The mathematical models for cutting force calculation during structural and corrosion-resistant steels` parts processing

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Abstract. The paper shows that conventional mathematical models for calculating the cutting force components during the turning process, represented in reference guides on engineering, give drastic errors reaching 100 percent or more for various tool-workpiece couples. These errors interfere with applying reference values of the cutting force for any further calculations, equipment selection, workpiece positioning scheme, workpiece deformation value due to the elastic of the technological system elements during processing and etc., because of the insufficient reliability of the results of such calculations. The paper proposes mathematical models obtained as a result of experimental studies, which allow for increasing the accuracy of the calculation of the components of the cutting force by introducing an additional parameter – i.e., the value of thermo EMF of the test running - into the calculation formulas. This approach enables to reduce the error in the calculation of the components of the cutting force up to $\pm 15\%$. In addition, the need for the development of specific mathematical models for various groups of materials machined is shown, which is due to the peculiarities of contact processes in the machining of various groups of steels, as well as to qualitative and quantitative indicators of the thermo-physical properties of the materials of tool-workpiece contact couples.

1 Introduction

One of the urgent issues in technological design is the issue of ensuring accuracy in the determination of the components of the cutting force. This question is especially acute when analyzing machining errors, more particularly when calculating machining errors due to deformation of the workpiece under the action of the radial component of the cutting force (deflection) or due to elastic displacements of the elements of the technological system [1]. In this case, errors in calculating the radial component of the cutting force lead to proportional errors in determining the processing error. This can lead to incorrect decisions when either choosing the scheme for positioning the workpiece or evaluating the magnitude of the predicted following error in relation to a set tolerance specification, and, as a consequence, to manufacturing defects

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As shown in [2], inaccuracies in determining the radial component of the cutting force P_y when calculating in accordance with various engineering reference books can reach 100 percent or more for the material of various tool-workpiece contact couples. The situation is similar with other components of the cutting force; i.e., P_z и P_x [2]. This paper emphasizes the determination of the radial component of the cutting force; however, the main highlights are valid for all components.

2 Main causes of errors in the calculation of the components of the cutting force according to conventional reference models

The causes of inaccuracies in the reference models are described in detail in [2], the main causes are as follows:

- spread in chemical composition within the metallurgical tolerance for manufacturing both from the side of the materials processed and from the side of tool materials, which leads to a corresponding spread in the physic-mechanical properties of tool-workpiece contact couples;
- use of reference books [3-7] of the average coefficients and corrections for tool and workpiece materials, the geometry of the cutting tool, etc. by the authors;
- use of outdated data obtained at lower cutting speeds (up to 50-60 m / min);
- reference models do not take into account the influence of thermal conductivity of the material processed and tool materials, as well as the features of contact processes during machining at cutting speeds above 50-60 m / min;
- lack of specific reference models for calculating the cutting force when machining groups of hard-to-work steels with due regard to the peculiarities of contact processes in the cutting zone.

These and some other reasons lead to the fact that using different reference guides in calculating the cutting force for the same conditions provokes both a difference in the values of the cutting force by tens and hundreds of percent and their difference from experimentally measured values.

Table 1. Scatter of values in the calculation of the components of the cutting force P_y in accordance with some reference books popular in Russia.

References of the authors		P_y , H
1	A.G. Kosilova, R.K. Meshcheryakov [3]	562
2	A.M. Dalskiy [4]	427
3	Y.V. Baranovskiy [5]	448
4	E.I. Struzhestrakh [6]	403
5	A.N. Ogloblin [7]	859
Scatter (max/min), %		213%

Table 1 shows P_y calculation data in accordance with some popular references for the following conditions:

- straight turning tool: $\varphi = \varphi_1 = 45^0$, $\gamma = 0^0$, $\lambda = 0^0$, $r = 1$ mm.
- tool material: T5K10;
- machining mode: $V = 110$ m / min, $S = 0.3$ mm / rev, $t = 2$ mm;
- workpiece material: steel 20.

Table 1 shows the spread more than 200 percent. This situation does not allow for the use of traditional reference data for further engineering calculations, prompting the technologist or machine operator to search for acceptable solutions via trial-and-error methods.

3 Method for determining the components of the cutting force based on information about the properties of materials used in tool-workpiece contact couples

3.1 Value of thermo EMF as an additional information parameter in determining the processing modes

To ensure the reliability of the calculation of various parameters for the processing modes, the authors of [1, 2] proposed an approach due to which mathematical models are introduced with an additional parameter of indirect assessment of the physicomachanical and thermo-physical properties of the materials in tool-workpiece contact couple; i.e., thermo EMF of the test running. In this case, in constant and well-defined cutting conditions, the machine does a test cut, during which the thermo EMF induced between the workpiece and the tool is measured.

As studies [2] show, this parameter has a high correlation with a change in the thermal conductivity of the materials of contact couples, in other physical and mechanical properties, in the geometry of the cutting tool, etc. This allows for the use of thermo EMF as a general method for express-control of both the machinability of the workpiece and the cutting properties of the tool.

