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QUALITY IMPROVEMENT IN MACHINING GFRP COMPOSITES BY PCD TOOLING USING RESPONSE SURFACE METHODOLOGY

Sarma P.M.M.S.
Department of Mechanical Engg., Sri Sai Ram Engineering College, Chennai – 44
E-mail: pmms_sarma@rediffmail.com

Karunamoorthy L.
Department of Mechanical Engg., Anna University, Chennai – 25
E-mail: karun@annauniv.edu

Abstract: *The present study proposed the analysis of cutting forces of GFRP pipes using PCD tool. The filament wound tubes with different fibre orientations are prepared for the purpose of a work specimen. The process parameters used are cutting speed, feed, depth of cut and fibre orientation. The tool forces are measured using KISTLER Dynamometer. The effect of process parameters on Cutting, Thrust and Feed forces is evaluated and the optimum cutting conditions for minimizing the tool forces are evaluated which result in high quality machined surfaces. Second order models have been developed between each of the responses and the process variables using response surface methodology. The predicted values and measured values are in close acceptance, which indicates that the developed models can be effectively used for the prediction of the respective tool forces in the machining of GFRP Composite pipes.*
Key words*: GFRP Pipes, Filament winding, Response Surface Methodology, PCD tool*

1. INTRODUCTION

Glass Fiber Reinforced Polymer (GFRP) Composites find diverse applications as composite armouring designed to resist explosive impacts, fuel cylinders for natural gas vehicles, windmill blades, industrial drive shafts, support beams of highway bridges and even paper making rollers. For certain applications, the use of composites rather than metals has in fact resulted in savings of both cost and weight. The usage in many fields demands several machining operations to be performed on GFRP composites. As such many researchers did experiments in machining of GFRP composites.

The analysis of the theory on machining of fiber-reinforced plastics is restricted to plane deformation of incompressible composites reinforced by strong parallel fibers [Everstine and Rogers, 1971]. In unidirectional Carbon Fibre Reinforced Polymers (CFRP), the cutting forces perpendicular and parallel to the fiber orientation are measured for various parameters and the results are correlated to the formation of chips and tool wear [Koplev et al, 1983]. The machinability of GFRP, chip formation, cutting force and surface quality in orthogonal cutting are evaluated with varied fiber angles [Takeyama and Lijama, 1988]. Mathematical models are developed to describe the wear-time and wear-force relationships for steady centre lathe turning conditions and an approach is proposed to detect tool failure using the variations of the ratio between the radial and vertical force components [Oraby and Hayhurst, 1991]. A comprehensive study had been conducted on orthogonal cutting of GFRP laminates using brazed carbide tools and governing equations were developed for cutting and thrust forces with the geometry of cutting [Bhatnagar et al, 1995].

The machinability of GFRP composites using single crystal diamond, poly crystal diamond and cubic boron nitride tools was investigated experimentally and for low cutting forces the use of single crystal diamond tool was recommended. It was also found that a tool with a straight edge is better than a tool with a round nose in respect of tool geometry [Lee, 2001]. A finite element method was used to analyze the effect of cutting parameters, tool geometry and fibre percentage on cutting and feed forces while machining the unidirectional glass fiber reinforced plastic composite material. The increase in tool rake angle decreased the cutting and feed forces whereas the increase in fibre percentage had increased the tool forces. [Vijayarangan and Abdul Budan, 2001].

The influence of various machining parameters on the thrust force and torque in drilling of glass fibe reinforced epoxy composite materials with different fiber volume fractions was investigated and found that increasing feed, drill size and fiber volume fraction led to increase the thrust force and torque. The thrust force and torque were decreased with increasing cutting speed [El-Sonbaty et al, 2004]. Using high-speed steel (HSS) drill, a series of vibratory drilling and conventional drilling experiments were conducted on woven glass fiber-reinforced plastics composites to assess thrust force. The thrust force was observed to increase distinctly with feed rate and it was smaller in vibratory drilling compared to conventional drilling. The process status during vibratory drilling was also assessed by monitoring acoustic emission from the work piece and vibratory drilling was found as the promising machining technique for facilitating chip breaking and reduction in thrust force [Arul et al, 2006].

