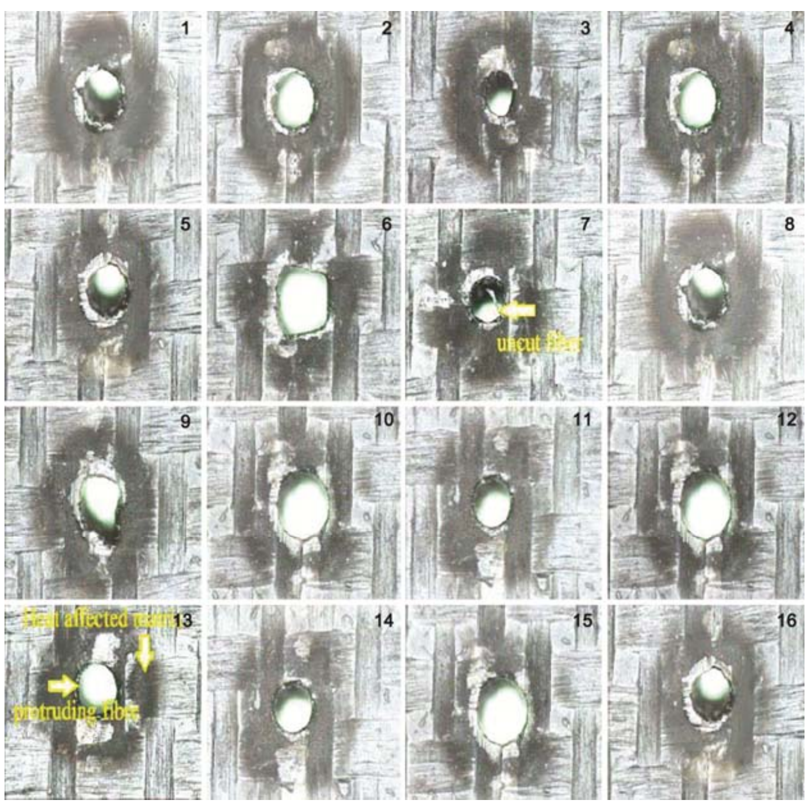

Fig. 10— Machined hole at the entry side in LD.

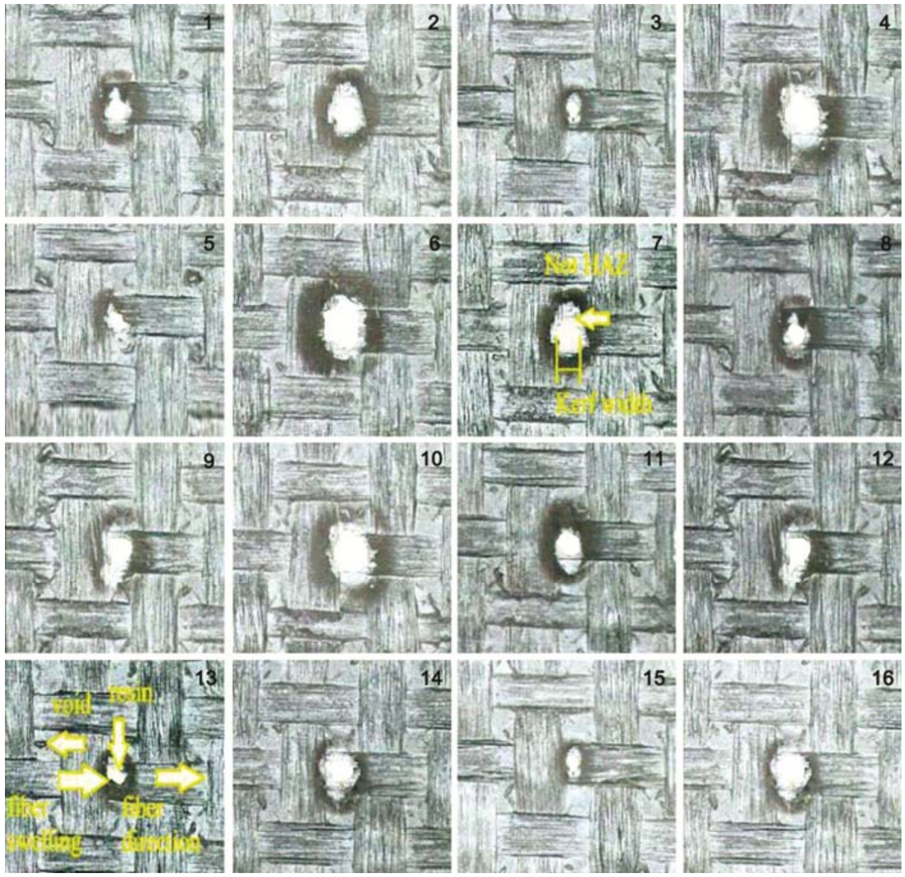

Fig. 11 — Machined hole at the exit side in LD.

