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EFFECT OF THE CUTTING PARAMETERS ON CUTTING FORCES IN HIGH SPEED FACE MILLING

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Original scientific paper

Machining system VBS was constructed and built at the Faculty of Mechanical Engineering in Sarajevo, for investigations of the phenomena in high speed milling. Since the requests for high speeds and accelerations of the main spindles and the transmitters for the feed motions require specific design and mechatronic solutions, this paper presents the selection of optimal design variety of components integrated in machining system VBS. The investigation of the effect of the cutting parameters on the cutting forces during high speed face milling (range of cutting speed from 750 m/min to 3000 m/min) was conducted on the machining system VBS. Investigations were carried out on hardened alloy steel EN 10083-3 (41Cr4). The results show that cutting force F_R decreases by increasing cutting speed. Also the investigations show that the feed per tooth has significant effect upon the values of cutting forces. This paper further presents the mathematical model for calculating cutting force in high speed cutting. Experimental results are compared with calculation results.

Keywords: *cutting forces, feed per tooth, machining system, mathematical model, ultra high cutting speed*

Utjecaj parametara obrade na sile rezanja pri visokobrzinskom čeonom glodanju

Orginalni znanstveni članak

Za istraživanje pojava pri visokobrzinskoj obradi glodanjem, na Mašinskom fakultetu u Sarajevu konstruiran je i izrađen obradni sustav VBS. Kako zahtjevi za visokim brzinama i ubrzanjima glavnih vretena i prijenosnika za pomoćna gibanja iziskuju specifična konstrukcijska i mehatronička rješenja, u članku je definiran pristup i odabir optimalne projektne varijante komponenti eksperimentalnog obradnog sustava VBS. Na sustavu VBS provedena su istraživanja utjecaja parametara obrade na sile rezanja kod čeonog glodanju s visokim brzinama rezanja (od 750 m/min do 3000 m/min). Istraživanja su provedena na legiranom čeliku EN 10083-3 (41Cr4) u poboljšanom stanju. Rezultati istraživanja su pokazali da pri zadržavanju konstantnog posmaka po zubu vrijednost rezultirajuće sile F_R opada s povećanjem brzine rezanja. Istraživanja su također pokazala da posmak po zubu ima veliki utjecaj na vrijednost sila rezanja. Primjenom regresijske analize razvijen je matematički model za određivanje sila rezanja te je napravljena usporedba dobivenih eksperimentalnih rezultata s rezultatima proračuna.

Ključne riječi: *matematičko modeliranje, obradni sustav, posmak po zubu, sile rezanja, ultravisoke brzine rezanja*

1 Introduction

Increasing demands for new and variety products, their rapid obsolescence, high costumers' requests for quality and accessible prices are properties of the advanced world market. In such conditions of global market competition, the imperative is to create rapid, cheap and quality products.

High speed machining has many advantages such as high removal rates, reduction in process time and low cutting forces, leading to excellent dimensional accuracy and surface finishing quality [1]. In high speed machining of difficult-to-cut materials, such as hardened steels or nickel-based super-alloys, many thermal/frictional problems occur, such as severe tool wear, high cutting temperature, etc. The authors, to improve tool life in high speed machining, have performed several studies [2, 3].

Manufacturing time, price and quality of made product directly depend on cutting parameters such as cutting speed, feed and depth of cut. The paper explores the high speed milling process, where high productivity is achieved by using high cutting speed and feed rate.

Allowing for the facts that cutting forces decrease [4, 5] during high speed machining and that face milling is the most widely used technique, the investigation of the effect of cutting parameters to the cutting forces especially during high speed machining of hardened steels is very important. Namely, the recognizing of cutting force values enables increasing of the accuracy and quality of processes, determination of the machining tool balance, verifying the static and dynamic stability of the machine tool and so on.

