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STUDY ON THE CUTTING FORCES DURING FACE MILLING OF A HARD STEEL

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Abstract: *Hard steels are often used in the die and mold industry, but also in other industries, such as the automotive and naval industries. These types of steels have certain difficulties in their machining processes, which is why these aspects must be analysed and understood in order to correctly determine the cutting tools, the technological devices used, and the technological parameters utilised. In this paper, the process forces for face milling of hard 55NiCrMoV7 steel are analysed. An elastic device with strain gauge marks is used to measure the cutting forces in three directions, and a face-centered composite design is implemented, in which the cutting depth, feed per tooth, and cutting speed are varying. The results highlight the influences of cutting parameters on process forces based on dependency equations. The study provides theoretical and technical support for the analysis of face milling of hard steels.*

Key words: *hard milling, hardened steel, face milling, force measurement, cutting force, design of experiments, central composite design.*

1. INTRODUCTION

With good dimensional and thermal stability, outstanding wear resistance, hard and extra-hard steels have a wide variety of uses in all industries, particularly in the mould and die industry. High hardnesses require heat treatment operations, resulting in an increase in hardness throughout the material structure with values exceeding 40 Rockwell C units. This hardening of the material leads to multiple difficulties in processing the material, especially by machining. At the same time, the resulting high cutting temperatures lead to microstructural changes that reduce the machinability of these types of materials. Thus, among the main aspects that need to be studied in the machining processes of these materials are the resultant forces [1–5].

Face milling is one of the most common machining processes [6, 7], almost any finished part requires a face milling. Currently, it is most common to use face milling cutters of the modular type with removable inserts. The variety of geometries for modular inserts used in milling processes satisfies requirements such as large volume of material removal or high surface quality.

In numerous scientific papers, equipment for determining the evolution of process forces is developed and used [8–13], which can be stationary [8, 10, 12] or rotary stations [9, 13, 14]. Original equipments are developed such as devices with elastic regions and strain gauge marks mounted on their walls in convenient areas in order to record micro-deformations as electrical signals [8, 9, 14] or devices with piezoelectric material [10, 11]. Most researchers resort to solutions developed by well-established companies, such as stationary devices with piezoelectric material [2, 7, 15–18].

An important aspect in the analysis of process forces is the use experimental designs that allow a statistical analysis of the results, established in advance by planning a series of experiments. A variety of such strategies have been developed [1, 4, 18–21] and most of them solve some important problems, providing argumentative and sufficient answers to establish some relationships between input parameters, represented by process parameters, and output parameters, such as forces, temperatures, etc. The dependencies are determined in most cases by mathematical regressions and, finally, the determination of equations [1, 18–20].

In this paper, the influence of cutting parameters on the process forces for the face milling process is studied when machining a steel with a hardness of 46 HRC. A device with strain gauge marks is used to measure the process forces, and to determine the dependencies of the process forces in relation to the cutting parameters: cutting depth - a_p, feed per tooth - f_z and cutting speed - v_c, it is used a face-centered composite design and response surface method. The analysis of cutting forces in milling processes is important because this parameter is closely related to the quality of machined surfaces and tool wear.

2. EXPERIMENTAL SETUP AND DESIGN OF EXPERIMENTS

2.1 Experimental setup

Face milling machining was carried out on a DMG MORI ecoMill70 CNC machine in a dry environment. Material removal was achieved by rotating the cutter at speed v_c and longitudinal feed of the cutter along the X-axis, shown in figure 1.

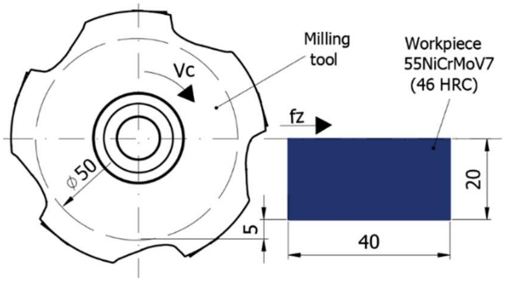


Fig.1. Sketch for milling hard steel

The tool used is a modular milling cutter for machining flat surfaces with a diameter of Ø50 mm and an angle of engagement of 45°, acquired from Sandvik Coromant. The cutter body code is 345-050Q22-13H and the insert code is 345R-1305M-PM 1130. The inserts are made of carbide metal and have PVD (Physical Vapor Deposition) coatings of AlTiCrN.

