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INFLUENCE OF MACHINING PARAMETERS ON SURFACE ROUGHNESS OF GFRP PIPES

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Abstract:
Composite pipes find various industrial applications such as transportation of corrosive fluids, desalination plants, oil and gas industries. The present scenario of the composite industry aims to get damage free surface after machining. The leading methods of manufacturing glass fiber reinforced plastic pipes (GFRP) are hand lay-up and filament winding processes. The objective of the present work is to analyze the influence of machining parameters on material characteristics of GFRP pipes while machining. The Effect of machining parameters on tool wear and machining force are also evaluated. To reveal the quality of the machined surfaces the samples are observed through Scanning Electron Microscope (SEM) and the images are presented. The quality of the machined surface is investigated and presented in detail in this paper. The machining parameters are also optimized through simple regression and cross product regression methods.

Key Words: GFRP, Machining, SEM, Surface roughness, Taguchi

1. INTRODUCTION

Machining techniques of Fibre Reinforced Plastic (FRP) were initially developed from either textile cutting, which are suited for prepregs, or from wood working and metal working processes [1]. Machining of fibre reinforced composite differs significantly from machining conventional metals and alloys, owing to the behaviour of matrix material, reinforcement and diverse properties of fibre, matrix, and orientation of fibre and volume fraction of fibers [2]. Glass fibre reinforced plastics (GFRP) are having a combination of properties such as high specific strength, high specific stiffness and light weight, which makes them attractive for applications ranging from aircraft to desalination plants. Machining of GFRP is necessitated to manufacture near-nett shaped components [3]. A few researchers carried out experimental investigations to study and analyze the machining characteristics of fibre reinforced composites either by drilling or turning. An attempt was made by Singh. I and Bhatnagar. N [4] to correlate the drilling-induced damages with drilling parameters of uni-directional glass fibre reinforced plastic composite laminates. The drill point geometry is a well known factor that influences the damages during drilling. Among the drill point geometries tested, four facet drills were not recommended. The results also reaffirm and agree with the earlier results that the cutting speed to feed ratio being an important variable which influences the drilling induced damages. A study has been attempted through wavelet packet transform by Velayudham. A *et.al* [5] to determine the drilling characteristics of high volume fraction fibre glass reinforced polymeric composites. A new machinability index was proposed by Paulo Davim and Francisco Mata [6&7] for the turning of hand laid up GFRP. Polycrystalline diamond and cemented carbide (K15) cutting tools were used as cutting tools. This investigation reveals that the polycrystalline diamond (PCD) tool performs well compared to cemented carbide (K15) tool in terms of surface roughness and specific cutting pressure. However the cost of PCD tools is higher.

Palanikumar K and Paulo Davim. J. [8] developed a mathematical model to predict the tool wear on machining of glass fiber reinforced composite. Regression analysis and analysis of variance were used to develop the model. Palanikumar *et.al* [9] has attempted to assess the influence of machining parameters on surface roughness in machining of GFRP composites. It concludes that the feed rate has more influence on surface roughness and it is followed by cutting speed. Evaluation of cutting parameters and the influence of matrix under cutting force, delamination factor and surface roughness in two types of polyester thermoset matrix material such as Viapal (VUP 9731) and ATLAC (382-05) was carried out with cemented carbide(K10) drill for machining FRP by Paulo Davim. J *et.al* [10]. Machining force also plays a key role in analyzing the machining process of FRP's. The value of machining force in the work piece is determined using the equation $Fm = \sqrt{Fx^2 + Fy^2 + Fz^2}$. Generally, machining force increases with feed rate and it decreases with cutting velocity [11]. Evaluation of machining parameters of hand-lay up GFRP related to machining force was also carried out by Paulo Davim *et.al* [12, 13] on drilling and milling by using cemented carbide (K10) drills and end mills. Mohan. N.S. *et al* [14] analyzed the influence of machining parameters on cutting force during drilling of glass fiber reinforced composite with the help of a commercially available software package MINITAB14. Similarly the influence of tool materials and tool geometries on cutting characteristics of glass fiber reinforced plastics was investigated by Sang-Ook An *et al* [15]. According to the author, a tool with a straight edge performs better than a tool having a round edge. Ramkumar. J *et al* [16] investigated the effect of work piece vibration on drilling GFRP laminates. By vibrating the work piece, there is a considerable amount of reduction in thrust force, tool wear, temperature, power and the surface roughness. A study on determining the effective hardness of tool material was carried out by Sreejith. P.S. *et.al* [17]. The cutting speed has a large influence on carbide tool wear/life. The tool wear has a strong influence on feed force and surface roughness [18]. Carbide tools offer better surface finish of acceptable range at a lower cost. It is inferred that the feed rate has more influence than the cutting velocity on surface finish [19]. Fiber orientation plays a vital role in the surface roughness during cutting. Peaks of roughness are generated with zero degree cut. Owing to the combined load of bending and compression at 45^0 cut, fibers are pulled out by kinking and breaking which resulted in poorest surface quality. Smoothened surface can be obtained through 90^0 cut [20]. Fiber orientation is a key factor that determines the surface integrity of a machined surface and 90^0 is a critical angle, beyond which a severe subsurface damage will occur. If the fiber orientation angle is greater than 90^0 the three distinct deformation zones namely chipping, pressing and bouncing will appear [21]. Aravindan et al investigated the machinability of hand lay up GFRP pipes using statistical techniques [22].Even though many attempts were made, still the machining characteristics of GFRP are unclear. This work is an attempt to analyze and compare the machining characteristics of filament wound and hand lay up GFRP pipes. The experimental values obtained are treated statistically.

