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PREDICTION OF CUTTING FORCE IN DRILLING UD-GFRP USING MATHEMATICAL MODEL

Andra PENA[1,*], Claudiu BÎŞU[2]

[1)] Lecturer PhD, Machines and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania
[2)] Lecturer PhD, Machines and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania

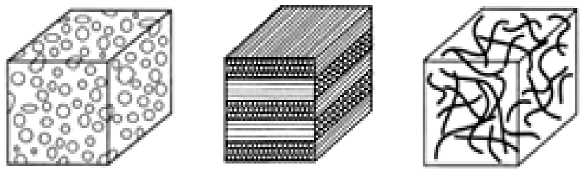
Abstract: *Currently there is a strong trend to replace the metallic materials with composite materials, particularly polymer composites because of their superior properties, properties that can be designed and refined to meet specific requirements. Implementation of polymer matrix composite materials, especially those reinforced with glass fiber, is determined, including the obvious availability of raw materials used, and by the diversity of materials used for the matrix and reinforcing elements and the possibilities of combining their quantitatively and structurally. Glass fiber reinforced plastics (GFRPs) composite is considered to be an alternative to heavy exotic materials. Currently it is estimated that the reinforcement of polymeric materials with glass fiber has a 90% share in the global composites industry. Compared to metal alloys, composite materials have a better ratio mass -stiffness - resistance and reduced susceptibility to fatigue and corrosion. According to the need for accurate machining of composites has increased enormously. During machining, the obtaining cutting force is an important aspect. The present investigation deals with the study and development of a cutting force prediction model for the machining of unidirectional glass fiber reinforced plastics (UD-GFRP) composite using regression modeling. The process parameters considered include cutting speed, feed rate and depth of cut.*

Key words: *UD-GFRP, drilling, cutting forces, cutting tool, regression model.*

1. INTRODUCTION

Glass fiber reinforced plastics composite are most widely used in various products including automobiles, sporting goods, marine bodies, plastic pipes, storage containers, etc. The transport industries are increasing their use of glass fiber reinforced plastics (GFRP) to decrease vehicle weight and boost fuel efficiencies. Fiber-reinforced composite materials have become an economic alternative to other materials in highly corrosive industrial applications. These material structures are synergistic combination of two or more micro-constituents that differ in physical form and chemical composition and which are insoluble in each other [8]. Composite materials are usually of two classifications – plies or lamina – and their usage has dramatically changed the traditional way of working with monolithic materials [12] (Fig. 1). The objective of having two or more constituents is to take advantage of the superior properties of both materials without compromising on the weakness of either. In glass fiber reinforced composite structures, the glass fibers carry the bulk load and the matrix serves as a medium for the transfer of the load [8].

Machining of these materials poses particular problems that are seldom seen with metals due to the inhomogeneity, anisotropy and abrasive characteristics of the composites. Conventional machining practices such as turning, milling and drilling are used with composites because of the availability of equipment and experience in conventional machining. Although some of the fibers used in composites are hard (sometimes even harder than the tool material) conventional machining is still used. [12]


a b c
Fig 1 Examples of composite materials: a) particulate composite; b) laminated composite; c) fiber reinforced composite

During the last decade, these materials and their manufacturing methods have become more popular and they are now being increasingly used in applications such as commercial aircrafts, ships, automobiles, machine tools and sports equipments. As composite materials become increasingly popular, greater emphasis is being placed on manufacturing and fabricating them to desired quality and cost. As structural materials, fastening of composite structures cannot be avoided. The fastening efficiency is largely dependent on the quality of machined holes. Due to their anisotropy, and non-homogeneity, FRP poses problems in drilling such as fiber breakage, matrix cracking, fiber/matrix detachment, fiber pullout, fuzzing, thermal degradation, spalling and delamination [1].

[*] Corresponding author: Splaiul Independenţei 313, Sector 6, 060042, Bucharest, Romania;
Tel.: 0040214029724;
E-mail addresses: *andra.pena@yahoo.com* (A. Pena), *cfbisu@gmail.com* (C. Bîşu)

Currently it is estimated that the reinforcement of polymeric materials with glass fiber has a 90% share in the global composites industry.

Drilling is the final operation during assembly of the aircraft and automotive structures. For example, for a small plane with one engine over 100 000 holes are machined, while for a large transport aircraft millions of holes are done.