2 Experiment preparation

Experimental investigations of the change of cutting forces during ultra-high face milling (up-cut and down-cut) of steel are carried out at the Faculty of Mechanical Engineering in Sarajevo. Investigations are conducted on the machining system VBS, Fig. 1. Machining system VBS is constructed by the adaptation of the stiff universal milling-drilling machine, by building modern high speed components which have primary characteristics: flexibility, high productivity and modularity. The process of the machining system set-up was accompanied by a number of expert and non-standard practices as well as investigations regarding the rigidity and vibrations that played an important role in the selection of the mounting [6, 7].

For achieving a high number of revolutions, the high speed motor spindle is mounted on the system VBS. The main demands for the motor spindle are high accuracy during work, high number of revolutions, higher power, high rigidity, low working temperature and high reliability. Because of today's technical possibilities, some of these demands are contrary to one another. For this reason, not all of them could be fulfilled at the same time, as it was necessary to define all possible functions for the selection of the design solution as well as analyze all critical limitations and possible disturbances of the system and the process, Fig. 2 [7, 8].

The solving of partial design functions, functions of limitations and disturbances were done in cooperation with the company HSTEC d.o.o. Zadar. Motor spindle type HSM 090-40000 was fitted on the machining system VBS. It has the following characteristics:

- Revolution system regulation: changing of frequency (from 200 Hz to 1500 Hz) and voltage by frequency regulator Yaskawa,
- Number of revolutions: from 5830 rpm to 40000 rpm,
- Tool interface: system HSK E,
- Balancing: according to DIN standard,
- Number of DN: 2×10^6 with the power of 18 kW and torque of 19 N·m,
- Lubrication system: pulsed oil/air – Vogel,
- Cooling medium: injection of water with corresponding additive under pressure of 3 bar,
- Bearings: ball – bearings of ceramic material,
- Preload of bearings: the front bearings by the setting tolerance and the rear bearings by spring.