Table 5 — Experimental data in MD

Exp. No.	OA/Process parameters		MD responses					
	Spindle speed (rpm)	Feed rate (mm/rev)	D (mm)	D (mm)	F_{dent}	F_{dext}	Ø (Degrees)	AR_{MD}
1	1000	0.01	0.541	0.549	1.115	1.122	0.081	5.507
2	1000	0.03	0.520	0.531	1.112	1.118	0.106	5.709
3	1000	0.06	0.518	0.526	1.122	1.135	0.072	5.749
4	1000	0.09	0.517	0.523	1.128	1.142	0.063	5.772
5	1500	0.01	0.538	0.544	1.091	1.101	0.057	5.550
6	1500	0.03	0.528	0.532	1.126	1.125	0.043	5.663
7	1500	0.06	0.518	0.526	1.119	1.124	0.076	5.747
8	1500	0.09	0.519	0.527	1.138	1.149	0.076	5.742
9	2000	0.01	0.534	0.539	1.101	1.109	0.048	5.597
10	2000	0.03	0.528	0.536	1.124	1.133	0.076	5.644
11	2000	0.06	0.521	0.527	1.135	1.134	0.057	5.731
12	2000	0.09	0.521	0.526	1.138	1.149	0.048	5.736
13	2500	0.01	0.534	0.541	1.115	1.126	0.067	5.587
14	2500	0.03	0.530	0.539	1.141	1.137	0.086	5.618
15	2500	0.06	0.527	0.530	1.142	1.140	0.029	5.682
16	2500	0.09	0.525	0.527	1.141	1.152	0.019	5.709
MIN			0.517	0.523	1.091	1.101	0.019	5.507
MAX			0.541	0.549	1.142	1.152	0.106	5.772

Table 6 — Experimental data in LD.

Exp. No.	OA/Process parameters			LD responses					
	Power (W)	Cutting velocity (mm/min)	Pressure (kpa)	K_{went} (mm)	K_{wext} (mm)	HAZ_{ent} (mm)	HAZ_{ext} (mm)	K_a (Degrees)	AR_{LD}
1	15	20	200	0.558	0.352	1.251	0.497	1.967	6.593
2	15	40	300	0.471	0.274	1.190	0.439	1.881	8.054
3	15	60	400	0.415	0.219	1.151	0.402	1.872	9.464
4	15	80	500	0.385	0.205	1.071	0.363	1.719	10.169
5	30	20	300	0.582	0.407	1.259	0.504	1.671	6.067
6	30	40	200	0.483	0.306	1.213	0.455	1.690	7.605
7	30	60	500	0.432	0.258	1.152	0.411	1.662	8.696
8	30	80	400	0.383	0.218	1.118	0.372	1.576	9.983
9	45	20	400	0.586	0.447	1.282	0.512	1.327	5.808
10	45	40	500	0.492	0.349	1.216	0.438	1.366	7.134
11	45	60	200	0.471	0.312	1.191	0.412	1.518	7.663
12	45	80	300	0.402	0.253	1.142	0.379	1.423	9.160
13	60	20	500	0.663	0.521	1.333	0.526	1.356	5.068
14	60	40	400	0.589	0.461	1.261	0.452	1.222	5.714
15	60	60	300	0.523	0.407	1.239	0.435	1.108	6.452
16	60	80	200	0.482	0.372	1.181	0.411	1.050	7.026
MIN				0.383	0.205	1.071	0.363	1.050	5.068
MAX				0.663	0.521	1.333	0.526	1.967	10.169

less than one and greater than 0.05 respectively. Therefore, the measured continuous data distributed were normal.