2. EXPERIMENTAL DETAILS

2.1 Materials and Processes

GFRP pipes were made using the resin composition of Isophthalic (50%) and Vinylester (50%). The volume fraction of the materials is 65:35 (Resin: Glass). Table I shows the mechanical and thermal properties of the selected GFRP materials. The fiber orientation angle of the specimen used for the tests is 90^0. The hand lay up pipe composite specimens were of 75mm length, 30mm and 55mm of inner and outer diameters respectively as shown in figure 1(a).

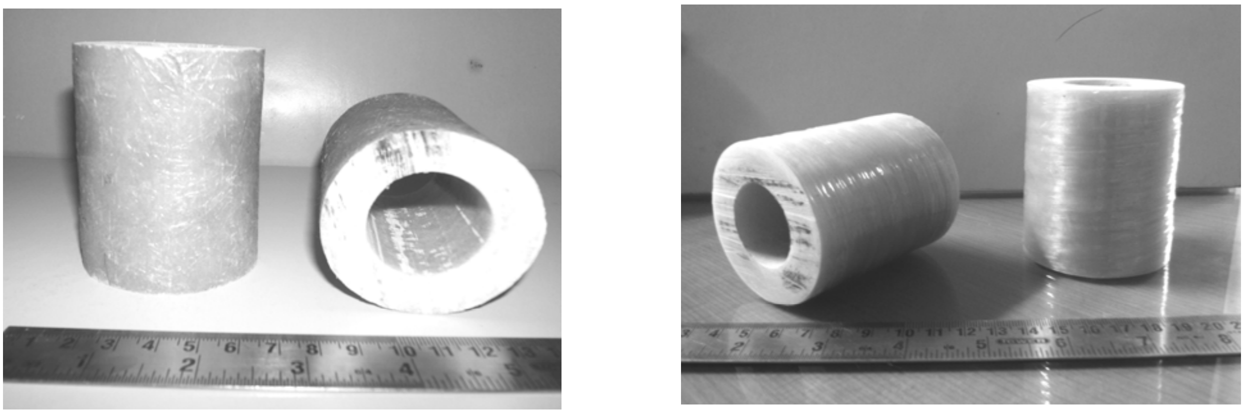
Table I : Mechanical and thermal properties of the GFRP materials.

Mechanical and Thermal properties	Value	
	Hand Lay up	Filament winding
Long term Hydrostatic strength (*MPa*)	95	140
Short term Hydrostatic strength (*MPa*)	150	240
Tensile Modulus (*MPa*)	169.75	280
Tensile strength (*MPa*)	60	95
Co-efficient of linear expansion ($m/m\ ^oC$)	2×10^{-5}	2×10^{-5}
Thermal Conductivity (*W/m K*)	0.29	0.29
Density ($Kg/m^{3)}$	1260	1800

The filament wound composite specimens were of 75mm length, 35mm and 65mm of inner and outer diameters respectively as shown in figure 1(b). A CNC lathe (FANUC) with 7.5KW spindle power and maximum speed of 4500rpm was used to perform the machining operation. The force measurement was carried out by using a Kistler dynamometer. The data acquisition was carried out by appropriate software called *Dynaware kistler*.

Coated Carbide tool inserts (K_{20} grade) were used for machining. The cutting tool inserts used for the machining are of readily available Kennametal make. The geometry of the cutting tool insert is as follows: rake angle -7^0 (negative), 7^0 clearance angle, 80^0 edge major tool cutting, 0^0 cutting edge inclination angle and nose radius of 0.8mm.

