ANALYSIS OF CUTTING FORCES WHEN DRILLING COMPOSITES

A. Humar and M. Piska

Production Technology Institute
Faculty of Mechanical Engineering
Brno University of Technology, 616 69 Brno, Czech Republic

Abstract: A study of the cutting force components (in axial and tangential direction) and wear process when drilling a glass fibre reinforced plastic and carbon prepreg was made. Four component piezoelectric dynamometer KISTLER 9272, fully controlled by a PC, and statistical assessment were used to measurement of the torque and forces. Multiple regression analysis was used to determine the complex relationships between cutting torque and forces versus the drill diameter, feed per revolution and machined material.

The recommended drilling material is sintered carbide (ISO grade K10-20) with the TiAlN coating because of the low cutting forces and the low wear rate. HSS and coated HSS suffers from the intensive flank wear, followed by high increments in the axial force and delamination of not-supported distal layers of the drilled material during drilling.

Keywords: composites, drilling, cutting force

1   INTRODUCTION

New progressive classes of construction materials are presented with fibre-reinforced plastics. These materials can be characterised by the wide range of physical and chemical properties, controlled by scientists. Lightness in weight, high strength, unique proportion of tensile strength to density, very good mouldability, excellent resistence to chemical corrosion and very good electrical insulation mark the materials as materials of the future. Anyway, we can meet them widely today in such industrial branches like space, aircraft, automotive, electronic and consumer-goods industries or sport. The biggest volume of production of the fibre reinforced plastics (FRP) materials is located in the U.S.A. and Japan namely, but there is a big rise of composites production in the countries of the European Unity at the present [1-3].

FRP is generally an engineering material that consists of a thermosetting resin and a various fibre reinforcement (up to 80% of volume). These two components have a very different properties like isolated materials, but together they create a new material with a quite new properties. There are at least six major family groups of resin used in FRP fabrication: polyester, vinylester, modified acrylic, epoxy, phenolic and urethane. The glass (namely), carbon, aramid and UHMWPE (Ultra High Molecular Weight Polyethylene) fibres are usually used like fibre reinforcement. The basic properties of FRP are, eg.: low specific gravity, excellent tensile strength and tensile modulus, high shock resistance, high corrosion resistance, low thermal conductivity, electric non-conductivity, zero attenuation of the electromagnetic waves, high dimension stability, flexibility of shape and colour, easy assembly and minimum requirements for a long-time maintenance. The basic presumption for the wide use of such materials is effective machining.

2   MACHINING OF FRP

One of the basic problem of the composite materials is their cutting and assembly. In spite of the big research focused on the adhesive clues (eg. kinds based on epoxy, methacrylate, polyurethane, etc.), mechanical fastening still remains as one of the simplest and the most reliable integrating methods, especially for the dynamically loaded parts. Drilling of the composite materials is the most common technological operation daily used in many companies.

Composite materials (and the class of the glass fibre reinforced plastics - GFRP) consist generally of the two different basic phases:

- *glass fibres,* that have different form, orientation and ratio to resin. The main factor which influences the machining process of the GFRP is the volume of the glass and its texture. Owing to its high strength and hardness, a cracking mechanism works during machining of the brittle material.

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Sharp tips of the fibres scratch the cutting wedge on the face and flank mainly. This abrasive wear has the main role in tool wear when machining GFRP. A different orientation of fibres makes an anisotropy of mechanical properties of FRP and is another negative factor for machining which tends to chattering. Cracking or delamination of surface layer on the machined surface or ball-shaped clots of fibres and resin can protrude from machined surface when the cutting conditions are inconvenient or the tools looses its cutting performance;

- *resin matrix,* that has a low thermal resistance, badly conducts heat and sticks on the tool face or in the grinding wheel pores. The very low thermal conductivity of FRP results in the problem that the all cutting heat must be conducted away by the tool or a coolant, scarcely applicable with regard to the water absorbability of FRP. Due to the excessive heat loading on the tool edge and the abrasive action of the fibres mentioned above a rapid wear process can be expected.

