THE RESEARCH OF THE POLYMER COMPOSIT MATERIALS DRILLING

Ph.D. docent Globa A., Postgraduate (P.G.) Bulakh I.
National Technical University of Ukraine «Kiev Polytechnic Institute», Kiev, Ukraine

Abstract: *The main issues which are investigated in this article: investigation of the process of holes machining in polymer composite materials (PCM); obtaining dependency between surface quality and the tool's geometry and material type during the drilling by the spiral drill with two and three cutting edges, step drills the carbon fiber, glass and material Twintex; obtaining mathematical models of the drilling process by the GMDH method.*

Keywords: *polymer composite, The drill with three cutting edges, step drills, hole quality, tool wear, the mathematical model.*

1. Introduction

With the modern development of manufacture it is of current interest to provide holes of high quality in polymer composite materials (PCM) for the reliability of fastening. PCM are extensively used in a variety of industries, and mostly - in the aircraft industry. Quality of the holes depends on quality of the tool and cutting conditions. Tool wears more rapidly during the PCM processing, than during processing of homogeneous materials, because PCM possess the high anisotropy and abrasive capacity. During processing there are the temperature and force interaction of the instrument with the cutting chip and the surface, leading to tool wear. Besides for new types of PCM, which are constantly being created, existing constructions of drills may not meet necessary quality and accuracy. The important task is to ensure high tool durability and high holes quality. So, it is important to predict the cutting process after modifying drill construction or the treatment process.

The aim of this work is to study dependency between tool wear magnitude, holes quality and instrument geometry; and to construct mathematical models of the cutting process. In particular, for critical axial force calculation, which eliminates the material delamination. To do the comparative analysis of drills with two and three cutting edges, two-step drills, and drills for processing of PCM with use of tool oscillating motion.

Results of the experiments will help optimizing design of the drill, increasing its durability and holes quality, as well as predicting the cutting process. Use of oscillating motion will prevent inter-layer delamination of material. It is inevitable when drilling occurs in one direction.

2.1. Preconditions and means for resolving the problem

Among the 100% of all delamination defects which arise during PCM drilling 70-80% is a delamination at the exit of drill, the others – is a exfoliation at the entrance of drill. During PCM drilling, layers which fall on the cutting edge of the tool are amenable to local bending deformation, which leads to delamination of material.

The delamination requires a small axial load and occurs with a decrease in the layer of uncut material. This process needs the mathematical description for the design and control.

PCM exfoliation model is presented on Figure 1, where cylinder that acts as a drill is shown: D – drill diameter, F - axial force, x - tool displacement, H - processed material thickness, h - thickness of the material is not cut off with tool, a - acceptable size of the crack.

During the drill movement uncut material layer deforms under the influence of axial force. If tension at the end of existing crack exceeds critical value, material delamination leading to crack occurrence will occur.

$$2G\left(a + \frac{D}{2}\right)da = Fdx - dU, \quad (1)$$

Formula 1 shows the energy balance in mechanical fracture [1].

There G - power indicator on the unit area, U - stored strain energy.

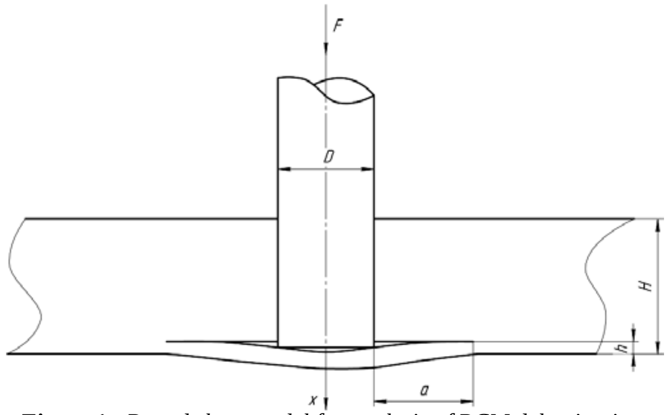

***Figure 1** - Round sheet model for analysis of PCM delamination during drilling*

$$U = \frac{8Mx^2}{\left(a + \frac{D}{2}\right)^2}, \quad (2)$$

Where x - drill displacement, measured from the start position of the exfoliation, M - elastic stiffness of the plate under the drill.

$$M = \frac{Eh^3}{12(1-\mu^2)}, \quad (3)$$

Where E - elastic modulus, μ - Poisson's ratio.

