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Methodology development for cutting force components determination for aerospace materials milling

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Abstract: The purpose of this paper is to develop a method to determine cutting force components for milling tough materials in different cutting conditions: VT23 titanium grade, 40HN2MA (4340 US Grade) and V95 of high tough aluminium grade. The basis of the method is calculation of the exponential function based on determination of instantaneous values of chip thickness depending on the angle position of the cutting edge. Several tests are used for determination of experimental cutting force for the milling process with tungsten carbide inserts of various geometry in different cutting conditions using industrial equipment, instruments and tooling. The method shows a good convergence with experimental data. It provides an accurate description of cutting force which is enough to determine some phenomenon of cutting force dynamics for these materials. Phenomena of F_x cutting force delay for milling of titanium grade are presented as an example. The nature of the cutting force component delay during the run-off from the single cut may be a case of future study.

1. Introduction

Milling at machining centers and other high-performance equipment with high productive cutting parameters are the most widely used methods of part production. Cutting force is a key factor for the surface quality, physicomechanical properties of the surface layers and the tolerances of part shape. The tendency towards toughening the work characteristics and new types of structural materials makes predicting the cutting process force parameters an important task. Therefore, the determination of the cutting force components is an important scientific task.

Currently, the issues of determining cutting force are most fully developed for steels turning and planning processes. Determination of cutting force during milling for hard-to-machine materials, stainless steels, Inconel and titanium alloys is less studied.

The purpose of this work is to develop a technique that combines the classical ideas about the cutting forces and modern software and hardware system for analyzing machining processes that is sufficient to determine key features of the force pattern for cutting in different machining conditions.

In the work [1] the authors developed expressions for the calculation of cutting forces during milling with the influence of the coating of the cutting tool on the formation of the cutting force characteristics of the process. The concept considered by the authors implies using a set of complexes for calculations. The calculation is presented for the 40X13 steel grade. It is necessary to determine a large number of complexes of empirical coefficients to implement this concept of calculations of cutting force for difficult-to-cut materials.

A. A. Gubanova and D. R. Khrapenko authors in [2] show a different concept, which consists of conventional methods with force exponential function dependencies and determining the instantaneous values of chip thickness in dependence on the angle of the tool cutting edge position. That conception is more promising in relation to this article.

O. Balla in his work [3] shows the method of semi-natural modeling of cutting forces during milling, including the case of one-time operation of several teeth of the mill. The machining of the VT20 titanium alloy with various types of cutting instruments is investigated using different experimental results. The author proposes to calculate particular dependences of the cutting force on the chip thickness and the width of cut.

The authors from the University of Laos in their article [4] offer a comprehensive analysis of the instantaneous values of cutting forces by splitting into elementary components and the subsequent reduction of expressions for the F_x, F_y, F_z component of cutting forces. The shapes of the graphs of components of the cutting forces correspond to the obtained data as described, for example, in [5] (figure 1).

