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Tool wear study in edge trimming on basalt fibre reinforced plastics

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Abstract

In machining of reinforced fibre composite parts, abrasive fibres and material heterogeneity produce poor surface finish, delamination and tool wear. In this research, basalt fibre reinforced plastic is machined with edge trimming in order to study tool wear, using a tool holder of diameter 25 mm, with two exchangeable uncoated carbide cutting inserts. Cutting conditions (cutting speed, feed per tooth and depth) and material characteristics (fibre volume fraction and fibre orientation) are evaluated to know their influence in the flank wear (Vb) of the tool. An analysis of variance (ANOVA) was performed to study flank wear and material removal rate, and a generalized linear model (GLM) was developed. More influence variables in the flank wear are the machining conditions, being the tool life suitable for this machining and material.

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Keywords: tool wear; polymer composites; edge trimming; basalt fibre

1. Introduction

Nowadays, aeronautical and automotive manufacturers use polymeric composites, because of their low weight and high mechanical resistance [1]. Manufacturing process for these materials (RTM, prepegs, vacuum infusion, etc.) allow to obtain parts with a geometry closer to their final dimensions. After curing, machining of composite parts is required to achieve final shape and tolerance requirements, being drilling and milling the most used processes [2]. However, composite parts have a different behaviour compared with metallic parts. Abrasive fibres

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produce poor surface finish, delamination and tool wear. The high mechanical resistance of the fibres affects the tool sharpness and produces an excessive tool wear. Sometimes, defects as delamination provokes the impossibility to machine the composite part.

Wear tool mainly depends on cutting parameters, material characteristics and tool characteristics [3]. Most works study tool wear in drilling process, but not in milling process. In addition, works study tool wear in milling process on carbon fibre composite parts, but focusing on slot milling, not edge trimming.

Different materials and coating (diamond coating, tungsten carbide, etc.) type tools (routers, etc.) and geometries are studied in the literature to evaluate tool behaviour and flank wear. Most tools used to develop these studies do not present a long tool life, being necessary to find a suitable tool for industrial applications, able to machine a high cutting length.

In relation to machining parameters that affect tool wear, different studies mainly evaluate cutting conditions (cutting speed and feed rate). Azmi et al. [4] study tool wear in slot milling and conclude that tool wear mainly depends on feed rate. Slamani et al. [5] develop different models to predict tool wear and cutting force taking into account cutting speed, feed and cutting length. Rimpault et al. [6] develop a statistic tool to check surface machined and tool condition using fractal analysis.

Most works that study fibre reinforced composites machining are focalized in glass and carbon fibres, however, there are no studies with basalt fibre reinforced plastic. Basalt is a natural mineral with good properties. It is inert, non-toxic, good electrical and thermal insulator and with a similar mechanical behaviour that carbon fibre [7].

In this paper, basalt fibre reinforced plastic is machined with edge trimming in order to study tool wear. Tool selection take into account a commercial tool suitable for edge trimming, with a high productivity due to a long tool life for choosen cutting parameters, and with a high cutting length. Cutting conditions (cutting speed, feed per tooth and depth) and material characteristics (fibre volume fraction and fibre orientation) are evaluated to know their influence in the flank wear of the tool.

This work develops an analysis of variance (ANOVA) and a generalized linear model (GLM) to study flank wear and material removal rate to evaluate the influence of each variable.

2. Procedures and methods

2.1. Experimental method

Basalt fibre reinforce plastic laminates used in this study are manufacturing using RTM (Fig. 1(a)). The material is a rectangular (420 x 260 mm) bidirectional panel with plies of plain weave basalt fibres impregnated with an epoxy resin (Prime 20 LV). The thickness of the material is 3.4 mm, a value that allows study the edge trimming process. Different laminates are manufacturing varying fibre volume and fibre orientation.

