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Application of Colding tool life equation on the drilling fiber reinforcement polymers

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Abstract

Fiber reinforcement polymer (FRP) is a hard-to-treat material used in different areas of up-to-date machine building. It has excellent mechanical properties making the material unique in different engineering solutions such as aircraft, aerospace and boatbuilding. The optimization of holemaking operations in FRP is the main aim of the current investigation. This paper presents an approach of defining the most effective cutting data and costs of drilling Saab's carbon fiber reinforcement plastic (CFRP) using cemented carbide and PCD drills. The experiment results included force and torque monitoring, tool wear defining and holes quality analyzing.

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Keywords: colding, drilling, holes, composite materials, quality

1. Introduction

Passenger aircraft flights are one of the most popular long-distance transfers in the world. The up-to-day aircraft manufacturing volume is increasing due to the air transferring rise. The efficiency of the aircraft flights mostly depends on engines performance and the aircraft weight [1]. Therefore, metal-based materials of aircraft components are replaced by non-metal fiber reinforcement polymer (FRP) composite materials [2] due to their unique properties such as high weight-to-stiffness, weight-to-strength etc. It makes possible to provide a lower weight and a higher strength of aircraft components [3].

The technological process of FRP forming, which includes fibers transfer molding, provides the possibility of manufacturing a high tolerance components with a complex geometry [4]. Consequently, the holemaking process is

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one of the most important stages of making joints between FRP components. Bolted and riveted types of joints are widely used in the aircraft industry. FRP drilling process is accompanied by forming specific defects, which are unusual for drilling of metal-based materials. This is mainly connected with the fibers high strength (4-9 GPa) and the multidirectional reinforcement [3]. Uncut fibers and delamination are among the main defects of drilled holes. They lead to the gaps formation in between FRP components joints. Gaps lead to loosening and slacking of the joints during the aircraft usage and are unacceptable for the aerospace industries for safety reasons [5]. By optimization of the drilling process, aircraft manufactures can increase production efficiency.

Optimization and prediction of cutting data and tool life is commonly done using tool life models. The most well-known tool life model is the Taylor equation [6] presented 1906 describing the link between cutting speed and tool life based on two constants. A more complex tool life model based on five constants was later presented by Colding 1981 [7] also including the theoretical chip thickness based on Woxen's equivalent chip thickness [8]. The Colding tool life model has proven to work well in predicting cutting data linked to tool life in turning and milling of metal-based work material [9-10].

The Taylor equation for tool life assessment on the FRP composites drilling was investigated by Merino-Pérez et. al [11]. The modelling was based on the criteria of the cutting edge flank wear. They concluded, that the Taylor model fits to the drilling process tool life prediction. The tool wear is one of the most important criteria which is correlated with the drilled holes quality, which was studied in different investigations [11-13]. The various FRP structure and composition do not allow to limit the range of the tool wear which can provide an acceptable drilled hole quality. Therefore, the tool life prediction is worthwhile to model not just according to a level of the tool wear but also the number of drilled holes with an acceptable quality. The current paper presents the modeling of the Colding model where criteria of the flank wear VB and a number of holes with an appropriate level of the quality.

The aim of this work is to compare traditional drilling of FRC using cemented carbide tools and drilling using a new tool setup based on PCD tooling. The possibility of using the Colding tool life model to model the tool performance of the two tooling concepts will also be investigated.

Nomenclature

FRP	fiber reinforcement polymer
CFRP	carbon fiber reinforcement plastic
PAN	polyacryl nitride
CC	cemented carbide
PCD	polycrystalline diamond
CE	cutting edge
CER	cutting edge radius
VB	flank wear

2. Experiments

2.1 Materials and methods

The experimental part of the current investigation included a number of CFRP drilling experiments. EMCO PC MILL 300 with a maximum rotation speed of 10000 rpm was used for drilling. Axial force and a torque measuring during drilling was done using a KISTLER 9129AA dynamometer with KISTLER 5070 amplifier and National Instrument 9223 ADC.