During drilling of composites, material is removed with a wedge shaped drill causing a series of fractures. This is associated with plastic deformation and sliding at high stress and strain rates and provides many sources for acoustic emission [13].

Wang and Zhang [21, 22] characterized the machining damage in unidirectional FRP subjected to cutting and developed a new mechanics model to predict the cutting forces. Mahdi and Zhang [15] presented a two-dimensional cutting model to predict the cutting forces in relation to fibre orientations and developed an adaptive three-dimensional finite element algorithm. Sun et al., [20] found that cutting force, cutting temperature and surface roughness increased with increasing cutting speed. Kim and Ehmann [11]demonstrated that the knowledge of the cutting forces is one of the most fundamental requirements. This knowledge also gives very important information for cutter design, machine tool design and detection of tool wear and breakage. Santhanakrishnan et al.[17] presented machinability in turning process of GFRP, CFRP and Kevlar fiber reinforced plastics composite using P20 carbide, Tic coated carbide, K20 carbide and HSS tool. Three parameters such as cutting speed, feed rate and depth of cut were selected to minimize surface roughness. Scanning electron microscope was use for micrograph. Cutting force, feed force and radial force were measured by using inductive type lath tool dynamometer. It was found that, the K20 carbide tool performed better in machining fiber reinforced plastics composites [12].

A number of research endeavors have been made in the recent past to fully characterize the drilling process for FRP composite materials. The efforts have been made in the direction of optimization of the operating variables and conditions for minimizing the drilling induced damage. Chen [23] observed that the effect of the cutting speed on the cutting forces is insignificant for the same drill material. The cutting forces on the other hand were found to be lower at lower feed rates. It was further concluded that in order to improve the hole quality at exit, the feed rate at exit needs to be decreased during the drilling process. Bhattarcharya et al. [3] studied hole drilling in kevlar composites under ambient and cryogenic conditions, the latter being obtained by the application of liquid nitrogen at the drill site. The drill bits under cryogenic conditions underwent a much lower wear rate, resulting in much lower thrust forces and material damage. Ramulu et al. [17] observed that in case of drilling with HSS and HSS-Co drills, the highest temperatures occurred at higher cutting speeds and lower feeds. Increasing speed leads to increased tool wear, larger entrance and exit burrs, larger damage rings and decreased number of holes drilled. Increasing feed leads to increased drill thrust and torque, smaller entrance and exit burrs, reduced damage width and increased number of holes drilled. Caprino et al. [4] stated that the type of damage induced in a composite material during drilling is strongly dependent on the feed rate. When the feed rates are high, the failure modes show the features typical of the impact damage, with step-like delamination, intralaminar cracks and the high-density micro failure zones. If the feed rate is sufficiently low, the failure consists essentially of delamination mainly originating near the intersection between the conical surface generated by the main cutting edges and the cylindrical surface of the hole. Hocheng et al. [9] stated that higher feed rates produce blockier chips by increasing the depth of the cut while higher cutting speed causes earlier material fracture by elevating the strain rate and reducing the chain sliding. The produced surface roughness was also observed and was found less than 1 micron for various cutting conditions. Ilio et al. [10] reported experimental studies on Aramid Fiber Reinforced Plastic (AFRP). It was stated that the large oscillations of the thrust force while drilling AFRP might be attributed to the inhomogeneity inside the single lamina and to the presence of interfaces in between the laminae. These oscillations can be interpreted as non-uniform distribution of the thrust force along the tool cutting edge and the poor interlaminar strength of the composites that can cause piercing effects at the interfaces [18].

There are several techniques and methods to solve optimization problems available in the literature. The optimum model is that one that finds the best possible solution for the objective function that is being optimized. Heuristic methods (or non-deterministic) are used to find a good solution (suboptimal solution) in complex problems, as the optimal solution determination in reasonable computation time can be very difficult or even impossible due to exploration the whole domain of possible solutions [2]. Heuristic algorithms such as genetic algorithms (GA), simulated annealing (SA), tabu search (TS) and ant colony optimization (ACO) are powerful methods which can serve such optimization of problems where non-linear multi-minima functions with numerous variables are engaged. The metaheuristic algorithms search the point that represents a solution using probabilistic rules and they have the advantage of not being arrested to minimum or maximum local [5]. Duran et al. [7] used GA and the expanded Taylor Tool Life Equation to accomplish the cutting parameters optimization (cutting speed and cutting depth), which guarantee the conditions of minimum cost and maximum production in a certain lathe operation [2].

