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Mathematical model to predict tool wear on the machining of glass fibre reinforced plastic composites

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Abstract

Glass fibre reinforced polymer (GFRP) composite materials are replacing traditional engineering materials owing to its properties. Accordingly, the need for accurate machining of composites has increased enormously. During machining, the reduction of tool wear is an important aspect. In the present work, a mathematical model has been developed to predict the tool wear on the machining of GFRP composites using regression analysis and analysis of variance (ANOVA) in order to study the main and interaction effects of machining parameters, viz., cutting speed, feed rate, depth of cut and work piece fibre orientation angle. The adequacy of the developed model is verified by using coefficient of determination and residual analysis. This model can be effectively used to predict the tool wear on machining GFRP components within the ranges of variables studied. The influences of different parameters in machining GFRP composite have been analysed in detail.

Keywords: Mathematical model; Turning; Glass fibre reinforced polymer composites; Tool wear; Analysis of variance

1. Introduction

Glass fibre reinforced plastics (GFRP) are increasingly being used for varieties of engineering applications from automotive to aircraft components because of their superior advantages when compared to the other engineering materials. The advantages include high strength to weight ratio, high fracture toughness and excellent corrosion and thermal resistances [1]. Eventhough GFRP parts may be produced by moulding process, they require further machining to facilitate dimensional control for easy assembly and control of surface quality for functional aspects [2]. The first theoretical work on FRP was presented by Everstine and Rogers [3]. They did the theoretical analysis on plane deformation of incompressible composites reinforced by strong parallel fibres. Sakuma et al. [4] and Bhatnagar, et al. [5] studied how the fibre orientation influenced both quality of the machined surfaces and tool wear. The machinability of composite materials is influenced by the type of fibre embedded in the composite, and more particularly by the mechanical properties. On the other hand, the selection of cutting parameters and the cutting tool are dependent on the type of fibre used in composite and which is very important in the machining process [6,7]. Davim and Mata [8] studied the influence of cutting parameters on surface roughness in turning glass-fibre-reinforced plastics using statistical analysis. This technique used orthogonal arrays and analysis of variance (ANOVA). The objective was to obtain the contribution percentages of the cutting parameters (cutting velocity and feed rate) on the surface roughness on the workpiece. Near same time, these authors conducted the new optimization study of surface roughness in turning GFRP's tubes manufactured by filament winding and hand lay-up, using polycrystalline diamond cutting tools. The objective was establishing the optimal cutting parameters to obtain a certain surface roughness in the GFRP workpieces, using multiple analysis regression [9].

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When GFRP composites are machined, it is clearly seen that the fibres are cut across and along their lay direction, leaving deformed projecting and partially disclosed fibres on the machined surface [10,11] and it produces rapid tool wear. Tool wear is an important response in machining process. The tool integrity plays an important role in the form of the machined surface of the work piece and the control of the cutting quality. Conventional machining of fibre-reinforced composites is difficult due to diverse fibre and matrix properties, fibre orientation, inhomogeneous nature of the material and the presence of high-volume fraction (volume of fibre over total volume) of hard abrasive fibre in the matrix.

Most of the studies on GFRP composite machining shows that minimizing the tool wear has been very difficult and is to be controlled [12–14]. In the present work a mathematical model has been developed to predict the tool wear on the machining of GFRP composites using statistical analysis in-order-to study the main and interaction effects of machining parameters namely cutting speed, work piece (fibre orientation) angle, depth of cut and feed rate. The developed model can be effectively used to predict tool wear in machining of GFRP composites with in the ranges of parameters.

2. Experimental work

From the literature [4,5,10] and the previous work done on this field by authors [13,14], the independently controllable machining parameters which are having greater influences on tool wear while machining of GFRP composite work piece have been identified. They are: (i) cutting speed (A), (ii) work piece (fibre orientation) angle (B), (iii) depth of cut (C) and (iv) feed rate (D), out of which fibre orientation angle has been specially applied to fibre reinforced composites. A detailed analysis has been carried out to fix the lower and upper limits of the factors. Based on the analysis, the upper and lower limits of the factors are identified and are given below.