The experimental part of the current investigation was carried out by drilling CFRP samples from Saab AB company (Sweden). It was a modern type of PAN-type CFRP composite materials, which is used in modern Saab aircraft constructions. The structural analysis of polished CFRP sample was obtained by a microscopy using Alicona Infinite Focus 3D optical microscope. The results are shown in Fig. 1a. CFRP samples were 4 mm of thickness with $[45/90/-45/0]_{5s}$ reinforcement scheme. Each fiber ply has a thickness of 200 μm. The CFRP included 70 % of fibers,

which have a diameter of 7 μm. Samples were in the form of plates which had a size of 70x70 mm. A special workpiece holder was developed and used. It allowed to drill 26 holes in each plate without a substrate.

The drilled holes quality was evaluated according to criteria of delamination and uncut fibers. Delamination criterion *Fd* was calculated by eq. 1, [3, 11-13] (Fig.1b), which is the ratio between the maximum diameter of delamination *Dmax* and hole nominal diameter *D* in. It is an approach for evaluation the relative value of delamination. The uncut fibers criterion *Cf* was calculated by eq. 2 (Fig.1c) [11-13], where *Sf* is an area of uncut fibers. Both criteria were calculated using developed MATLAB scripts for automatic processing images of drilled holes. Images were captured using Alicona Infinite Focus 3D optical microscope.

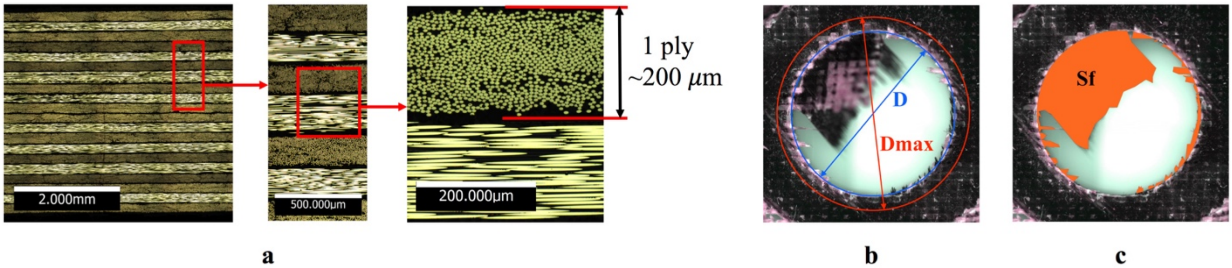

Fig. 1. (a) Structure of Saab CFRP; (b) parameters for evaluation of delamination quantity; (c) parameters for evaluation of uncut fibers quantity.

$$\mathrm{Fd} = \mathrm{Dmax}/\mathrm{D} \tag{1}$$

$$\mathrm{Cf} = 4 \cdot \mathrm{Sf}/\pi \cdot D^2 \tag{2}$$

2.2 Cutting tool and cutting data

PCD and cemented carbide drill bits were used. The PCD drill bit (Fig. 2a) [13] was developed and produced by the Institute for Superhard materials (Kiev, Ukraine). Coated cemented carbide SECO SD203A-8.0-27-8R1 drill bit (Fig. 2b) was used for reference testing. The rake and flank surfaces were grinded. Therefore, this drill bit was used as uncoated cemented carbide. The geometry was measured using Alicona Infinite Focus 3D optical microscope (Fig. 2) and a special Edge Master Module software.