Drilling of composite materials is different than drilling of metals as drill has to pass alternatively through plastic (matrix) and fiber (reinforcement) which have different properties. The difference in the physical and chemical properties of the constituents makes the understanding of the mechanism of material removal quite complex. Material removal during drilling of composites involves series of fractures aided by diverse nature and uneven load sharing between matrix and fiber [3]. The drilling action results in damage of the composite material around the hole. It affects the surface finish of the drilled hole and also results in performance deterioration of the final composite product [6]. This damage can be estimated and characterized [16].

Table 1

Material properties

Properties	Units	Fibers	Matrix
Density	kg/m^3	2550	1230
Elasticity modulus	kN/mm^2	72.4	3.7
Poisson's ratio	-	0.32	0.42
Shear modulus	kN/mm^2	27.4	1.3
Coefficient of thermal expansion	$10^{-6}/^0$C	2.8	100

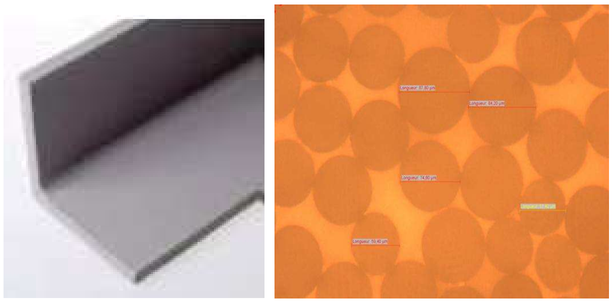


Fig. 2 Material used for experiments.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1. Workpiece details

The material used for experiments is a 10 mm thickness pultruded glass fiber composite with uni-directional fiber. Pultrusion process is an effective method to manufacture strong light weight composite materials. Fibers are pulled from spools through a device that coats them with a resin. They are then typically heat treated and cut to length. The word Pultrusion describes the method of moving the fibers through the machinery. The reinforcement is E-glass type and the matrix is Bisphenol – A vinyl ester. The material properties are presented in table 1. The fiber volume fraction is approximately 42%. (Fig. 2)

The material properties are presented in Table 1.

2.2. Experimental details

The machine tool used for experiments is a CNC Machining Center MCV 300 First with a max spindle speed of 8 000 rpm and spindle motor of 11 kW. For measuring the force evolution is used a 3 component quartz dynamometer Kistler type 9 257 B used for mechanical actions measurement in three directions. The experimental setup is presented in Fig. 4 in which the workpiece is mounted on the dynamometer on the table of the MCV300 First. The tools used are a 9 mm diameter carbide drill (made by Promat,), general purpose, 118^0, standard straight shank and a rapid machining steel 9 mm drill (Fig. 3).

2.3. Plan of experiments

In Table 2 the plan of experiments used for drilling the glass fiber reinforced composite is presented.

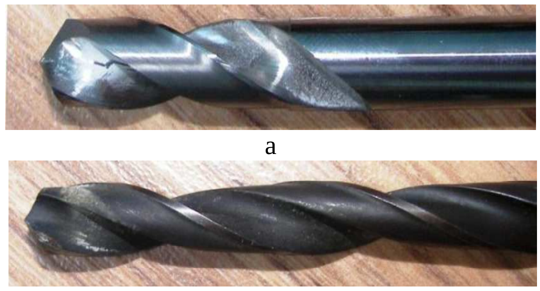


Fig. 3. Drills used: *a* – carbide; *b* – high speed steel.

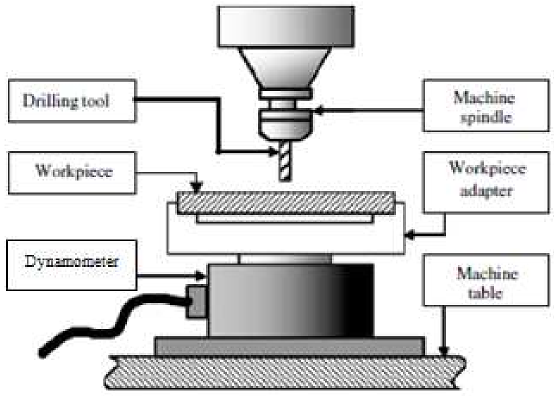


Fig. 4. Structure of experimental stand.