(i) Previous studies indicated that, the tool wear increases with increase of cutting speed and vice versa. The higher cutting speed was found to cause a large deformation rate of glass fibre and severe tool wear [15] and hence the cutting speed has been set at low level and is between 75 and 175 m/min.
(ii) The fibre orientation angle plays an important role for deciding the tool wear. At larger fibre angles, the shear takes place along the fibres and it generates compressive stress on the rake face of the tool [10] which leads to high tool wear. For the present study, the fibre orientation angle considered is between 30° and 90°.
(iii) The depth of cut plays only a small role in composite machining process compared to cutting speed and feed rate [16], but the higher depth of cut cause a deleterious effect on surface quality in GFRP machining and it also leads to more tool wear and hence low limits of depth of cut are chosen for the present study. The depth of cut considered in this work is between 0.50 and 1.50 mm.
(iv) The increase in feed rate increased the heat generation and hence, tool wear, which resulted in the higher tool wear [13]. The increase in feed rate also increase the chatter and it produces incomplete machining at a faster traverse, which leads to more tool wear and hence low feed rates are selected and is between 0.10 and 0.50 mm/rev.

For experimentation, design of experiment in statistics has been used. Due to the narrow ranges of parameters selected, it has been decided to use a two level full factorial design. The notations, units and their levels chosen are summarized in Table 1. For the convenience of recording and processing the experimental data, the upper and lower levels of the parameters are coded as +1 and –1. The coded value of any intermediate levels can be calculated by using the following expression [17]:

$$X_i = \frac{X - \left[\frac{X_{\max}+X_{\min}}{2}\right]}{\left[\frac{X_{\max}-X_{\min}}{2}\right]} \quad (1)$$

where $X_{\max}$ is the upper level of the parameter, $X_{\min}$ is the lower level of the parameter and X_i is the required coded values of the parameter of any value of X from $X_{\min}$ to $X_{\max}$.

The composite pipes used in this experimental study have been produced by filament winding process. The material specification and mechanical properties of fibre, resin and composite are given in Tables 2 and 3. In the present investigation, experiments were conducted for turning operation on all geared lathe. The ISO specification of the tool used for the turning operation is a WIDAX tool holder PC LNR 1616 K12. The insert used is a coated carbide tool having Composition: Co 6.0%; composite carbide 8.0%; WC rest. The coating layer system is: CVD- TiC + -Ti(C, N) + Al_2O_3 and layer thickness used was 11 μm.The machining operations were carried out as per the condition given by the design matrix at random to avoid systematic errors. The design matrix [18–20] and corresponding response are given in Table 4.

During the process of composite machining, the pressure and temperature prevailing over the tool-work interface can result in severe adhesion, abrasion, diffusion, mechanical chipping or fracture. There are four general wear zones on a typical cutting tool due to the consequences of the above mechanism, viz. crater wear, flank wear, nose radius wear and notch wear. The tool flank wear (V_b) has been considered in this

Table 1
Control parameters and their levels

S. No.	Parameter	Notation	Unit	Levels			
				Original		Coded	
				Low	High	Low	High
1	Cutting speed	*A*	m/min	75	175	−1	+1
2	Fibre orientation angle	*B*	°	30	90	−1	+1
3	Depth of cut	*C*	mm	0.5	1.5	−1	+1
4	Feed rate	*D*	mm/rev	0.10	0.50	−1	+1

Table 2
Specification of fibre and resin

Fibre: E Glass- RO99 2400 P566	Resin: Epoxy
Manufacturer: Saint Gobain Vetrotex India Ltd.	Manufacturer: CIBA GEIGY
RO99- Multi filament roving	Product: Araldite LY556
2400- Linear density (Tex)	(Bisphenol –A epoxy resin)
P566- sizing reference for vetrotex	Hardener: HT 972
	(Aromatic amine hardener)

Table 3
Mechanical properties of fibre, resin and composite material

Material	Tensile strength, σ_u (MPa)	Tensile modulus, *E* (GPa)	Shear modulus, *G* (GPa)	Poisson's ratio, *v*	Mass density, ρ (kg/m^3)
Fibre	1724	70	30	0.25	2500
Resin	83	6	2.3	0.35	1200
Composite	930	$E_1 = 46$ $E_2 = 13$	5	$v_{12} = 0.3$ $v_{21} = 0.08$	1876