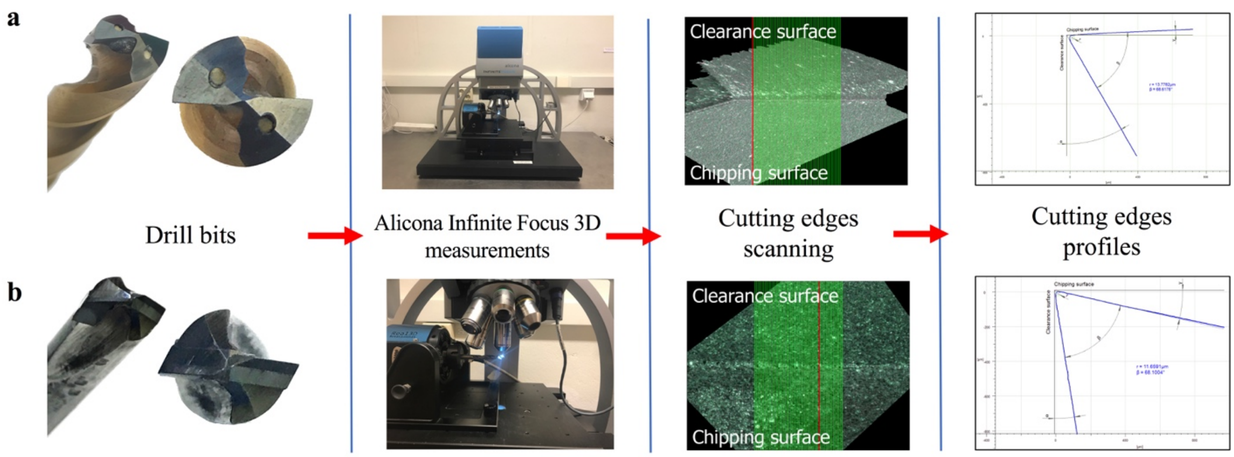

Fig. 2. Optical scanning and defining profiles of (a) SECO cemented carbide, (b) PCD drill bit main cutting edges.

The measured geometry is shown in table 1. All geometry parameters except CER of drill bits are different by less than 5%. The CER of PCD drill bit is ~10% lower than in the ground SECO drill bit. It is connected with the materials structure difference. Carbide inclusions of cemented carbide grains have a larger size than polycrystalline in the PCD. Cutting edges profiles were obtained by optical scanning (Fig. 2).

The Colding modelling require at least 5 cutting data points for high-accuracy modelling of any machining process. The FRP machining is connected with a high cutting speed and low feed rate due to high defects formation phenomena. The cutting speed from 100 to 180 m/min was used. The feed rate for cemented carbide drill bit was 0.05 to 0.15 mm/rev and from 0.02 to 0.05 mm/rev for PCD drill bit. The difference between feed rate values is caused by preliminary experiments results and reflects an acceptable cutting data range for each drill bit.

Table 1. Drill bits geometry.

Drill bit type	Diameter, mm	Angle, degree clearance	rake	point	Cutting edge radius, μm
Cemented carbide	8	20.4	2.1	120.6	13.7
PCD	8	20.6	2	120	11.6

2.3 Results of experiments

CFRP drilling is accompanied by unstable cutting conditions due to CFRP non-homogeneous structure. The fibers/matrix content in the CFRP sample is inconstant by the reason of the complicated technological process of the composites manufacturing. Therefore, the drilling process has a chaotic character and could not be fully predicted and invariable. The measured signals of axial force and torque have illustrated a variety of the current CFRP drilling (Fig.4). It is connected with the different holes quality with the identical cutting conditions. Some low-quality holes are accompanied by higher axial force and torque, but sometimes, this correlation has an opposite relation. It could be linked to changes of the tool micro- and macro-geometry, the anisotropy of the composite materials properties and structure. This subject needs further investigations, therefore, anomaly points were excluded from the modelling.

Table 2. Results of experiments.

Drill bit type	Cutting speed V_c, m/min	Feed rate F, mm/rev	Tool wear VB, µm	Holes with an appropriate quality, pcs	Engagement time, sec
CC	100	0.05	29	53	1.41
	100	0.1	46	71	0.95
	100	0.15	35	35	0.31
	140	0.1	39	78	0.74
	180	0.05	34	51	0.77
	180	0.15	32	44	0.22
PCD	100	0.02	21	135	8.99
	100	0.05	24	52	1.39
	140	0.035	22	73	1.98
	180	0.02	21	215	7.96
	180	0.05	20	68	1.01