Tool wear was measured using Passing and Reflection type Tool Maker's microscope having a least count of 0.5micron. Flank wear was measured by the width of wearland on the flank below the cutting edge. The crater wear was measured by the depth of cup in the rake face. The surface roughness was evaluated using a surface roughness measuring instrument of Kosaka Lab, Japan. The cut off length of the instrument is 0.80 mm. The machined surfaces are studied through SEM analysis.



(a) Hand Lay- Up pipes (b) Filament Winding pipes

Figure 1: GFRP Composite Pipe Specimens.

2.2 Taguchi Method

Robust design is an engineering methodology for obtaining product and process conditions, which are minimally sensitive to the various causes of variation to produce high quality products with low development and manufacturing costs [23]. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize design for performance, quality and cost. Taguchi methods which combine the experiment design theory and the quality loss function have been applied to the robust design of products and process and have solved even complex problems in manufacturing. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The experimental results are then transformed in to a Signal-to-Noise (S/N) ratio. Taguchi recommends the use of S/N ratio to measure the quality characteristics deviating from the desired value. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics [24].

2.3 Plan of experiments

The methodology of Taguchi for three factors at three levels was used for the implementation of the plan of experiments. The orthogonal array L_{18} is selected as shown in Table II, which has 18 rows corresponding to the number of tests with the required columns. The plan of experiments comprises of eighteen tests where the second column is assigned to the cutting velocity (V), the third column is assigned to the feed rate (f) and the fourth is to the depth of cut (d). The factors and their levels required for the experiments are also presented in Table II. Both hand lay up and filament wound pipes were machined by using L_{18} orthogonal array separately with the same machining parameters for each of the eighteen test conditions. The quality characteristics to be studied are machining force, flank wear, crater wear and surface roughness. The experimentally collected data are then subjected to optimization using ANOVA obtained from regression analysis. In this study both simple regression and cross product regression methods were used and compared.

Table II: Orthogonal array L_{18} of Taguchi along with assigned values.

TCN	X1	X2	X3	V	f	d
1	1	1	1	100	0.05	0.5
2	1	2	2	100	0.1	1
3	1	3	3	100	0.2	2
4	2	1	1	150	0.05	0.5
5	2	2	2	150	0.1	1
6	2	3	3	150	0.2	2
7	3	1	2	200	0.05	1
8	3	2	3	200	0.1	2
9	3	3	1	200	0.2	0.5
10	1	1	3	100	0.05	2
11	1	2	1	100	0.1	0.5
12	1	3	2	100	0.2	1
13	2	1	2	150	0.05	1
14	2	2	3	150	0.1	2
15	2	3	1	150	0.2	0.5
16	3	1	3	200	0.05	2
17	3	2	1	200	0.1	0.5
18	3	3	2	200	0.2	1

3. RESULTS AND DISCUSSION

The machinability in this work was evaluated by the parameters such as surface roughness (R_a), machining forces and tool wear. The results obtained through experiments are presented in Table III. The Taguchi's Design of Experiments and Regression analysis are applied to identify the best levels of cutting parameters and their significance. Also these techniques are effectively used for optimization of parameters and for modeling as well. By considering the cutting velocity, feed rate and depth of cut and their interactions, the number of experimental trials required was determined as 18 and the experiments were conducted with different cutting inserts of the same specification to obtain more data.

Machining of GFRP is continued with the same insert up to a maximum material removal of 30 $cm^{3.}$ For such constant volume of material removal, the tool wear, machining force and surface finish are measured under different machining conditions. The Taguchi's approach to experiment design is described in the flow chart which is presented in figure 2. The first step in Taguchi method is to determine the quality characteristic which is to be optimized. The output or response variable which influence effectively on the quality of the product is known as quality characteristic. In this study, the tool wear, machining force and surface roughness are the quality characteristics. In the second step, the control parameters or test parameters which have significant effects on the quality characteristic are identified with the required number of levels. In the third step, the appropriate orthogonal array for the control parameters is selected after calculating the minimum number of experiments required to be conducted by considering the interactive effects.

Table III: Responses for different test conditions.