6.2 Control chart analysis

I-MR charts were employed to calculate the upper control limit and lower control limit. The control limits were utilized to control and monitor the process capability of the quality characteristics. The top portion of the graph was represented as an Individual (I) chart that plots the response values of each individual observation data and provides a means to assess the process center. The bottom portion of the graph represented as Moving Range (MR) chart that plots machining process variation as calculated from the ranges of two or more successive observations. The green line on each chart was indicating the mean and the red line was indicating the upper and lower control limits.Process capability was a group of calculations used to assess whether process performances characteristics statistically capable to meet the design specifications. In order to achieve and assess the quality characteristics of process and/or machines specification and within control limit except for LD kerf angle as shown in Fig. 13. In the MR chart of LD kerf angle, the machining response variations were in control. Therefore MR chart was in control. I chart having the process variation which was out of control. The reasons for this out of control were due to the variation of standard deviations and center line. Minitab was regenerated up to an eight special-cause machining response variation tests for I chart and indicates problem observations with a red symbol and number of failed test.

Test Results for I Chart of LD Kerf angle discussed below:

TEST 1 reported that one point more than 3.00 standard deviations from the center line. Therefore the experimental test number failed at points: 1, 2, 3, 14, 15, and 16.

TEST 2 reported that 7 points in a row on the same side of center line. Therefore the experimental test number failed at points: 7, 8, 15, and 16.

TEST 5 reported that 2 out of 3 points more than 2 standard deviations from the center line (on one side of CL). Therefore the experimental test number failed at points: 2, 3, 4, 6, 10, 14, 15, and 16.

TEST 6 reported that 4 out of 5 points more than 1 standard deviation from the center line (on one side of CL). Therefore the experimental test number failed at points: 4, 5, 6, 7, 13, 14, 15, and 16.

This was the LD strongest evidence test report that responses were out of control. Therefore, the drilling process was found to be stable based on the I-MR (Individual-Moving range) chart. Mechanical drilling

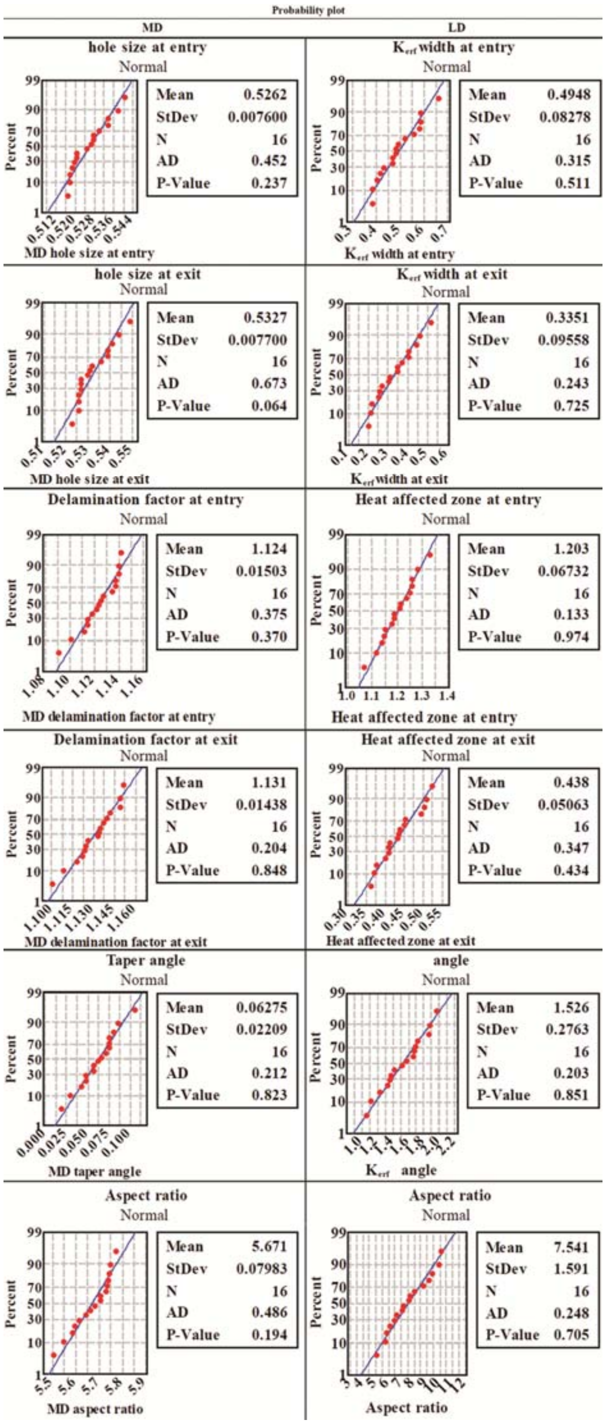

Fig. 12 — Normality graphs of MD and LD.

