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MODELING OF CUTTING FORCE RELATIONSHIP AS A FUNCTION OF CUTTING CONDITIONS AND TOOL WEAR

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Abstract:
In the paper, experimental investigations were conducted under various cutting conditions, as planned, during face milling. The cutting force components and tool wear parameters are listed concerning time. The research observed that the cutting force components increase with time and/or tool wears. The relationships between cutting force components versus cutting conditions and tool wear parameters were mathematically expressed by models in powder form. Individual relationships of machining parameters as a function of cutting force changes are presented in graphical form, as well as a tabular presentation of the relationship between tool wear and cutting force components. Determined relationships are valid with strong correlation coefficients and are suitable for process monitoring.

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Milling machine, Cutting force, Cutting conditions, Tool wear, Surface roughness

1. INTRODUCTION

Cutting conditions of machine tools are crucial factors that determine the surface quality of the machined object and the overall process efficiency [1-3]. To achieve better surface quality, several studies have been conducted on cutting force, tool wear, and surface roughness [4,5]. The effects of tool wear affect the quality of the machined surface through the following three aspects: increasing surface roughness, affecting surface finish, and creating shape errors [6].

During the milling process, increased interaction forces are generated between the milling cutter and the workpiece, resulting in wear of the milling cutter [7,8]. Downtime caused by tool wear accounts for 20% of all working hours, i.e., they cause economic losses that account for 15 to 40% of total costs [9,10]. Cutting forces and vibrations can affect normal cutting processes, reducing the surface quality of machined parts and accelerating tool wear, while loose connections shorten the life of machines [11-13]. To reduce vibration, it is necessary to define specific positions of the cutter end and the workpiece to ensure minimal machined surface roughness [14].

Research on the progress of cutting force as a function of tool wear is relatively new. It is the result of the need for indirect monitoring of tool wear. The correlation between the increase in these parameters and tool wear enables the continuous indirect measurement of tool wear using any of these parameters to obtain information about the current state of tool wear. It is crucial to have reliable information about machining parameters and investigate their influence and relationships.

Various research is being conducted today, and various industrial applications have been made for monitoring cutting tools during face milling. During end milling, force and tool wear are used to find a correlation [15]. Research [16] has established technological parameters to describe the time course of tool wear and the components of cutting forces during the milling process. The prediction of the mechanical force system in face milling operations was carried out in research [17]. The examination of machinability parameters in the prediction of single-tooth and multi-tooth cutter

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parameters in operation [18]. Research [19] determined the tool wear models and the most important machining parameters in the face milling process.

It is important to note that the experimental models formed represent the basis for adaptive control of highly sophisticated machine tools. The relationships between regime parameters and output characteristics of the machining process created in this way represent the basis for the application of today's widely used models based on artificial intelligence.

2. CUTTING FORCE COMPONENTS RELATIONSHIP

To show the cutting force components, the Kienzle-Victor relationship, which is based on the next unit cutting force k11 is used very often [20]:

$$F_i = b \cdot h^{1-C_i} \cdot k_{i11} \tag{1}$$

where $b \cdot h$ is the chip cross-section and i=1,2,3 for cutting force components.

If tool wear is taken into consideration, equation (1) is extended with the parameter - *l,* which represents cutting length:

$$F_{iw} = b \cdot h^{1-C_{iw}} \cdot k_{i111} l^{C_{il}} \tag{2}$$

Constants C_{iw} and C_{il} depend on cutting conditions and the work material, where the unit cutting force is determined for a cutting length of l=1 m.

$$k_{i111} = k_i \left(b = 1mm, h = 1mm, l = 1m\right) \tag{3}$$

Investigations of the correlation between the time and wear behavior and the cutting force components have been conducted in research [15]. A mechanical cutting force model for multi-tooth cutting processes, where initial position errors in radial and axial direction, eccentricity and edge wear were considered, was presented in [17].

In general, the cross-section of the cutting layer has the most significant influence on the value of the components of the cutting forces, which Kincle's equations show (1,2).

Due to economic considerations, tool life evaluations in both face and end milling processes are frequently conducted using single tooth cutters. The outcomes of these evaluations can apply to multi-tool cutters provided that the radial and axial movement is relatively minimal ($\leq \pm$ 0,002 mm). This is valid for cutting force [18] and tool wear [18,19]. In this research, experiments were conducted with a single tooth cutter. Cutting tests reveal that the predictive model of the cutting force components shows a strong correlation between the cutting conditions and the actual wear on the tool flank.

3. MATERIAL AND METHODS

3.1 Modeling of Cutting Force

According to previous investigations, the most important machining process parameters like cutting forces, cutting temperature, and surface roughness were functions of tool wear [8]. In the mathematical model *W*, the width of flank wear and *VB* were taken as the most important tool wear parameters, which are the easiest to measure.