Test Condition Number	Filament wound pipes					Hand Lay up pipes				
	Flank Wear (mm)	Crater Wear (mm)	R_a (micron)	F_m (N)	S/N ratio of 100% CO	Flank Wear (mm)	Crater Wear (mm)	R_a (micron)	F_m (N)	S/N ratio of 100% CO
1	0.059	0.011	2.35	57.23	25.16	0.023	0.018	3.95	17.50	16.70
2	0.066	0.009	4.06	83.18	28.50	0.018	0.048	8.21	47.50	24.88
3	0.088	0.007	3.95	95.68	29.63	0.028	0.018	6.22	17.50	17.78
4	0.068	0.009	2.81	51.78	24.44	0.017	0.018	4.25	17.70	16.92
5	0.078	0.008	3.61	77.47	27.85	0.048	0.015	8.52	15.00	17.97
6	0.109	0.006	3.65	86.48	28.76	0.025	0.015	5.03	15.00	16.28
7	0.085	0.007	3.71	71.48	27.21	0.018	0.008	6.07	7.50	13.41
8	0.108	0.006	4.07	68.14	26.88	0.018	0.013	6.07	12.50	15.82
9	0.112	0.006	3.67	43.98	23.34	0.023	0.012	6.34	11.50	15.55
10	0.067	0.009	3.63	58.24	25.55	0.025	0.013	4.73	12.80	15.18
11	0.064	0.010	2.87	50.39	24.23	0.020	0.030	6.14	30.00	21.19
12	0.079	0.008	3.13	47.91	23.89	0.020	0.023	7.51	22.50	19.79
13	0.071	0.009	3.88	74.57	27.58	0.025	0.025	3.81	25.00	19.12
14	0.087	0.007	2.74	83.32	28.34	0.016	0.013	4.03	12.50	14.59
15	0.090	0.007	3.39	69.61	26.95	0.015	0.008	3.73	7.50	11.47
16	0.096	0.007	3.26	132.97	32.30	0.023	0.008	4.41	8.00	12.40
17	0.089	0.007	2.58	40.66	22.44	0.028	0.018	8.12	17.50	18.59
18	0.122	0.005	3.99	66.29	26.65	0.023	0.012	5.08	12.00	15.02

In the Taguchi method of optimization, the signal-to-noise ratio is used as the quality characteristic of choice. The different S/N ratio characteristics are given as,

Nominal the best characteristic: $$S/N = 10log\frac{\bar{y}}{S_y^{\ 2}}$$

Smaller the better characteristic: $$S/N = -10\log\frac{1}{n}\sum\bar{y}^2$$

Larger the better characteristic: $$S/N = -10\log\frac{1}{n}\sum\frac{1}{\bar{y}^2}$$

where,

$\bar{y}$ - Average of observed values, $S_y^{\ 2}$ - Variance of y

n - Number of observations and y - Observed data

In this study, “the smaller the better” characteristic is applied to determine the S/N ratio for tool wear, machining force and surface roughness, since all these parameters are to be minimized.

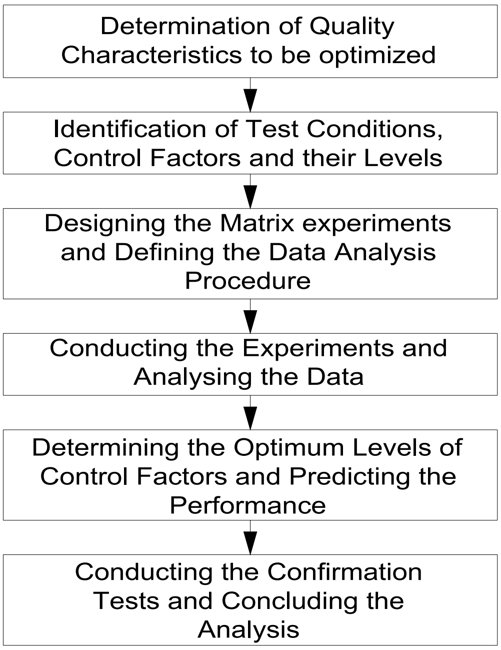


Figure 2: Flow chart for DOE.

Optimal combinations of parameters are determined based on assumed weightage of 1: 2: 3: 4 for crater wear, flank wear, machining force and surface roughness respectively. The weightage of parameters was assumed on the basis of physical significance of each parameter during machining. Surface roughness plays an important role in many areas and is a factor of greater importance in the evaluation of machining accuracy [9], and hence it is given maximum weightage. Machining force plays the next prominent role after surface roughness [15], and therefore the next best weightage was assumed to it. Apart from surface roughness and machining force, tool wear also contributes significantly in determining the optimum machining characteristics. Mostly flank wear is considered, since it largely affects the stability of the cutting wedge and consequently the dimensional tolerance of the machined work surface [25]. And hence the weightage for flank wear is assumed as the third best, while the weightage for crater wear was assumed to be the least. The S/N ratios of flank wear, crater wear, machining force and surface roughness are calculated and presented in Table III. The best values of various parameters for the combined objective (combined objective with 10% to crater wear, 20% to flank wear, 30% machining force and 40% to surface roughness) of minimized tool wear, machining force and surface roughness are identified. The optimal combinations of parameters for filament wound GFRP pipes for better values of tool wear, machining force and surface roughness are identified as $V_2f_1d_3$ and the optimal combinations of parameters for hand lay up GFRP pipes for better values of tool wear, machining force and surface roughness are identified as $V_1f_2d_{2.}$ as shown in figure 3.