The material used for the experiments is a nickel-chromium alloy steel 55NiCrMoV7, with a hardness throughout the material of about 46 HRC. It is mainly used for moulds, for which machining by milling is necessary to achieve the functional surfaces, according to the requirements of the technical specification. The workpiece used is a prismatic body, with dimensions of 20 mm × 40 mm × 40 mm, as can be seen in figure 1 and figure 2. The length and width of the blank were set so as to allow the study of the cutting force on a single tooth of the cutter, starting from a maximum chip thickness to a minimum chip thickness when the tooth passes through the cutting area. The height of the workpiece was set so that it could be used for all the experiments foreseen by the experimental design.

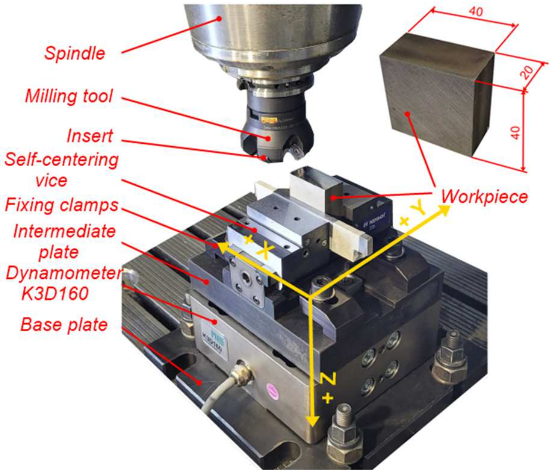


Fig.2. Photo of the experimental setup

The workpiece is oriented and fixed in a self-centering vise that is secured to an intermediate plate with clamps and bolts, as shown in figure 2. The intermediate plate is mounted on the force-measuring device - an elastic dynamometer with strain gauge marks (Meßsysteme model K3D160) which can measure forces up to 20kN in all directions along its three axes X, Y and Z. In turn, the dynamometer is mounted on a base plate with screws, and this is mounted on the machine tool table with T-channel bolts, washers and nuts.

The electrical signals (electrical resistivities associated with the elastic micro-deformations of the dynamometer) are taken from the elastic dynamometer, amplified by the NI 9237 module, then recorded on a computer unit using the Matlab R2022b software in the Analog Imput Recorder module, shown in figure 3. The resistivity values thus measured are transformed into force values based on the calibration equation of the elastic dynamometer.

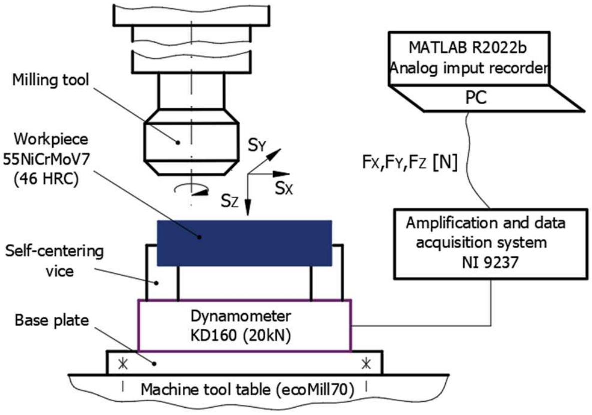


Fig.3. Sketch of the experimental system

2.2 Design of Experiments

In the milling process there are many input variables that influence the response of the output variables, but in this study only depth of cut - a_p, feed per tooth - f_z and cutting speed - v_c were varied. These are the most significant analysis factors for milling processes as studied in several scientific papers [16,17,19].