Table 2

Plan of experiments

Level	Cutting velocity (m/min)	Feed rate (mm/rev)
1	50	0.02 0.04 0.08 0.16
2	100	0.02 0.04 0.08 0.16
3	140	0.02 0.04 0.08 0.16

3. RESULTS AND CONCLUSIONS

3.1. The determination of the regression relationships for the drilling axial force

The existing models in the literature concerning the calculation of forces and moments when drilling composites consider Young's modulus, Poisson's ratio, ply thickness, critical energy propagation of cracks, flexural stiffness matrix. Since the studied material is obtained by pultrusion and has a structure close to that of homogeneous materials, the calculation for determining the optimal formula of the forces and moments takes into account Taylor's relationship.

Because the cutting moment has small values and no clear trend, the formula will be made only for the axial force.

The general relationship of the axial force that depends of the cutting parameters in drilling is given in the literature by Taylor's relationship:

$$F = C_F D^{x_F} f^{y_F} v_c^{z_F} \quad (1)$$

where: F is the axial force [N], D – the drill diameter [mm], f – feed rate [mm/rev], v_c – cutting velocity [m/min], CF – experimentally determined constant, xF, yF, zF – polytropic exponents.

Are taken into account all the factors that influence the values, because each has a significant share.
By the linearization of the relationship is obtained:

$$\lg F = \lg CF + xF \lg D + yF \lg f + zF \lg vc \quad (2)$$

3.2. Determination of the regression relationships for the axial force when using a Ø9mm carbide drill.

In Eq. 2 the data obtained in machining are introduced resulting a system of 12 equations with 4 unknowns see Eq. 3. This yields in a oversized system whose outcome is achieved using the method of least squares using the MatLab program [14].

$$\left\{\begin{array}{l}
\lg 18=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 50,\\
\lg 22=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 50,\\
\lg 26=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 50,\\
\lg 34=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 50,\\
\lg 20=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 100,\\
\lg 24=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 100,\\
\lg 32=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 100,\\
\lg 40=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 100,\\
\lg 20=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 140,\\
\lg 26=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 140,\\
\lg 33=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 140,\\
\lg 40=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 140,
\end{array}\right. \quad (3)$$

CF = 1,
xF = 1.5785,
yF = 0.3251,
zF = 0.1694.

Therefore the Taylor's relationship for the axial force in drilling a unidirectional glass fiber reinforced composite that contains 60% fiber glass using a 9 mm carbide drill is:

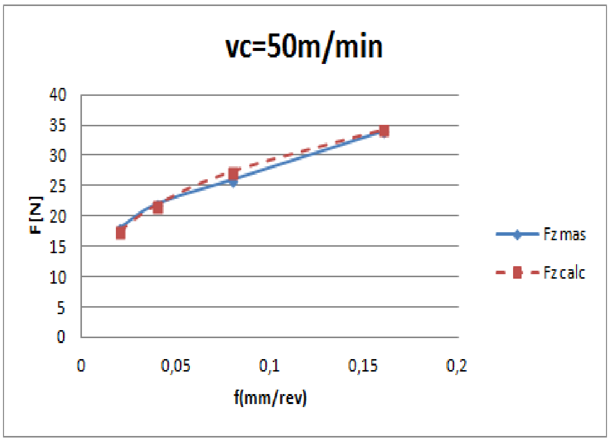
$$F = D^{1.5785} f^{0.3251} v_c^{0.1694}. \quad (4)$$

In Table 3 are presented by comparing the values obtained in machining and those obtained by calculation using Taylor's relationship.