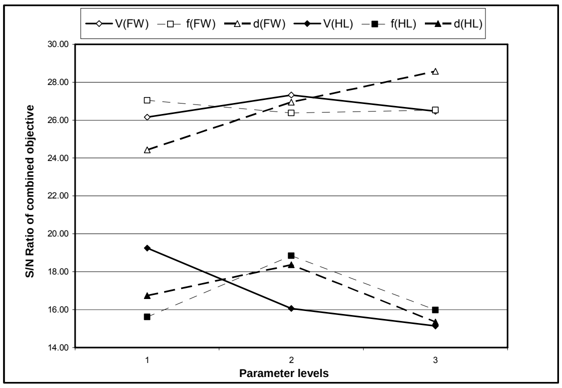


Figure 3: S/N ratio of combined objective for various parameter levels.

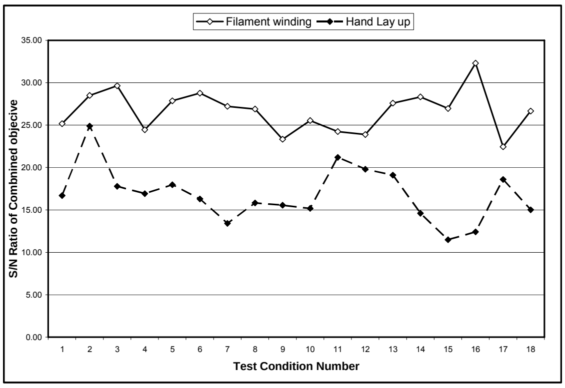


Figure 4: S/N ratio of combined objective for various test conditions.

Figure 4 represents the S/N ratio of combined objective for various test conditions. From figure 4, it is observed that almost filament wound and hand lay up pipes follow an identical trend. Figure 5 represents the average S/N ratio of combined objective for various parameter levels. And it is observed that the average S/N ratios of combined objective of filament wound pipes are slightly more than the hand lay up pipes. Normally filament wound pipes are having better mechanical properties when compared to hand laid up pipes, (as observed in Table I) due to the existing complexities in the processes. The reason for the higher S/N ratio for filament pipes is due to the nature of good mechanical properties of filament wound pipes compared to hand lay up pipes. The higher the average S/N ratio will significantly result in good surface finish. Figure 6 shows the S/N ratio of combined objectives obtained through simple and cross product regression for various test conditions. From figure 6, it is observed that both simple regression as well as cross product regression follows an identical trend for both the pipes. Figure 7 represents the percentage deviation between experimental and model S/N ratio values for various test conditions.

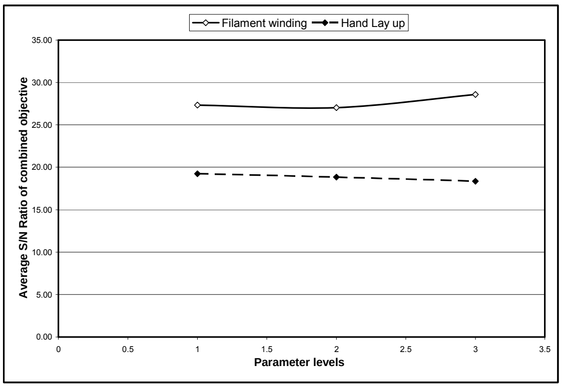


Figure 5: Average S/N ratio of combined objective for various parameter levels.

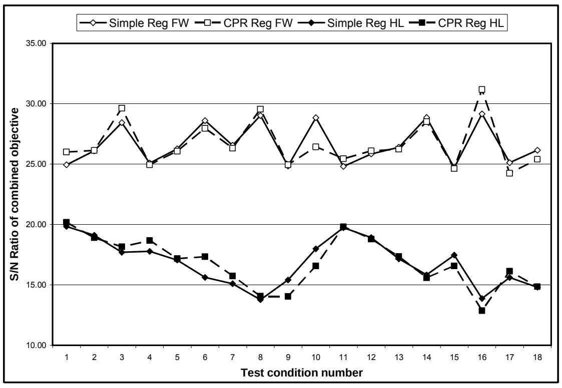


Figure 6: S/N ratio of combined objective for various test conditions through regression.

From figure 7, it is understood that the percentage deviation of S/N ratio for both simple as well as cross product regression follows an identical trend for both the materials. Hence both simple regression as well as cross product regression methods is well suited for optimizing the machining parameters of GFRP pipes.

