MILLING OF CARBON FIBER-REINFORCED PLASTICS: ANALYSIS OF CUTTING FORCES AND SURFACE ROUGHNESS

L. Sorrentino* and S. Turchetta
Department of Mechanics, Structures and Environment, University of Cassino, 03043 Cassino, Italy
*sorrentino@unicas.it

Keywords: *CRFP, milling, cutting forces, surface roughness, analysis of variance (ANOVA).*

Abstract

Machining of fiber reinforced composites is an important activity in the integration of these advanced materials into engineering applications. Machining damage due to excessive cutting forces may result in rejecting the composite components at the last stages of their production cycle. Therefore, the ability to predict the cutting forces is essential for selecting process parameters that would result in minimum machining damage. In this paper, the effect of cutting conditions on cutting force are reviewed. In particular the aim in this work has been to investigate the relationship among the cutting force and surface roughness with the relevant cutting parameters, such as the cutting speed, axial depth of cut and the feed rate.

1. Introduction

Milling composite materials is a rather complex task owing to its heterogeneity and the number of problems, such as surface delamination, that appear during the machining process, associated with the characteristics of the material and the cutting parameters.

Milling is the machining operation most frequently used in manufacturing parts of fiber-reinforced plastics, because components made of composite materials are commonly produced by net-shape that often require the removal of excess material to control tolerances, and milling is used as a corrective operation to produce a well defined and high quality surfaces [1]. The machinability of fiber-reinforced plastics is strongly influenced by the type of fiber embedded in the composite and by its properties. Mechanical and thermal properties have an extremely importance on machining FRP. The fiber used in the composites has a greater influence in the selection of cutting tools (cutting edge material and geometry) and machining parameters. It is fundamental to ensure that the tool selected is suitable for the material. The knowledge of cutting mechanisms is indispensable in view of cutting mechanics and machinability assessment in milling [1,2]. Composite materials such as carbon fiber-reinforced plastics (CFRPs) made by using carbon fibers for reinforcing plastic resin matrices, such as epoxy, are characterised by having excellent properties as light weight, high strength and high stiffness. These properties make them especially attractive for aerospace applications [2]. Surface roughness is a parameter that has a greater influence on dimensional precision, performance of mechanical pieces and on production costs. For these reasons, research developments have been carried out with the purpose of optimising the cutting conditions to reach a specific surface roughness [3,4]. For achieving the desired quality of the machined surface, it is necessary to understand the mechanisms of material removal, the kinetics of machining processes affecting the performance of the cutting tools [5]. The works of a number of authors [6–12], when reporting on milling of FRP, have shown that the type and orientation of the fiber, cutting parameters and tool geometry have an essential paper on the machinability. Everstine and Rogers [6] presented the first theoretical work on the machining of FRPs in 1971, since then the research made in this area has been based on experimental investigations. Koplev et al. [7], Kaneeda [8] and Puw and Hocheng [9] concluded that the principal cutting mechanisms correlate strongly to fiber arrangement and tool geometry. Santhanakrishman et al. [10] and Ramulu et al. [11] carried out a study on machining of polymeric composites and concluded that an increasing of the cutting speed leads to a better surface finish. Hocheng et al. [12] studied the effect of the fiber orientation on the cut quality, cutting forces and tool wear on the machinability. In Enemuoh et al. [13] has been realized that with the application of the technique of Taguchi and a multi-objective optimization criterion, it is possible to achieve cutting parameters that allow the absence of damage in drilling of fiber reinforced plastics. Paulo Davim et al. [14] have studied the cutting parameters (cutting velocity and feed rate) under specific cutting pressure, thrust force, damage and surface roughness in drilling Glass Fiber Reinforced Plastics (GFRP's). A plan of experiments, based on the techniques of Taguchi, has been established considering drilling with prefixed cutting parameters in a hand lay-up GFRP material. Sheikh-Ahmad et al. [15] have studied the comprehensive model for orthogonal milling of unidirectional composites at various fiber orientations. Devi Kalla [16] has studied the mechanistic modelling techniques for simulating the cutting of carbon fiber-reinforced polymers (CFRP) with a helical end mill. A methodology has been developed for predicting the cutting forces by transforming specific cutting energies from orthogonal cutting to oblique cutting.