Three theoretically eligible cutting materials have been found for drilling of composite materials (number in the brackets shows a price for the diameter 10 mm and year 1999, got from the same producer, without VAT):

- coated HSS (~ 30 DM),
- coated sintered carbides (~ 92 DM),
- diamond (~ 535 DM).

Our preliminary tests and analyses [4] of the typical time sequence plots of the axial forces andcutting torque moments confirmed these facts - see **Fig. 1, 2**:

- the physical variables strongly vary during drilling - during one stroke and even each revolution,
- drilling undergoes three different time phases - penetration of the drill tip, quasi-stabilised drilling and outgoing of the drill from the material,
- a peak value of the variables at the third phase can be dangerous - the drill is prone to break out the unsupported distal layers; or due to the drive feed slack of the spindle the axial force can be strongly changed - from compression mode to the tensile mode with a tendency to tearing of the adherent lower layers of the composite materials instead of cutting. Regarding the fact that these layers are frequently the stress transmitting means, a reduction of the feed in the finishing (from 30 to 50%) is normally recommended.
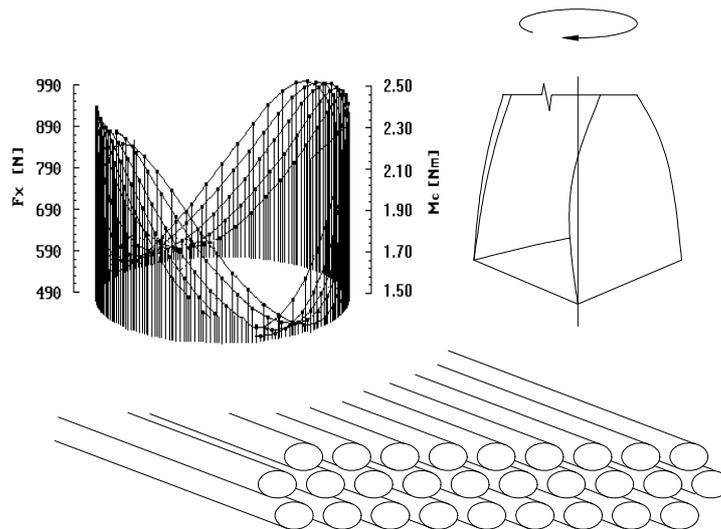

Figure 1. Typical oscillations of the feed force and torque during five rotations of the drill due to fibrous structure of the composite. Mitsubishi sintered carbide drill GP 20 M (with TiN coating), diameter 14.5 mm, v = 32.3 m/min, f = 0.32 mm. Machined composite - carbon prepreg.

Comment: A very small particles of chips are made from the reinforcing fibres when machining FRP. These particles are expanded to the space like dust and they have very negative influence on the environment and human health. Because of this fact, the tool machines must be provided with very effective dust extractors so they comply with the stringent hygienic principles. The content of the microparticles normally must not exceed 3-5 mg/m^3 with the recommended limit up to 0.5 mg/m^3 in the near time horizon [5].

3   DRILLING TESTS

Two basic series of tests have been made:

- measurement of the mean values of the feed force and the torque, dependent on the cutting conditions - for the GFRP and CP composite;
- wear test (drilling performance) of the selected twist drills for the GFRP composite.