Table 3

Forces values

Fz measured [N]	Fz calculated[N]
18	17.45668
22	21.86736
26	27.39246
34	34.31356
20	19.63026
24	24.59012
32	30.80317
40	38.58604
20	20.78095
26	26.03156
33	32.60881
40	40.84789



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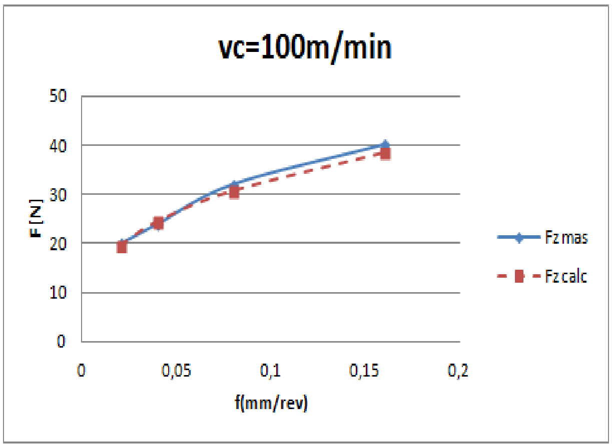

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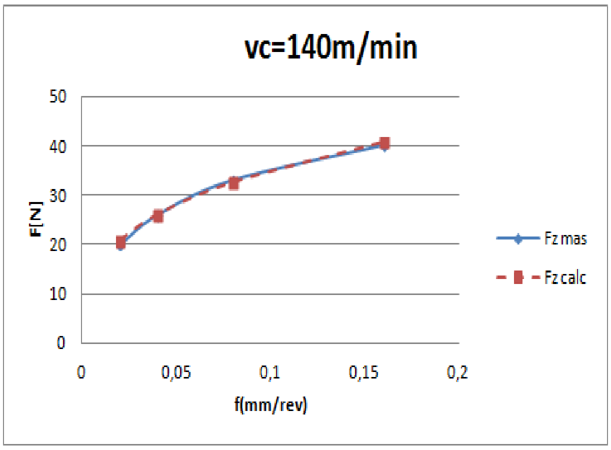

c

Fig. 5. Comparative values for the measured axial force and the calculated one using the mathematical model for: $a - v_c = 50$ m/min; $b - v_c = 100$ m/min; $c - v_c = 140$ m/min.

Using these data are plot the charts in order to analyze the gap between the measured values during drilling and the values obtained by computing with the proposed formula.

For lower values of the feed rate, the differences between the calculated values and those recorded during the measurement is below 1%, while increasing the advance, these differences reach 7%.

3.3. Determination of regression relationships of the axial force when using a Ø9mm high speed steel drill

In analogy with the calculation made for the carbide drill, experiments and calculation are made for the HSS drill. The resulting system is:

$$\begin{cases} \lg 26=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 50, \\ \lg 44=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 50, \\ \lg 65=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 50, \\ \lg 100=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 50, \\ \lg 38=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 100, \\ \lg 70=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 100, \\ \lg 110=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 100, \\ \lg 200=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 100, \\ \lg 58=\lg C_F+x_F\lg 9+y_F\lg 0.02+z_F\lg 140, \\ \lg 120=\lg C_F+x_F\lg 9+y_F\lg 0.04+z_F\lg 140, \\ \lg 260=\lg C_F+x_F\lg 9+y_F\lg 0.08+z_F\lg 140, \\ \lg 400=\lg C_F+x_F\lg 9+y_F\lg 0.16+z_F\lg 140, \end{cases} \quad (5)$$

CF = 1.01,
xF = 0.9275,
yF = 0.7902,
zF = 1.0567.

Therefore the Taylor's relationship for the axial force in drilling a glass fiber reinforced composite using a Ø9 mm classic high speed steel twist drill is:

$$F = 1.01 D^{0.9275} f^{0.7902} v_c^{1.0567} . \quad (6)$$

From the graphs and tables it can be seen that after calculating using Taylor's formula the values obtained are close to those recorded during the experiments (between 1 and 7%). This is true for carbide drills for which the wear is negligible. For the speed steel drill it can be observed a greater difference between the calculated and measured values, leading to a gap of 20% between measured and calculated values. This is due to a sharp cutting tool wear, for which the axial force is elevated. In general, equations that fully estimate the values of axial force and moment will not exist for any cutting process due to the many unknown factors generally friction, which has great influence on the axial force and moment. Therefore for force calculation in drilling glass fiber composites it should be considered the cutting tool material because with a pronounced wear the friction coefficient (Eq. 7) increases. This is the case for the drill made from steel that wears more faster comparing with the one made from carbide.