In summary, it can be noticed that the works carried out on the machinability of FRP, are basically related on the wear of cutting tools and the quality on the surfaces, as a function of the cutting conditions, the distribution of staple fibers in the polymeric matrix and the angle of inclination of staple fibers.

The aim of this work is to value cutting forces of Carbon Fiber-Reinforced Plastics during the milling machining. This work aims to investigate the relationship among the cutting force and surface roughness with the relevant cutting parameters, such as the cutting speed, axial depth of cut and the feed rate.

2. Experimental set-up

Experiments have been undertaken on a CNC milling machine with 15 kW spindle power and a maximum spindle speed of 15000 rpm has been used to perform the experiments, see Figure 1.

Fig.1. CNC milling machine

A end mill commonly used on the machinability of FRP has been used, whose diameter are 40 mm, four tooth cutting (insert APMT1135PDER-H1 UTi20T of MITSUBISHI).

The composite material used in the tests (epoxy matrix reinforced with 50% of carbon fiber) has been produced by autoclave with a fiber orientation of 0/90°, Figure 2. The experiments have been carried out in a laminate plate, made up with 40 alternating layers of fibers with 13 mm of thickness.

Fig.2. Sample after milling machining

Three cutting speed values, four axial cutting depth values and two feed per tooth per revolution have been taken into account; they have been chosen in order to reproduce the commonly used industrial range of process variables. Each cut has been replicated three times, yielding a total of 108 measured force. The designed plan is shown in Table 1.

The cutting conditions have been represented by the angular position of the cutter. The experimental cuts have been performed in a random sequence, in order to reduce the effect of any possible systematic error.

Table 1. Experimental plan

Factors	Levels [#]	Levels
Axial cutting depth [mm]	3	1.0 - 1.5 - 2.0
radial cutting depth [mm]	4	10 - 20 - 30 - 40
Feed rate [mm/min]	3	100 - 250 - 468
Cutting speed [m/min]	1	100
Replications	3	
Total cuts	108	

The cutting force F_x, F_y and F_z have been measured by a Kistler piezoelectric platform dynamometer (Type 9257 BA), see Figure 3. The signals acquired by the dynamometer have been sampled at different frequencies and for different time intervals in order to set the acquisition parameters giving the whole information about force signal with the minimum time waste. The signal along x, y and z axes has been periodic and 16384 acquisition points seem to be enough to keep the whole signal information. Therefore, the output of the dynamometer has been fed into an A/D converter and sampled at 10 kHz by a PC. Each observation consisted of about 1.6384-s time signal.

The quality of surface has been valued by roughness measurement on all machining surface. The roughness values acquired along X and Y axis have been measured according to the scheme showed in Figure 4: roughness measurement in up/down milling area. Every measurement has been replied five times.

