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INFLUENCE OF TOOL MATERIAL ON DYNAMICS OF DRILLING AND DAMAGE ANALYSIS OF UD-GFRP COMPOSITES

Andra LIȚĂ[1], Claudiu BÎŞU[2], Constantin MINCIU[3]

Prelucrarea materialelor compozite a fost întotdeauna o provocare datorită dificultăților întâlnite cum sunt delaminarea, smulgerea fibrelor, exfolierea. Găurirea reprezintă principala operațiune prin care se realizează asamblări cu bolțuri în industrie. Proprietățile şi calitatea găurilor obținute cum ar fi cilindricitatea, rugozitatea suprafeței interioare pot cauza tensiuni în asamblare ce duc la cedarea acesteia. Acest articol prezintă analiza comparativă a forțelor axiale rezultate la găurirea unui material compozit cu fibre unidirecționale lungi, cu o concentrație de fibră de sticlă de 60%. S-au determinat parametrii optimi pentru fiecare sculă utilizată în ceea ce priveşte calitatea găurii obținute şi variația forței față de medie.

Machining of composite materials has always been a challenge due to multitude of difficulties encountered such as delamination, fiber pulling out, peeling. Drilling is the principal operation to make bolted or riveted assemblies in industry. The properties and quality of drilled holes such as cylindricity, roughness can cause high stresses leading to failure. This paper presents the comparative analysis of axial forces in drilling an UD-GFRP composite material, with a concentration of glass fiber of 60%. The optimum parameters for each tool it was determined with respect to the hole quality and the force variation from the average value.

1. Introduction

Machining of glass fiber-reinforced polymer (GFRP) composite materials have always been a challenge due to multitude of difficulties encountered such as fiber pulling out, fiber fuzzing, matrix burning, and fiber-matrix detachment leading to subsurface damage, reduced strength, and short product service life. In addition to this, a large number of variables in the form of tool geometry, operating parameters, individual mechanical properties of constituents, and different fiber-matrix bond properties make the machining analysis of GFRP materials a complex one. GFRPs are an important class of materials in advanced structural applications due to their lightweight, high modulus, and specific strength, high specific strength, high specific stiffness, high damping, low thermal expansion, good dimensional stability and an unusual combination of properties

[1] PhD student., Machines and Production Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: andra_lita@yahoo.com
[2] Lecturer, Machines and Production Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: cfbisu@gmail.com
[3] Prof, Machines and Production Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: constantin_minciu@yahoo.com

not obtainable with metal alloys. However, because of the anisotropic and heterogeneous nature of the materials, it has been difficult to predict the cutting forces reliably. There have been many studies in the machining of GFRPs [1].

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 [3-12].

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 drilled while for a large transport aircraft millions of holes are necessary, mostly for fasteners such as rivets, screws and joints.

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.

2. Experimentation

2.1. Workpiece details

The machined material is a UD-GFRP made by pultrusion provided by Fiberline with a thickness of 10 mm and 60% glass content in weight. Pultrusion is a process for continual production of composite profiles with constant cross section and material properties which are manufactured for specific purposes. The method ensures consistent quality that can be reproduced. Pultrusion is done by continuous reinforced material being pulled through a guide where the fibers are placed precisely in relation to the profile cross section. The fibers are then led through processing equipment where the fibers are impregnated with the matrix material. The combined mixture of fibers and matrix is pulled on through the heated equipment where the profile is cured in its final geometry. The fully cured profile is then pulled forward to a floating suspended saw which cuts the profiles into define lengths.

The mechanical properties of this material valid in the temperature range of -20^{0}C to 60^{0}C are presented in the tables below [13]:

Table 1.

