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Kuzinovski, M., Trajčevski, N., Cichosz, P.

INVESTIGATION OF CUTTING FORCES DURING MACHINING PROCESS BY HIGH SPEED TURNING

Abstract: *This paper presents the obtained mathematical models of cutting forces during machining process by high speed turning as a function of processing parameters* v, f, a *and* r_e. *The machining process by turning is performed on NC lathe using ceramic cutting tool inserts and the workpiece material is* **C** *1630 (DIN C 55). Processing parameters are varied in range between* v *=300 and 700 m/min,* f *=0,16-0,32 mm/rev, a=0,5-1,6 mm and* r_e*=1,2-2,0 mm. Cutting forces measurement is done at the Institute of Production Engineering and Automation of the Wroclaw University of Technology, Poland using computerized experimental setup with three component piezoelektric dynamometer type Kistler. Experiments are realized acording first order four factorial experimental plan. Mathematical processing is performed at the Faculty of Mechanical Engineering in Skopje using the program CADEX combined with MATLAB.*
Key words: *Machining by turning, cutting forces, mathematical models, factorial experiments*

1. INTRODUCTION

Knowing the magnitude of the cutting forces in the turning process as function of the parameters and conditions of treatment is necessary for determining of cutting tool strength, cutting edge wearing, limit of the maximum load of the cutting machine and forecasting the expected results of the processing. In particular, during machining with high cutting speed, using modern materials and modern cutting machines imposes the necessity of studying physical phenomena in the cutting process and their mathematical modeling. Moreover, analysis of physical phenomena has shown that conditions are created for processing by material removal, in substantially different conditions, primarily due to the use of larger cutting speeds [1]. In such circumstances the creation of possibilities for identification of physical phenomena in the cutting process allows: the creation of the basis for selection of optimal processing parameters, forecasting the process of wear of the cutting edge, determination of time to change the cutting tools, quality management of workpiece surface layer, optimization of cutting tool stereometry, chip shape and removal conducting, upgrading the technology of production of cutting tool inserts and their properties. During intensive machining conditions, monitoring of the cutting forces is possible only with the use of computer aided research systems [2]. Experiences show that the determination of cutting forces in an analytical way not fully reflect the real situation [3]. Basis of mathematical models for cutting forces obtained in an analytical way are spreadsheet data obtained in surveys, conducted in certain treatment conditions that can be changed. From here emerges the justification for carrying out research activities for the determination of mathematical models to describe the change of cutting forces as a function of processing parameters.

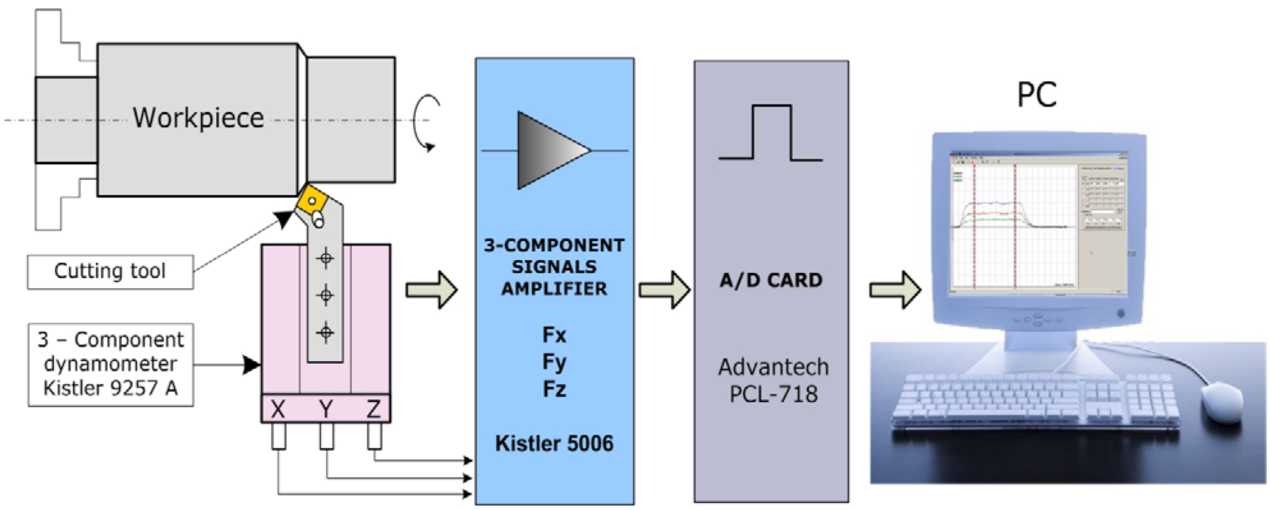

Fig. 1. Schematic view of the research experimental setup

2. EXPERIMENTAL CONDITIONS

2.1 Cutting tool

The processing is performed by use of ceramic cutting tool inserts type SNGN 120712- 120716- 120720 made of zircon-oxide ceramics AC 5 (Al_2O_3 +10% ZrO_2) and cutting tool holder type CSRNR 25x25 M12H3, manufactured by HERTEL. Cutting tool stereometry is:

$$\chi = 75°,\ \chi_1 = 15°,\ \gamma = -6°,\ \alpha = 6°,\ \lambda = -6°,$$

$$\gamma_f = -20°,\ b_f = 0{,}2\,\text{mm}$$

2.2 Workpiece

Material C 1630 (DIN C 55), normalized to the hardness of 200 HB.

2.3 Metal cutting machine

NC lathe TUR 50 SN-DC, with power P = 18,5 kW with the area of continuous change in the numbers of revolutions n=50-2250 rev/min.

2.4 Cutting parameters

Cutting speed v = 300-700 m/min, feed f=0,16-0,32 mm/rev, depth a=0,5-1,6 mm, cutting tool insert top radius r_ε=1,2-1,6-2,0 mm.

2.5 Experimental plan

It is used first-order full four factorial plan of experiments (2^4 + 4), presented in Table 1. Power function is accepted for the mathematical model to describe the changes of cutting forces [1, 6]. Mathematical processing is performed at the Faculty of Mechanical Engineering in Skopje with the application of program CADEX in connection with *Model-Based Calibration (MBC) Toolbox Version 1.1,* contained in the *Matlab* software package, which is intended for design of experiments and statistical modeling. Using the advanced features of *Matlab* and *MBC* provides significant advantages in the realization of experimental studies, with an option for graphic interpretation of results.

2.6 Research equipment

Monitoring of cutting forces *Fa*, *Fr* and *Ft* in the cutting process is done with computer aided research experimental setup, presented in Fig. 1. Part of the research setup is three-component piezoelectric dynamometer type Kistler 9257 A. Measurements are done at the Institute of Production Engineering and Automation of the Wroclaw University of Technology, Poland. The software FORTMON does graphical presentation of the measurement data, shown on Fig. 2, [4].

3. RESEARCH RESULTS ANALYSIS

The changes on cutting forces *Fa*, *Fr* and *Ft* were monitored in the research. The power function has been adopted for describing these changes:

$$F_a, F_r, F_t = C\, v^x f^y a^z r_\varepsilon^q \quad \text{..............} \quad (1)$$

Experiment plan and results are presented in Table 1. Some graphical interpretation of the influence of cutting speed - *v*, feed - *f*, cutting depth - *a*, and

Obs No	Independent variables - Real matrix				Result		
	v [m/min]	f [mm/rev]	a [mm]	r_ε [mm]	F_{aav} [N]	F_{rav} [N]	F_{tav} [N]
1	300,00	0,16	0,50	1,20	140,55	224,37	272,21
2	700,00	0,16	0,50	1,20	105,55	165,75	235,24
3	300,00	0,32	0,50	1,20	156,95	296,94	431,46
4	700,00	0,32	0,50	1,20	110,02	221,01	327,86
5	300,00	0,16	1,60	1,20	468,82	347,80	744,78
6	700,00	0,16	1,60	1,20	395,21	295,06	675,11
7	300,00	0,32	1,60	1,20	638,83	500,41	1241,52
8	700,00	0,32	1,60	1,20	520,05	419,39	1063,80
9	300,00	0,16	0,50	2,00	121,86	248,47	285,39
10	700,00	0,16	0,50	2,00	103,01	206,30	262,47
11	300,00	0,32	0,50	2,00	179,85	382,75	525,69
12	700,00	0,32	0,50	2,00	138,78	304,31	427,61
13	300,00	0,16	1,60	2,00	461,87	442,69	789,79
14	700,00	0,16	1,60	2,00	403,47	392,22	739,88
15	300,00	0,32	1,60	2,00	596,41	642,49	1302,48
16	700,00	0,32	1,60	2,00	489,69	530,27	1146,87
17	458,26	0,23	0,89	1,55	267,85	349,18	563,28
18	458,26	0,23	0,89	1,55	250,31	338,25	546,02
19	458,26	0,23	0,89	1,55	264,66	351,44	571,50
20	458,26	0,23	0,89	1,55	256,86	341,94	556,54

Table 1. First order four factorial experimental plan

cutting tool insert tip radius - r_ε on the changes of axial Fa, radial Fr and tangential force component Ft are shown on Fig. 3.