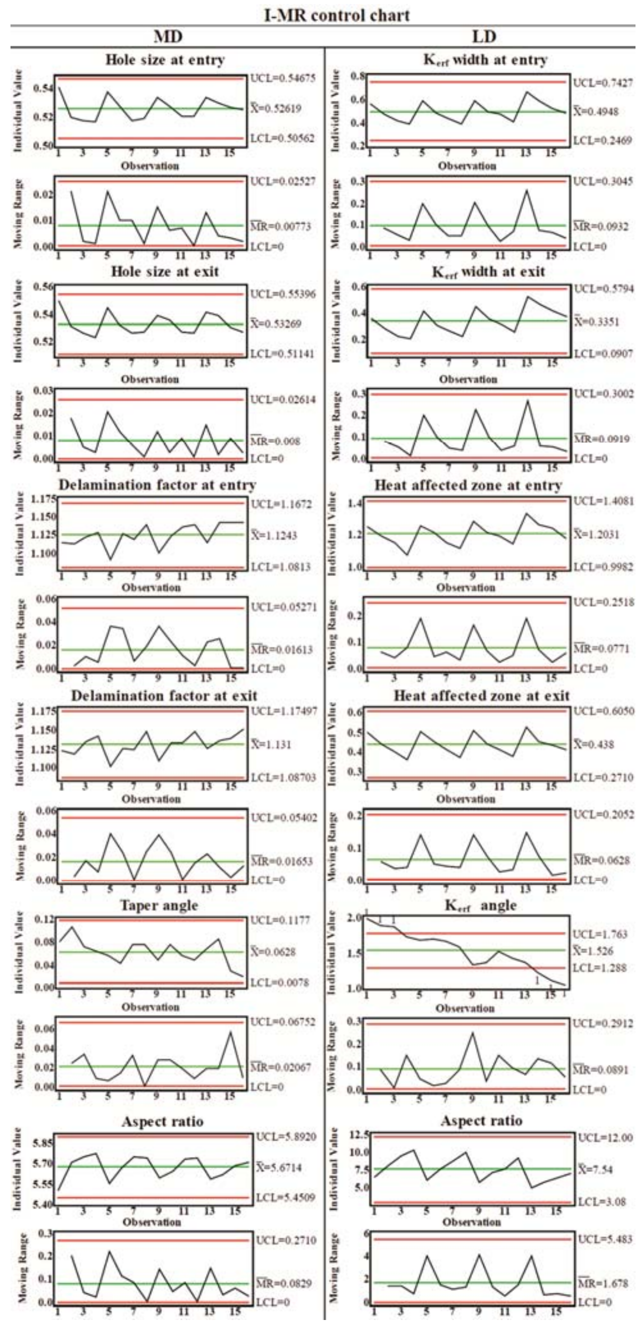

Fig. 13 — IMR control charts of MD and LD.

test showed the best within the I-MR control chart as clearly shown in Fig. 13.

6.3 Process capability analysis – Case I

After confirming that the machining process was in statistically control, it was necessary to find either the process was capable or not and can be meet the design specifications and generate "good" hole in MD and LD. Then, the process capability was found by comparing the response data spread in process variation with the width of specification limits. In case, the process responses were not in control, it led to an incorrect estimation of process capability. In Minitab, the process capability can be evaluated by graphically. These graphs were used to evaluate the distribution of the response data and verify either the process was in control or not. Capabilities indices were used to find the way to assess process capability and process information was reduced to a single number and comparing the process capability of one process to others. Minitab has capability analysis in many distribution forms such as weibull, normal, exponential, poisson, gamma, and binomial. Normal distribution was taken for this analysis and subgroup size one was taken for this analysis. The upper specification limits (USL), lower specification limits (LSL), target value and calculated C_p and C_{pk} for each quality characteristics are given in Table 7. The target value itself was taken as LSL except for aspect ratio. The maximum experimental values of quality characteristic were taken as upper specification limits. Based on the constrained limit of an upper specification and lower specification the process capability of MD and LD were calculated as shown in Fig. 14 and the best was identified. The C_p value of hole size at entry and exit, delamination at entry and exit, taper angle and aspect ratio in MD were one or greater than one. It represented the MD process was capable of achieving the target set for all the above-said quality characteristics. The C_{pk} value for hole size at entry, aspect ratio in MD were greater than one and that for other qualities characteristics studied were less than one. But comparatively better than that in LD. Whereas C_p value and C_{pk} value for all quality characteristics in LD were found to be less than one except for kerf angle. Therefore, it was concluded that the MD process was comparatively better than the LD process for micro-drilling of CFRP.