Table 1. Specifications of Fiber and Resin

Fiber: E-glass – RO99 1200 P556	**Resin: Polyester**
Manufacturer: Saint Gobain Vetrotex India Ltd. RO99 - Multi-filament Roving, 1200 - Linear Density, Tex P 556- sizing reference for vetrotex	Manufacturer: Mechemco Product: Mechster:1110W (Isopthalate Resin) Thinner: Styrene

In the present study, the effect of the process parameters chosen on cutting, thrust and feed forces in machining GFRP composites has been studied. Optimum values of these parameters are suggested. High quality surfaces can be obtained by carrying out machining at these optimum values due to the minimum tool wear present. The experiments are designed using Central Composite Design (CCD) of response surface methodology approach in design of experiments and are conducted in a lathe using poly-crystalline diamond (PCD) tool. Second order models have been developed for all the three forces in terms of process parameters. The process parameters chosen are speed, feed, depth of cut and fiber orientation angle of filament wound pipes. The predicted values and experimental values are in close correlation indicating that the developed models can effectively be used for determining the forces during turning of GFRP composites.

2. EXPERIMENTATION

GFRP composite pipes of 60 mm internal diameter with 10 mm wall thickness are prepared as samples for using as work piece in machining. The GFRP pipes consists of E-Glass fibers and polyester resin whose specifications are given in Table 1 and are made by filament winding process in a CNC filament winding machine. The orientation of the fibers has been varied for different values during the manufacturing of pipes.

The pipes are turned in a BHARAT make all geared lathe of model NAGMATI – 175 with a maximum speed of 1200 rpm and power of 2.25 kW. The ISO specification of the tool holder used in the turning is a WIDAX tool holder PC LNR 1616 K12 and the tool material used for the study is Polycrystalline Diamond (PCD) which is a synthetic diamond product that is produced by sintering together selected diamond particles with a metal matrix using sophisticated technology. Polycrystalline tipped tools are exceptionally resistant to wear compared to tungsten carbide or ceramic tools. In certain applications, PCD tool life can exceed carbide cutting tool life by 50 to 100 times. The tool insert is PLANSEE-TIZIT make and of type CNMG 120408.

The experiments are conducted as per central composite design. The machining operations are carried out at random to avoid systematic errors. A KISTLER quartz 3-component dynamometer type 9257 B is attached to the lathe before starting machining operation. The dynamometer measures the active cutting force regardless of its application point. It is connected to a 3-channel charge amplifier through a connecting cable which in turn is connected to the PC. The dynamometer is calibrated for the cutting force in the range from 0 to 1000 N. During machining all the three components of the cutting forces in x, y and z directions are measured. To get the accuracy in measuring the forces are measured three times and average for each force has been taken for the analysis. The schematic layout of the experimental set up is shown in Fig.1. A sample output of the dynamometer has been shown in Fig.2.

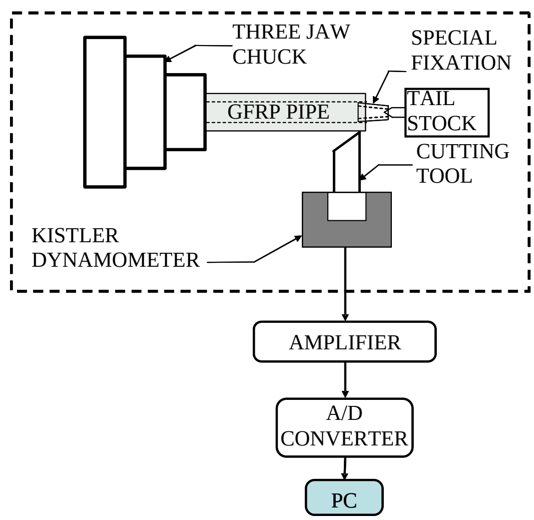


Fig.1 Schematic Layout of Experimental Setup

3. DESIGN OF EXPERIMENTS

The experiments in the present study have been designed as per the central composite rotatable second order design of response surface methodology. The number of variables considered in this study is four viz., x_1, x_2, x_3 and x_4 and the number of experiments conducted is 31 as per the CCD. The plan consists of (2^4) factorial design, plus eight star points and seven center points with a selected alpha value of 2. The process parameters chosen are cutting speed (V) in m/min, feed (f) in mm/rev, depth of cut (d) in mm and fiber orientation angle of the work piece (ϕ), in degrees which are independently controllable. The selected process parameters, their notations and their limits are given in Table 2.