A three-variable (a_p, f_z and v_c) face-centered composite experimental design was selected for the design of the experiments, and the response surface method was used to analyze the results. This method is a numerical and statistical procedure that allows the analysis of the influence of some input parameters on the system response and is a robust method for a study with several input factors. The general regression equation to be obtained is a second-order polynomial equation, expressed as equation 1, where z values are the natural independent variables, B values are the coefficients corresponding to these variables, and Y is the response of the equation.

$$Y = B_0 + \sum_{i=1}^{k} B_i z_i + \sum_{i=1}^{k} B_{ii} z_i^2 + \sum_{i=1}^{k\text{-}1} \sum_{j=i+1}^{k} B_{ij} z_i z_j \qquad (1)$$

The limits of the input variables in the experimental design are shown in table 1, where the upper +1 and lower -1 limits are specified and the intermediate level is set as the arithmetic mean between the upper and lower limit. These limits were chosen in accordance with the recommendations of the insert manufacturer and the limitations of the machining technology used, especially in relation to the feed per tooth. The number of experiments required was obtained with equation 2, where N is the number of experiments to be performed and k is the number of independent factors. The free element n_0, represents the number of replications, whose recommended value [22] for an experimental design of this type is six replications.

$$N = 2^k + 2k + n_0 = 2^3 + 2 \cdot 3 + 6 = 20 \qquad (2)$$

Table 1

Limits of the input variables in the design of the experiments.

Normalized independent variables	Levels	Zi_{min} = -1	Zi_{max} = +1
Physical independent variables	$X_1 = a_p$ [mm]	1	2
	$X_2 = f_z$ [mm/ tooth]	0.1	0.2
	$X_3 = v_c$ [m/min]	90	150

Therefore, 20 experiments are required, which can be represented schematically as in figure 4, with eight experiment points at the extreme points, six points in the middle of the surfaces and six points in the centre of the experimental setup. The distribution of input variables within each experiment is shown in table 2.

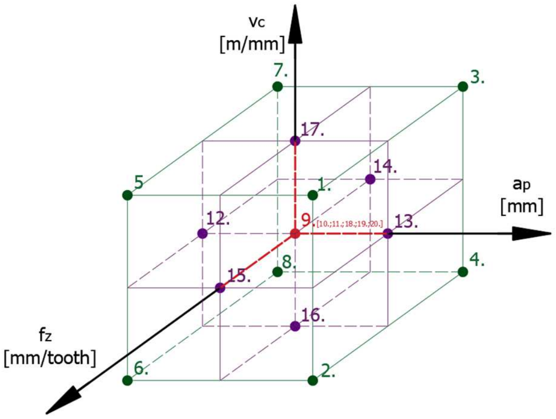


Fig.4. Graphical representation of the face-centered composite design with 3 factors

Table 2

Experimental design variables.

No. exp.	**Normalized independent variables**			**Physical independent variables**			**Maximum resultant forces**		
	a_p [mm]	**f_z [mm/tooth]**	**v_c [m/min]**	**a_p [mm]**	**f_z [mm/tooth]**	**v_c [m/min]**	**F_{Xmax} [N]**	**F_{Ymax} [N]**	**F_{Zmax} [N]**
1.	1	1	1	2	0.2	150	180.7	1165.5	310.2
2.	1	1	-1	2	0.2	90	268.4	1316	347.1
3.	1	-1	1	2	0.1	150	175.6	751.9	260.5
4.	1	-1	-1	2	0.1	90	211.1	836	290.8
5.	-1	1	1	1	0.2	150	96	615.7	194.8
6.	-1	1	-1	1	0.2	90	137.7	708.3	205.4
7.	-1	-1	1	1	0.1	150	95.2	409.5	154.5
8.	-1	-1	-1	1	0.1	90	110.6	438.8	165.1
9.	0	0	0	1.5	0.15	120	136.8	798.8	265.3
10.	0	0	0	1.5	0.15	120	146.5	801.7	271.9
11.	0	0	0	1.5	0.15	120	149.6	801	271.6
12.	-1	0	0	1	0.15	120	99.2	557.7	202.3
13.	1	0	0	2	0.15	120	189.8	1046.5	335.2
14.	0	-1	0	1.5	0.1	120	143.9	620.7	243.1
15.	0	1	0	1.5	0.2	120	150.3	966.4	288.5
16.	0	0	-1	1.5	0.15	90	175.8	826	260.6
17.	0	0	1	1.5	0.15	150	141.4	741.8	247.5
18.	0	0	0	1.5	0.15	120	150.3	805.2	276
19.	0	0	0	1.5	0.15	120	143.4	799.3	269.6
20.	0	0	0	1.5	0.15	120	145.4	802	265.4

3. ANALYSIS OF CUTTING FORCES

For each experiment, a detailed analysis of the evolution of the cutting forces was first carried out for each axis, the direction of the axes being shown in figure 2. This paper presents, as an example, the detailed analysis of the evolution of the cutting forces for the first experiment in the design, carried out at one extreme point, where the parameters of the cutting operation were: cutting depth of 2 mm, feed per tooth of 0.2 mm/tooth and cutting speed of 150 m/min, as shown in figure 5. The graph in figure 5 shows a cutting initiation zone, a cutting end zone and a process stability zone, in which the cutter is fully engaged in machining and the force evolution is constant.