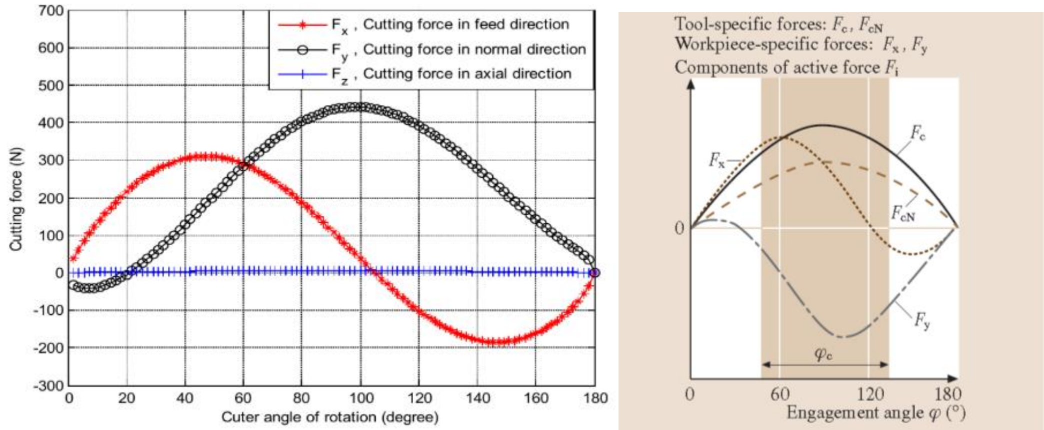

Figure 1. Cutting force vector projections regarding [2] and a similar diagram according to [5].

2. Materials and methods

A series of experiments have carried out to determine cutting force components for the milling of various materials. Experimental studies take place at the engineering centre of SKIF-M LLC.

The HaasVF-2SS machining centre is used as the main machining equipment. Measurements of the cutting force components are investigated using a multicomponent piezoelectric dynamometer based on the KISTLER 9255C plate.

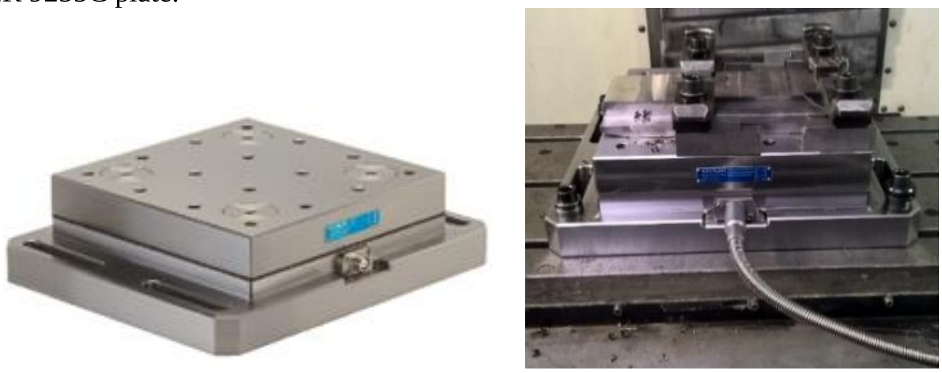

Figure 2. Experimental setup.

Face and end mills with inserts manufactured by SKIF-M LLC are used as a cutting tool for the experiments. Cutting force measurements are made under various process conditions. The cutting

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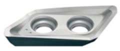
conditions are the same as those for operability test of the assembled tool in accordance with the standards of the SKIF-M LLC engineering centre. Cutting parameters are presented in table 1.

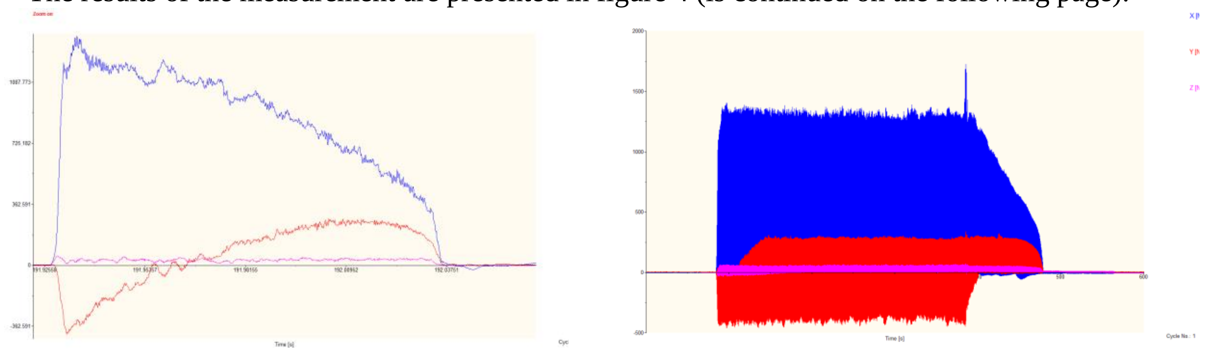
Table 1. Cutting data for the experiments