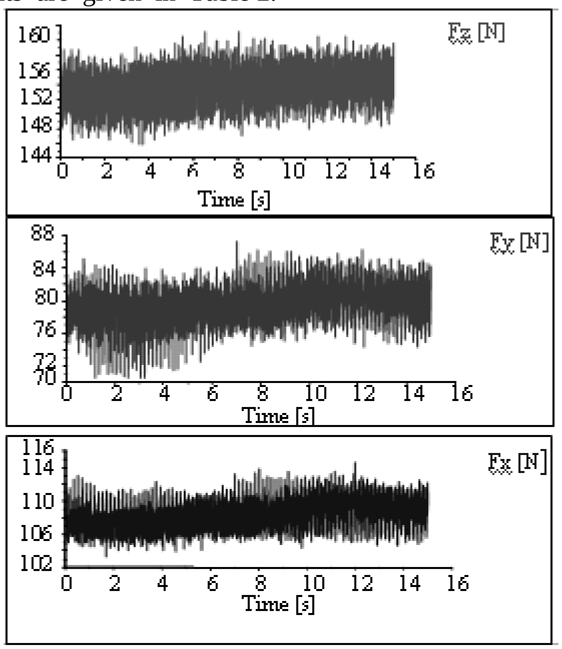


Fig.2 A sample output of KISTLER dynamometer

Table 2. Process Parameters, their notation and their limits

Process Parameter with units	Notation	Variable	Levels				
			-2	-1	0	+1	+2
Cutting Speed, m/min	V	x_1	54	82	126	194	302
Feed, mm/rev	f	x_2	0.048	0.096	0.143	0.191	0.238
Depth of cut, mm	d	x_3	0.25	0.5	0.75	1.0	1.25
Fiber orientation angle, deg	ϕ	x_4	30	45	60	75	90

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize the response [Montgomery, 1991]. A suitable approximation for the true functional relationship between the response and the set of independent variables is found by RSM. A second order model has been utilized in the present study and the coefficients are calculated using the following equations.

$$b_0 = 0.142857(0y) - 0.035714 \sum(iiy) \quad (1)$$

$$b_i = 0.041667(iy) \quad (2)$$

$$b_{ii}=0.031250(iiy)+0.003720\sum(iiy) -0.035714(0y) \quad (3)$$

$$b_{ij} = 0.0625(ijy) \quad (4)$$

The experimental values of the forces are analysed and the following relations are obtained for cutting , thrust and feed forces in coded units.

Cutting Force,

$$F_z = 365.52 + 28.71V + 22.78f +11.84d + 3.64\phi -17.59V^2 -6.49f^2 -4.15d^2 - 6.49\phi^2 + 2.81\, V * f - 0.3\, V * d - 0.05\, V*\phi -0.3\, f*d -0.05\, f*\phi -0.43\, d*\phi \quad (5)$$

Thrust Force,

$$F_y = 151.49 + 4.27V + 5.37\, f + 4.72\, d + 24.8\, \phi - 9.41V^2 - 10.4\, f^2 - 9.73\, d^2 - 10.36\phi^2 + 0.06\, V * f - 0.15\, V * d + 0.96V*\phi + 0.13\, f*d +0.17\, f*\phi + 0.51d*\phi \quad (6)$$

Feed Force,

$$F_x = 208.88 + 6.29V + 6.38\, f + 6.23\, d + 30.98\, \phi - 11.03V^2 - 11.43\, f^2 - 17.73\, d^2 - 20.34\phi^2 - 0.19\, V * f + 0.41\, V * d - 0.28V*\phi + 0.34\, f*d - 0.30\, f*\phi + 0.16\, d*\phi \quad (7)$$

thrust force and feed force are represented in Fig.3, Fig.4 and Fig.5 respectively. Also the probability plot for all the three forces is shown in Fig.6. From the analysis of all these graphs, it has been found that there is no abnormal variation between the experimental values and predicted values and hence the developed models are highly significant and can be used for the prediction of cutting, thrust and feed forces in machining of GFRP composites by PCD tool.

4. RESULTS AND DISCUSSION

The variation of trends observed for different process parameters with respect to the cutting, thrust and feed forces in machining of GFRP composites by PCD tool is presented in Figures 7 – 10. The graphs are drawn with the help of response surface models developed. Figure 7 shows the variation of cutting, thrust and feed forces with respect to cutting speed. It has been observed that all the three forces increase with increase in cutting speed and at high speed (above 194 m/min) they start decreasing. This is in line with the observations made in earlier research [Santhanakrishnan et al., 1988].