Edge trimming operation is conducted by a Kondia B-500 milling machine, with a spindle power of 6 KW and a maximum rotation speed of 6000 rpm. A milling tool holder of diameter 25 mm, with two exchangeable uncoated carbide cutting inserts is used to machining (Fig. 1(b)). To avoid vibrations and displacement of the material, the fixture used in the milling machine is shown in Fig. 1(c).

Fig. 1. (a) RTM process; (b) milling tool; (c) fixture in milling machine.

Cutting conditions (cutting speed, feed per tooth and depth) and material characteristics (fibre volume fraction and fibre orientation) are considered to know their influence in the flank wear of the tool. In addition, material removal rate (MRR) has been evaluated. MMR is the volume of material removed per minute. Therefore, it is a direct indicator of how efficiently is the machining process and how profitable is the operation. Table 1 shows the variables and levels used to carry out the sixteen experiments.

Table 1. Experimental parameters.

TEST	Cutting speed vc (m/min)	Feed fz (mm)	Depth ap (mm)	Fibre volumen Fv (%)	Fibre orientation Fo (º)
E01	470	0.1	1.5	40	90
E02	300	0.1	1.5	40	45
E03	300	0.4	0.5	40	45
E04	300	0.4	1.5	60	45
E05	470	0.1	0.5	60	90
E06	470	0.4	0.5	40	90
E07	300	0.1	0.5	60	45
E08	470	0.4	0.5	60	45
E09	470	0.1	0.5	40	45
E10	300	0.1	0.5	40	90
E11	300	0.1	1.5	60	90
E12	300	0.4	0.5	60	90
E13	470	0.4	1.5	40	45
E14	470	0.4	1.5	60	90
E15	300	0.4	1.5	40	90
E16	470	0.1	1.5	60	45

In every experiment, a tool with new inserts has machined without coolant during 80 minutes. Different stops (5, 30, 50, 60, 70 and 80 minutes) are made to measure flank wear in both cutting inserts.

Measuring of flank wear is carried out recording and analysing images of the clearance face of the tool (Fig. 2). Tool is positioning in a measuring device equipped with a digital camera. Image processing software with pixel calibration has been used to measure flank wear. Measurements are repeated two times in every insert and maximum value has been chosen for every experiment.

Fig. 2. Flank wear images.

2.2. Statistical procedures

First, in order to study the effect of factors involved in the Vb and MRR parameters, an analysis of variance (ANOVA) was developed. Second, a Generalized Linear Model (GLM) was used to obtain a predictive model. In the literature, GLMs have been commonly used to analyze the effect of different explanatory variables in response variables. The form of a GLM is given by:

$$I(E(Y \mid X)) = \eta(x) = \beta_0 + \sum_{i=1}^{p} \beta_i x_i \tag{1}$$

where Y is the observed dependent response variable, X are the observed independent covariates, E is the expected value of Y with known values of X, $\sum_{i=1}^{p} \beta_i x_i$ is a linear combination of unknown parameters β and independent variables x_i and p is the number of independent variables. The link function I is considered to be the same as a linear function of the predictors, $\eta(x)$. In this paper, the explanatory variables included are showed in Table I: cutting speed (Vc), feed (fz), depth (ap), fibre volume (Fv) and fibre orientation (Fo). Two dependent variables have been analyzed: flank wear (Vb) and material removal rate (MRR).

Stepwise regression technique has been used to determine a final model. Stepwise regression is a systematic method for adding and removing terms from a regression model, i.e. Vc, fz, etc., based on their statistical significance in explaining the variable response, i.e. flank wear. At each step, the method searches for terms to add or remove from the initial model based on the value of a selection criterion. In this case, deviance criterion is used.

3. Results

In most of the experiments, after machining 80 minutes, flank wear does not reach the maximum tool wear to avoid machining, having a linear behaviour. In experiment E14, material presents machining damages (delamination) that affect the part quality and do not allow continue machining after 40 minutes. Obtained values of Vb in each experiment are presented in Fig. 3.