The introduction of thermo EMF in the working formulas for calculating the cutting speed, durability, surface roughness, components of the cutting force, etc. allows one to increase the reliability of the calculation of these cutting parameters by reducing random factors, average estimates, etc.

- The use of thermo EMF has the following advantages:
- thermo EMF signal always accompanies the cutting process;
 - thermo EMF signal is quite easy to measure;
 - thermo EMF has a high correlation with the physicomachanical and thermophysical properties of the materials used in the workpiece-tool couple, as well as with the geometry of the cutting tool.

The disadvantages of using thermo EMF deal with the lack of the industrial models of current collectors for lathe machines, which makes it further complicated to use this method in manufacturing conditions.

One more shortcoming is associated with the lack of a wide thermo EMF database, which does not allow for engineering calculations without preliminary measurements. Also, specific acceptance inspection measures should be introduced into production for testing batches of workpieces and tools.

3.2 Mathematical models for calculating the radial component of the cutting force in the machining of constructional and corrosion-resistant steels

To synthesize a mathematical model of the radial component of the cutting force, a series of experiments was carried out, consisting in sequentially sorting the selected factors including cutting speed, feed, cutting depth, and thermo EMF of the testing run. The factor matrix is represented in Table 2.

Table 2. Factor-matrix compiled in the experiment for the regression analysis.

#	<i>E</i> , mV	<i>t</i> , mm	<i>S</i> , mm /	<i>v</i> , m / min
1	8.8	1.0	0.15	90
2	10.6	1.5	0.20	110
3	12.2	2.0	0.30	130

The following materials were used in the tool-workpiece contact couples:

- 1) Cutter T30K4 – steel 45.
- 2) Cutter T15K6 – steel 45.
- 3) Cutter T5K10 – steel 45.

The main geometric parameters of the cutter were as follows: - major cutting edge angle $\varphi = 45^{\circ}$; - rake angle $\gamma = 10^{\circ}$; - main cutting edge inclination $\lambda=0^{\circ}$; - topping radius $r = 2$.

After a set of experiments, a regression analysis was conducted. Having compared different types of regression models, a power-law model was preferred due to its smallest relative error.

In accordance with the mentioned hereinabove, the mathematical model for calculating the radial cutting force when machining constructional steels is as follows:

$$P_y = 156 \cdot E_{test}^{1.3} \cdot t^1 \cdot S^{0.5} \cdot v^{-0.3},$$

(1)

Where E_{test} – thermo EMF of the testing run (mV);
 t – cutting depth (mm);
 S – feed (mm / rev);
 v – cutting speed (m / min).

It should be noted that the relative error of the proposed model is $\pm 15\%$ in comparison with the experimental data. This is confirmed by the data in Table 3, obtained for the following conditions: $v = 100$ m / min; $t = 2$ mm; machining without lubricant coolant.

Table 3. Comparison of the reference P_y values with the measured values.

#	Material of the workpiece	Material of the tool	Thermo EMF, E_{test} , mV	S , mm / rev	Reference value, P_y , H	Mesured peak value, P_{ye} , H	Discrepancy, %
1	Steel 20	T5K10	13.5	0.15	863	780	-10.7
2	Steel 20	T15K6	14.5	0.14	905	850	-6.4
3	Steel 40X	BK8	14.2	0.07	625	710	12.0
4	Steel 40X	T15K6	10.5	0.09	502	460	-9.1
5	18XIT	T5K10	11.8	0.09	574	630	9.0

In a similar way, a mathematical model was obtained for determining the radial component of the cutting force during the treatment of corrosion-resistant steels. This model has the following formula:

$$P_y = 700 \cdot E_{test}^{0.4} \cdot t^{0.55} \cdot S^{0.9} \cdot v^{0.1}.$$

(2)

According to the studies published in [8], this model also gives an acceptable error not exceeding $\pm 15\%$ compared with the experimentally measured P_y values.

3.3 Necessity of applying specific calculation models, cutting force components, when machining various groups of steels

As previously noted, contact processes proceed in different ways in the machining of different groups of steels. Therefore, one of the reasons for inaccuracies in the calculation models of the cutting force components from various engineering reference guides is the lack of specific models for various groups of steels, in particular for those of hard-to-machine steels. Moreover, paper [2] notes that in some reference books there are no recommendations for calculating the radial component of the cutting force for hard-to-

machine steels. And in some other references, the radial P_y and axial P_x component of the cutting force is recommended to be determined as a percentage of the value of the key component of the cutting force (P_z). All this leads to a decrease in the reliability of the calculations.

Paper [8] exemplifies that contact processes in the cutting zone during the machining of corrosion-resistant steels do not allow for the calculation of the components of the cutting force in accordance with the general model. It is necessary to conduct experimental studies to revise the mathematical models and to adjust them for a particular steel group. It should be noted that the structural mathematical model may not change, but it is necessary to revise the coefficients and exponents based on regression analysis and experimental data.

Thus, this paper views the issues of developing reliable mathematical models for determining the components of the cutting force in the machining of various groups of steels.

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