Mechanical properties of UD-GFRP

Typical strenght values (dry condition)			
		[MPa]	
Flexural strength, 0^0	$f_{b,0^0}$	240	
Flexural strength, 90^0	$f_{b,90^0}$	100	
Tensile strength, 0^0	$f_{t,0^0}$	240	
Tensile strength, 90^0	$f_{t,90^0}$	50	
Compressive strength, 0^0	$f_{c,0^0}$	240	
Compressive strength, 90^0	$f_{c,90^0}$	70	
Shear strength	f_τ	25	
Pin-bearing strength, longitudinal direction	$f_{cB,0^0}$	150	
Pin-bearing strenght, transverse direction	$f_{cB,90^0}$	70	
Typical stiffness figures and transverse contraction (dry condition)			
		[MPa]	[--]
Modulus of elasticity	E_{0^0}	23000/28000	
Modulus of elasticity	E_{90^0}	8500	
Shear modulus	G	3000	
Poisson's ratio	$\nu_{0^0,90^0}$		0.23
Poisson's ratio	$\nu_{90^0,0^0}$		0.09

2.2. Cutting tools and equipment

The machine tool used for experiments is a CNC Machining Center MCV 300 First with a max spindle speed of 8000 rpm and spindle motor of 11 kW. For measuring the force evolution is used a 3 component quartz dynamometer Kistler type 9257B used for mechanical actions measurement in three directions. The experimental setup is presented in fig.1 in which the work-piece is mounted on the dynamometer on the table of the MCV300 First.

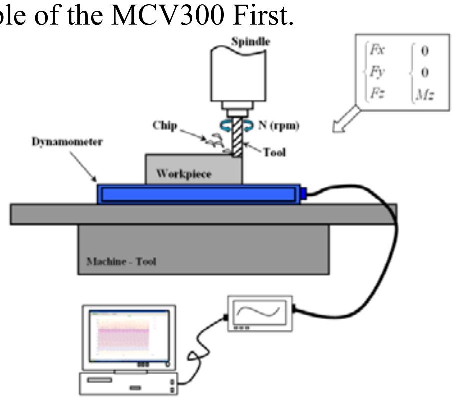


Fig. 1. Structure of the experimental stand

The signals are generated by the drilling process, sent to the dynamometer in mV and transmitted to the amplifier where it is converted to volts and passed to the Kistler acquisition board. Signal processing is done through DynoWare program with a 1000 Hz sample acquisition frequency [14].

The used tools are a solid carbide DK460UF (K40) 9 mm diameter drill made by Promat, and a HSS drill general purpose, 118^0 point angle, standard straight shank. The tools are presented in figure 2.

a.

b.

Fig. 2. Drills used in experiments: a.HSS drill; b. Promat drill

2.3. Plan of experiments

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

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 discussion

During drilling, the material ahead of the drill point undergoes bending and consequently fiber breakage/pullout and crazing of matrix material. This is reflected in detachment, delamination and hole shrinkage [2].

3.1. Monitoring of thrust

Thrust force, a direct indicator of the status of the cutting wedge, is usually used as a process indicator. Any change in the thrust force can be attributed to change in the status of cutting wedge either by deformation, chipping and other modes of wear of tool material over the cutting edges or possible reactions between the tool and glass fiber that is very abrasive. Figure 3 shows the typical monitored relationship between the thrust force and cutting parameters for drilling with HSS drill. For a given cutting speed, the thrust is increasing with feed. From the experiments it is ascertained that for the drilling of UD - GFRP, the optimum cutting parameters are 50 m/min cutting speed and 0.02 mm/rev feed rate for minimum thrust force.

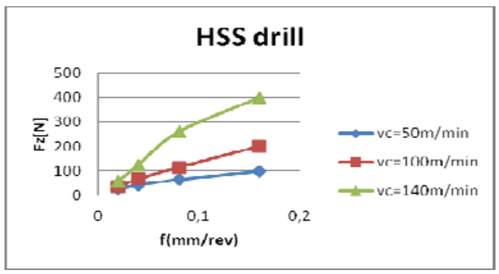
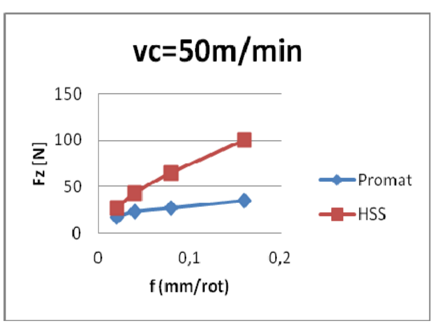