No	Material	Diameter, mm	Lead angle,	a_p, mm	a_e, mm	V_c, m/min	F_z, mm	Insert shape
1	VT23	50	90	4	16	24	0.1	SOMT120408 
2	VT23	50	90	4	6	24	0.1	SOMT120408 
3	40HN2MA	40	90	2	30	120	0.15	SDMT08T308 
4	VT23	25	00 (round)	2	8	35	0.125	RDNT0802EN 
5	V95	40	90	5	15	250	0.08	XDGX170524 

The DynaWare software is used in the course of experiments for cutting force registration. The orientation of cutting force is accepted according to figure 4. All of three cutting force components are simultaneously recorded during the cutting process for each test in the form of graphs. Passes along the Y-axis are made in each experiment (the direction is considered as positive on the coordinate axis).

Figure 3. System axis orientation.

The results of the measurement are presented in figure 4 (is continued on the following page).



(a) (b)

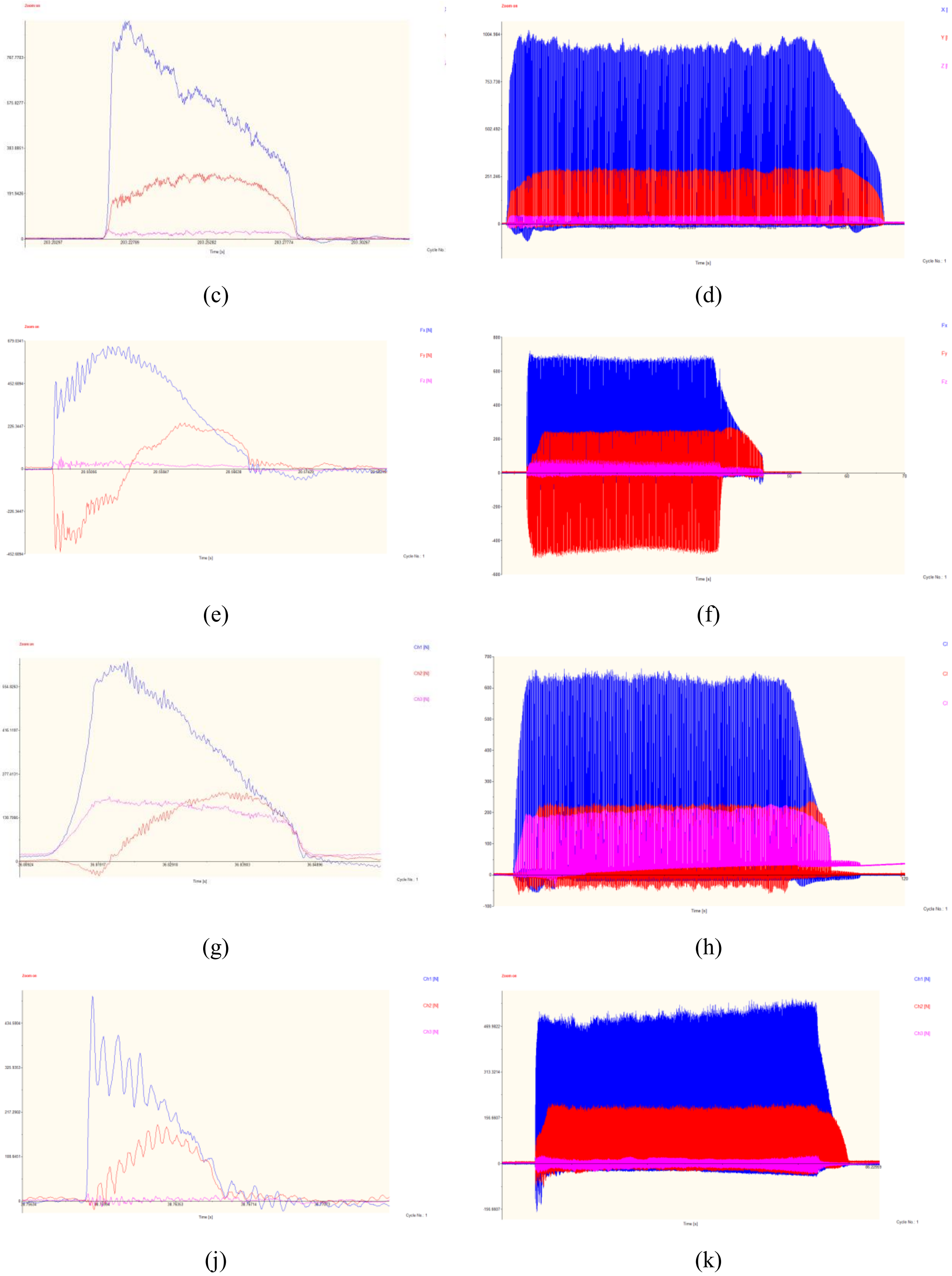
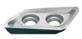