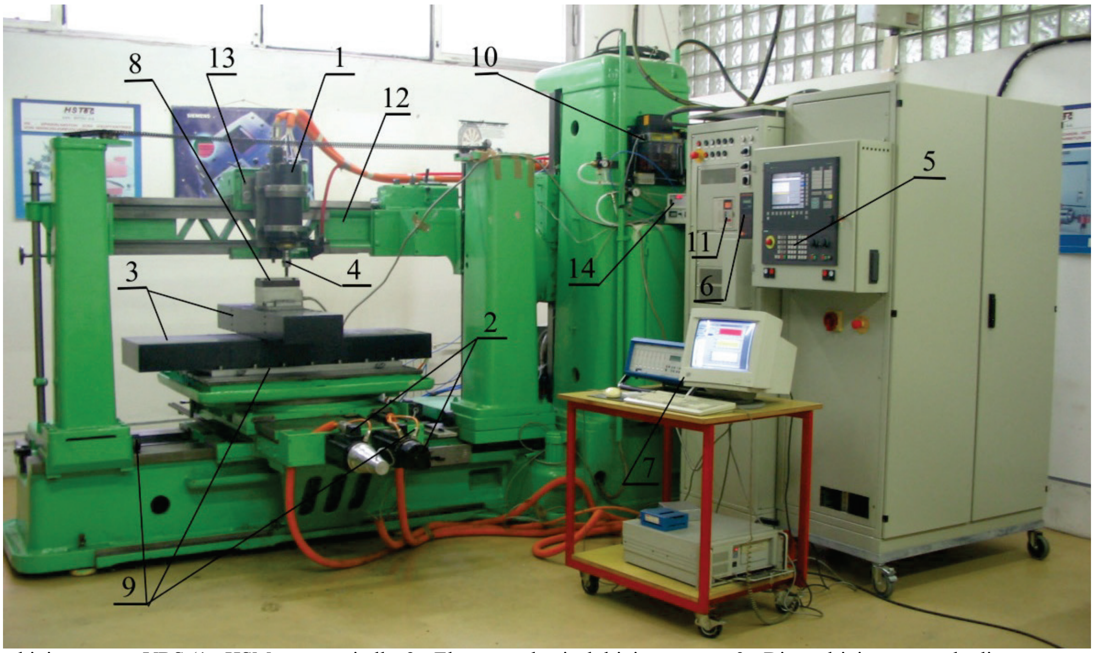

Figure 1 Machining system VBS (1 - HSM motor spindle, 2 - Electromechanical driving system, 3 - Direct driving system by linear motors, 4 - System tool – tool interface, 5 - Control unit SINUMERIK 840D, 6 - Control unit CLM 01, 7 - Equipment for measuring of cutting forces, 8 - Workpiece, 9 - Safety system, 10 - Lubrication system of motor spindle –Vogel, 11 - Frequency regulator of motor spindle Yaskawa, 12 - Bracket arm, 13 - Motor spindle carrier, 14 - Cooling control of motor spindle and linear motors)

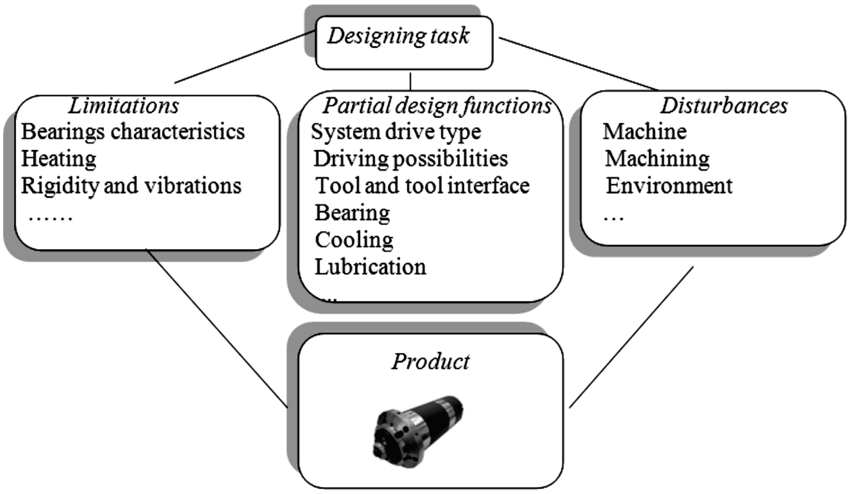

Figure 2 Functions during design of high speed motor spindle

High speed machining demands an adequate system for feed motion that has to realize: high feed rate, high acceleration and high dynamic accuracy of the tool path. Two separate drives of the worktable are built-in on the machining system VBS: electro-mechanical drive and direct drive by linear motors SIEMENS (development of the worktable drive was ultimately performed during preparations of the experiment). Direct drive by linear motors is used for experimental investigations that have the following characteristics:

- Maximum feed rate in direction x axis: 100 m/min
- Maximum feed rate in direction y axis: 60 m/min
- Maximum stroke in directions x, y and z axes: $180 \times 350 \times 400$ mm
- Acceleration up to 30 m/s^2.

For recording cutting forces, a 3-component dynamometer "KISTLER" with the piezoelectric transmitter type 9265B and a clamping platform for work piece type 9443B is used.

Experimental investigations are conducted in down-cut and up-cut face milling, with the following parameters: cutting speed from 750 m/min to 3000 m/min and feed per tooth from 0,05 mm to 0,25 mm. Milling depth and milling width are 0,10 mm and 12 mm, respectively. The machining process is carried out such as always; just one tooth of the cutting tool was engaged with the work piece. Cutting tests are carried out under dry machining conditions. A new cutting edge is used for each machining experiment.

Data acquisition is performed with "Test Point" software. The average components values of cutting force in three orthogonal directions *x*, *y* and *z* are analysed. A special code which is programmed in Visual Basic is used for processing the collected data by "Test Point" software for giving the average cutting force components. With the goal of obtaining valid results, all combinations are repeated from 5 to 10 times. The total average cutting force is calculated using formula:

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2}, \text{ N.} \tag{1}$$

Experimental investigations are conducted on the hardened alloy steel EN 10083-3 (41Cr4) that is performed for tightening on the clamping platform of the dynamometer. Manufacturer of the material is BH Steel-Željezara, Zenica. Mechanical properties and chemical composition of the examined steel are given in Tab. 1. During implementation of the experimental investigations a milling tool with exchangeable inserts of hard metal was used manufacturer SANDVIK Coromant. Basic data for the cutting tool is given in Tab. 2. The cutting tool is clamped to the motor spindle HSM by a tool interface HSK 40E, and it is produced in Technical office of SandvikCoromant in Germany as per the design prepared by the authors of this work.