The displacement x is expressed as follows:

$$x = \frac{F\left(a + \frac{D}{2}\right)^2}{16M}, \quad (4)$$

As a result of mathematical transformations, the expression for critical force, at which crack propagation starts, becomes:

$$F_{кр}(h) = \sqrt{32MG_{1c}},$$

$$F_{кр}(h) = \sqrt{\frac{8G_{1c}Eh^3}{3(1-\mu^2)}}, \quad (5)$$

To avoid exfoliation, the axial force must not exceed this value. The maximum axial force depends on the thickness h of undrilled material and material characteristics; and is proportional to $h^{3/2}$.

Ration between critical thrashing force F_c at the axial direction and maximum cutting force F_p is the following:

$$k_з = \frac{F_з}{F_p}, \quad (6)$$

Where k_c - thrashing factor, defined by angle of drill helical groove and coefficient of friction between tool and work surface.

After replacement of F_{kr} with F_p, and of h with $h_d = H - h$, the expression for the critical axial force will look so:

$$F_{кр}(h) = \sqrt{\frac{8G_{1c}E(H-h)^3}{3(1-\mu^2)}}, \quad (7)$$

Expression (7) can be used as a more rational solution for drilling without material exfoliation.

Mathematical model for the step drill.

Figure 2 shows diagram of the material load during processing with step drill. [2] The expression for calculation of critical force of the exfoliation is:

$$F_T = \frac{\sqrt{2}\pi}{1-\upsilon}\left[\frac{32 G_{IC} M \left\{(1-\upsilon)+2(1+\upsilon)\xi^2\right\}^2}{(1+\upsilon)\left\{2(1-\upsilon)(1+2\upsilon^2)-(12-4\upsilon+3\upsilon^2+3\upsilon^3)\xi^2-8(1+3\upsilon)\xi^2\ln\xi\right\}}\right]^{1/2}$$

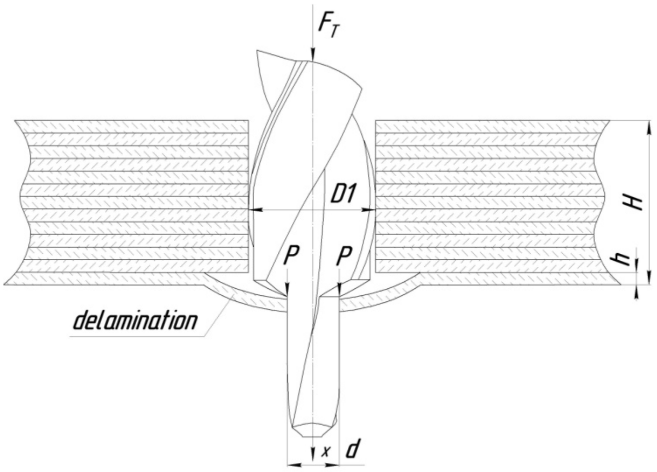

Figure 2 *– The scheme of material loading with wide stage of drill*

Here E - Young's modulus, KI - intensity of the load index, v - Poisson's ratio, h - thickness of the material, G_{IC} - strain energy release rate in the normal separation, $M = D$ bending stiffness, $\xi = d/D_1$ - ratio of step drill diameters.

2.2. Results and Discussion

Studies of PCM processing with frills of different constructions, such as spiral drills with two and three cutting edges, two-step, and drill of a special design using oscillating motion were conducted.

Fiberglass, carbon fiber (cross-reinforced by organic net) and material Twintex were used as processing materials. The drills with two cutting edges (Fig. 4,b) have been developed using Stepanov A. and others recommendations. Designs of the three cutting edges (Fig. 4c) and two-step (Fig. 5b) drills were developed at the Department of ITM in NTU "KPI". [2] Step drill design was developed following Tsao methodology [4].