Fig. 3 shows the behavior of flank wear (Vb) versus machining time. In experiment E14, machining damages (delamination) were observed which did not allow continue machining after 40 minutes. Different behavior is observed in the time evolution of the flank wear depending on experimental conditions. Thus, for example, experiment 13 shows the highest wear values during the 80 minutes of machining.

In Fig. 4 it is observed the values obtained in the different experiments for the two variables analyzed MMR and Vb (in T=80 minutes). Thus, if for example the maximum allowed value of Vb is 0.1 mm the best machining conditions correspond to the experiment E15 in which the highest MRR value is obtained.

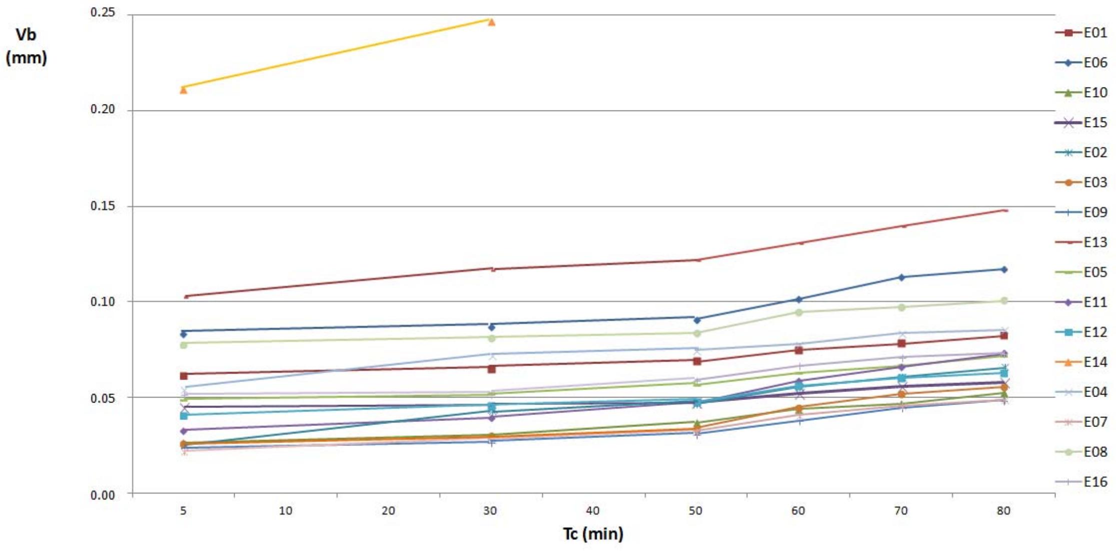


Fig. 3. Flank wear versus machining time

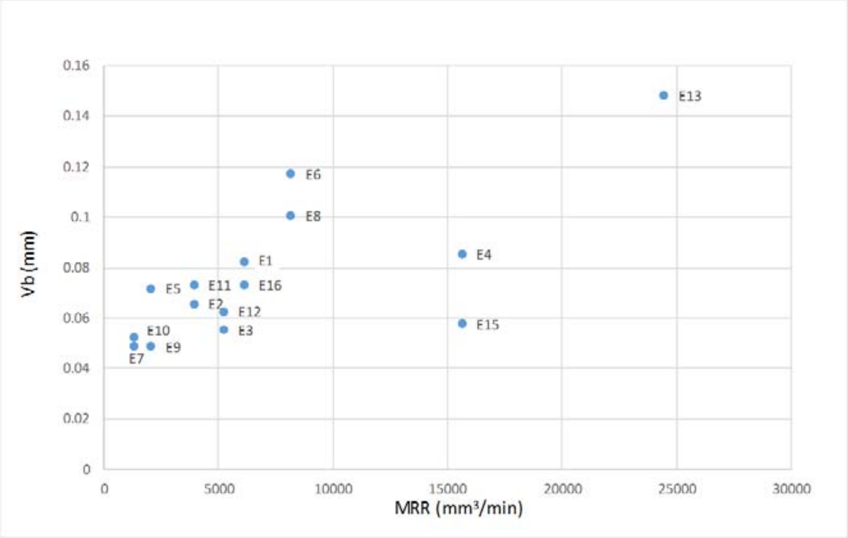


Fig. 4. Material removal rate vs flank wear.