Table 1 Mechanical properties and chemical composition of steel EN 10083-3 (41Cr4)

EN 10083-3 (41Cr4)	Mechanical properties								
	Tensile strength 1175 MPa		Yield strength 1099 MPa		Hardness 363 HB		Extension, A_5 11,2 %		Constriction, Z 54,4 %
	Chemical composition, %								
		C	Cr	Si	Mn	P	S	Cu	Ni
	Attest	0,45	1,37	0,22	0,70	0,020	0,025	0,12	0,05

Table 2 Basic data of cutting tool

Cutting tool	
Milling tool	R390-040Q16-11M
Type/Diameter	Arbor/40 mm
Number of teeth	4
Insert mark	R390-11 T3 32M-PM
Radius of tool tip, mm	3,2
Coating of inserts	GC1025 - PVD coating

3 Results analysis

Graphical presentation of the measured components of cutting forces F_x, F_y, F_z and the total average resulting cutting force F_R during high speed down-cut face milling for feed per tooth of 0,05 mm are given in Fig. 3, and for feed per tooth of 0,25 mm in Fig. 4. Cutting forces during high speed up-cut milling using feed per tooth of 0,05 mm and 0,25 mm are represented in Figs. 5 and 6, respectively.

On the basis of Figs. 3, 4, 5 and 6 it can be observed that the cutting forces decrease with the increase of cutting speed. In some cases, the cutting forces remained constant or slightly grew after reaching a specific cutting speed. Fig. 6 shows, that the cutting force F_R in the range of cutting speed from 1000 m/min to 1250 m/min and from 1500 m/min to 1750 m/min has the largest downward trend. Fig. 5 shows the cutting force F_R decreases until reaching the cutting speed of 2000 m/min, but it increases in the range of cutting speed from 2000 m/min to 2250 m/min. In this range of cutting speed, the cutting force value is still lower than in the case of the cutting speed of 750 m/min.

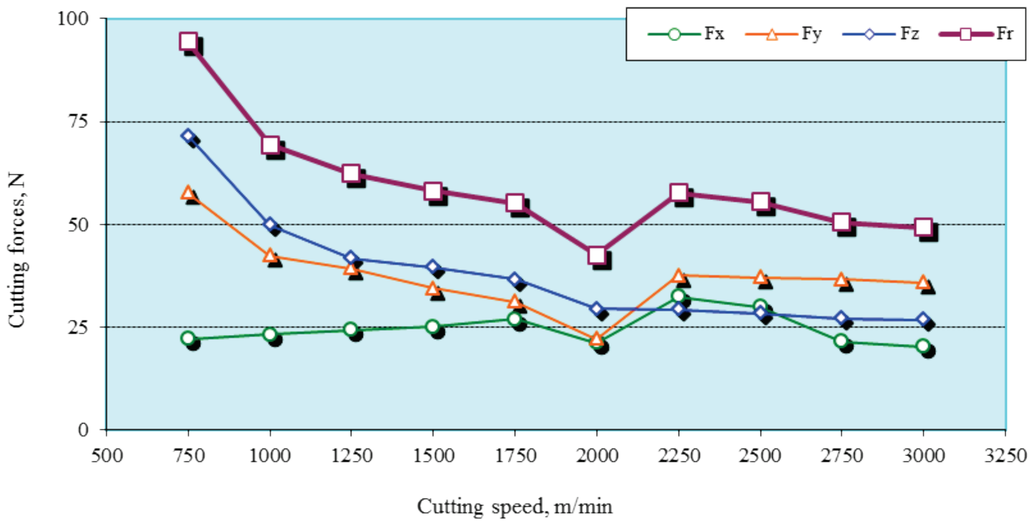

Figure 3 Effect of cutting speed on the components of cutting force F_x, F_y, F_z and the resulting force F_R (down –cut, f_z = 0,05 mm, a = 0,1 mm)