3.1 Workpiece material:

Two different composites were selected for the tests:

- glass fibre reinforced plastic made by pultrusion (**GFRP**), polyester matrix, 70% glass volume, thickness 9.5 mm, width 76 mm, cut length 100 mm, produced by the company PREFA, Brno, the Czech Republic;

- carbon fibre reinforced prepreg (**CP**), thickness 9.5 mm, width 44 mm, cut length 200 mm, produced by the Institute of Aviation, Faculty of Mechanical Engineering, Technical University of Brno.
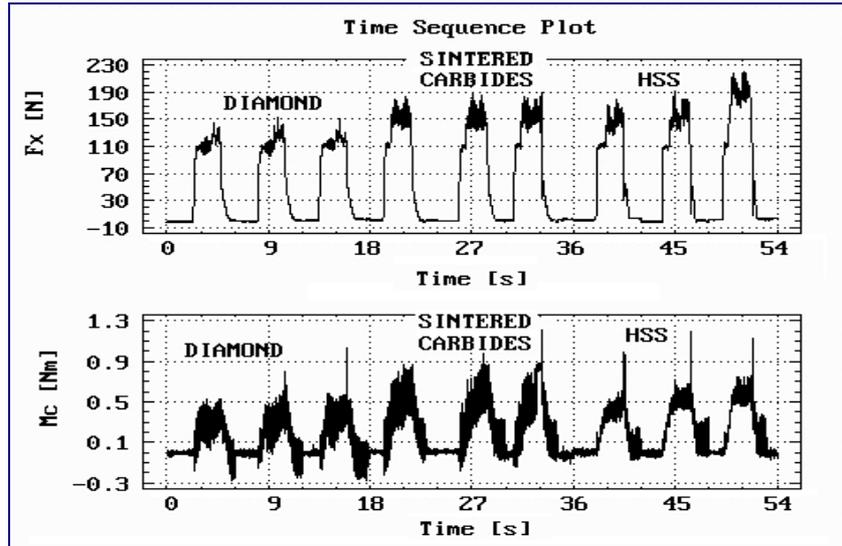

Figure 2   Loading of the drills made from different materials during three passes of the drills. Diameter 10 mm, f = 0.2 [mm/rev]; diamond: v = 37 [m/min]; HSS : v = 30 [m/min]; sintered carbides: v = 35 [m/min]; GFRP, 9.5 mm**.**

Table 1. Approximate mechanical properties of the machined materials.

Material	Longitudinal Direction		Transverse Direction		
	Tensile Strength [MPa]	Compression Strength [MPa]	Tensile Strength [MPa]	Compression Strength [MPa]	Shear Strength [MPa]
GFRP	650-900	600-900	20-25	90-120	45-60
CP	850-1500	700-1200	35-40	130-190	60-75

3.2   Drills and drilling conditions

A description of the drills (real geometry was measured before the testing) and selected cutting conditions both kind of tests is listed in the following **Tab. 2.**

Table 2. Cutting conditions for testing of feed force F_f and torque moment M_c and the wear test.

Drills	Diameter D [mm]	Revolutions n [min⁻¹]	Cutting speed v_c [m min⁻¹]	Feed per Revolution f [mm]	Description
Zo	13.5	710	30.1	0.20	e_r = 120°, l = 30°
	8.6	1120	30.3	0.20	High Speed Steel (HSS)
	5.3	1800	30.0	0.20	ZBROJOVKA, a.s.
	9.0*	*1120**	*31.7**	*0.2**	(Czech Republic)
So	14.5	710	32.3	0.20	e_r = 130°, l = 24°
	9.6	1120	33.8	0.20	HSS
	6.0	1800	33.9	0.20	STIM-ZET, a.s.
	9.6*	*1120**	*33.8**	*0.2**	(Czech Republic)
Go	10.0	1120	35.2	0.20	e_r = 120°, l = 30°
	6.0	1800	33.9	0.20	HSS + TiN coating
	10.0*	*1120**	*35.2**	*0.2**	Gühring (Germany)
gk	14.0	710	33.9	0.12- 0.20 - 0.32	e_r = 118°, l = 30°
	10.0	1120	35.2	0.12- 0.20 - 0.32	solid sintered carbide ISO K10/K20
	6.0	1800	31.2	0.12- 0.20 - 0.32	with TiAlN coating
	10.0*	*1800**	*56.5**	*0.2**	Gühring (Germany)
* Asterix means the wear test drills and cutting conditions.					