The suggested mathematical model was in a linear:

$$F_i = a_i + C_i \cdot VB \tag{4}$$

or in a powder form:

$$F_i = e_i VB^{u_i} \tag{5}$$

where:

VB - is the width of flank wear,

a_i, e_j, u_i and C_j, constants depend on the work material and cutting conditions

The paper used the least square method for one-factorial, 2-factorial, 2 and 3-factorial experimental designs for cutting force relationship determination. Based on the investigation, cutting force is a function of cutting time and cutting conditions [20]:

$$F_i = f_1(s_z, a, t) \tag{6}$$

Any of the tool wear parameters is a function of the cutting conditions and the cutting time:

$$W_i = f_2(s_z a, t) \tag{7}$$

By substituting the cutting time from equation (6) into equation (7), it is possible to predict the relationships between the components of the cutting force and the cutting conditions along with the selected parameter of tool wear:

$$F_i = f_3(s_z, a, W_i) \tag{8}$$

In the research, relationships for cutting force components were predicted in the next form:

$$F_i = C_i \cdot s_z^{x_i} \cdot a^{y_i} \cdot VB^{z_i} \tag{9}$$

where are:

s_z - feed per tooth and

a - is the depth of cut.

3.2 Experimental Method

The measurements were arranged for measuring cutting force components and tool wear parameters, as shown in Fig. 1.

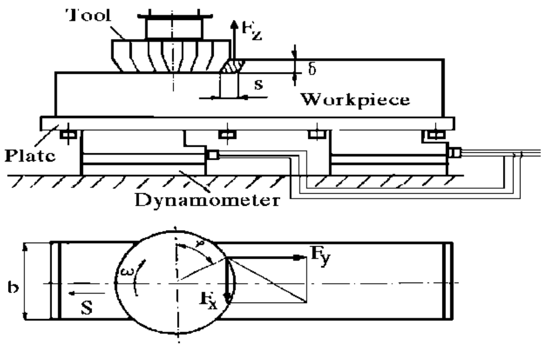

Fig. 1. Measuring arrangement for cutting forces and tool wear

The research was conducted at the Faculty of Technical Sciences in Novi Sad at the Department of Material Removal Processing. The work material was steel EN 1.0601 or AISI 1060. A steel bar measuring 600x120x100 mm^3 was attached to two Kistler piezoelectric platforms for measuring the cutting force components in three directions during the test (Fig. 1). Cutting tests were performed on a 14 kW vertical milling machine without coolant. A face milling cutter of 125 mm diameter, with the cemented carbide P 25 inserts SPAN 12 03 ER with 8-tooth positions, was used while cutting tests were performed with a single tooth.

When cutting was interrupted, the wear parameters of the cutting tool were measured on a microscope. The cutting tool wear parameters were measured on a microscope when the cutting was interrupted. The cutting force signal from the dynamometer after the charging amplifier was transmitted via an AD converter to the computer. The computer eventually saved and analyzed the recorded values of the cutting forces and tool wear metrics. All functional relationships and graphs in the continuation of the research were created by computer data processing.

The experiment was carried out using different combinations of cutting speed (v), depth of cut (a) and feed (sz) per tooth. The width of the cut was b = 100 mm, and the central position of the cutting tool was aligned with the workpiece.

4. RESULTS AND DISCUSSION

The diagrams in Figs. 2 to 4 show part of the experimental research. The variable components of the orthogonal cutting forces Fx, Fy and Fz, as a function of the processing regime, show the corresponding dependence that has been achieved up to the set tool wear criterion, in the form of the width of flank wear land VB, and all as a function of the cutting time.

The cutting forces components in the investigated range change due to varying cutting conditions and the ongoing wear of the cutting tool.

The effect of cutting speed on cutting parameters is evident in Fig. 2. It has been experimentally proven that tool life decreases significantly with increasing cutting speed. However, an approximately constant value is observed for the cutting force components, Fig. 2. This is expected considering that in Kincle's equations for change, the components of the cross-section have the greatest influence, i.e. feed per tooth and depth of cut, which is not the case with cutting speed.

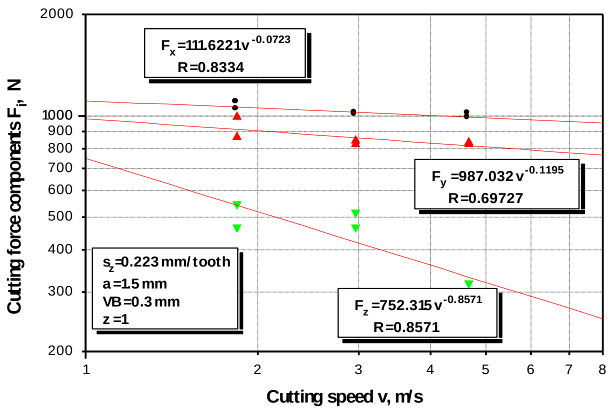

Fig. 2. Cutting forces versus speed

The effect of feed per tooth is evident in Fig. 3. It can be observed that as the feed rate increases, the cutting force components also increase, and indirectly, this causes a reduction in tool life.