From the process stability area, shown in figure 5, is detailed an analysis of an area corresponding to a full rotation of the cutter. This is detailed in figure 6, showing that the evolution of each tooth is slightly different. This is due to deviations in the orientation and fixing of the inserts in the slot in the cutter body.

The cutting force evolutions on each of the three axes, for a complete rotation of the tool in the investigated area, are detailed in figures 7, 8 and 9. It can be seen that:

- in the X direction, the cutting forces for the five teeth of the cutter are relatively constant during a full rotation of the cutter;
- in the Y-direction, the cutting forces for the five teeth of the cutter move in a negative direction of the axis;
- in the Z-direction, the cutting forces for the five teeth of the cutter move in the positive direction of the axis.

Such a detailed analysis was carried out for each experiment in the experimental design, finding the same dependencies.

Subsequently, for each experiment, the arithmetic averages of the maximum cutting force values for each of the five teeth of the milling cutter were determined and are shown in table 2. These values were finally used in the response surface method analysis of the influence of the cutting conditions parameters on the cutting forces.

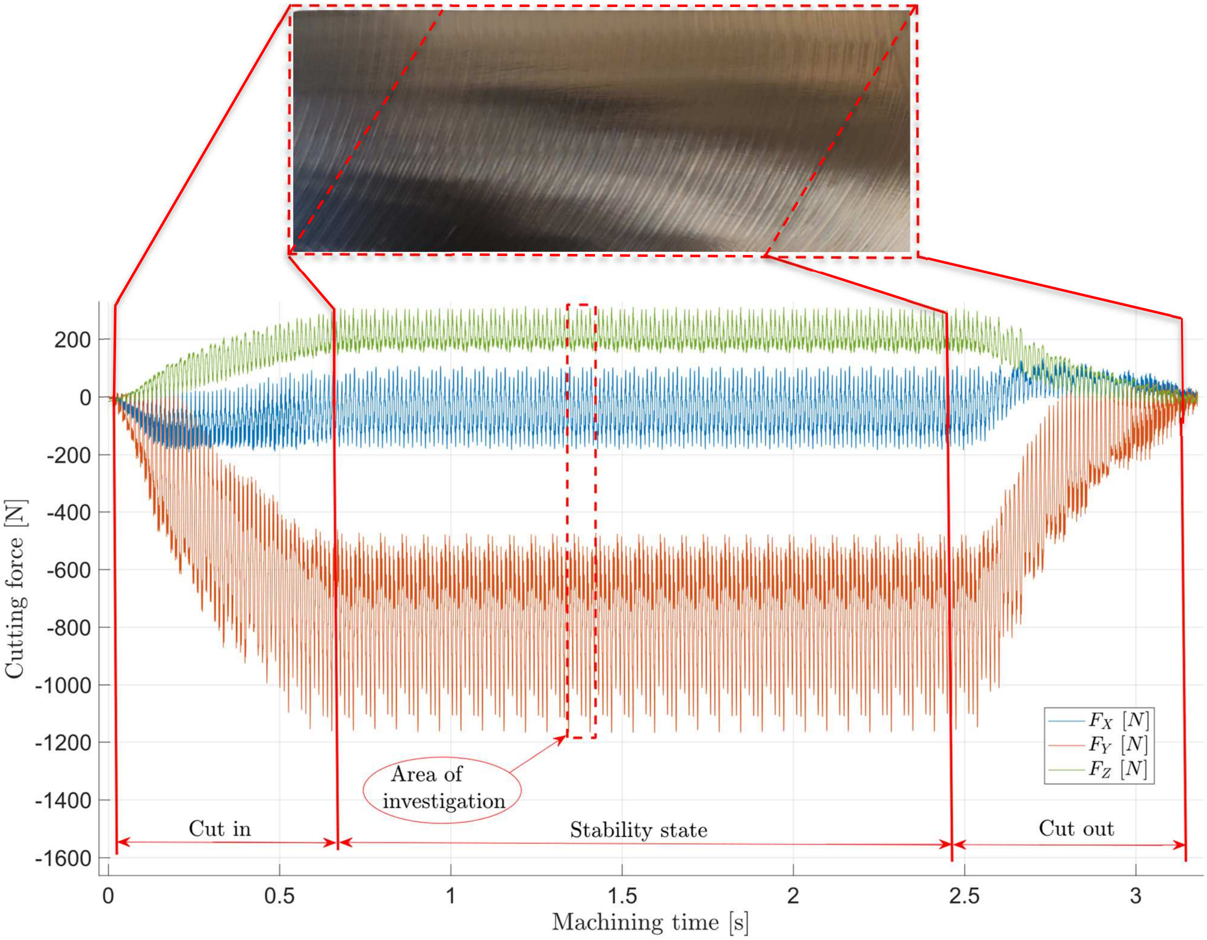


Fig.5. Evolution of cutting forces in relation to the machined surface

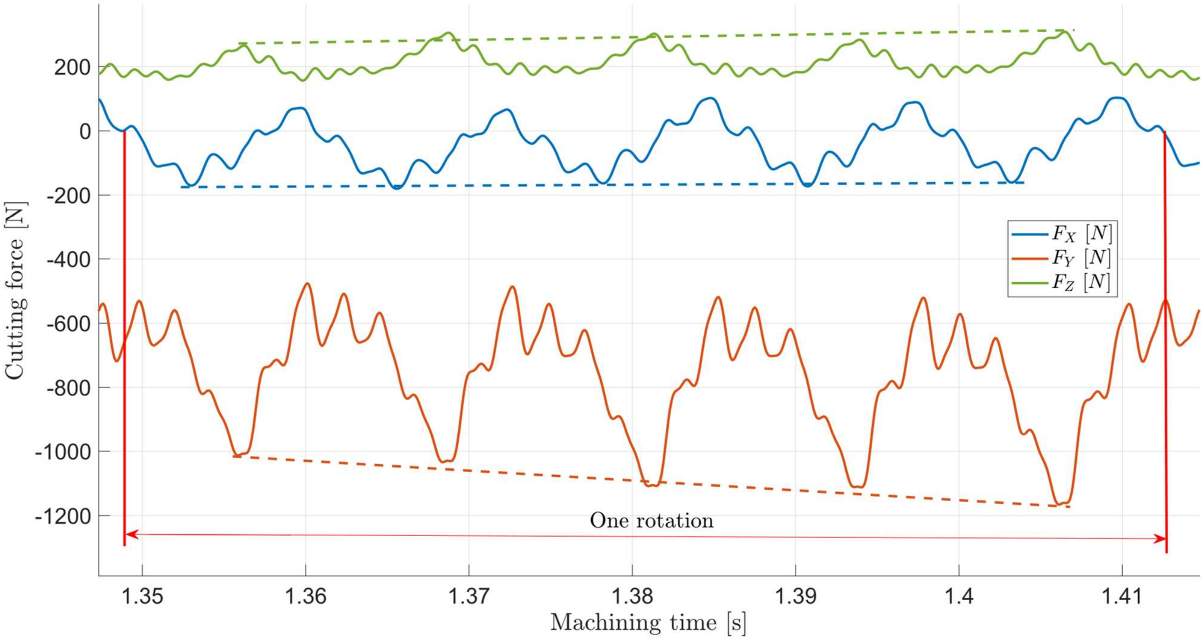


Fig.6. Force progression for full tool rotation in the process stability zone

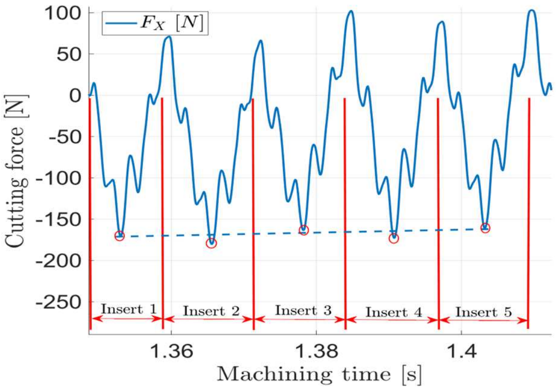


Fig.7. Forces in X-axis direction

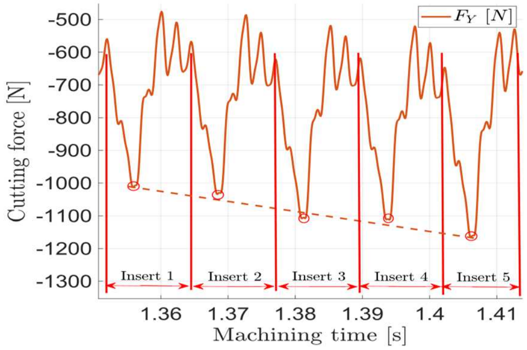


Fig.8. Forces in Y-axis direction

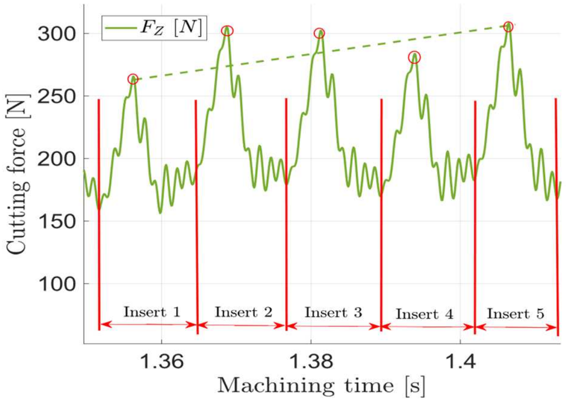


Fig.9. Forces in Z-axis direction

4. RESULTS AND DISCUSSIONS

The regression study and application of the response surface method uses the results obtained for the maximum cutting forces in the process stability region in the face-centered composite experimental design, is in table 2.

Minitab Statistical Software was used for the regression analysis. The mathematical equations obtained for the cutting forces on each of the three axes Fx, Fy and Fz are shown in equations 3, 4 and 5, and the residuals and deviations of the results are shown in figures 10, 11 and 12 for each of the X, Y and Z axes.