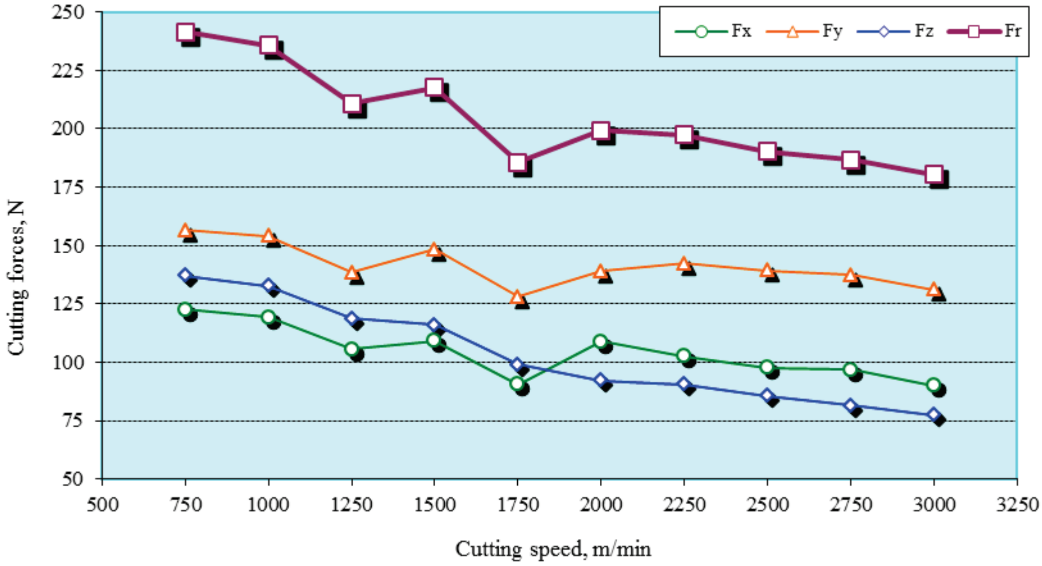

Figure 4 Effect of cutting speed on the components of cutting force F_x, F_y, F_z and the resulting force F_R (down –cut, f_z = 0,25 mm, a = 0,1 mm)

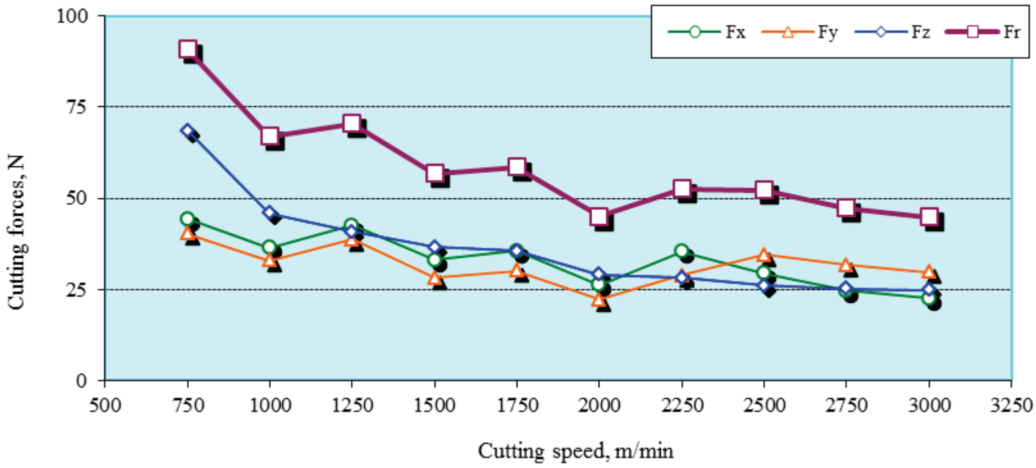

Figure 5 Effect of cutting speed on the components of cutting force F_x, F_y, F_z and the resulting force F_R (up –cut, f_z = 0,05 mm, a = 0,1 mm)