Figure 4. Cutting force measurement results: on the a, c, e, g, j – single cut; on the b, d, f, h, k – cutting force data during the whole stroke. The data for experiments: No 1 - a, b; No 2 - c, d; No 3 - e, f; No 4 -g, h; No 5 -j, k.

3. Results and discussion.

Let us summarize the obtained information in table 2 with the averaged values of the mean loads of the cutting force components. All the data are shown in dependence on the insert shape and key cutting parameters.

Table 2. Cutting forces proportion in accordance with the insert shape

No	Insert shape	a_p	a_e	F_x	F_y	F_z	$F_x/F_y/F_z$
1		4	16	1350	360	60	1:0.266:0.044
2		4	6	900	255	40	1:0.283:0.044
3		2	30	680	450	10	1:0.662:0.015
4		2	8	600	200	180	1:0.333:0.300
5		5	15	480	170	10	1:0.354:0.020

3.1. Data analysis

Experiment No 1 aims to evaluate the key features of the cutting force components for milling difficult-to-cut materials.

The formula (1) that is shown in [6] is used for determining the main component of the cutting force P_z:

$$P = C\,B^{\omega} Z S_z^{\,y} t^{x} D^{u} V^{n} K. \tag{1}$$

Let us reduce that dependence to the following form:

$$P_z = C_p S_{zm}^{k} t^{\mu} \tag{2}$$

$$P_r = 0{,}7 P_z \tag{3}$$

where C_p is the coefficient depending on the machining conditions, S_{zm} is the instantaneous thickness of the chip, $t = a_p$ is the cutting depth, k and μ are empirical coefficients, P_r is the component of the cutting force that is normal to the direction of the main cutting edge.

Let's make the calculation according to the principle similar to that used in [2] to determine instantaneous values of S_{zm}. We will use the trochoids construction instead of using two circles with the f_z distance between the centers. For cross section determination, we will use the instantaneous center of rotation determination for each angle position of the cutting edge during the moving in the material.

The trochoid shape of the cutting edge path is presented in figure 5.

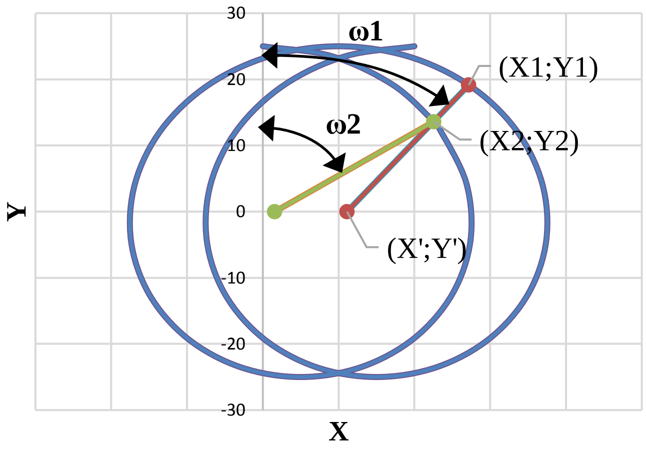


Figure 5. Trajectory of cutting edge.