Table 3

Forces values

Fz measured [N]	Fz calculated[N]
26	22.065
44	38.15732
65	65.986
100	114.1105
38	45.89891
70	79.37364
110	137.262
200	237.3691
58	65.49617
120	113.2635
260	195.8681
400	338.7175

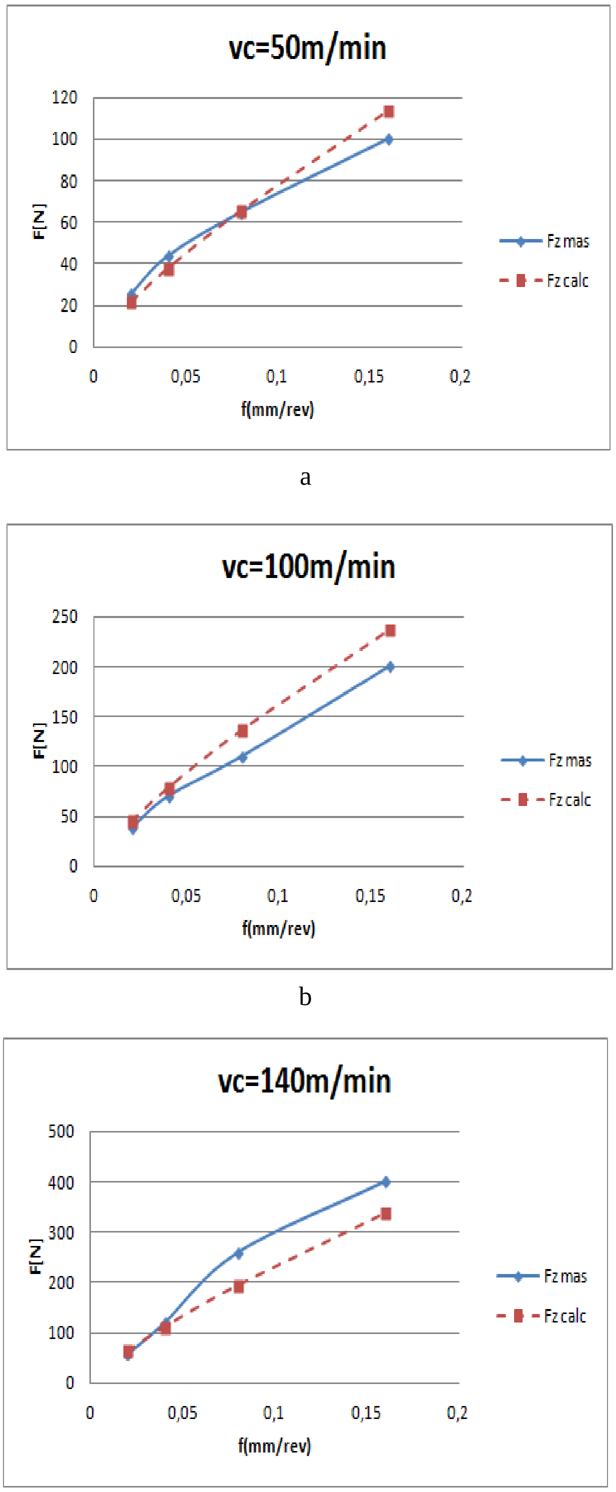

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Fig. 6. Comparative values for the measured axial force and the calculated one using the mathematical model (using a 9 mm classic high speed steel drill) for: *a* – v_c = 50 m/min; *b* – v_c = 100 m/min; *c* – v_c = 140 m/min.

4. CONCLUSIONS

Following conclusions can be drawn from the literature on drilling of composites:

The machining of polymer matrix composites is considered that this differs from the machining of metallic materials, so special attention should be given in establishing the cutting regimes and constructive and geometrical parameters of cutting tools, depending on the workpieces properties.

The modeling of drilling process in polymer–matrix composites (PMCs) so far has been done mostly using neural network or fuzzy logic and there is only one classical model available for drilling of CFRP composites. All other classical models available are of drilling in conventional metals.

The material studied has a behaviour similar to that of conventional homogeneous materials. Therefore to calculate the forces the formula used for metallic materials is applied and not specific mathematical models for composites.

The law according to which as cross edge drill is large relative to the cutting edge, the axial force is greater is respected.

The main goal in finding equations for estimating axial force and moment is to get good benchmarks.

From the graphs and tables it can be seen that after calculating using Taylor's formula the values obtained are close to those recorded during the experiments (between 1 and 7%). For the speed steel drill it can be observed a greater difference between the calculated and measured values, leading to a gap of 20% between measured and calculated values.

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