$$\begin{aligned} F_{X_{\max}} = {} & 97.2 + 148.1 a_p + 513 f_z - 2.43 v_c \\ & - 3.5\, a_p^2 + 689\, f_z^2 + 0.01469\, v_c^2 \\ & + 172.5\, a_p \cdot f_z - 0.551\, a_p \cdot v_c \\ & - 6.54\, f_z \cdot v_c \quad [N] \end{aligned} \tag{3}$$

$$\begin{aligned} F_{Y_{\max}} = {} & -447.5 + 252.7 a_p + 2381 f_z + 5.887 v_c \\ & + 7.91\, a_p^2 - 2629\, f_z^2 - 0.01803\, v_c^2 \\ & + 2089.5\, a_p \cdot f_z - 0.9392\, a_p \cdot v_c \\ & - 10.808\, f_z \cdot v_c \quad [N] \end{aligned} \tag{4}$$

$$\begin{aligned} F_{Z_{\max}} = {} & -392 + 199.1 a_p + 1172 f_z + 5.302 v_c \\ & - 15.9 a_p^2 - 2775\, f_z^2 - 0.02076\, v_c^2 \\ & + 127\, a_p \cdot f_z - 0.383\, a_p \cdot v_c \\ & - 0.55\, f_z \cdot v_c \quad [N] \end{aligned} \tag{5}$$

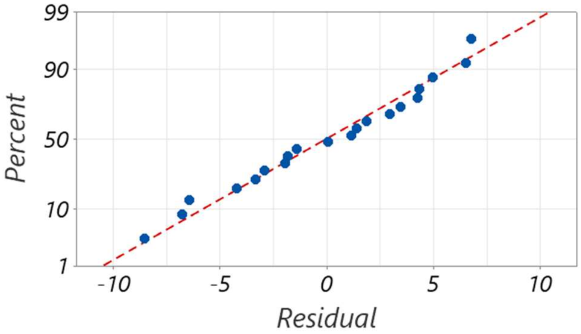


Fig.10. Residuals for force equations in X-axis direction

The point value distributions are found to have a high degree of proximity to the normal line, which demonstrates that the regression model considered is suitable for determining the dependencies of cutting forces on the cutting parameters.