We construct a trochoid according to the following system of equations:

$$\begin{cases} X=\frac{D}{2}sin(\omega)+\frac{\omega}{360}f_z; \\ Y=\frac{D}{2}cos(\omega)\,; \\ \omega\in[0..720] \end{cases} \tag{4}$$

where ω is the angle of the cutting edge position in degrees, plotted from the Y axis; *D* is the diameter of the cutter; f_z is the feed per tooth; *X, Y* - coordinates of trochoid points.

The task of determining the instantaneous section of the cut layer in the main cutting plane is reduced to determining the length of the segment *(X1; Y1) - (X2; Y2)* obtained by crossing the line at the inclination angle *ω* corresponding to the point X1; Y1 with the previous turn trochoid (figure 5).

The expression for finding the point X1, Y1 is:

$$\begin{cases} X1=\frac{D}{2}sin\,(\omega 1)+\frac{\omega 1}{360}fz, \\ Y1=\frac{D}{2}sin(\omega 1)\,, \\ \omega 1\in[360..720]. \end{cases} \tag{5}$$

Point *X2*; *Y2* is located at the intersection of the trochoid and the straight line of the form (a straight line at an angle *ω* corresponding to the point (*X1; Y1*):

$$\frac{X2\text{-}X'}{X1\text{-}X'}=\frac{Y2\text{-}Y'}{Y1\text{-}Y'} \tag{6}$$

where *X'* and *Y'* are the instant center point for the trochoid point (*X1; Y1*).

The expression for finding the *X2, Y2* point as for the trochoid point is:

$$\begin{cases} X2=\frac{D}{2}sin\,(\omega 2)+\frac{\omega 2}{360}fz, \\ Y2=\frac{D}{2}sin(\omega 2)\,, \\ \omega 2\in[0..360]. \end{cases} \tag{7}$$

We get the following system of equations after combining equations 5-7 into a system of equations and expressing *X2* and *Y2* from it:

$$\begin{cases} Y2=\frac{X2\text{-}\omega 1\cdot fZ}{ctg(\omega 1)}, \\ X2=\sqrt{\frac{D^2}{4}\text{-}Y2^2}+acos(\frac{2Y2}{360}. \end{cases} \tag{8}$$

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We use the graph-analytical method to find the points *(X1; Y1)* and *(X1; Y1)* for the corresponding values of ω.

Obviously, it is possible to use an analytical method for determining instant chip thickness values for calculating limiting values of the angles ω_1 and ω_2 by finding self-intersection points of trochoid. But this would be just an optimization of the calculation. However, this will not change in the basic concept of study. The main subject of this article is to check the adequacy of this method that does not depend on calculation methods.

To determine C_p, k, μ coefficients, let us analyze the cutting force data obtained from different points of the single cut graph shown in figure 6.