Drills samples were taken with different double major angle in the plan, for the two-step drills - with different angle 2φ of the second stage of the drill. Tools Material - R6M5 to study wear patterns in a relatively small set of experiments.

Experiment was analyzed determining and comparing the magnitude and rate of tools wear, the processing time and holes quality (roughness and deviation from roundness) [5]. Magnitude and speed of tool wear were determined by recording and computer processing of vibro-acoustic signal. The signal, picked up by the sensor, was passed through the amplifier and analog-to-digital converter and then was fed to PC for processing with Cool Edit Pro2.

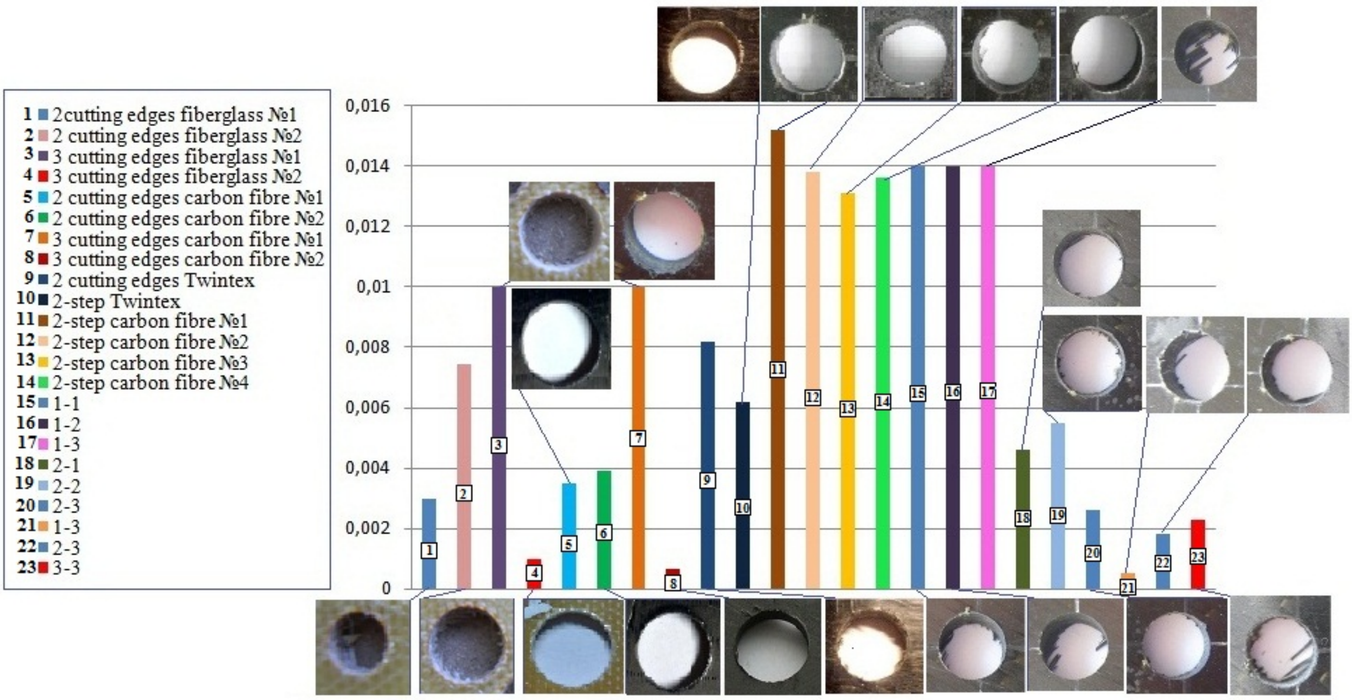

Figure 3 *– The diagram of tool wear and drilled hole types*

Then, with the help of a special program magnitude and rate of tools wear were calculated. This program had been developed by V. Kokarovtsev [3] for studying metal processing and was adapted for the PCM needs by the authors.