The drilling experiments were carried out until losing acceptable quality of the drilled holes. The acceptable value of the quality was determined empirically for current types of CFRP. An example of drilled samples using CC drill bit (the cutting speed of 180 m/min, the feed of 0.05 mm/rev) is illustrated in the Fig.4. The tool wear VB of 0.92 mm was obtained after drilling 78 holes. While, the delamination criterion *Fd* was changing gradually from 1.07 to 2.4,

uncut fibers *Cf* criterion increased significantly from 0.02 to 0.98. That makes us to evaluate the total holes quality according to the uncut fibers level due to the fact, that the delamination had more stable character. As a result of this experiment, 52 holes with an appropriate quality and 34 μm of VB were received, respectively. The results of all experiments shown in the table 2 will be used in the Colding modelling in the next stage.

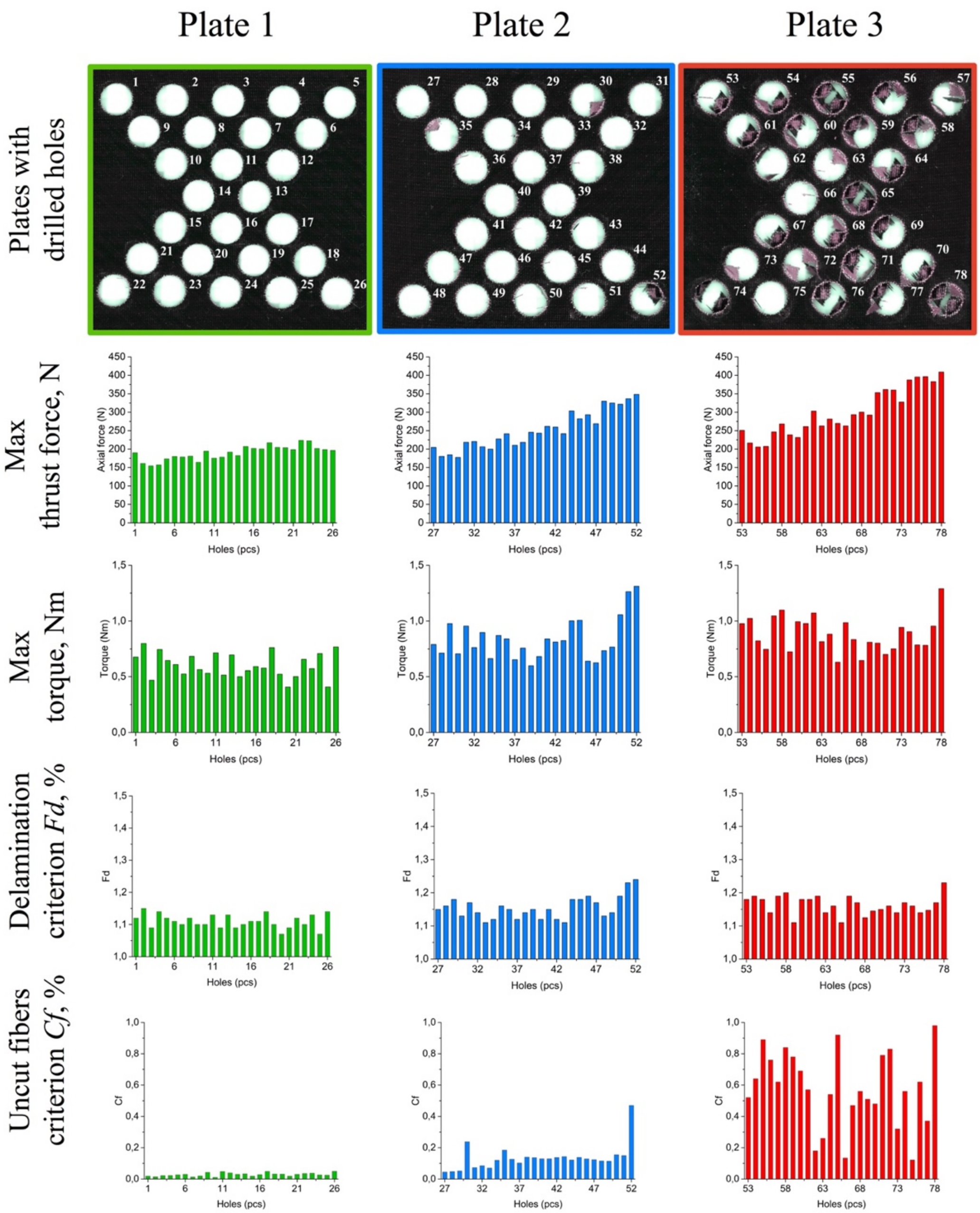

Fig. 3. Results of the drilling CFRP (cemented carbide drill bit, cutting speed 180 m/min, feed rate 0.05 mm/rev).

Colding modelling

3.1 Background

When modeling tool life a wear criterion such as a maximum flank wear VB is commonly selected. For this setup, it was not sufficient to use flank wear as the tool life criterion but rather the number of holes drilled by the tool with sufficient quality as described previously. The Colding equation is presented in equation (3) where