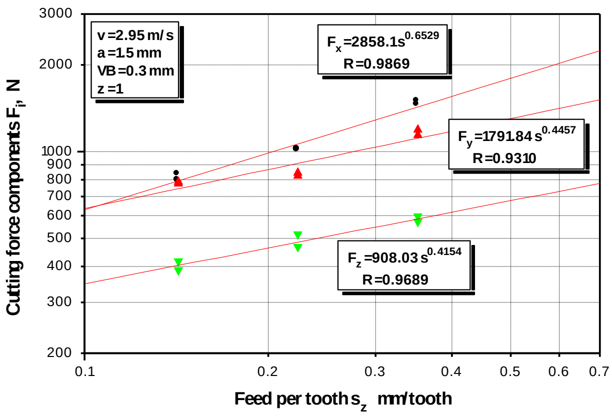

Fig. 3. Cutting forces versus feed

The effect of the depth of cut is evident in Fig. 4. As the depth of cut during cutting increases, the cutting force component also increases significantly. As for the tool life, it can be stated that even with increased cutting depth, it remains similar to the blunting criterion of VB=0.3 mm. The trend of increasing tool wear parameters over time is similar, even when the depth of cut increases and the curves are parallel to each other, shifting to higher values for greater depth of cut.

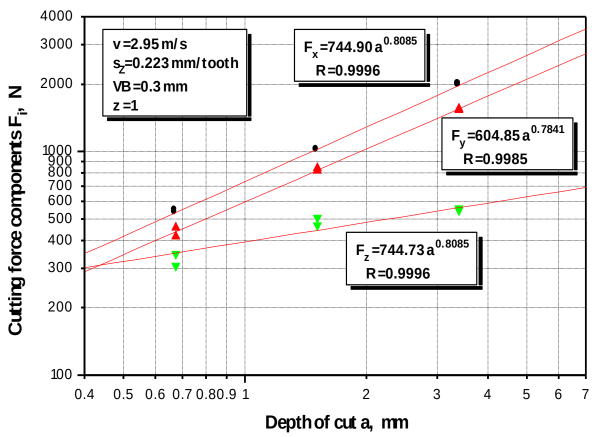

Fig. 4. Cutting forces versus depth of cut

Correlations between cutting force components and cutting conditions are shown in Figs. 2, 3 and 4. All cutting correlations are valid, with very high correlation coefficients, except those between cutting force components and cutting speed.

From Figs. 2, 3 and 4, it can be seen that the cutting force components increase over time and/or with tool wear, and this trend is similar to the tool wear curves.

The time progress of the investigated cutting force components can be divided into three distinctive stages. A rapid increase characterizes the first stage. The second or normal stage generally occurs at a constant tool wear rate. The final stage of time progression often occurs rapidly, with a greater likelihood of tool failure.

The following three tables show the functional dependence of the cutting force components in relation to the tool wear parameter.

Relationships are presented linearly on a logarithmic scale with a strong correlation coefficient. Table 1 shows determined constants in the function of cutting force components versus feed per tooth and width of flank wear. Table 2 shows determined constants in the function of cutting force components versus depth of cut and width of flank wear. Table 3 shows determined constants in the function of cutting force components versus feed per tooth - s_z, depth of cut and width of flank wear - *VB* are shown in Table 3.

Table 1. Constants in cutting-force models

$F_i = C_s\, s^x\, VB^z$ (10)			
	C_s	x	z
F_x	3924.91	0.735	0.182
F_y	2806.77	0.616	0.208
F_z	1743.23	0.442	0.509

Table 2. Constants in cutting-force models

$F_i = C_s\, v^y\, VB^z$ (11)			
	C_s	y	z
F_x	912.37	0.847	0.182
F_y	745.71	0.870	0.208
F_z	776.57	0.340	0.509

Table 3. Constants in cutting-force models

$F_i = C_i \cdot s_z^{x_i} \cdot a^{y_i} \cdot VB^{z_i}$ (9)				
	C_i	x_i	y_i	z_i
F_x	2701.77	0.735	0.847	0.182
F_y	1923.20	0.616	0.870	0.208
F_z	1511.56	0.442	0.340	0.509

The sensors for adaptive control of the milling process can be developed based on these relationships, equations (9), (10) and (11), which agree with [1,8].

The cutting force components of a single and multi-tooth milling cutter is similar if radial and axial throws are very small (≤±0,002 mm) [6,7]. According to these, the experimental results of single-tooth can be applied to the multi-tooth milling cutter parameter prediction. The width of the cut simultaneously influences the number of teeth in the cut and also is connected with the cutting conditions as well.

5. CONCLUSIONS

The main results of this research were:

- There is consistency in the increase in cutting force components with changes in tool wear parameters, i.e., its durability.
- Strong correlation relationships between the cutting force components and cutting conditions and the width of the flank wear land VB are determined.
- The suggested power form relationship fits the correlations between tool flak wear and cutting force components.
- Determined are the constants in relationships.
- The ratios of cutting force components were investigated to monitor tool wear indirectly.
- All presented experimental models are the basis for adaptive control, i.e. the application of some modern modeling techniques, such as artificial intelligence.

Conflicts of Interest

The authors declare no conflict of interest.

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