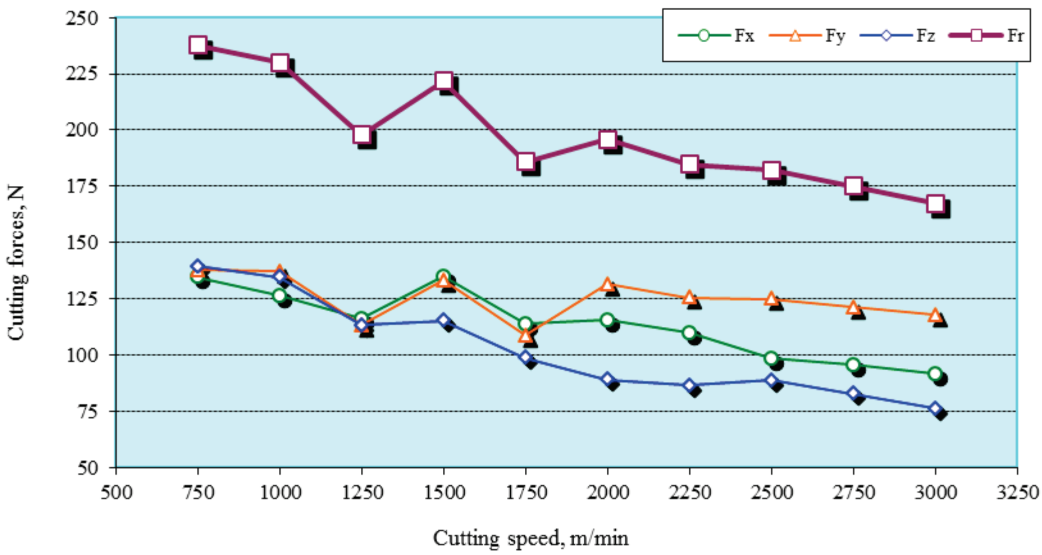

Figure 6 Effect of cutting speed on the components of cutting force F_x, F_y, F_z and the resulting force F_R (up –cut, f_z = 0,25 mm, a = 0,1 mm)

Furthermore, it is concluded that milling direction (up-cut and down-cut) has no great effect on the resulting cutting force. Investigations also show that the feed per tooth has great effect on the cutting forces. Cutting forces increase with the increase of feed per tooth.

4 Mathematical modelling of the process

Mathematical model for calculating of resulting cutting force F_R is approximated with second order polynomial expression:

$$Y_i = F_R = b_0 + b_1 \cdot X_1 + b_2 X_2 + b_{12} X_1 X_2 + b_{11} X_1^2 + b_{22} X_2^2, \quad (2)$$

where are:
F_R – resulting cutting force, N
b_0, b_1, b_2, b_{12}, b_{11}, b_{22} – model coefficients which would be determined after experiment was executed,
X_i – variables.

Namely, the parameters that have significant effect upon the cutting force during high speed milling are:

- cutting speed v_c, m/min, and
- feed per tooth f_z, mm.

The following factors have been considered as external factors during executing experiments:

- examined material - alloy steel EN 10083-3 (41Cr4),
- cutting tool (basic data is given in Tab. 2),
- high speed face milling,
- milling depth of 0,1 mm,
- milling width of 12 mm,
- experimental machining system VBS,
- 3–component dynamometer for measuring cutting forces.

Whereas the experiment is executed with two factors, the total number of experiments required (based on central composition plan) is:

$$N_e = n_k + n_\alpha + n_0 = 2^k + 2k + n_0 = 2^2 + 2\cdot 2 + 5 = 13, \quad (3)$$

where are:
N_e – total number of experiments, N_e=13
k – number of basic factors, k = 2
n_k – number of first order plan points, $n_k = 2^k = 4$
n_α – number of plan points on central axis, $n_\alpha = 2k = 4$
n_α– number of plan middle points, n_0=5.