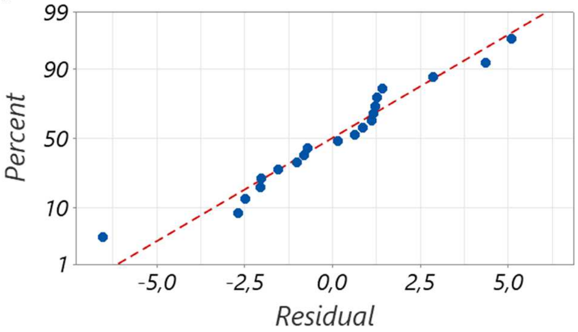


Fig.11. Residuals for force equations in Y-axis direction

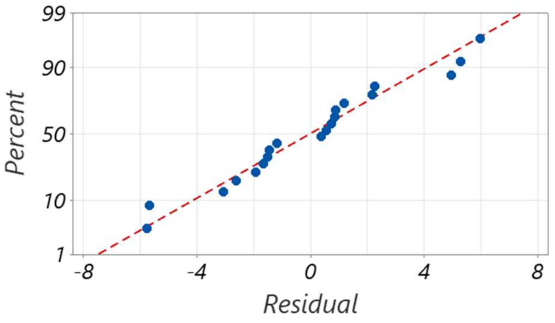
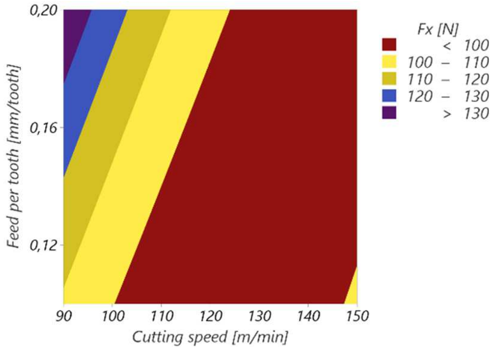


Fig.12. Residuals for force equations in Z-axis direction

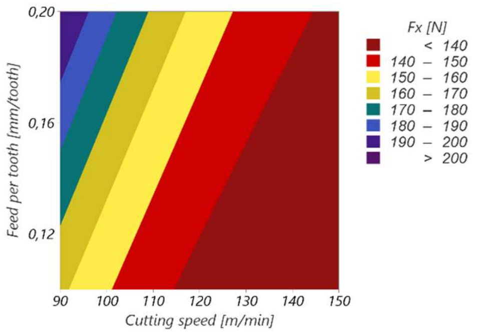
Using equations 3 - 5, which express the dependence of the cutting forces on the cutting parameters, interpretations can be made for each of the three axes as follows.

In the X-axis direction, illustrated in figures 13 a, b and c, the cutting force values increase with increasing machining depth. This increase is more pronounced for the parameters associated with the cutting operation: feed per tooth = 0.2 mm/tooth and cutting speed = 90 m/min, compared to the parameters associated with the cutting operation: feed per tooth = 0.1 mm/tooth and cutting speed = 150 m/min. It is also shown that the values of cutting forces increase with increasing feed rate per tooth, for each of the machining depths and at any of the cutting speeds, due to the increase in the energy required for chip formation when considerable plastic deformation is concentrated.

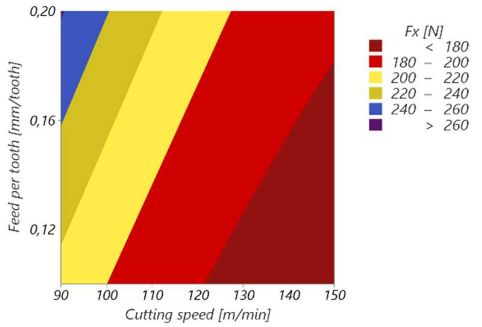
In the Y-axis direction, from the analysis of figures 14 a, b and c, it can be seen that the highest values for the cutting forces were obtained. The highest values always result for the pair of parameters of the cutting operation: feed per tooth = 0.2 mm and cutting speed = 90 m/min, and the lowest values for the pair of parameters: feed per tooth = 0.1 mm and cutting speed = 150 m/min.