Fig. 3. Axial force evolution for the HSS drill

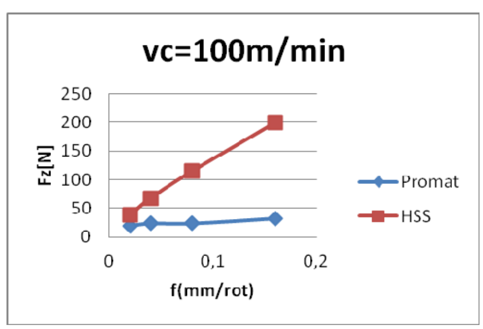
According to literature, for the drilling of composite materials reinforced with fibers, drills made from high speed steel are not recommended. This is confirmed by analyzing the graphs that illustrate the dependence of axial force with cutting speed. There is an exponential increase with the increase of cutting speed - if the cutting speed is doubled, the value of the axial force is also double due to the great wear of the tool.

It can be observed from the graphs that for the HSS drill, the evolution with the feed is more significant than for the carbide drill. Also the value of the axial force for the same cutting conditions (cutting speed 140 m/min, feed of 0.16 mm/rot) is 10 time higher for the HSS drill in respect to the carbide drill.

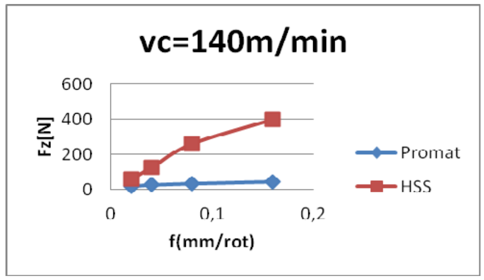
3.2. The effect of tool materials on thrust



a.



b.



c

Fig. 4. Comparative evolution for the two drills used: a) cutting speed 50 m/min; b) cutting speed 100 m/min; c) cutting speed 140 m/min

3.3. The effect of tool materials on hole shrinkage and delamination factor

During drilling, glass fiber reinforced polymeric composite exhibited geometrical inaccuracies such as bell mouth formation at entry, fluffing over hole boundary at exit of the drilled hole. Breakage of fibers and fiber pullout resulting in debonding and also matrix crazing, which can contribute to the relaxation of the material, and consequent shrinkage [2]. Figure 6 illustrates the relative hole quality between the tool materials. It can be seen that the stress whitening layer around the entry of the hole increases with the feed.

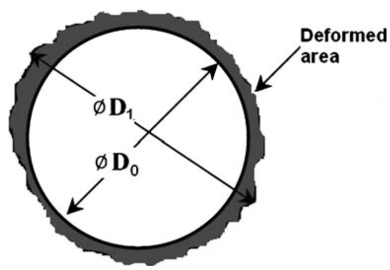
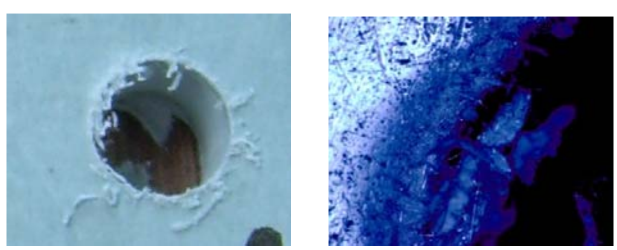
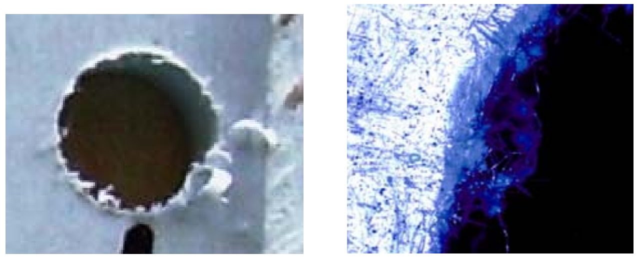


