ANALYTICAL AND EXPERIMENTAL STUDY OF CUTTING FORCE COMPONENTS IN FACE MILLING

Abstract: This paper presents experimentally obtained cutting force components patterns for one revolution during face milling. Measurement of cutting force and results presentation are done by data acquisition system set by authors. The virtual instrument used for measuring the cutting force during face milling was set by use of graphical programming software. Results of experiments are presented in graphical forms and mathematical model for cutting forces components are determined. Influence of cutting speed, feed and depth of cut on the cutting force orthogonal components are analyzed.

Key words: Milling, Cutting forces, Data acquisition, Virtual instrumentation.

1. INTRODUCTION

Cutting force and their moments have significant importance in engineering technology and general in the theory of material machining technology. They represent the basic categories of cutting mechanics.

It is commonly known that during the metal cutting process, the tool geometry changes as a result of tool wear and that these changes can have undesirable effects on process performance. The most significant variation from sharp tool operation is an increase in cutting forces, which can lead to variations in process stability, part accuracy and part surface finish.

Researches in the field of metal processing technology, chip removal, in most of his works, were focused on machinability of material. Machinability of material defining features of tool life, cutting forces, surface quality, cutting temperature and chip form. Knowing these features, as well as important technological characteristics of the material, it is important to both the classical and the design of technology for automated cutting process. In accordance with that is to create a database of machinability and optimization of cutting parameters.

The importance of knowledge of cutting force, as one of the most important machinability functions is large, which is why this issue is constantly attracted the attention of researchers in this field. Knowing the value of cutting force provides to: determine the energy balance of machine tools, perform the calculation and dimensioning kinematics elements of machine tools, perform the calculation and dimensioning of cutting tools and auxiliary equipment, perform optimization of machining processes (based on calculation of optimal values of the elements of the regime and equations whose description of the cutting force), adaptive control machining systems and others. Cutting forces in milling are intensively studied both analytically and experimentally [1]. In Figure 1 are shown the orthogonal cutting forces in face milling process.

Face milling process particularity like multi tooth that simultaneously cutting with difference in chip cross section of one tooth, influenced development of variety of models for cutting force calculation. Variation in chip cross section gives difference in intensity of cutting forces and thermal load of single tooth.

![Fig. 1 Plan of cutting forces during face milling](image)

Fig. 1 Plan of cutting forces during face milling [2]

Force $F_x$ changes in direction and intensity during a tooth cutting, so its components $F_x$ and $F_y$ are different intensity according the angle change from $0^\circ \to 180^\circ$.

The position $\varphi = \xi_1$ component $F_x = 0$, and the $F_y$ has the feed motion direction, and $F_x = F_p$, where $F_p$ is feed force. If the direction of $F_x$ is perpendicular to the feed then $F_y = 0 \ (\varphi = \pi/2 + \xi_2)$. If components $F_x$ and $F_y$ are known it can be calculated on the basis of their force $F_x$.

Two other components that may decompose the force $F_a$ are the forces in tangential and radial direction. These are the main cutting force $F_a$ and the (passive) penetration cutting force $F_t$. 

If are considered two positions of milling teeth in cut, so the first position is for \( \varphi < \pi / 2 \), in the second is for \( \varphi > \pi / 2 \). The equations that connect these forces are:

**Position I:**

\[
F_x = -F_g \cdot \sin \varphi + F_r \cdot \cos \varphi \\
F_y = F_g \cdot \cos \varphi + F_r \cdot \sin \varphi \\
F_z = F_a
\]  

(1)  

(2)  

(3)

Solving the system of equations (1) (2) and (3) gives:

\[
F_x = -F_g \cdot \sin \varphi + F_y \cdot \cos \varphi \\
F_y = F_r \cdot \cos \varphi + F_y \cdot \sin \varphi \\
F_z = F_a
\]

(4)  

(5)  

(6)

Feed force in the direction of feed motion \( F_p \) at any time is equal to the force \( F_y \), respectively:

\[
F_p = F_g \cdot \cos \varphi + F_r \cdot \sin \varphi = F_y
\]

(7)