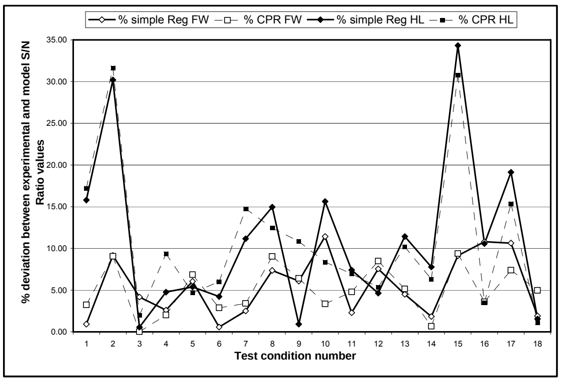


Figure 7: Percentage deviation between experimental and model S/N ratio values for various test conditions.

3.1 Confirmation Test

By using the optimized machining parameters obtained from the experimental results, a validation experiment is conducted for both hand lay up as well as for filament wound pipes. Through this validation experiment the values obtained for hand lay up pipes are 0.015mm, 0.0075mm, 12.50N and 3.30 micron for flank weak, crater wear, machining force and surface roughness respectively. Similarly the values for filament wound pipes are 0.230mm, 0.018mm, 51.14N and 2.69 micron for flank wear, crater wear, machining force and surface roughness respectively. For verifying the validated result, the estimated mean (T_{em}) of S/N ratio is calculated based on the experimental results. A 95% confidence interval (CI) is also predicted for mean S/N ratio on confirmation test for regression model. Since the S/N ratio value of the validated results falls in between (T_{em} – CI) and (T_{em} + CI), the results obtained in validated trial are confirmed. From these results, it is inferred that moderate cutting velocity, lower feed rate and higher depth of cut are the best machining conditions for machining filament wound GFRP pipes. And lower cutting velocity, moderate feed rate and moderate depth of cut are the best machining conditions for machining hand lay up GFRP pipes.

3.2 SEM analysis of cutting tool

Cutting tools are required to operate under high loads and at elevated temperatures. In addition, severe frictional conditions occur between the tool and the chip and between the tool and the just machined work-piece surface. Hence, the tools should have high temperature, physical and chemical stability. During machining of GFRP pipes, the cutting zone experiences both thermal and mechanical stresses. Under such conditions, the cutting nose may be subjected to localized dynamic loading, due to the difference in stiffness and strength properties of the fibre and matrix. Figure 8, 9, 10 shows the micro structure of the cutting tool nose of unused cutting tool, cutting tool with maximum wear and cutting tool with minimum wear respectively. As observed in figure 9 the wear is more due to the improper selection of machining parameters and subsequently the tool damage can be clearly seen on the cutting tool nose. From figure 9, it is also observed that the cutting edge remained intact. However notching over the secondary edge, spalling and cracks over the rake face can be noticed. Notching and cracks observed at the rack face of the tool. Abrasive nature of glass fibers and the raise in temperature at the tool work interface are the probable reasons for such cracks. This has been considerably reduced by optimizing the machining parameters. The minimum tool wear condition is represented in figure 10.

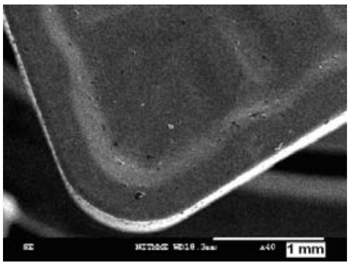


Figure 8: New cutting tool.

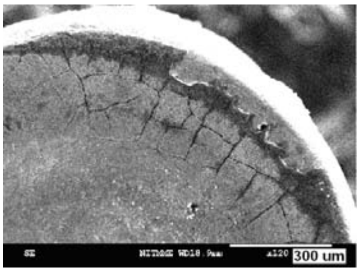


Figure 9: Worn out tool (Maximum wear condition).

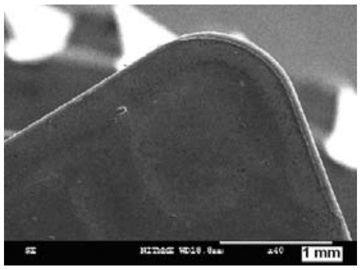
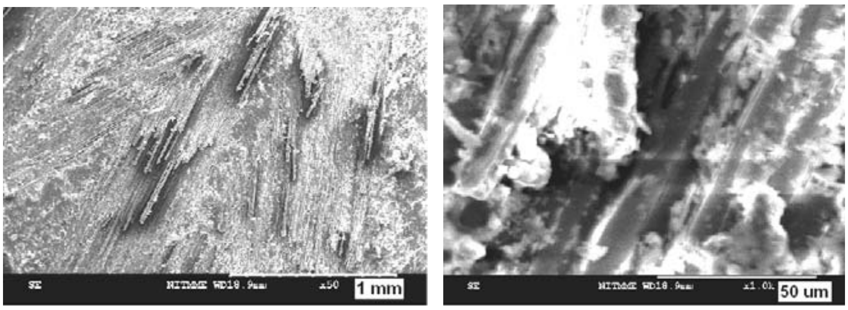


Figure 10: Worn out tool (Minimum wear condition).