Fig. 5. Deformation zone of drilled glass fiber-reinforced polymer [1]

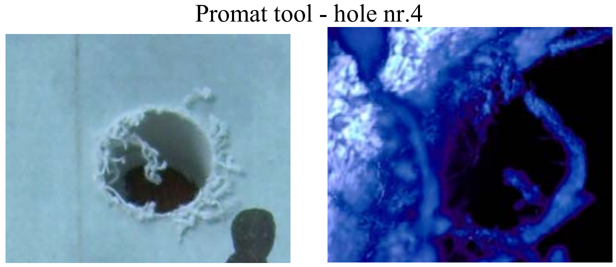


a. b.

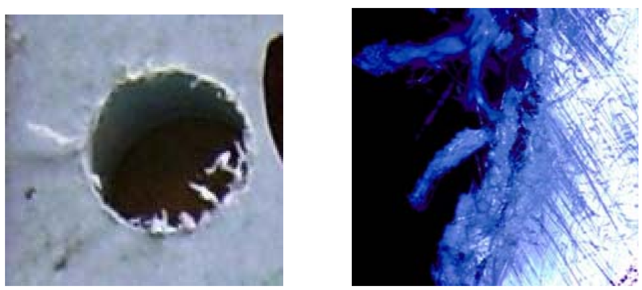
HSS - hole nr.4



Promat tool - hole nr.4



HSS tool - hole nr.8



Promat tool - hole nr.8

Fig. 6. Hole quality for the two tools: a) photo; b) microscope image; hole nr.4:vc=50 m/min, f=0.16 mm/rot; hole.nr.8: vc=100 m/min, f=0.16 mm/rot

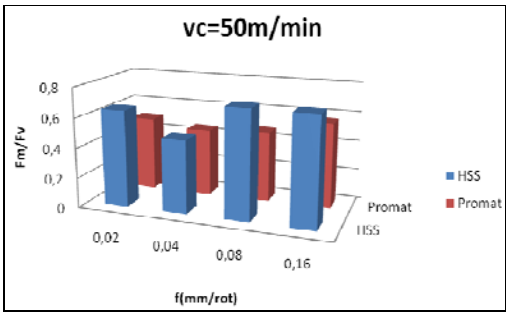
It can be seen from the figures that the hole quality is better for the solid carbide tool that for the HSS toll for the same cutting conditions. Also the surface quality decreases for both tools with the increase of cutting speed and feed. The ratio DF = D_1/D_0 is higher for the HSS drill that for the carbide twist drill.

Vibration and noise occurring in the operation of machine tools and those existing in the environment have negative influence on safety in the operation of these machines, the productivity and precision mechanical processing and humans.

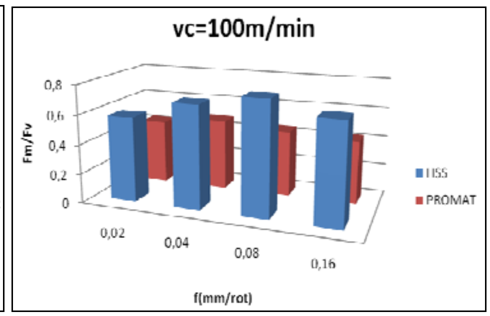
Vibrations from a piece of industrial equipment is not only a problem for employees, but can also lead to future machine problems or failure [15].

As the thickness resisting stiffness reduces, the ply layers bend elastically under the influence of applied thrust force. If the thrust force is larger than the interlaminar bond strength, then a crack is initiated which propagates and results in a finite damage around the hole.