Processing of obtained results includes analysis of mathematical models with and without mutual effect, determination of 95% confidence interval for analyzed models, evaluation of significance of coded polynomial coefficients, determination of experiment error, check of mathematical model adequacy and determination of multiple regression coefficient. Analysis performed, after the complete computer processing, showed adequacy of obtained mathematical models (2), (3) and (4).

$$F_a = 2355{,}2 \cdot v^{-0{,}26} \cdot f^{0{,}34} \cdot a^{1{,}14} \cdot r_\varepsilon^{-0{,}019} \quad (2)$$

$$F_r = 2714{,}55 \cdot v^{-0{,}25} \cdot f^{0{,}5} \cdot a^{0{,}48} \cdot r_\varepsilon^{0{,}47} \quad (3)$$

$$F_t = 4403{,}58 \cdot v^{-0{,}17} \cdot f^{0{,}68} \cdot a^{0{,}89} \cdot r_\varepsilon^{0{,}22} \quad (4)$$

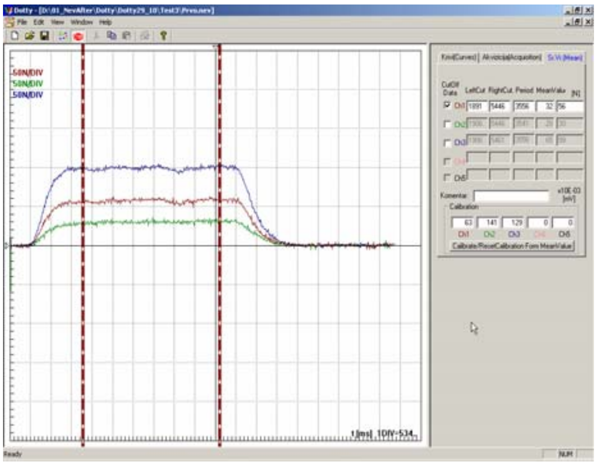

Fig. 2. Graphical presentation of measurements results by using FORTMON software

Researches show dominant influence of feed and cutting depth on cutting force change. This is explained by the fact that by feed increase, contact increase is caused between chip and face surface of cutting wedge as result of increased removed material thickness. Therefore friction between chip and face surface of cutting tool is increased, which alternatively causes higher chip ramming. Actually, a higher plastic deformation is present.

Cutting depth has direct influence on contact length between chip and face surface of cutting wedge. Therefore higher influence of cutting depth outcomes onto axial Fa, then on tangential Ft, and smallest on radial component Fr. It can be concluded that cutting depth has higher influence on force Fa and Ft than cutting feed. It is vice-versa for the radial component Fr, where feed shows higher influence than cutting depth.

The cutting speed influence onto cutting forces change is interesting. At its increase the contact between face surface of cutting wedge and chip decreases, which causes reduction of chip ramming. The last is connected also to reduction of friction coefficient between chip and face surface of cutting tool as a result of increased temperature caused by cutting speed increase. This indicates cutting forces decrease by cutting speed increase.

It can be noticed from equations 2-4 that cutting speed has higher influence onto axial Fa and radial Fr, while as smaller onto tangential component Ft. Such influence order of cutting speed upon cutting components is explained by the occurrence of various temperature conditions.