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3.3 Research technique

Cutting forces and torque were measured with the four components piezoelectric dynamometer KISTLER 9272 and special PC-software with high recording speed frequency up to 8 kHz in every channel. Tool wear was measured with a common workshop microscope and recorded with Olympus stereo-microscope using CCD camera.

4   RESULTS

4.1 Mean cutting forces and torque moments

The changes of the cutting force and torque values were cyclical during every revolution of the drill, according to the orientation of reinforcing fibres for both of machined materials (these values were lower perpendicularly to fibre axes and higher along to fibre axes). This fact is evident from **Fig. 1**, where the time sequence record of **F_f** and **M_c** (for five revolutions of the drill) was shown. Nevertheless, Gauss normal distribution of the both variables was found. The values are valid for the whole drill, it means for the two main cutting tool edges.

Multiple-linear regression analysis was used to estimate the constants and exponents for calculation of the mean values of axial force F_f and torque moments M_c (see **Tab. 3**) as a function of the drilled material, diameter of the drill and feed in the following formulae:

$$F_f = C_{F_f} . D^{x_{Ff}} . f^{y_{Ff}}$$

(1)

$$M_c = C_{M_c} . D^{x_{Mc}} . f^{y_{Mc}}$$

(2)

where: F_f [N] is the total feed (axial) force,
M_c [Nm] is the total torque moment,
D [mm] is drill diameter (in the range of diameters from 6 to 14 mm)
f [mm] is feed per revolution (in the range of feeds from 0.12 to 0.32 mm).

Table 3. Constants and exponents for cutting forces and torque mean values calculations.

Drill	Machined	Constants		Exponents			
Coating	Material	C_{Fx}	C_{Mc}	x_{Ff}	x_{Mc}	y_{Ff}	y_{Mc}
Gühring,	GFRP	218.8	0.0118	0.387	2.143	0.786	0.712
SC - K10/K20 TiAlN	Carbon prepreg	151.8	0.0223	0.627	2.029	0.554	0.509

The higher values of force and torque for carbon fibre prepreg can be expected by the higher mechanical properties (higher tensile strength) of the carbon fibres and its proportion in the mass.

The influence of the cutting speed was not statistically significant in the range of used values. This aspect can be expected in a higher speed interval (due to softening of the resin matrix, deteriorating the quality of the machined surface).

When drilling the glass fibre reinforced plastics the maximum values of **F_f** are about 30% higher and maximum values of **M_c** are about 60% higher compared to their mean values. When drilling of carbon prepreg the maximum values of **F_f** and **M_c** are about 50% higher compared with their mean values as calculated according to the formulae mentioned furthermore (1,2).

Furthermore, it was found that not only the cutting force and torque change during every revolution of the drill (it influences all specific variables such as specific cutting force, shear angle, and coefficient of friction [6]). Those oscillations make a very affecting loading of the drill edge and a rapid wear occurs.

4.2 Tool wear

The wear intensity of the *high speed steel drills* on the flank has been found very high when drilling of GFRP (as it had been expected). As can be seen from **Fig. 3**, the width of facet (VB) at the drill land clearance has reached values bigger than 1.2 mm for non-coated HSS drills and value bigger than 1.0 mm for coated HSS drill, after two minutes of drilling. The effect of the wear-protective TiN coating on HSS for this application was negligible and useless.