**Position II:**

\[
F_x = -F_g \cdot \cos \left( \frac{\pi}{2} - \varphi \right) - F_r \cdot \sin \left( \frac{\pi}{2} - \varphi \right) \\
F_y = -F_g \cdot \sin \left( \frac{\pi}{2} - \varphi \right) + F_r \cdot \cos \left( \frac{\pi}{2} - \varphi \right) \\
F_z = F_a
\]

(8)  

(9)  

(10)

Taking into account the addition formula:

\[
\sin \left( \frac{\pi}{2} - \varphi \right) = \sin \varphi \cdot \cos \frac{\pi}{2} - \cos \varphi \cdot \sin \frac{\pi}{2} = -\cos \varphi
\]

(11)

\[
\cos \left( \frac{\pi}{2} - \varphi \right) = \cos \varphi \cdot \cos \frac{\pi}{2} + \sin \varphi \cdot \sin \frac{\pi}{2} = \sin \varphi
\]

(12)

equations (8) (9) and (10) are reduced to equations (4) (5) and (6), whose solution has already been shown.

2. EXPERIMENTAL INVESTIGATION

In this work, using the developed system for monitoring, acquisition and measurement of cutting forces in milling process, by use of virtual instrumentation (VI) was performed measurements of milling forces. The aim of the task was to make the analysis of the influence of machining elements on the value of cutting force components. Calculation of the measured cutting force components; main cutting force, the force of penetration and force feed motion in time domain duration for a tool revolution will be made as well.

Additionally was performed a comparison of relationships between the main cutting force for two different steel (\( \dot{\text{C}} 1530 \) and \( \dot{\text{C}} 4732 \)) at the same machining conditions.

3. ACQUISITION SYSTEM FOR THE FORCE DURING FACE MILLING

3.1. Characteristics of acquisition system

Measuring acquisition system must meet the following requirements [3, 4, and 5]:

- High efficiency and accuracy of results;
- Involvement of existing laboratory resources and their compatibility;
- Rational use of time and laboratory resources, with very little consumption of workpiece materials, cutting tools and time;
- To be suitable for serial testing in a large number of materials for the formation of computer databases on machinability material cutting;
- Good portability and compatibility;
- To enable the display of results and monitoring processes in real time;
- And finally, to enable the acquisition, storage and processing of data.

Figure 2 shows the measuring acquisition system scheme for the cutting force during face milling.

From Figure 2 we can see that the system consists of the following components:

- Machine Tool (vertical milling machines - FAS-GVK-3)
- Tools (milling head with interchangeable cutting plates)
- Sensor measurement system (three component piezoelectric dynamometer - "Kistler"-9257A)
- Amplifier measurement system (capacitance-amplifier "Kistler" - CA 500)
- Dial-up panel for connecting the module with the actual acquisition process (ED429-UP)
- Acquisition Module - A / D converter - ED428
- Computer System
3.2. Virtual instrument

Virtual instrument (VI) used for measuring the force in face milling was developed using graphical programming software Lab VIEW 8.0. VI is designed to allow easy reading voltage with dynamometer, which correspond to the forces of cutting during face milling $F_x$, $F_y$ and $F_z$. View, change the values in the form of diagrams and tables, and display the maximal values of in a single measurement.

VI contains of three components:
- The front panel (front panel) - serves as a graphical user interface
- Block diagram (block diagram) - contains graphic VI source code, which defines its functionality.
- Connector and icon (icon and connector panel) - identifies the VI so that it can be used in another VI. VI in another VI is called SubVI and corresponds to subroutine in text-oriented programming languages.

4. ANALYSE AND DISCUSSION

Using the system shown (Fig. 2) measurements were performed and acquisitions orthogonal cutting force components during milling.

During the experimental study measured were the orthogonal cutting forces $F_x$, $F_y$, $F_z$, and based on them were obtained through the computational processing components $F_g$, $F_r$, $F_p$ and $F_a$ according equations (1) to (10). Figure 3 shows the change of cutting force during face milling with milling cutter diameter $D = 125$ [mm], and with one tooth (insert of hard metal) [6]. Experimental testing was provided with new and worn cutting insert. Workpiece material was a steel $C1530$ and $C4732$. The graph on Fig 3 presents the cutting forces measurements versus tooth position for the following cutting regimes: $v=177$ [m/min] $a=1.5$ [mm], $s_z=0.223$ [mm/t].