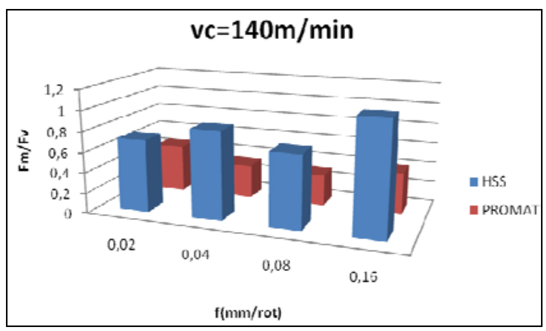
The organic matrix composites have essentials damping properties mainly due to the viscoelastic nature of the matrix and the properties of fiber-matrix interface. These mechanical properties are not strongly dependent on the excitation frequency and temperature. For the composite materials, these properties are directional dependent: this material is an anisotropic absorbing medium.



a.



b.



c.

Fig. 7. Ratio average/variation force evolution for the two drills

In Fig. 7, the evolution of average value for the thurst force in relation with its variable part is presented. As we can see with the increase of feed, this ratio increases too.

The variable part of the force has a close value to the average force on Z direction. This can be explained by the fact that the fiber density is greater than that of the matrix, and also the elasticity modulus is greater for the fibers than for the matrix. (see tabel 1). The variation of force on Z direction is significant.

The ratio between the variable part of the force and his average value is greater than 1, which means that the variable part is much smaller than the average value.

Table.3

Elasticity modulus for different materials

	Steel	Aluminium	CFRP	GFRP
Elasticity modulus E	$2.1 \cdot 10^{11}$Pa	$0.7 \cdot 10^{11}$Pa	$1.3 \cdot 10^{11}$Pa	$2.3 \cdot 10^{11}$Pa
n(rpm)	5305	15000	1000	7000
f(mm/rot)	0.3	0.4	0.02	0.16
Fm/Fv	5.33	6	5.11	0.70
n_{mat}/n_{GFRP}	0.75	2	0.14	-
f_{mat}/f_{GFRP}	1.8	2.5	0.12	-

The first three materials presented (steel, aluminium and CFRP composite) have the value of ratio variable/ average close one to an other. Instead, in the case of the material that we present (reinforced with glass fiber), although the elasticity modulus is high and close to CFRP, the ratio is smaller than 1 – the variable part is greater than the average. This material does not respect the law according to which a material is more rigid when the elasticity modulus is greater. The analyzed material vibrates much more than the other materials to which it is compared.

4. Conclusions

Composite materials have a great importance in industrial applications and are increasingly replacing conventional materials. Such an application is the one that we develop in this paper.

From the cutting parameters, the feed rate is more influential in the surface roughness of the drilled hole wall than the cutting speed. Therefore, it is effective to reduce the feed rate to improve the drilled hole quality. Another important factor that influence the hole quality is the tool material. For the HSS tool, the force level is higher than for the carbide drill, and the surface quality is lower. That is the because of the abrasive character of the glass fibers in the material. The wear for the HSS drill is higher than for the carbide drill. So, the high speed steel tool is not suitable for drilling this material. Also, the appropriate cutting parameters, no matter the tool material, are the cutting speed of 50 m/min and the feed between 0.02 and 0.08 mm/rev.

Another objective of this paper is the understanding and determination of dynamic phenomena that occurs during drilling of UD-GFRP material in order to develop a model to optimize the cutting parameters. For this, the experimental protocol was designed in order to determine the cutting forces during drilling. It could be seen the variable evolution of forces, especially in axial direction (Fz) due to elastic nature of the material. The quasi linear character of axial force evolution from the ratio average force/variable force was examined. This finding requires a thorough analysis from the dynamic point of view at macro and micro level of the material.

Almost every structure is subjected to dynamic loads. When a structure is subjected to dynamic loads, whether cyclical or one time impact, every natural frequency of the structure is excited. Therefore, it is important to determine the important natural frequencies, and this will be discussed in further work.

Acknowledgment

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