During drilling with two-step tool, drills with 2φ angles of wide steps 110º, 120º, 130º and 140º (further, 1, 2, 3 and 4, respectively) were taken. During processing using drill with oscillating motion (Fig. 5c), drills with 2φ angle of wide steps 110 º, 120 º, 130 º and 140 º (then 1, 2 and 3 respectively) were taken.

The drilling was held in 3 modes: 1 - without oscillating motion with a spindle rotation frequency of 480 r/min; 2 - using oscillating motion with spindle rotation frequency of 480 r/min; 3 - using oscillating motion with spindle rotation frequency of 880 r/min. Oscillating motion frequency of drill varied in accordance with rotation frequency of the machine spindle. [8]

After conducted study of fiberglass and carbon fiber processing with the drills having two and three cutting edges, it turned out that wear rate of the cutting edges for 3-cutting edges drills is much lower than in the case of 2-cutting edges drill.

The smallest deviation from circularity of processed holes is obtained when drilling with 3-cutting edges drills. The 3-cutting edges drill with split point №2 showed especially high accuracy of holes for carbon fibre. In case of fiberglass processing, it was the 3-cutting edges drill with a split point №1.

It should be emphasized, that the deviation from circularity of processed holes, in the case of 3-cutting edges drill is 2,5 times less than in the case of 2-cutting edges drill which is standard for the PCM. The surface roughness of the processed holes for 3-cutting edges drills at 2.5 half as much than for 2-cutting edges drills. Figure 3 shows diagram of tools wear magnitude and types of produced holes. Figures 4 and 5 show the cyclograms with tools parameters. The results presented in such form, allow determining the optimal construction of a tool for PCM processing. In the cyclograms the magnitude and rate of tools wear, holes deviation from circularity, roughness of holes surface, processing time, maximum number of drilled holes, which are possible for the tools of such geometry, were considered.

Another important parameter is cauterization around the hole, but this defect is unacceptable and leads to the fact that the resulting hole is no longer suitable for use. Therefore cyclograms do not represent this type of defect. Drilling was performed using cutting tool construction and cutting modes preventing cauterization.

Taking into account high cost of the tool, mathematical simulation of the cutting process to predict results of processing, with changing number of process parameters and tools geometry, is important.

Based on results of drilling by the two-step drills, mathematical model using single-factor experiments in a form of function $h = C \cdot N^Y$, were obtained. Here h - tool wear magnitude, N – the number of holes, C and Y - unknown constant coefficient and exponent.

The following empirical dependencies for tools with different construction (Table 1) were obtained.