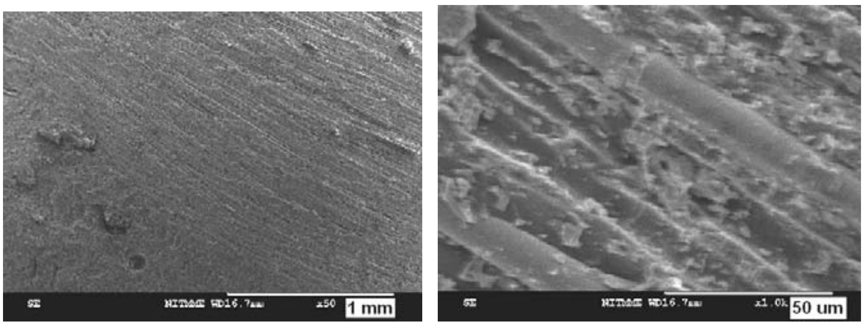
3.3 SEM analysis of filament wound pipes

The SEM images of machined surface of filament wound pipes for poor surface finish with lower and higher magnifications are shown in Figures 11(a) and 11 (b) respectively. The surface roughness of these surfaces was found to be 4.07 μm. The increased surface roughness is due to the poor selection of machining parameters. The surface damages are clearly observed from the figure. Fiber pull out, fiber damages and cracks in the matrix material are observed. Figure 12(a) & (b) represents the microstructure of machined surface of filament wound pipes of best surface finish with lower and higher magnifications respectively. The observed value of surface roughness for this case is 2.35 μm. From the figures, it can be understood that by using suitable machining conditions, damage free surfaces can be produced. Figures 13(a) & (b) represents the machined surface of validated experiment for filament wound GFRP pipes with lower and higher magnifications respectively. The observed value of surface roughness for this case is 2.69 μm. From figures 13 it is observed that the microstructure of the machined surface of the validated experiment is damage free both in lower as well as in higher magnifications.



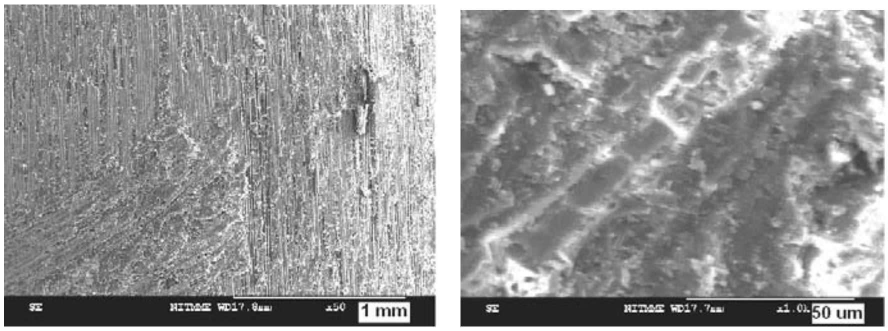
(a) (b)

Figure 11: Machined surface of Filament wound pipes - worst surface finish.



(a) (b)

Figure 12: Machined surface of Filament wound pipes - best surface finish.

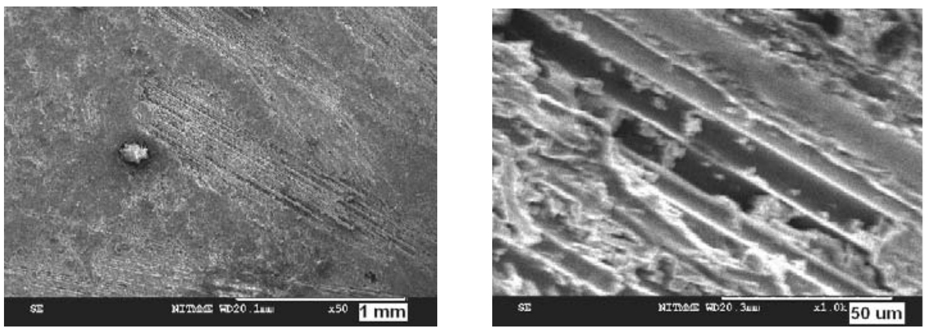


(a) (b)

Figure 13: Machined surface of Filament wound pipes –Validated Experiment.