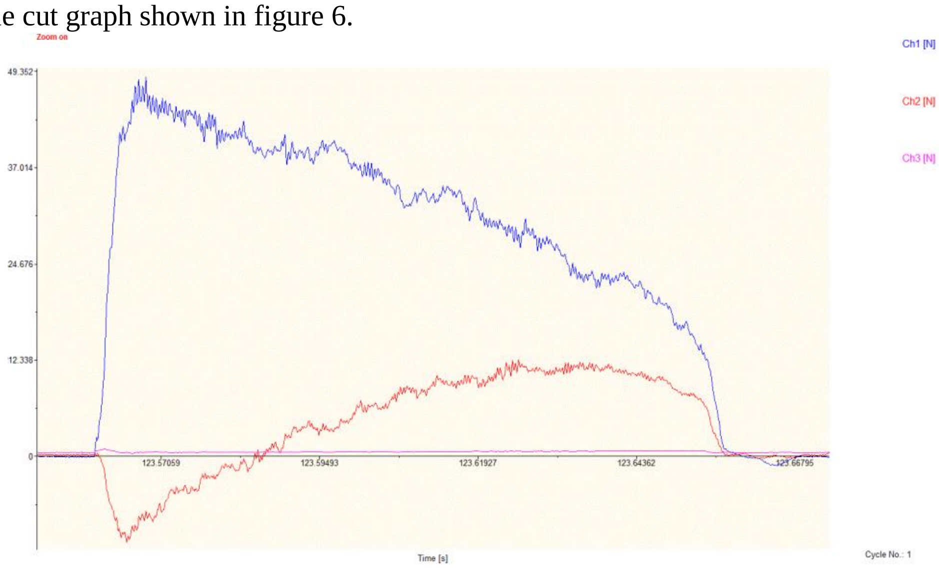

Figure 6. Cutting forces applied to the stock (Ch1 – *Fx*, Ch2-F_y, Ch3-F_z).

We use the directions of the components of the vector of total cutting force shown in figure 7 to recalculate values to P_z and P_r from F_x and F_y.

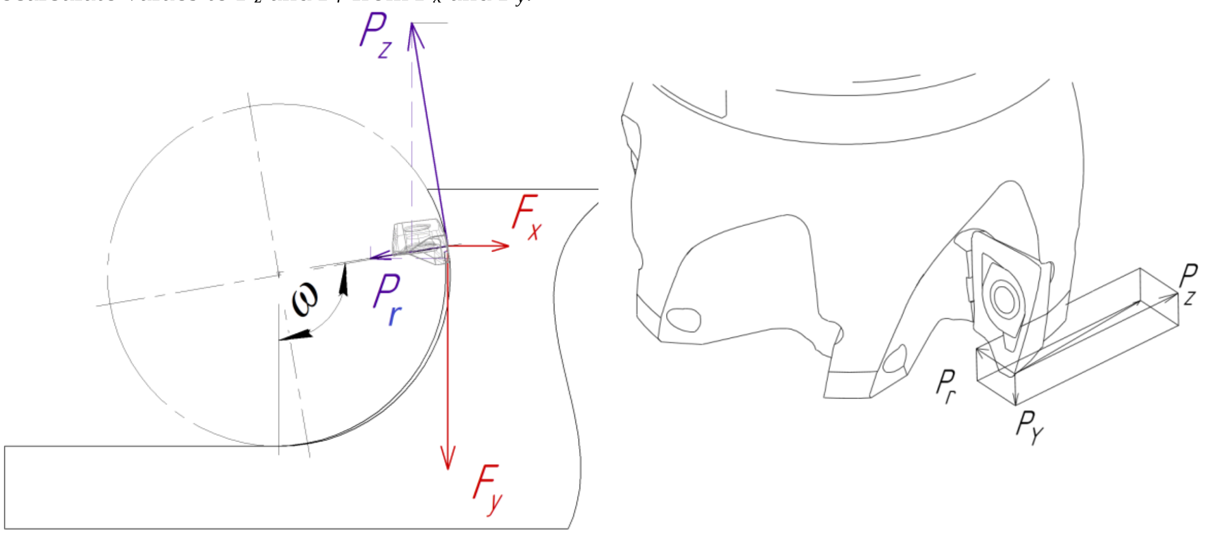

Figure 7. Orientation of accepted cutting force vectors.