6.4 Process capability analysis – Case II

In addition process capability studies, Interval plots were drawn based on mean line value of each response and individual standard deviation of each response as shown in Fig. 15. Hole size obtained in MD || kerf width obtained in LD, delamination factor obtained in MD || HAZ obtained in LD, taper angle obtained in MD || kerf angle obtained in LD, aspect ratio obtained in MD || aspect ratio obtained in LD are assumed to be studied quality characteristics.When were compared the MD & LD based on similar characteristics. The hole size obtained both at entry and exit in MD was found to be nearer to 0.5 mm which means the size of the drill. The SD of this was very less. The kerf width obtained at the entry in LD was found to be nearer to 0.5 mm with high SD whereas the same at the exit was deviating more with high SD. Hence, it was concluded that the MD was superior to the LD for micro-drilling CFRP composites. The delamination factor obtained both at entry and exit in MD was found to be nearer to 1 which means the damage diameter was less. The SD of this was very less.

The HAZ obtained at the entry in LD was found to be nearer to 1 with less SD whereas the same at the exit was deviating more with less SD. Hence, it was concluded that the MD was superior to the LD for micro-drilling CFRP composites. The taper angle obtained in MD was found to be nearer to zero which means the taper angle of holes were minimal. The SD of this was very less. The kerf angle obtained in LD was found to be higher (i.e. 1.5) with high SD. Hence, it was concluded that the MD was superior to the LD for micro-drilling CFRP composites. The aspect ratio obtained in MD was found to be nearer to 5 which means that the deviations of in diameter for the given length of hole. The SD of this was very less. The aspect ratio obtained in LD was found to be higher

Table 7— Specifications limits of process capability.

Quality characteristics	USL (mm)	LSL (mm)	Target value (mm)	C_p	C_{pk}
		MD			
Hole size @ entry (mm)	0.555	0.500	0.500	1.34	1.27
Hole size @ exit (mm)	0.555	0.500	0.500	1.29	1.05
Delamination @ entry	1.152	1.000	1.000	1.77	0.65
Delamination @ exit	1.152	1.000	1.000	1.73	0.48
Taper angle (Degrees)	0.11°	0°	0°	1.00	0.86
Aspect ratio in MD	6	5	6	2.27	1.49
		LD			
Kerf width @ entry (mm)	0.555	0.500	0.500	0.11	-0.02
Kerf width @ exit (mm)	0.555	0.500	0.500	0.11	-0.68
Heat affected zone @ entry (mm)	1.340	1.000	1.000	0.83	0.67
Heat affected zone @ exit (mm)	1.340	1.000	1.000	1.02	-3.36
Kerf angle (Degrees)	2°	0°	0°	4.22	2.00
Aspect ratio in LD	11	5	11	0.67	0.57