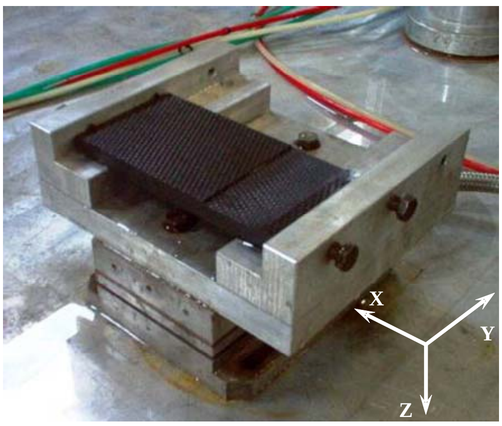

Fig.3. Gripping system/dynamometer/sample

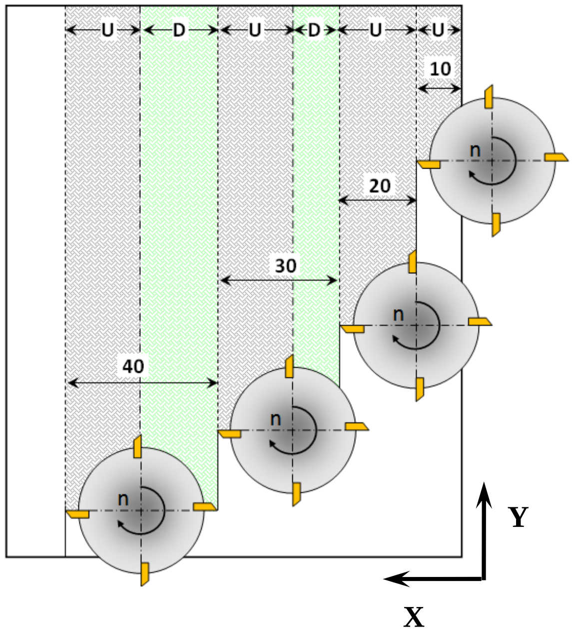

Fig.4. Scheme of milling machining

3. Results and discussion

During milling tests the cutting forces F_x, F_y and F_z have been measured and analyzed in time domain; moreover the F_{xy} force (resultant of F_x and F_y force) has been analyzed. The typical trends of F_z and F_{xy} cutting force components have been showed in Figures 5 and 6.

By ANOVA analysis it has been possible to point out that the cutting force components F_z e F_{xy} depend on three main parameters: feed speed (Va), radial depth of cut (P_r) and axial depth of cut (P_a). In particular it has been possible to note like the value of these components increases as a function of these parameters; the most important parameter for component F_z is P_r and for component F_{xy} is P_r and Pa. The main effect plot of cutting force components "F_z" versus the process parameters have been showed in Figure 7. The main effects plot of F_z and F_{xy} components versus the process parameters are reported in Figures 7 and 8.

The regression analysis has been made and it has been possible to define the model to calculate the values of the cutting force components according to the following formula:

$$F_z = -19.1 + 4.52 P_r + 4.10 P_a + 0.179 V_a \qquad (1)$$

$$F_{xy} = -108 + 3.49 P_r + 107 P_a + 0.059 V_a \qquad (2)$$

The coefficients of determination have been higher than 95%, while the hypotheses (normality and homogeneity of variance) about the residuals have been satisfied.

By ANOVA analysis it has been possible to analyze how the surface roughness R_a depends on three process parameters (V_a, Pr and P_a). In particular it has been possible to note how Ra decreases as a function of: i) decreasing of axial depth of cut (P_a); ii) increasing of the radial depth of cut (P_r). The surface roughness value is not influenced by measurement in directions X and Y.

Moreover the roughness value depend on up/down milling area: minimum values of surface roughness has been obtained for down-milling area. The main effects plot of roughness parameter "R_a" versus the process parameters are reported in Figure 9.