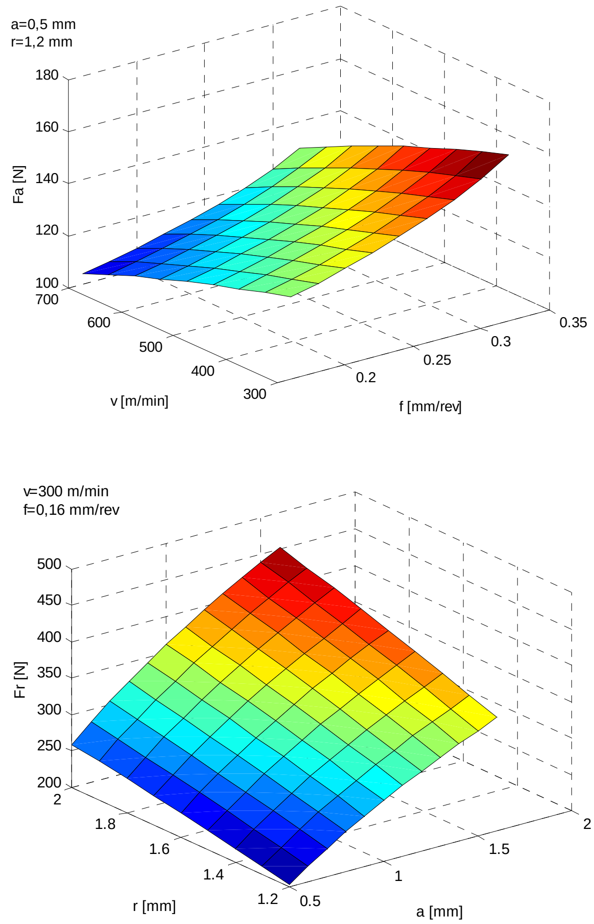

Fig. 3. Graphical interpretation of the influence of cutting speed - v, feed - f, cutting depth - a, and cutting tool insert tip radius - r_ε on the changes of axial Fa, radial Fr and tangential force component Ft

Namely, by cutting speed increase the contact surface in radial direction decreases, where due to higher temperature gradients there is reduction of mechanical characteristics of machined material and significant reduction of friction coefficient between cutting tool insert tip and machined surface. In addition to this is also the fact that cutting speed increase causes temperature and mechanical load change onto cutting blade. Similar is the condition also in direction of force Fa, where contact between cutting blade in initial stage is theoretically linear, which causes smaller heat discharge i.e. high temperature occurrence near cutting blade [5].

From this outcomes friction coefficient reduction between rear surface of cutting tool and machined surface. Here, mechanical properties of machined materials are reduced due to high temperature. The condition on face surface of cutting wedge is different, where reduction of tangential component *Ft* is smaller due to larger contact surface between chip and cutting tool. Areas with plastic deformation and abrasive wearing of surface layer of cutting tool insert are noticed here [5]. This indicates existence of various friction coefficients i.e. various terms when chip wears against face surface.

Tip radius of the cutting tool insert r_ε has a different but proportional influence upon change of cutting forces components. Its increase causes contact length increase between cutting blade and machined surface, which indicates a possibility for larger decrease of axial force *Fa*. However, axial resistance *Fa* insignificantly decreases by increase of r_ε. This is caused by reduction of setting angle of cutting tool χ positioning, by increase of r_ε, which, actually, is different on the circular part against cutting blade length. Radial *Fr* and tangential *Ft* cutting force component increase by increase of r_ε. Then, higher is the influence of r_ε onto the radial component mostly due to larger contact with machined surface.

4. CONCLUSIONS

From the exhaustive experimental researches performed, obtained mathematical models, as well the analysis of results, following remarks and conclusions can be reached:

- The statistical analysis indicated that the describing of changes in cutting forces *Fa, Fr* and *Ft* as function of machining parameters *v, f, a*, and cutting tool insert tip radius r_ε, by means of power function, correctly describes the physics of change of forces as function of machining parameters;

- All factors adopted in models are significant, apart in model (2), and their influence is as follows:

- cutting speed affects cutting forces counter-proportionally, meaning that cutting forces decrease by cutting speed increase;
- feed, as well as cutting depth, have proportional influence on cutting forces change;
- cutting tool insert tip radius r_ε influences cutting forces in a mode where by its increase causes significant increase of forces *Fr* and *Ft*, and insignificant increase of *Fa*;
- cutting depth - *a* and feed - *f* have higher influence, smaller r_ε, and smallest and counter-proportional cutting speed *v* on the change of main cutting force.

- Since small differences of influences are gained and when in a research an influence sign change occurs, justified is to perform more intensified research activities in sense of reducing uncertainty of results that are gained from measurements and determination of the confidential interval onto the influence of separate factors, all with the purpose of reducing or eliminating the negative influence that outcomes from research hardware equipment, the validity of the application of adopted machining parameters, the experiment planning methodology, the mathematical processing of results and applied software solutions.

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Authors: **Prof. Kuzinovski Mikolaj, PhD,** University "Ss. Cyril and Methodius", Faculty of Mechanical Engineering, Skopje, Macedonia. **Trajčevski Neven, MSc,** Military Academy - Skopje, Macedonia. **Prof. Cichosz Piotr, DSc,** Institute of Production Engineering and Automation of the Wroclaw University of Technology, Wroclaw, Poland.
E-mail: mikolaj@mf.edu.mk
neven.trajchevski@gmail.com
piotrc@itma.pwr.wroc.p