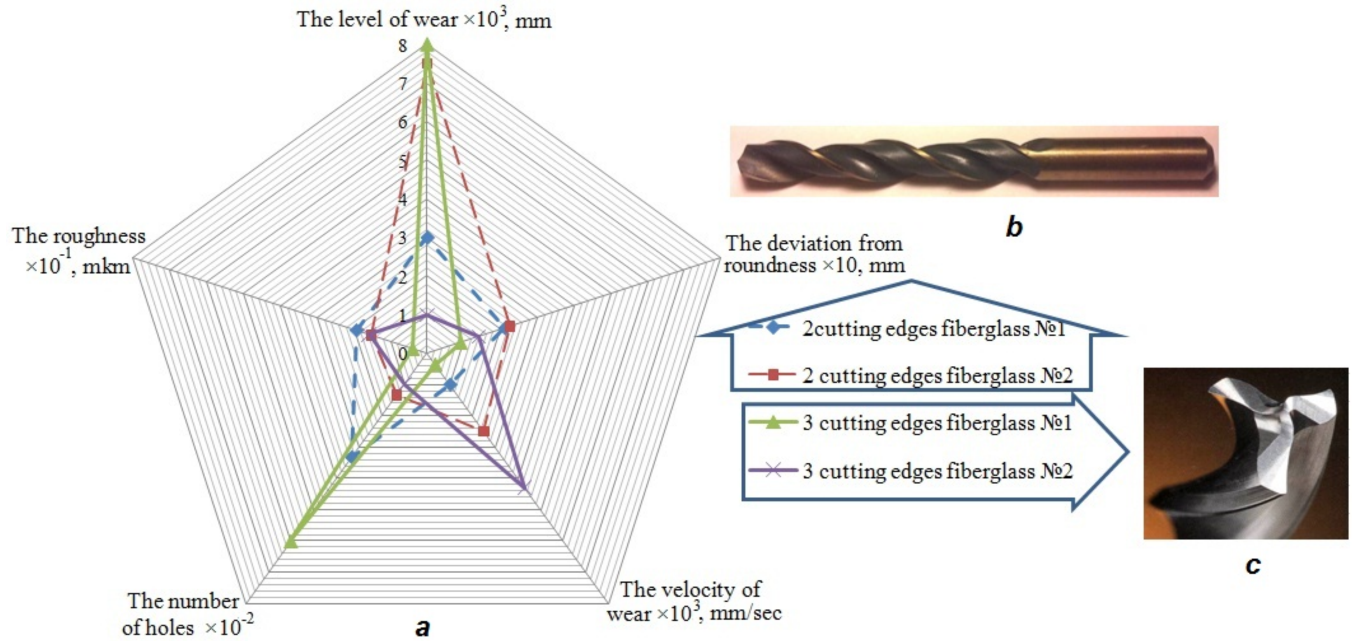

Figure 4 *- The cyclogram of fiberglass processing with instrument of a different construction*

Table 1 - Obtained empirical dependency and model error

Tool number	Resulting model	Model error (%)
1	$h = 0{,}013553 \cdot N^{0{,}077272}$	7,098
2	$h = 0{,}013531 \cdot N^{0{,}013344}$	1,186
3	$h = 0{,}011005 \cdot N^{0{,}115064}$	1,203
4	$h = 0{,}012684 \cdot N^{0{,}049943}$	0,812

Such model is uninformative because it takes into account only one process parameter, also way to obtain such model does not take into account the physics of the process.

Mathematical models were derived using different methods, and based on the analysis it was concluded that the group method of data handling (GMDH) is the best optimal method of forecasting in cutting. GMDH method - is one of the most effective methods of structural-parametric identification of complex objects, processes and systems based on experiments and observations. The less informative data entered, the harsher the mathematical model is. Important feature of this method is the ability to produce different types of mathematical models with the same input parameters of the process. The essence of the method is to build several models and choose optimal among them for minimizing the optimality condition parameter (for example, the model error).

Possibility of using GMDH method for materials processing has been proven in studies by prof. Ravska N., prof. Ostafjev V., prof. Lupkin B., Kykot V., Globa A. [6, 7], and others. Experiments for use of GMDH method in machining different kinds of materials showed high precision and accuracy of the mathematical models obtained by this method.

For two-step drill the following mathematical model based on one parameter of the process was obtained:

$$h = 4{,}6 \cdot 10^{-3} \cdot N + (-0.000{,}33 \cdot 10^{-3}) \cdot N^2$$

Where N - number of holes, h - the tool wear.

Correction factors of mathematical model:

The correction factor for the number of holes - 0,004624

The correction factor for model performance – 0,029417

Correction factor for depreciation (constant term) - 0,01313.

During study of drilling with use of tool for PCM processing using tool oscillating movement, the objective was to obtain the mathematical model which considers several parameters of the process to improve result prediction accuracy. [8].

Resulting mathematical model of tool wear magnitude:

$$\boldsymbol{h} = 0{,}4244 \cdot (3{,}410^{-3} + 1{,}00308 \cdot (\boldsymbol{L}^* 0{,}1 \cdot 10^{-3} -$$
$$- \boldsymbol{t}^* 0{,}4 \cdot 10^{-3}) + 1{,}306 \cdot (9{,}8 \cdot 10^{-3} - \boldsymbol{k}^* 9{,}72 \cdot 10^{-3}) + 0{,}7076 \cdot (21{,}04 \cdot 10^{-3} -$$
$$- \boldsymbol{n}^* 1{,}2 \cdot 10^{-5} - \boldsymbol{f}^* 7{,}564 \cdot 10^{-5})) + 0{,}577 \cdot ((4{,}4210^{-3} -$$
$$- \boldsymbol{t}^* 0{,}571 \cdot 10^{-3} + 1{,}015 \cdot (13{,}9 \cdot 10^{-3} - \boldsymbol{k}^* 10{,}1 \cdot 10^{-3})^* 1{,}357 \cdot ((4{,}78 \cdot 10^{-3} -$$
$$- \boldsymbol{t}^* 0{,}62 \cdot 10^{-3} - 0{,}3711) + 1{,}29 \cdot (\boldsymbol{L}^* 9{,}95 \cdot 10^{-5} - 4{,}66 \cdot 10^{-3}) + 1{,}01^*$$
$$^*(17{,}7 \cdot 10^{-3} - \boldsymbol{n}^* 0{,}76 \cdot 10^{-5} - \boldsymbol{k}^* 9{,}7 \cdot 10^{-3}))$$

Where L – distance covered by the drill;

t – drilling time;

k - factor, which indicates the presence (1) or absence (0) of the oscillating movement of the tool;

n – spindle rotation frequency;

f - the double main angle of drill;

h - tool wear magnitude;

Coefficient of resulting model disability: $k^* = 0{,}086944$

Conclusion

In this paper the results of several studies on the processing of PCM (fiberglass, carbon fiber, Twintex) by the instrument with a different construction (spiral drills with two and three cutting edges, two-step drill, special drill for PCM with using the oscillating motion) are presented. Tool's wear magnitude was determined by analyzing the vibro-acoustic signal during the drilling process. Also quality and accuracy of the holes were determined. Mathematical modeling was performed using group method of data handling (GMDH) to be able to predict the cutting process by changing some parameters. It has been shown that for the two-step drill the tool with 2φ = 130° is optimal, for 3-cutting edges drill optimum angle is 2φ = 120°, for 2-cutting edges drill - 110°, for the tool with oscillating motion - 120° at a rotational frequency of spindle 480 r/min. Comparing to 3-cutting edges drill, temperature of the two-step drill decreased by 10%, for drill using oscillating movement - by 8%. Additional sharpening based on material type is important parameters for 3-cutting edge drills. Perspective research direction is addition of cutting temperature to the model and optimization of tool geometrical parameters depending on the type of material.