The recalculation formulas are:

$$P_r = F_x cos(\omega) + F_y sin(\omega)$$

$$P_z = -F_y cos(\omega) - F_x sin(\omega) \quad (9)$$

$$F_x = P_r cos(\omega) + P_z sin(\omega)$$

$$F_y = P_z cos(\omega) - P_r sin(\omega).$$

The following values of the coefficients obtained by the enumeration method: C_p =1150, k=0.2, μ=-0.07

We will perform the calculation for the position angle of the cutting edge and S_{zm}. The resulting data reduced to the form of previously constructed table 3. We select the position angle in the range from 70° (which corresponds to the contact angle of the tool) to 0°.

Table 3. Instantaneous values of calculated cutting force

ω, °	S_{zm}, mm	P_z, N	P_r, N	F_x, N	F_y, N	F_x meas., N	F_y meas., N
70	0.075204	639.5799	447.7059	754.1329	–201.957	783.966	–141.815
60	0.069332	599.3065	419.5146	728.772	–63.657	706.238	–22.6135
50	0.061357	543.4922	380.4445	660.8842	57.91263	676.3	64.9109
40	0.051518	472.5734	330.8013	557.1728	149.3772	602.509	119.934
30	0.040114	386.8466	270.7926	427.9366	199.6227	542.816	174.957
20	0.027488	285.9016	200.1311	285.8458	200.2107	469.116	196.93
10	0.014023	166.8687	116.8081	144.0099	144.05	386.444	178.619
0	0	0	0	0	0	22.7051	10.2539

The graph obtained by combining the graphs of calculated cutting forces and actual experimental data are presented in figure 8.

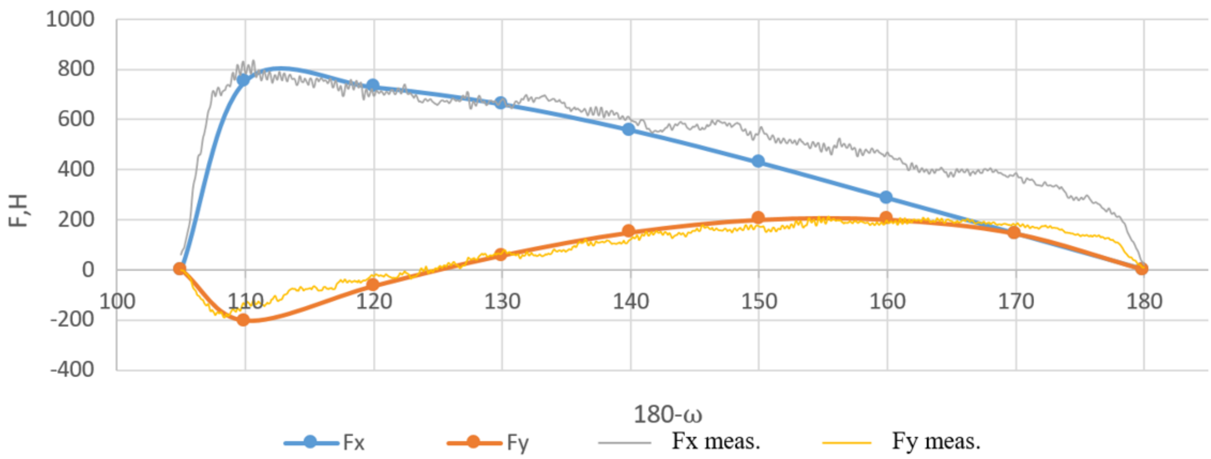

Figure 8. Calculated cutting force data combined with results of cutting force measurement.

We can see significant differences between the actual values of the forces acting on the work piece obtained in the experiment, and the values obtained by calculations for this processed material. There is a significant delay of the F_y measured value from the calculated value. This is true for any values of Cp, k, and μ. Current effect appears in the relief area of cutting forces (the area of disengagement). To determine the nature of this phenomenon, we make a similar calculation for experiment No 3 that is presented in table 4.