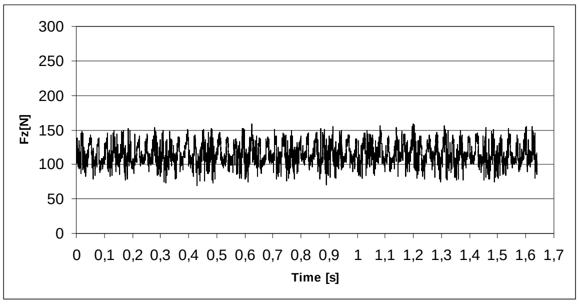

Fig.5. Time domain signal monitored in Z direction

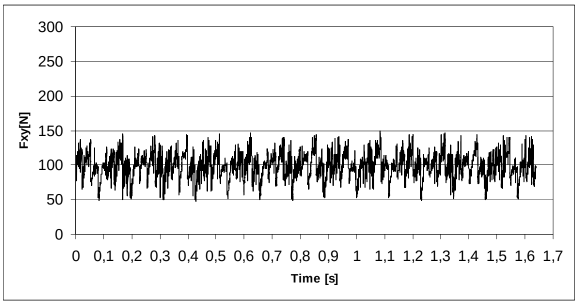

Fig.6. Time domain signal monitored in XY direction

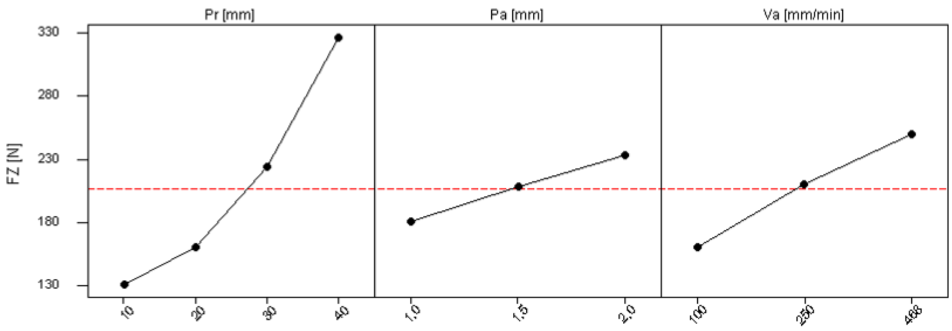

Fig.7 Main Effect Plots of F_z signal vs. feed speed (Va), radial depth of cut (Pr) and axial depth of cut (Pa)

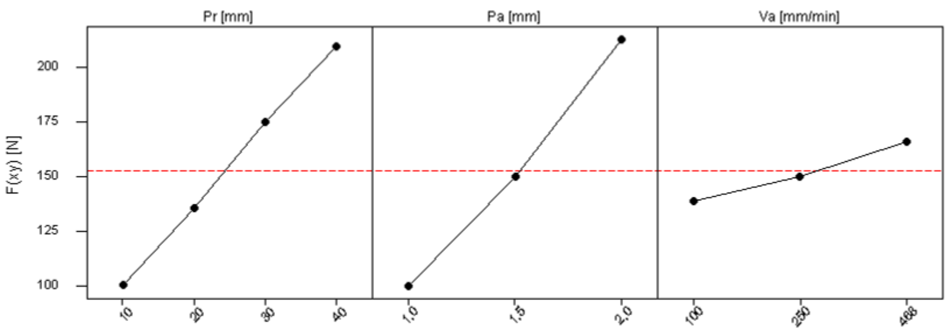

Fig.8. Main Effect Plots of F_{xy} signal vs. feed speed (V_a), radial depth of cut (P_r) and axial depth of cut (P_a)

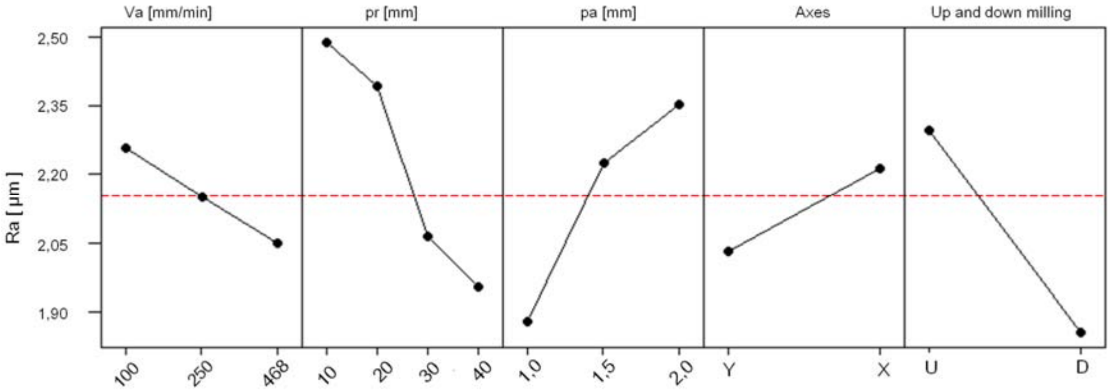

Fig.9. Main Effect Plots of R_a vs. feed speed (V_a), radial depth of cut (P_r), axial depth of cut (P_a), measurement axial directions and up/down milling.

4. Conclusion

In this paper the cutting force and the surface roughness of a CRFP during a milling machining has been valued.