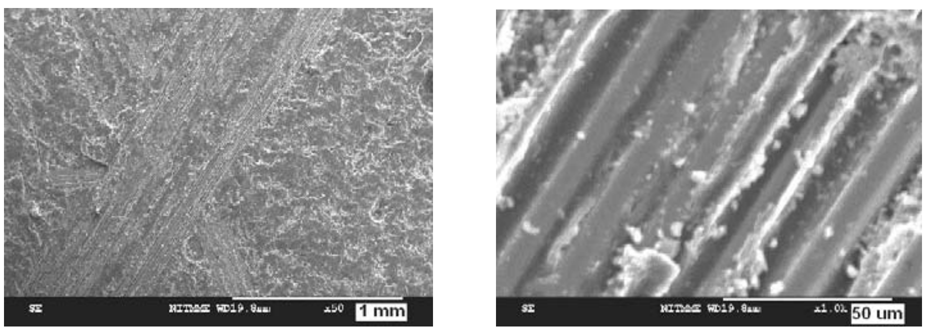
3.4 SEM analysis of Hand Lay up pipes

The SEM images of machined surface of hand lay-up pipes for poor surface finish with lower and higher magnifications are shown in Figures 14(a) and 14 (b) respectively. As observed from the figure, debonding and fiber breakage are the reasons for the poor surface finish. Figures 15(a) & (b) represents the microstructure of machined surface of hand lay up pipes for best surface finish with lower and higher magnifications respectively. Figure 16(a) & (b) represents the microstructure of machined surface of validated experiment for hand lay up GFRP pipes with lower and higher magnifications respectively. Under some specific cutting conditions the surface of machined specimens is damage free. From figure 16 it is observed that the microstructure of the machined surface of the validated experiment is damage free both in lower as well as in higher magnifications. Compared to filament wound pipe, the damages observed in hand laid up pipes are more. More number of porous sites and damaged zones are observed in the case of hand laid up composite tubes. The average surface roughness of the machined hand lay up composite tubes is comparatively of larger order due to inherent pores during manufacture and induced damages during machining.



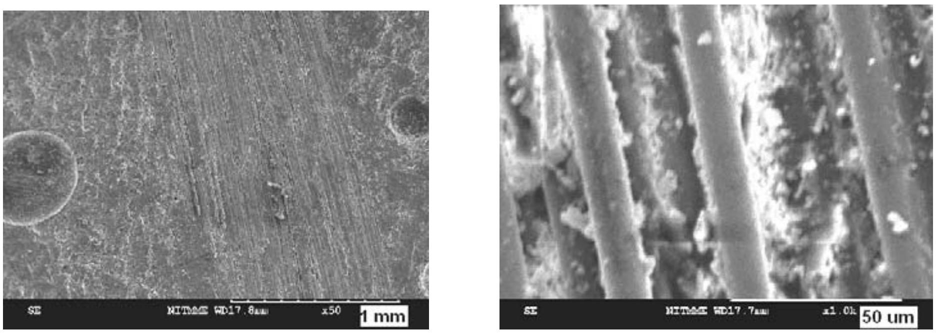
(a) (b)

Figure 14: Machined surface of Hand Lay up pipes - worst surface finish.



(a) (b)

Figure 15: Machined surface of Hand Lay up pipes - best surface finish.



(a) (b)

Figure 16: Machined surface of Hand Lay up pipes – Validated Experiment.

4. CONCLUSION

In this work, the machining characteristics of GFRP pipes made by hand lay up and filament winding process are thoroughly analyzed. From this work, the following conclusions are drawn.

- Lower cutting velocity, moderate feedrate and moderate depth of cut are the ideal machining conditions for machining hand lay up GFRP pipes.
- Moderate cutting velocity, Lower feed rate and higher depth of cut are the ideal machining conditions for machining filament wound GFRP pipes.
- The machining force and tool wear while machining filament wound GFRP pipes are of larger order compared to that of hand lay up GFRP pipes. But the quality of the machined surface of filament wound GFRP pipes is better than the hand lay up GFRP pipes.
- Debonding and fiber breakage often takes place in the case of conventional cutting conditions. To get damage free surfaces, optimized machining parameters have to be used. The SEM analysis of the validated machined surface confirms that these optimized parameters not only reduces the tool wear but, also reduces the damages and failures on the machined surface.
- Under optimized specific cutting conditions the surface of the machined specimen is damage free and exhibits better surface integrity.

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