Table 4. Cutting data for experiment No 4

Workpiece material	Cooling	Tool dia., mm	Lead angle, °	a_p, mm	a_e, mm	V_c, m/min	F_z, mm
Forged 40XH2MA GOST 8479-70	Without cooling fluid	40	90	2	30	120	0.15

We obtain the following values of the coefficients: C_p = 1320, k=0.2, μ=-0.05, P_r=0.3P_z

The angle of introduction of the cutting edge for this test is 120°. We also combine the data obtained by calculation and the actual data in one graph for the previous experiment. The effect of the delay of the F_x value described above is not observed.

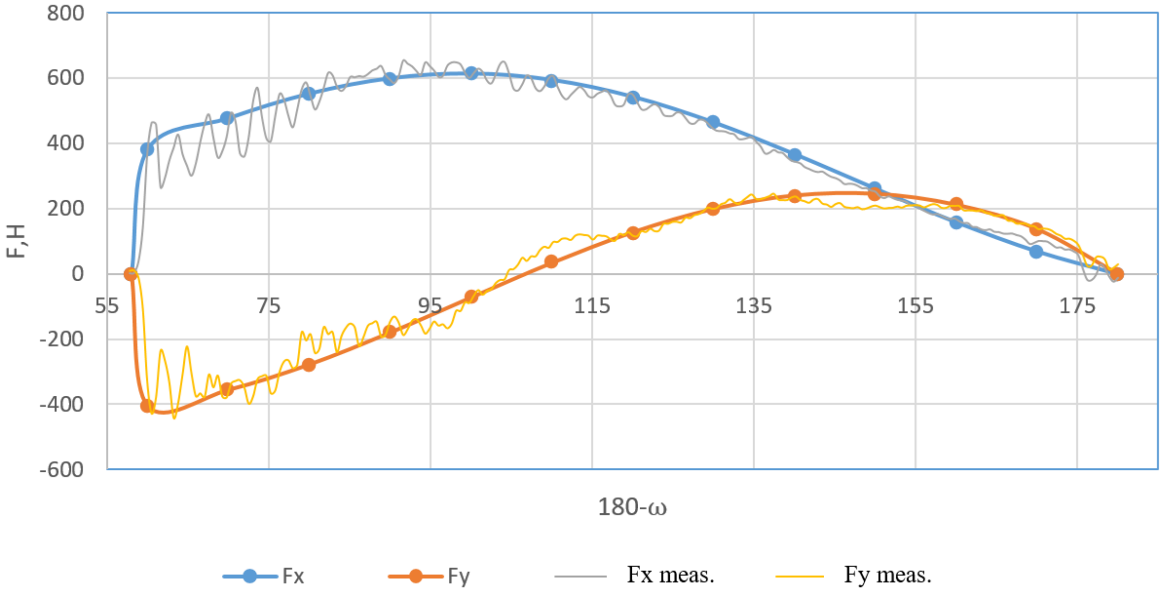

Figure 9. Calculated cutting force data for experiment No 1 combined with the results of measuring of cutting force.

4. Conclusion

The following conclusions are proposed based on the presented graphs.

1) The presented method allows calculating cutting forces with the accuracy that is sufficient to determine the average cutting forces, the direction of the cutting force components vectors, the moment of transition of one of the components through 0 (F_x in the presented calculation).

2) It is necessary to analyse the nature of the cutting force components to clarify the dependence on cutting parameters for a more accurate calculation (for example, to determine the optimal value of the k-factor for the rounding of the cutting edge). The graph clearly shows the increase in the difference between theoretical and practical data in the area of disengagement of the cutting edge from the cutting zone. The nature of this delay of cutting forces also serves as a subject for additional study. It should be noted that the effect exists only for difficult-to-cut material. The presented method allows getting accurate values of the cutting forces acting on the work piece for 40XH2MA steel.

3) The form of the presented graphs for the calculated values of cutting forces does not contradict well-known concepts (for example, in [5]).

5. Acknowledgments

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