In the second experiment (Figure 4.) machining is performed with the same cutting regime and the same workpiece material, but this time was used worn cutting insert. Flank wear land was 0.4 [mm], but there was concentrated tool wear at the corner of the insert tip with the maximal amount of 2 [mm].

Fig. 3 Change cutting forces components versus the position angle for new cutting tool

Fig. 4 Change cutting forces components versus the position angle for the worn cutting tool

Analyze of diagrams in Figure 3 and 4, shows that the machining with worn cutting insert increases the value of cutting force in relation to the case when the cutting was done with new insert.

In further processing of results was examined dependence on changes in the orthogonal cutting force constant depth $a = 1$ [mm] and the cutting speed $v = 2.32$ [m/s], and different feed $s_z$ in interval of (0.178 [mm/t], 0.223 [mm/t], 0.280 [mm/t]) (Figure 5). Also was varied depth, with constant cutting speed and feed (Figure 6). In this case the value of cutting depth $a_1=1$[mm], $a_2=1.5$ [mm] and $a_3=2.25$[mm]. The value of cutting speed for this case was constant $v = 2.32$ [m/s], and feed $s_z=0.178$ [mm/t].

Fig. 5 Change orthogonal cutting force for constant cutting depth and feed, and different speeds with worn cutting tool

The analysis of the diagram in Figure 6, shows that with increasing values of feed and depth of cut the cutting force increase. Change of cutting speed has no
great influence on the change of cutting force. The largest increase in cutting force is according to the variation of depth of cut (Figure 7).

![Image of Figure 6: Change of orthogonal cutting force components for constant cutting depth and cutting speed, and different feeds with worn cutting tool]

Fig. 6 Change of orthogonal cutting force components for constant cutting depth and cutting speed, and different feeds with worn cutting tool.

![Image of Figure 7: Change of orthogonal cutting force components for constant cutting speed and feed and for different depths of cut with worn cutting tool]

Fig. 7 Change of orthogonal cutting force components for constant cutting speed and feed and for different depths of cut with worn cutting tool.

At the end analyzed were relationships for the major cutting force for Č1530 and Č4732 for the same machining conditions (Fig. 8).

![Image of Figure 8: Cutting forces for different machined materials (Č1530 and Č4732) and same cutting conditions]

Fig. 8 Cutting forces for different machined materials (Č1530 and Č4732) and same cutting conditions.

From Figure 8 can be seen that the steels with lower sulfur content (Č1530) is difficult to machining (more major powers) versus the steel with higher sulfur content (Č4732). This can be explained by the fact that the increased content of sulfur allows the creation of a larger number of MnS particles, which can easier plastically deform during the cutting process, unlike the tiles in perlite cementite that break. The presence of MnS particles reduces the length of contact on the rake face of tools. Shorter length of contact with cutting tool results in thinner chips and smaller cutting force components [1].

5. CONCLUSION

Investigation of cutting forces is a key part in the development of cutting technology itself. They are one of the main criteria for evaluating machinability of material and as such attract the attention of many researchers in this field. Exact knowledge of the characteristics and values of cutting force in the face milling is needed to study the dynamics of cutting process in interaction with the dynamics behavior of the machine tools structure.

According suggested equations determined were the main cutting force $F_c$ and the (passive) penetration cutting force $F_r$ versus tooth position for a revolution.

The experimental results analyze shows influence of cutting regime on cutting force.

6. REFERENCES


Authors: Prof. Dr. Pavel Kovac, Assistant M.Sc. Borislav Savkovic, Assoc. Prof. doc. Dr. Milenko Sekulic, dipl.ing. Aleksandar Mijic, University of Novi Sad, Faculty of Technical Sciences, Production Engineering Institute, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia, Phone.: +381 21 485-2320, E-mail: pkovac@uns.ac.rs savkovic@uns.ac.rs milenkos@uns.ac.rs aleksandarmijic@gmail.com

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