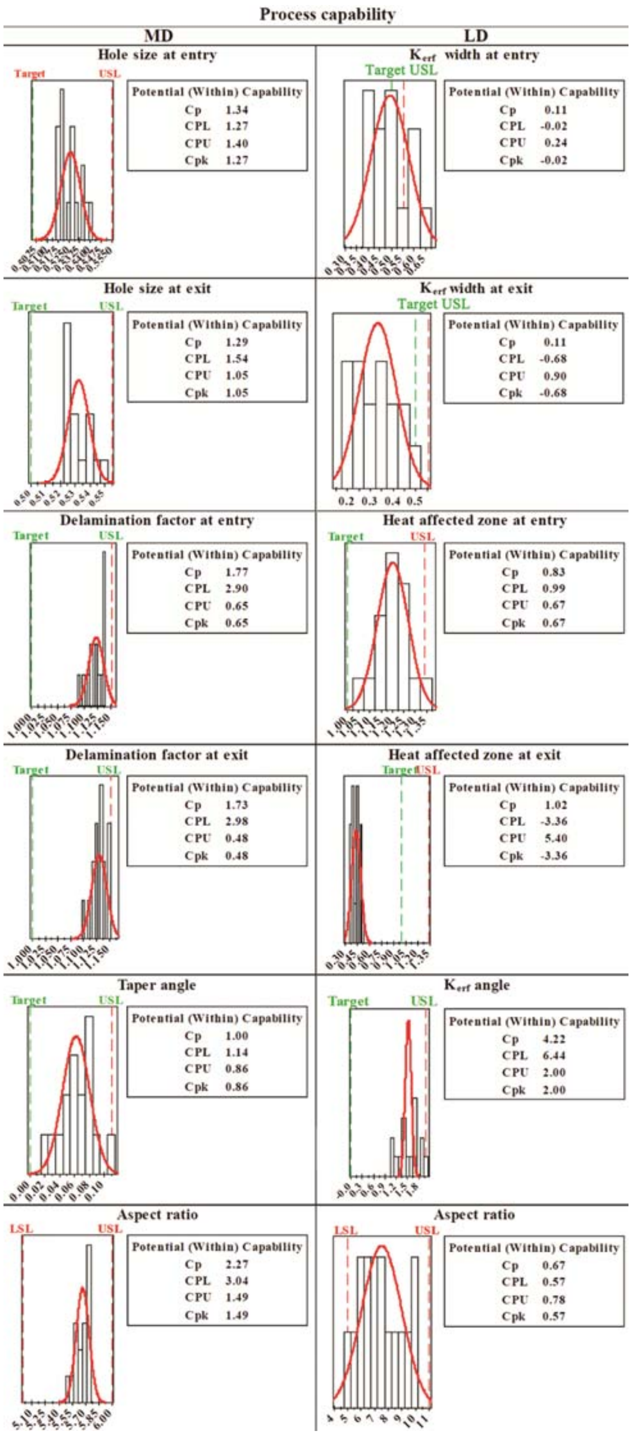

Fig. 14 — Process capabilities for both MD and LD.

(i.e. 7.5) with high SD. Hence, it was concluded that the MD was superior to the LD for micro-drilling CFRP composites**.** The reason for higher SD may be due to the effects of laser process parameter on quality characteristics and may be an improper selection of process parameter.

6.5 The technical reason for rejection of laser drilling

In laser drilling, high process temperature results were in significant damage to the composite material. The damages were characterized by micro-structural changes such as matrix melting and fiber swelling around the hole area and elliptical hole formation. This was due to the preferential heat conduction along the fiber direction. It was also observed that the carbon fiber-reinforced composite material was losses both tensile and compressive strength in laser drilling. This was also due to the damage around the hole. There were various factors that have to be taken into account when was lasers used as drilling tools, the main considerations were including the absorption of the energy and how this were varies with the temperature of the material, the thermal diffusivity of the material (as this controls how rapidly the heat is conducted away from the cutting zone) and thirdly the reaction temperature (of melting/vaporization/ decomposition). There were other considerations such as the dimensions of the heat-affected zone, which was the zone where the capability of stress transfer from the matrix to the fibers was reduced or absent. Further concerns include the formation of burrs and dross, thermal expansion of the material and consideration of the tolerances were required, reaction products, the assist gas and finally safety. All of these elements must be considered.

Another problem with the laser drilling of composites has occurred because the constituents of the material were completely different. Because of the properties of various fibers and resins, there was a vast range of temperatures at which the materials melt (or soften or decompose). The laser beam has a certain power and thus has a defined heat input into the material. However, because of the different properties of the fiber and matrix, the two components can react very differently to the thermal input. In general, the energy was needed for the vaporization of the fibers was higher than that required for the matrix, the instance where this was most noticeable being when cutting carbon fiber composites. Carbon fibers were good conductors of heat and so a large amount of the thermal energy introduced in laser cutting was conducted away. The disassociation temperature of carbon was also very high. These factors combine to make the cutting of carbon fiber reinforced composites very difficult. When a laser was employed to cut these composites, a large volume of resin was vaporized in the process also, since so much heat was required to vaporize the fibers and overcome the