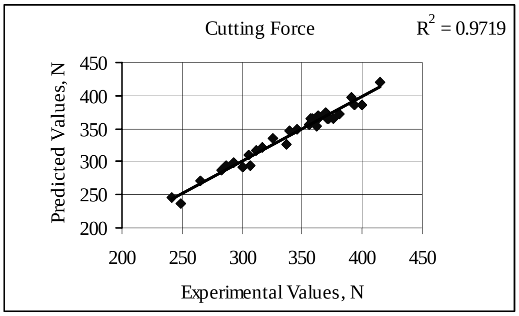


Fig.3 Relation between experimental and predicted values of cutting force

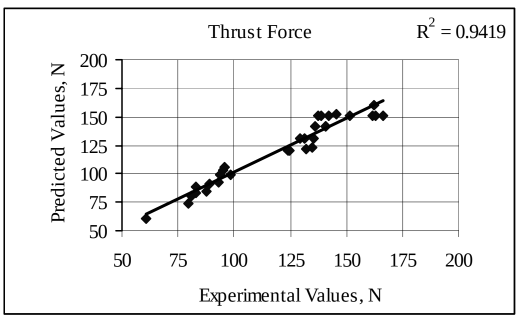


Fig.4 Relation between experimental and predicted values of thrust force

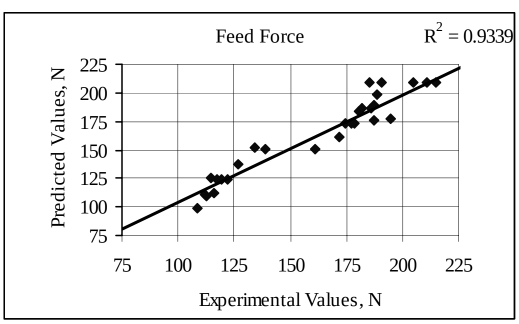


Fig.5 Relation between experimental and predicted values of feed force

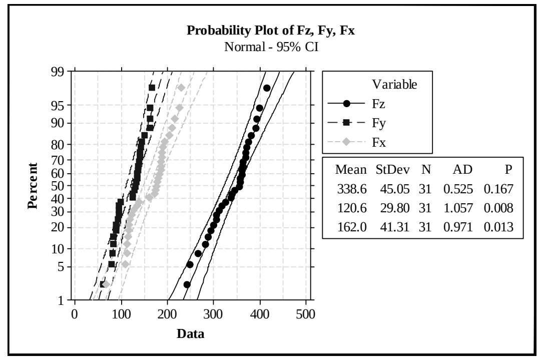


Fig.6 Probability plot for F_x, F_y and F_z

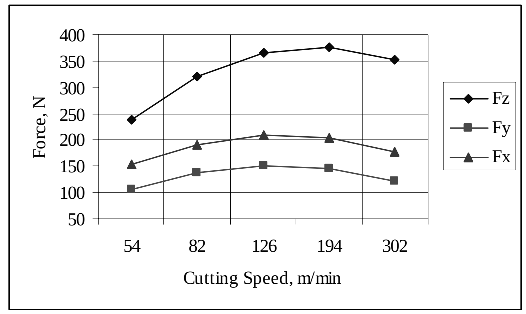


Fig.7 Variation of forces with cutting speed for f= 0.143 mm/rev, d=0.75 mm and $\phi = 60^0$

In Fig. 8 the variation of the three forces with respect to feed is plotted. It is observed that the cutting force increases with increase in feed rate. In machining, the increase of feed increases the load on the tool which in turn produces high heat and tool wear. This accounts for high cutting force with respect to high feed. A small reduction in thrust and feed forces is observed at high feeds.

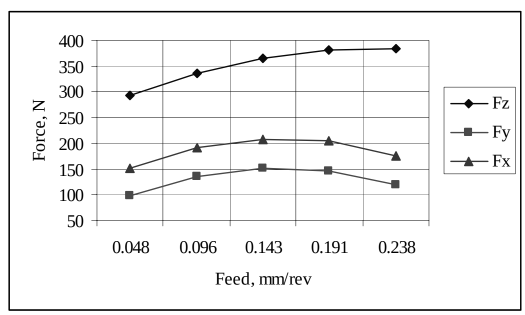


Fig.8 Variation of forces with feed for V= 126 m/min, d=0.75 mm and $\phi = 60^0$

Fig.9 shows the variation of cutting, thrust and feed forces with respect to depth of cut for the central values of other process parameters. It is observed that depth of cut has very little influence on the forces of machining. The cutting force increases a little with increase in depth of cut. The thrust and feed forces increase slowly with increase in depth of cut and very little reduction is observed in them at higher depth of cut.