ANOVA analysis has pointed out the dependence of cutting force components on process parameters considered. It has been especially pointed out that F_z component of the cutting force increases when three process parameters considered increase (feed speed, axial cutting depth and radial cutting depth) with values between 140-300N. Analogous states have been noticed for the resultant of the cutting force components in the X,Y plan. This components assumed values in range 100-200N. By a regression analysis it has been noticed that cutting force components and process parameters are correlated. For every cutting test, "R_a" surface roughness measuring have been valued by considering milling surface. Roughness measuring have been carried out towards X,Y axes by considering up-milling and down-milling areas.

In relation to surface finishing the ANOVA analysis has pointed out that the surface roughness decrease (with minimum value around 2µm) by increasing the feed speed. Minimum values of surface roughness has been obtained for down-milling area.

Acknowledgements

The authors acknowledge to AgustaWestland, Anagni plant, for providing the CFRP composite material used on the experimental tests. They also acknowledge to the graduate in Mechanical Engineer Vincenzo Vellucci for their participation in the experimental work. A special thank to Martina, Lorenzo and Tiziana S.

References

[1] S. Jahanmir, M. Ramulu, P. Koshy, Machining of Ceramics and Composites, Marcel Dekker, Inc., New York, 2000, pp. 267–293.

[2] W. F. Smith, Principles of Materials Science and Engineering, McGraw-Hill, 1990, pp. 743–768.

[3] M. Ramulu, C.W. Wern, J.L. Garbini, Effect of the direction on surface roughness measurements of machined graphite/epoxy composite, Compos. Manuf. 4 (1) (1993) 39–51.

[4] E. Erisken, Influence from production parameters on the surface roughness of a machine short fibre reinforced thermoplastic, Int. J. Machine Tools Manuf. 39 (1999) 1611–1618.

[5] P.S. Sreejith, R. Krishnamurthy, S.K. Malhota, K. Narayanasamy, Evaluation of PCD tool performance during machining of carbon/ phenolic ablative composites, J. Mater. Process. Technol. 104 (2000) 53–58.

[6] G.C. Everstine, T.G. Rogers, A theory of machining of reinforced materials, J. Compos. Mater. 5 (1971) 94–106.

[7] A. Koplev, A. Lystrup, T. Vorm, The cutting process, Composites 14 (4) (1983) .371–376.

[8] T. Kaneeda, CFRP Cutting mechanism, in: Proceeding of the 16th North American Manufacturing Research Conference, 1989, pp. 216–221.

[9] H.Y. Puw, H. Hocheng, Anisotropic chip formation models of cutting of FRP, in: Proceedings of ASME Symposium on Material Removal and Surface Modification Issues in Machining Processes, New

York, 1995.
[10] G. Santhanakrishman, R. Krishnamurthy, S.K. Malhota, Machinability characteristics of fibre reinforced plastics composites, J. Mech. Working Technol. 17 (1988) 195–204.
[11] M. Ramulu, D. Arola, K. Colligan, Preliminary investigation of effects on the surface integrity of fiber reinforced plastics, PD-Vol-64-2, Engineering Systems Design and Analysis 2, ASME, 1994, pp. 93–101.
[12] H. Hocheng, H.Y. Puw, Y. Huang, Preliminary study on milling of unidirectional carbon fiber-reinforced plastics, Compos. Manuf. 4 (2) (1993) 103–108.
[13] Enemuoh, Ugo E., El-Gizawy Sherif A., Chukwujekwu Okafor A. An aproach for development of damage-free drilling of carbon fiber reinforced thermosets. International Journal of Machine Tools and Manufacture 2001;41(12):1795–814.
[14] J.Paulo Davima, Pedro Reisa, C.Conceicao Antonio, Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up, Composites Science and Technology, vol. 64, (2004), pagg. 289–297.
[15] J. Sheikh-Ahmad, J. Twomey, D. Kalla, P. Lodhia, Multiple regression and committee neural network force prediction models in milling FRP, Machining Science and Technology 11 (3) (2007) 391–412.
[16] Devi Kalla, Jamal Sheikh-Ahmad, Janet Twomey, Prediction of cutting forces in helical end milling fiber reinforced polymers, International Journal of Machine Tools & Manufacture, vol. 50 (2010), pagg. 882–891