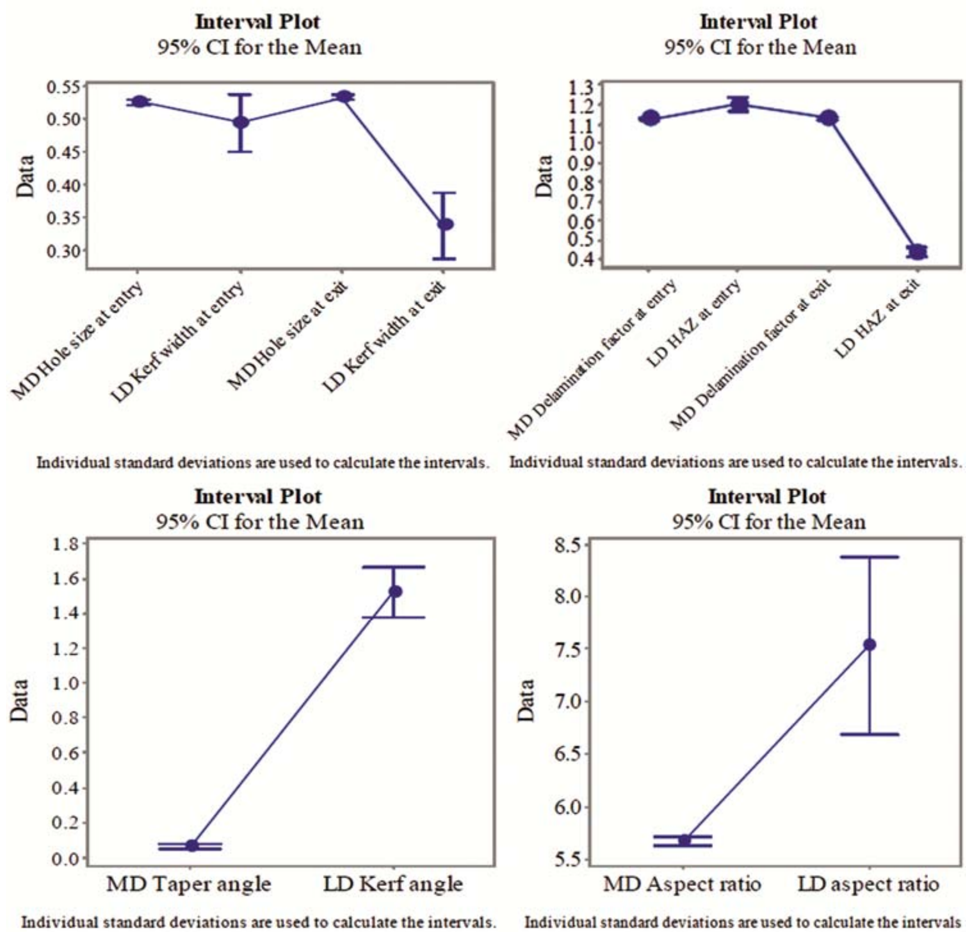

Fig. 15 — Interval plot for MD and LD.

thermal diffusion effects: this can cause delamination of the composite. This was also the reason for rejection of LD of CFRP.

6.6 Structural damages

The local structures around the holes drilled by MD process such as delamination factor, burrs, sub surface damages, cracks propagation, matrix debonding, adhesive fracture, cohesive fracture, fiber pulled out/in, rough and serrated failure surface, matrix cracking, spalling, fuzzing and concave surfaces, will reduce the quality of the component due to the increased stress concentration and will lead to service failure. The local structures around the holes drilled by LD process such as heat affected zone, kerf width, kerf angle, matrix recession, fiber burnout, sideways burning at the bottom edge of the workpiece delamination also reduce the quality of the component and lead to service failure because of increased stress concentration. These local structures around the holes of CFRP mostly influence the stress intensity factor of the hole.

7 Conclusions

The process capability of MD and LD were successfully evaluated while micro-drilling CFRP composites. In order to evaluate the best hole making process normality test, control chart, evaluation of process capability and interval plot were used. From the above analysis, the following conclusion was drawn

(i) The micro-holes with diameter 0.5 mm were precisely drilled using MD process.

(ii) The quality characteristics of MD and LD were normal and are in control. The kerf angle obtained in LD was exceptional.

(iii) The SD values are high in the LD process and therefore it can be concluded to be an inferior process.

(iv) Based on the selection of machining condition, specifications limit and target values the MD is found to be the best process for processing CFRP composites.

(v) The C_p and C_{pk} value is very useful to identify the process capability of the different machine.

(vi) This experimental result is only applicable for CFRP with the following material specification: 3 mm thickness, 55% carbon fiber, 45% epoxy resin, 12 layers, and 0°/90° fiber orientation. However if the sample specification is slightly varied. These results can be used. If the variation in sample specification is large, the user can develop their own model taking this work an example.

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