Previous analysis of the significance of estimation of coefficients from model (2) shows that coefficients b_2, b_{12} are insignificant. Therefore, the new model for cutting force is defined by:

$$Y_i = F_R = b_0 + b_1 \cdot X_1 + b_{11} X_1^2 + b_{22} X_2^2, \quad (4)$$

Mathematical model (4), based on calculated coefficients, can be written as:

$$F_R = 241{,}193 - 0{,}223 X_1 + 6{,}1 \cdot 10^{-5} \cdot X_1^2 + 2490{,}74 \cdot X_2^2. \quad (5)$$

Results of investigation of resulting force values F_R for some machining parameters (cutting speed and feed per tooth) are given in Tab. 3.

Table 3 Testing results of resulting force F_R using model (5)

No. of measuring N_e	Variables		Results of research	
	v_c / m/min	f_z / mm	$F_R^{(E)}$ / N	$F_R^{(M)}$ / N
1	1250	0,05	62,3	63,9
2	2250	0,05	57,7	54,2
3	1250	0,25	210,8	213,3
4	2250	0,25	197,5	203,7
5	1750	0,15	94,2	93,6
6	1750	0,15	96,4	93,6
7	1750	0,15	97,1	93,6
8	1750	0,15	94,5	93,6
9	1750	0,15	93,8	93,6
10	1050	0,15	132,4	130,2
11	2450	0,15	118,2	116,7
12	1750	0,01	30,0	37,8
13	1750	0,29	250,4	247,1

Estimation of the significance of the calculated coefficients in the mathematical model has been done by using t-test with the following condition $t_{ri} > t_{(f_E, \alpha)} = 2{,}776$, where $f_E = n_0 - 1 = 5 - 1 = 4$ and significance level is $\alpha = 0{,}05$. Regression model testing is done by using the Fisher test with condition $F_a = 14{,}05 < F_{t(f_a, f_E)} = F_{t(4,4)} = 16$ and for significance level of $\alpha = 0{,}01$.

Coefficient of determination R^2 = 0,996 shows very good interactive dependence between variables X_i and force value F_R. Thus, it can be concluded that mathematical model (5) describes the resulting cutting forces with good accuracy and reliability (P =0,99, where P – is probability) during ultra high speed face milling of alloy steel EN 10083-3 (41Cr4) within the experimental domain, Fig. 7.

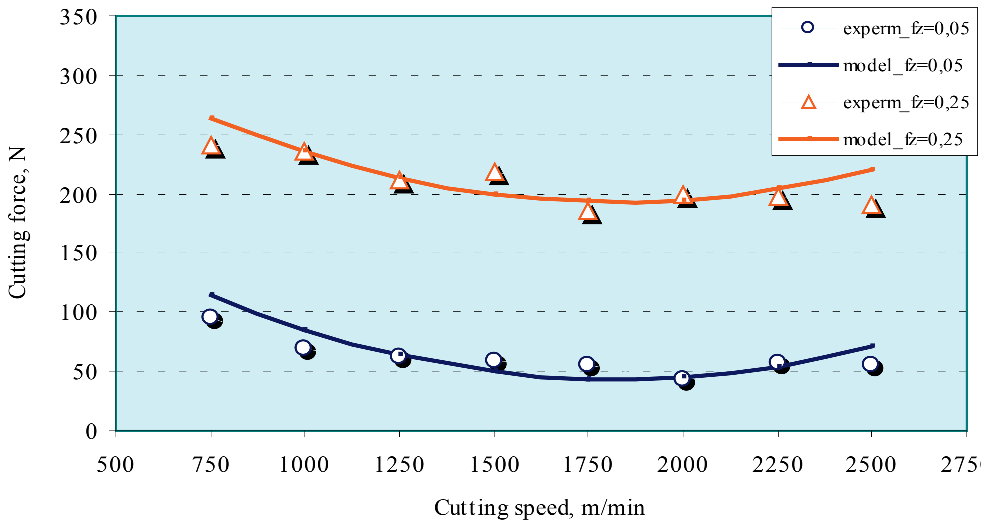

Figure 7 Comparison of experimental results and calculated values for resulting force F_R during machining of steel EN 10083-3 (41Cr4)