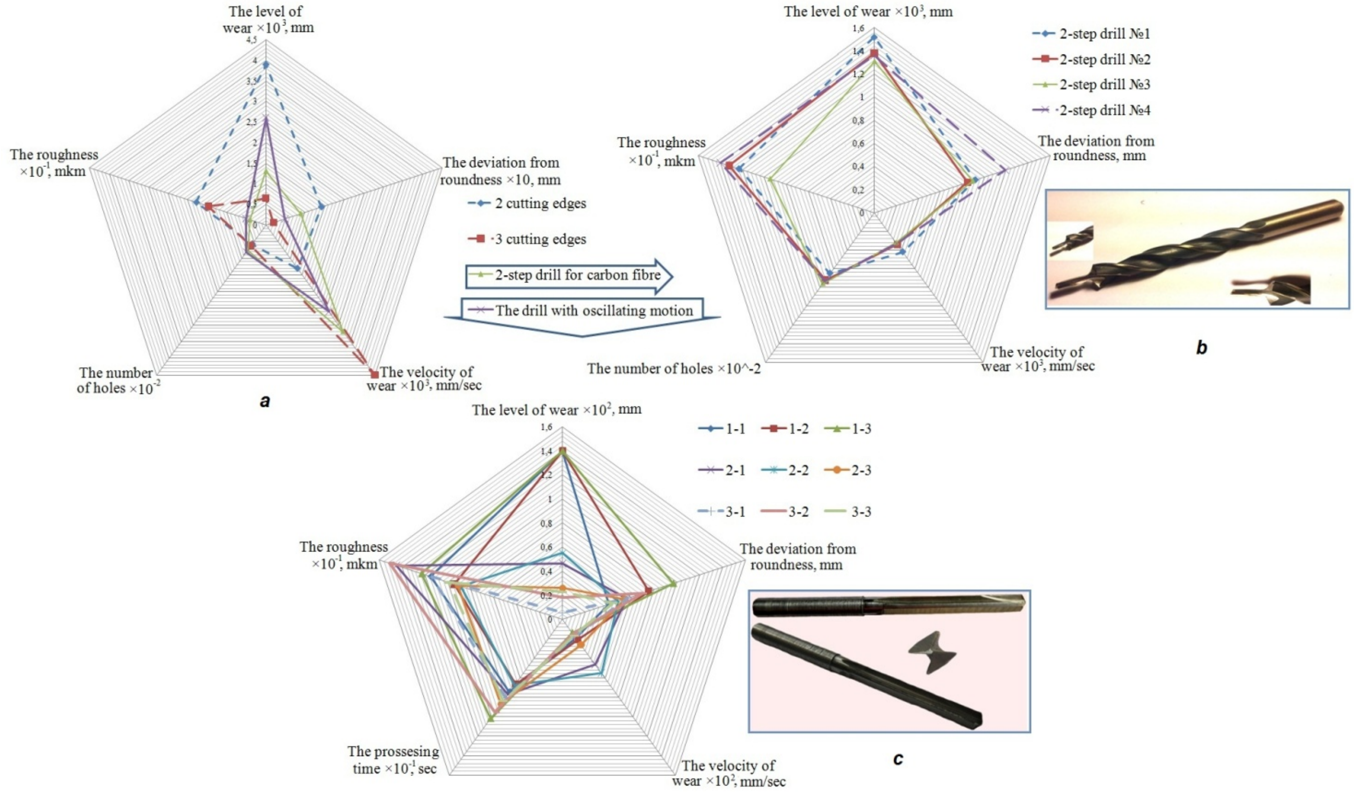

***Figure 5** – cyclograms for processing the carbon fiber with tools of different design*

Literature

1. Ozaki, M. Supervisory Control of Drilling of Composite Materials, Berkeley: University of California, 2000, P. 74.
2. 2. Globa A.V. Analytical calculation the critical efforts of delamination during processing of composites by step drills and determination of the optimal step value - Collection of science papers “Reliability of the tool and optimization of technological systems” - Kramatorsk, №28, 2011. – P. 51-54 (O.V. Globa, O.V. Kuhanovskiy)
3. Kokarovtsev V.V. The monitoring methods of quality and process of metal machining based on vibro-acoustic signal - dissertation for the degree of candidate of technical sciences: 05.03.01, - Kiev, 1994, 139 p.
4. C.C. Tsao Influence of Geometry in Drilling Carbon Fiber Reinforced Plastics / C.C. Tsao // - Advanced in machining and Manufacturing Technology IX, - Swizerland, 2008. – P. 236-240.
5. Globa A.V. The influence of drill geometry on its stability and accuracy of drilling holes in composite materials - Technical modernization of aircraft production - the key to success in the markets of aircraft: Mater. of the second Technical conference of the Ukrainian branch SAMPE - 2012, Kyiv, AO UkrNIIAT, November 15, 2012 - Kyiv, 2013. - S. 23 - 29. (A.V. Globa, I.A. Bulakh, S.N. Mylokost).
6. Ostafjev V.A. Identification of regulatory relations for purposes of the cutting on the basis of advanced production experience - Machines and tools, № 2, 1987 p., P. 20 - 21. (Ostafjev V.A., Globa L.S.).
7. Lupkin B.V. The methods of experimental data processing - Dep. VIMI NDO 7411 of 04.13.88, 1988 (Lupkin B.V., Kykot V.S.).
8. Globa A.V. Investigation of the drilling PCM quality with using an oscillating motion of the tool, - Collection of science papers “Reliability of the tool and optimization of technological systems” - Kramatorsk, №32, 2013 – P. 56-62. (A.V. Globa, I.A. Bulakh, S.N. Mylokost).