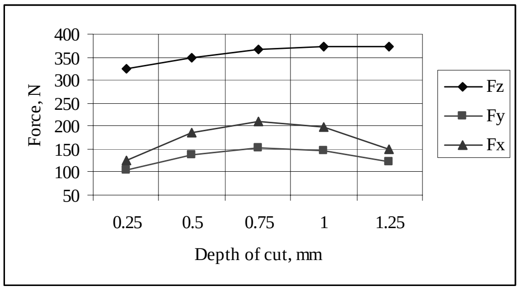


Fig.9 Variation of forces with depth of cut for *V*= 126 m/min, *f*=0.143 mm/rev and $\phi = 60^0$

The variation of the forces during machining with respect to fiber orientation angle has been shown in Fig.10. It can be observed from the graphs that the cutting force as well as the thrust force increase gradually with increasing fiber orientation angle. These findings are in close acceptance with the conclusions made by previous researchers [Takeyama and Lijama, 1988]. A small reduction in feed force is observed for 90^0 fiber orientation angle

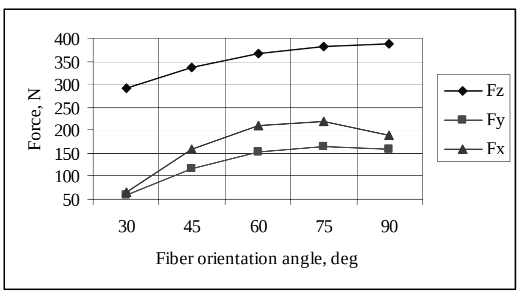
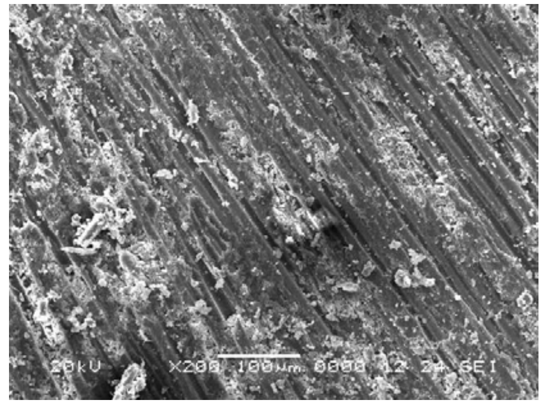
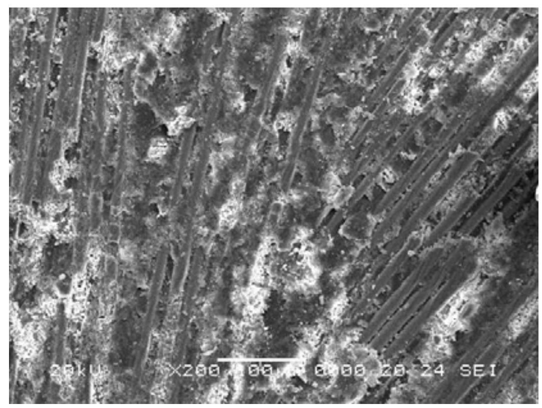


Fig.10 Variation of forces with fiber orientation angle for *V*= 126 m/min, *f*=0.143 mm/rev and d= 0.75 mm

SEM micrographs of the machined surfaces at different machining conditions are shown in Fig.11 (a) and (b). Broken fibers and a non-uniform flow of the polyester resin in between the fibers can be observed from the graphs which indicate that the GFRP composites are anisotropic and inhomogeneous in nature.



(a)



(b)

Fig.11. SEM micrographs of GFRP machined surfaces at different cutting conditions

5. CONCLUSIONS

1. By machining GFRP composites using PCD tool, chips are obtained only in powder form.
2. Second order models have been developed for correlating the process parameters chosen with the forces measured during machining.
3. The developed models are significant at 95% confidence level showing that the developed models can be effectively used to determine the forces in turning of GFRP composites within the range of process parameters chosen.
4. The effect of different process parameters on cutting force, thrust force and feed force has been studied.
5. It is concluded that the optimal conditions for machining GFRP composites are high cutting speed, low feed, and low fiber orientation angle to have minimum forces. Depth of cut has no effect on these forces. Machining at these optimal conditions result in high quality finished surfaces of GFRP composites.
6. The effectiveness of the models can be further improved by using more number of independently controllable variables.

6. REFERENCES

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