v_c is the cutting speed, f the feed, T the total time of tool engagement and $K, H, M, N0$ and L are model constants. As the geometry of the drills were held constant, the equivalent chip thickness was not used to describe the theoretical chip thickness but rather the feed.

$$v_c = e^{\left[K - \frac{\left(ln\left(\frac{f}{2}\right) - H\right)^2}{4 \cdot M} - \left(N0 - L \cdot ln\left(\frac{f}{2}\right)\right) \cdot ln(T)\right]} \tag{3}$$

The collected data presented in table 2 was used to create the Colding models for cemented carbide and PCD using the least square method to calculate the model constants. The model liner mean error was then calculated to determent the accuracy of the model.

3.2 Results and discussion of modeling

Table 3 presents the calculated constants for the Colding models of the CC drills and the PCD drills. The mean error of the Colding model is 4.23 % for the CC drills and 17.94 % for the PCD. The error of the Colding model for the PCD drills is rather large and it appears that the Colding model is not managing to model the tool life accurately.

Table 3. Colding model parameters

Type	Colding model constants					Average
	K	H	M	N0	L	error, %
CC	5.089	-3.45	0.098	1.673	-0.157	4.23
PCD	6.867	-5.385	0.392	2.104	-0.293	17.94

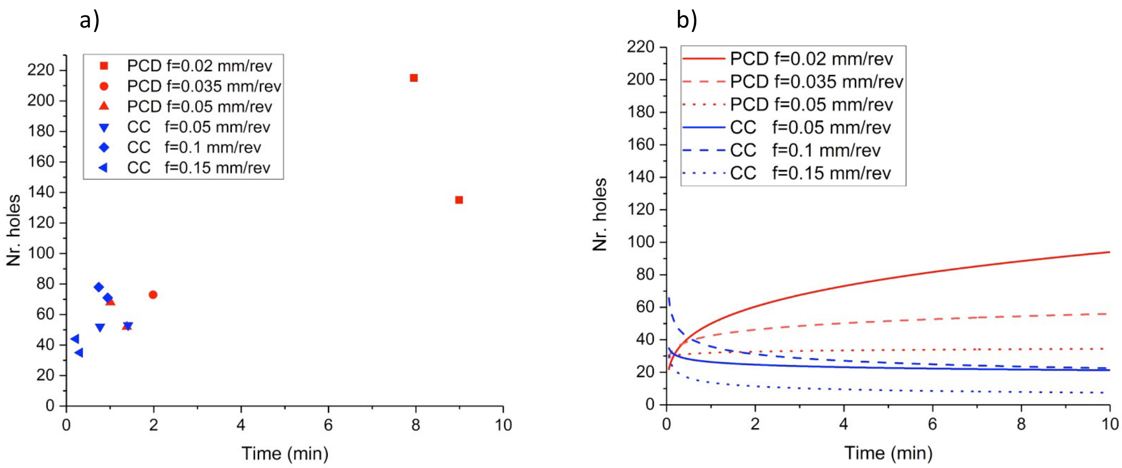

Fig. 4 a) Number of holes produced using CC or PCD drills with different feeds 4; b) the modeled number of holes produced.