An analysis of Variance (ANOVA) has been performed to quantify the effect of the machining factors on the responses. For analyzing the significant effect of the factors on the responses F test with a level significance of 0.05 has been used. Table 2 and Table 3 show the results of ANOVA for Vb and MRR, respectively.

Table 2. ANOVA table for Vb.

Source	Sum of squares	df	Mean square	F ratio	p value
Fz	0.00333091	1	0.00333091	29.62	0.0006
Vc	0.00397524	1	0.00397524	35.35	0.0003
ap	0.00168447	1	0.00168447	14.98	0.0047
Fo	0.0000896369	1	0.0000896369	0.09	0.7658
Fv	0.000104633	1	0.000104633	0.11	0.7477
RESIDUALS	0.000899688	9	0.000112461		
TOTAL (CORRECTED)	0.00913555	14			

Table 3. ANOVA table for MRR.

Source	Sum of squares	df	Mean squares	F-ratio	p-value
Fo	0.32417	1	0.32417	0.35	0.5693
Fv	0.32417	1	0.32417	0.35	0.5693
ap	16.8468	1	16.8468	18.13	0.0021
Fz	25.3941	1	25.3941	27.32	0.0005
Vc	2.23328	1	2.23328	2.40	0.1555
RESIDUALS	8.36425	9	0.929361		
TOTAL (CORRECTED)	51.3815	14			

From ANOVA results obtained in Table 2 it is concluded that cutting speed, feed and depth of cut have significant effect on flank wear. It is observed that cutting speed is more significant factor than other parameters, while depth is the least significant factor. If the results showed in Table 3 are analyzed, it is observed that feed and depth have a significant effect on material removal rate, while fibre orientation, fibre volume and cutting speed have not significant effect (0.95 level confidence).

The influence of each factor can be represented using a mean plot with uncertainty intervals. The mean plot shows the change in the response when the factor varies from level 1 to level 2. The plots for Vb and MRR are showed in Fig. 5 and Fig. 6.

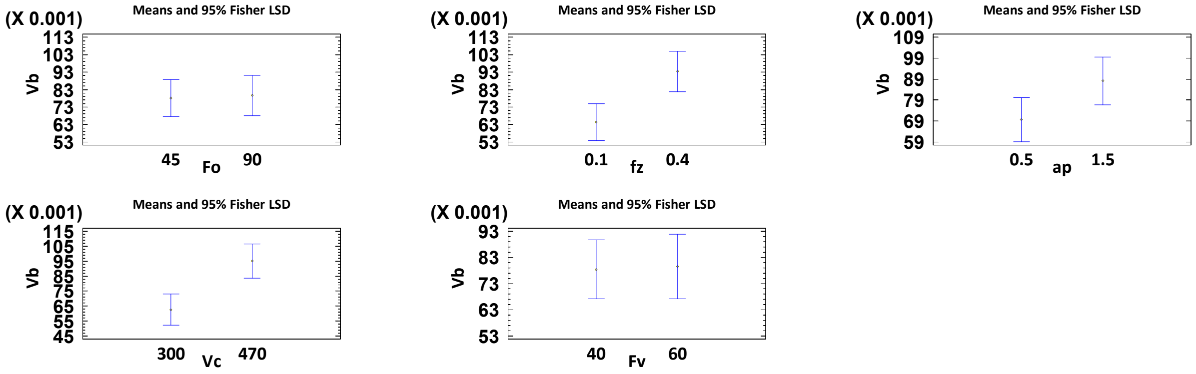


Fig. 5. Mean Plot and LSD intervals for flank wear.