5 Conclusion

Considering the comprehensive experimental research in which 400 measurements were performed, the statistical treatment results that followed and the detailed theoretical investigations and analyses conducted, the following may be concluded:

- Results of measured cutting forces during ultra high speed face milling confirm the basic high speed machining characteristic which states that increasing cutting speed causes a decrease in cutting forces. Namely, with increasing cutting speed a change of the character of chips generation occurs. In other words, instead of the predominant plastic flow, shear conditions appear thus decreasing the required force. Actually, this force causes the shear conditions.
- Mathematical model (5) describes well the resulting cutting force F_R as a function of cutting speed and feed per tooth during face milling with ultra high cutting speed within the experiment domain. One of the future research directions is the development of a unique mathematical model in which cutting force will be represented as a function of machining parameters, material of the work-piece, tool material, tool geometry, etc.
- The VBS machining system, located at the Faculty of Mechanical Engineering in Sarajevo, provides excellent conditions for research of phenomena inherent during ultra-high speed milling.

6 References

[1] Dudzinski, D.; Molinari, A.; Schulz, H. Metal cutting and high speed machining. Kluwer Academic/Plenum Publishers, New York, 2002.

[2] Sokovic, M.; Kopac, J.; Dobrzanski, L.A.; Adamiak, M. Wear of PVD-coated solid carbide end mills in dry high-speed cutting. // Journal of Materials Processing Technology, 157–158, (2004), pp. 422-426.

[3] Dolinsek, S.; Sustarsic, B.; Kopac, J. Wear mechanisms of cutting tools in high-speed cutting processes. // Wear, 250, 1-12 (2001), pp. 349-356.

[4] Fang, N.; Wu, Q. A comparative study of the cutting forces in high speed machining of Ti-6Al-4V and Inconel 718 with a round cutting edge tool. // Journal of Materials Processing Technology, 209, (2009), pp. 4385-4389.

[5] Dewes, R. C.; Aspinwall, D. K. A review of ultra high speed milling of hardened steels. // Journal of Materials Processing Technology, 69, (1997), pp. 1-17.

[6] Kulenović, M.; Čekić, A.; Begić, Đ. The access to organizations of the investigations cutting forces and cutting temperature in high speed milling. // Annals of DAAAM for 2003 & Proceedings of the 14th Int. DAAAM Symposium/ Vienna, 2003, pp. 249-250.

[7] Kulenović, M.; Goja, Ž.; Čekić, A.; Begić-H, Đ. Development of the experimental system for investigating the phenomena in high speed milling. // DAAAM Int. Scientific Book 2004, Vienna 2004, pp. 333-340.

[8] Goja, Ž.; Čekić, A.; Husnjak, M. Driving possibilities and limitations of main spindles in high speed machining cells. // Annals of DAAAM for 2004 & Proceedings of the 14th Int. DAAAM Symposium, Vienna, 2003, pp. 165-166.

Used symbols

a	-	Milling depth, mm
f_z	-	Feed per tooth, mm
F_a	-	Calculating ratio of Fisher's criteria
f_E	-	Degree of freedom of experimental error
$F_{t(f_a, f_E)}$	-	The value of Fisher's criteria
F_R	-	Resulting cutting force, N
$F_R^{(E)}$	-	Experimental data of resulting force F_R, N
$F_R^{(M)}$	-	Model data of resulting force F_R, N
F_x	-	Component of resulting force in x direction, N
F_y	-	Component of resulting force in y direction, N
F_z	-	Component of resulting force in z direction, N
P	-	Probability
R^2	-	Determination coefficient
$t_{(f_E, \alpha)}$	-	The value of t – test
t_{ri}	-	Calculated value of t – test
α	-	Significance level.

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