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There was a statistically significant correlation (probability 95%) between the tool wear and cutting torque and feed force. The values of torque M_c have increased approximately 2,5 times in accordance with the tool wear increase (**Fig. 3**) and values of axial cutting force F_f have increased almost 7 times after about two minutes of tool work.
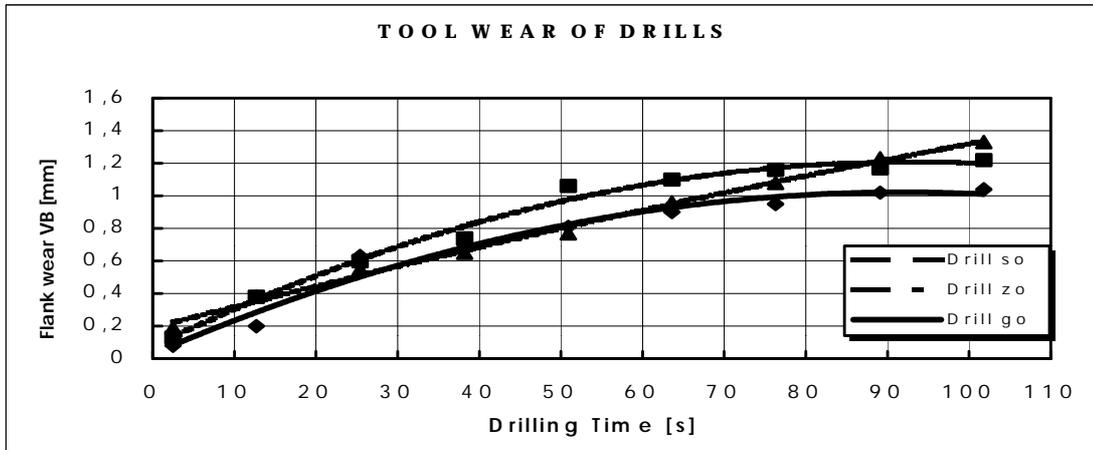
Figure 3. Time sequence plot for the wear test.

The wear of the *coated solid carbide drill* stabled at the value of **VB** = 0.12 mm after the first stage of very short drilling, and stagnated without any remarkable changes for more than five minutes of work, in spite of the fact, that this drill worked at a higher cutting speed (v_c = 56,5 m min^{-1}) in comparison with high speed steel drills (v_c = 31,7-35,2 m min^{-1} - see **Tab. 1**). The values of torque and axial cutting force were growing only very slowly owing to the low tool wear of the solid carbide drill.

5   DISCUSSION

The cyclical courses of the axial cutting force F_f and torque M_c during every revolution of drill can be explained as follows:

- if the drill edge cuts the reinforcing fibres *perpendicularly* to their axes, the penetration of the cutting edge is much easier: fibres can flow along the tool face up to the moment when bending and shear components of loading can exceed the limit tensile strength of the fibres and chips are separated. The friction at flank and face is lower, and a lower energy and cutting force are needed for cutting process in this case;
- if the drill edge cuts the reinforcing fibres *along* to their axes then fibres are pressed by the edge up to limit elastic deformation of the fibres, and brittle fracture follows. The edge cuts across the fibres and its contact areas and adherent side of flank are severely loaded.

From this angle of view the resin matrix does not present any important role in this chip making mechanisms due to its low mechanical properties unless it clogs the drill flutes.

6   CONCLUSION

The tests evidenced that cutting forces and torque are much lower when drilling the fibre reinforced plastics in comparison with drilling of steels. The anisotropy of mechanical properties, owing to the fibres space arranging, has very big influence on the dynamic changes of forces, torque and other physical variables during every revolution of drill. Reinforcing fibres have a big abrasive effect, and this fact is the main reason for very intensive wear of high speed steel drills (including the coated high speed drills). Solid carbide drills can ensure high material removal at very favourable economical costs. Long term tests with the carbide and diamond drills are currently in progress.

ACKNOWLEDGEMENT

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AUTHORS: A. HUMAR and M. PISKA, Technical University of Brno, Faculty of Mechanical Engineering, Production Technology Institute, Technicka 2, 616 69 Brno, The Czech Republic, Phone: 00420 5 4114 2407 (2555), Fax: 00420 5 4114 2104, E-mail: humar@kst.fme.vutbr.cz, piska@kst.fme.vutbr.cz.