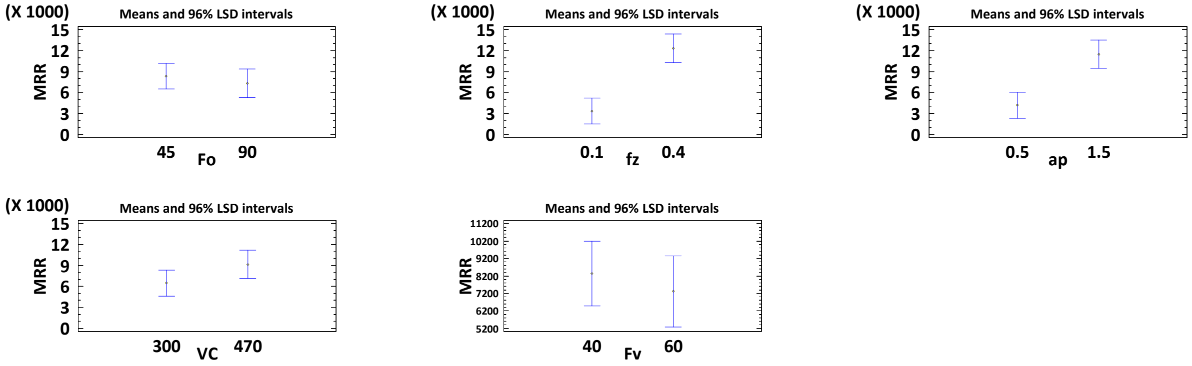


Fig. 6. Mean Plot and LSD intervals for material removal rate.

Fig. 5 and Fig. 6 show the effect of the parameters on Vb and MRR. The results showed in Fig. 5 indicate that an increase of fz, ap and vc increase the Vb value. Therefore, for example, the increment of vc increases flank wear up to 0.03 mm as shown in Fig. 5. Fig. 6 shows that an increase of fz and ap increases the MRR value.

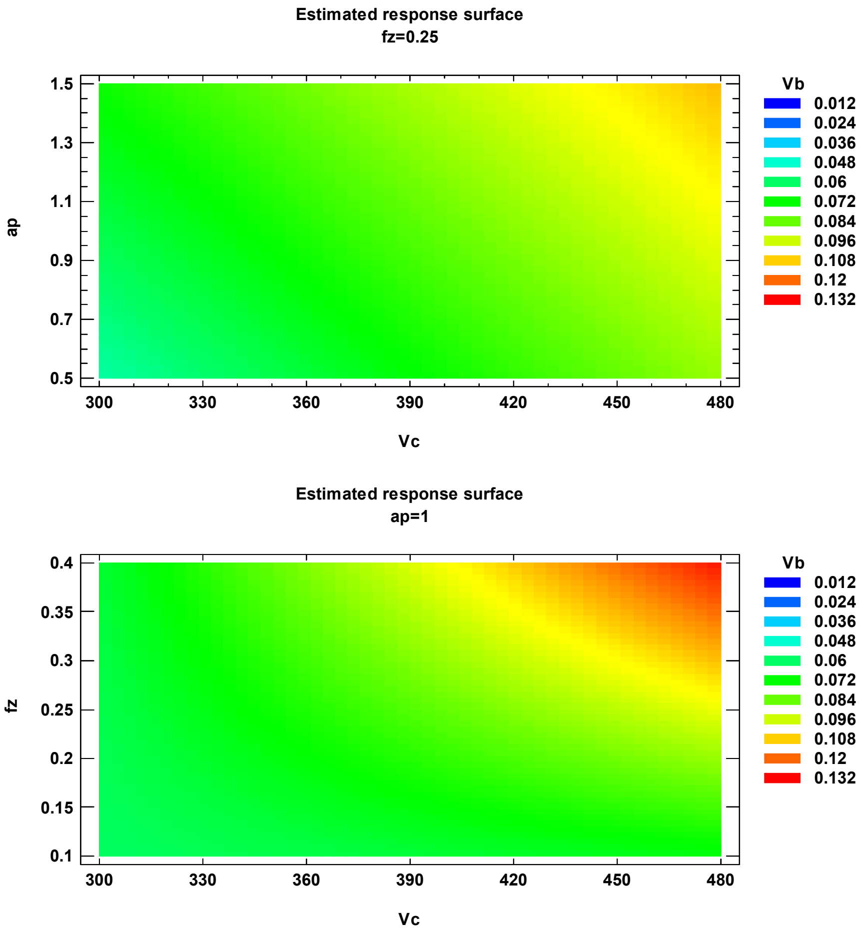
The relationship between response and independent variables requires the use of a statistical model. A GLM model has been used to analyze the effect of the different factors and the responses. The following models are the empirical relationship between responses and independent variables. Dependent variables selected are Vb and MRR and the models have been adjusted for Tc=80 minutes. The final estimated model for Vb and MRR are given, respectively, by:

$$Vb = 0.0516461 - 0.000046815 \cdot Vc + 0.0204939 \cdot ap - 0.281839 \cdot fz + 0.000999962 \cdot Vc \cdot fz \quad (2)$$

$$MRR = -2.03376 + 2.13806 \cdot ap + 8.76087 \cdot Fz \quad (3)$$

being the value of the adjusted R^2 equal to 0.83 and 0.80 for Vb and MRR, respectively.

Fig. 7 and Fig. 8 show the estimated response surface for Vb and MRR.


Estimated response surface
fz=0.25

Estimated response surface
ap=1

Fig. 7. Estimated response surfaces for Vb.

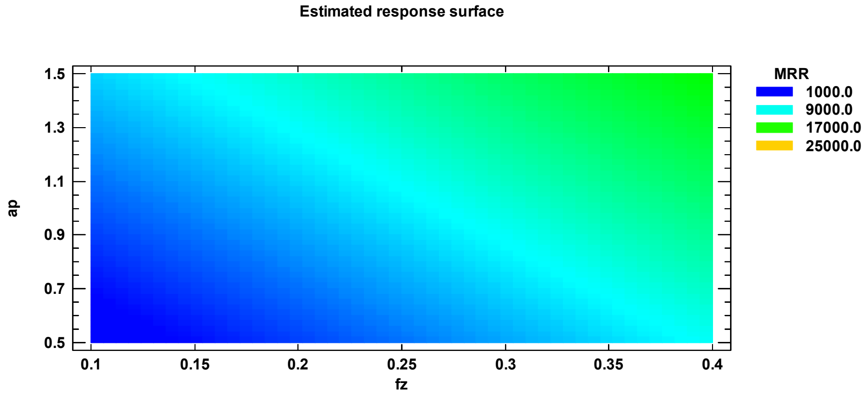

Estimated response surface

Fig. 8. Estimated response surface for MRR.

4. Conclusions

Edge trimming of basalt fibre reinforced plastics with a two uncoated carbide cutting inserts tool allow machining this material with high productivity, being suitable for industrial applications. Values of flank wear (Vb) are linear along the cutting time studied, meaning that tool can continue machining to obtain a high cutting length.

An analysis of variance (ANOVA) shows that the most influence variables in the Vb are the cutting conditions. Vc is the most important variable and ap has the minimum influence. In the study of MRR, the most influence variables are ap and fz.

A GLM model is developed for Vb and MRR, being the value of the adjusted R^2 equal to 0.83 and 0.80 for Vb and MRR, respectively. E15 is the best experiment, having maximum values of ap and fz, with a high MRR and low Vb values.

A linear prediction model to optimize the relation between flank wear and MRR will be developed in further works. In some experiments, delamination has influence in flank wear, so it will be necessary to evaluate correlation between delamination and flank wear in the composites machining.

Acknowledgements

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