Fig 4a shows the number of holes for the given tool life of the collected data. Fig 4b presents the modeled number of holes that can be produced as a function of time. The models underestimate the number of holes produced for larger tool life in PCD and underestimate the number of holes produced for low tool life in CC. It can clearly be noted, that the PCD drills can produce large number of holes within given quality when feed is reduced and longer tool life is allowed compared to the CC drills.

3. Conclusions

The current paper presents the study of drilling woven PAN-CFRP materials from Saab AB company using PCD drill bit which were developed by Institute for superhard materials of Ukraine and grinded CC drill bit which has the same geometry. The Colding model was used for tool life predicting. The average error of CC and PCD drill bits were 4.23 and 17.94 % respectively. The large error of PCD drilling could be explained by CFRP anisotropy properties which is usual for woven reinforcement materials. This phenomenon can be explained by axial force, torque and quality analysis showed anomalous data points, which prove the structure variety of used CFRP on drilling by PCD drill bit. The uncut fibers formation was more pronounced than delamination phenomenon of drilled holes. Therefore, the appropriate total drilled holes quality was mainly based on criterion of uncut fibers level, which was increasing with the tool flank wear. According to presented experimental results and modeled data, PCD drilling showed significantly higher tool life. It proves that the Colding equation can be used for tool life prediction on the drilling of woven composite materials. The accuracy of the modelling could be increased on account of implementation of criteria of the composite material structure anisotropy.

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References

[1] P.W. Beaumont, C. Soutis, A. Hodzic, The Structural Integrity of Carbon Fiber Composites (2017).
[2] D. Aleksendric, P. Carlone, Soft Computing in the Design and Manufacturing of Composite Materials: Applications to Brake Friction and Thermoset Matrix Composites, Woodhead Publishing, 2015.
[3] H. Hocheng, Machining Technology for Composite Materials: Principles and Practice, Elsevier, 2011.
[4] P.W.R. Beaumont, C. Soutis, The Structural Integrity of Carbon Fiber Composites: Fifty Years of Progress and Achievement of the Science, Development, and Applications, Springer International Publishing : Imprint: Springer, Cham, 2017.
[5] P.P. Camanho, ed., Composite Joints and Connections: Principles, Modelling and Testing, Woodhead Publ, Oxford, 2011.
[6] F.W. Taylor, On the Art of Cutting Metals: An Address Made at the Opening of the Annual Meeting in New York, December, 1900 [Ie 1906]., Amer. Soc. of Mechanical Engineers, 1907.
[7] B.N. Colding, The Machining Productivity Mountain and Its Wall of Optimum Productivity, Society of Manufacturing Engineers, 1980.
[8] R. Woxén, A Theory and an Equation for the Life of Lathe Tools..., Central tryckeriet, 1932.
[9] S. Hägglund, Methods and Models for Cutting Data Optimization, Chalmers University of Technology, 2013.
[10] D. Johansson, S. Hägglund, V. Bushlya, J.-E. Ståhl, Procedia Manufacturing 11 (2017) 602–609.
[11] A. Faraz, D. Biermann, K. Weinert, International Journal of Machine Tools and Manufacture 49 (2009) 1185–1196.
[12] J.P. Davim, P. Reis, C.C. Antonio, Composites Science and Technology 64 (2004) 289–297.
[13] S. Gaugel, P. Sripathy, A. Haeger, D. Meinhard, T. Bernthaler, F. Lissek, M. Kaufeld, V. Knoblauch, G. Schneider, Composite Structures 155 (2016) 173–183.
[14] A. Hrechuk, A. Globa, L. Devin, Bulletin of National Technical University Of Ukraine “Kyiv Polytechnic Institute” (2017) 80–85.http://dx.doi.org/10.20535/1970.54(2).2017.119556 (in Ukrainian).