a)

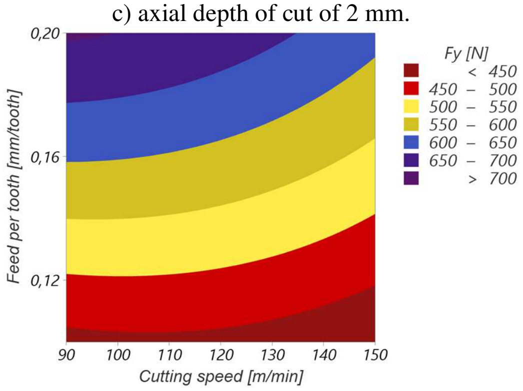


b)

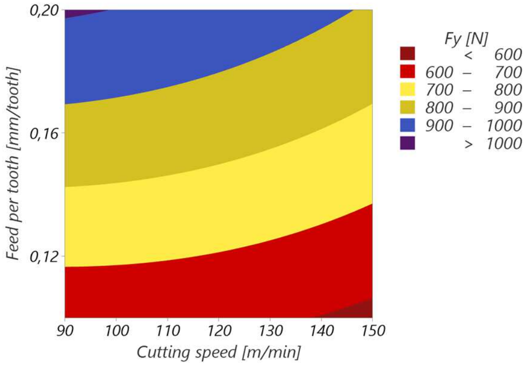


c)

Fig.13. Response surface for values of maximum cutting forces along the X-axis as a function of cutting speed and feed per tooth for:
a) axial depth of cut of 1 mm,
b) axial depth of cut of 1.5 mm and
c) axial depth of cut of 2 mm.



a)



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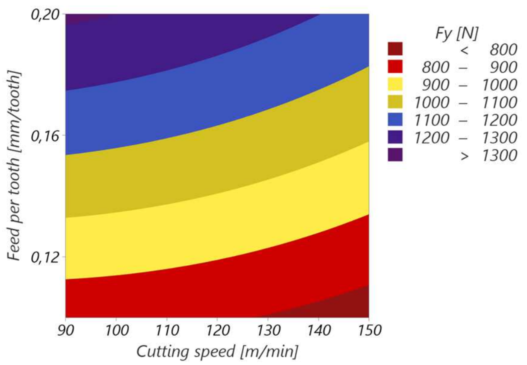
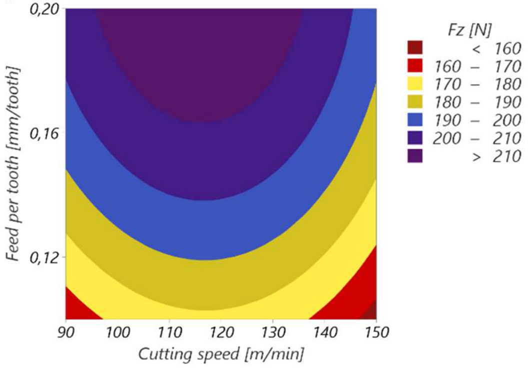


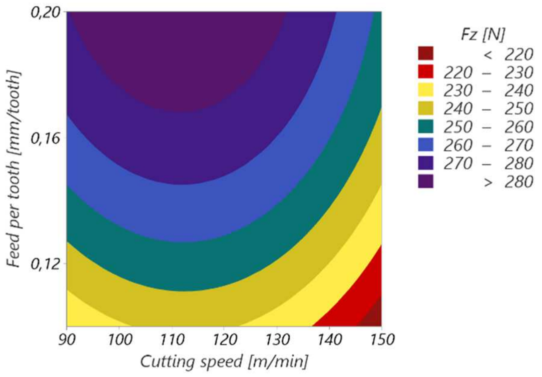
c)

Fig.14. Response surface for values of maximum cutting forces along the Y-axis as a function of cutting speed and feed per tooth for:
a) axial depth of cut of 1 mm,
b) axial depth of cut of 1.5 mm and
c) axial depth of cut of 2 mm.

In the Z-axis direction, from the analysis of figures 15 a, b and c, it follows that the cutting gaps on this axis increase with increasing the cutting depth, but also with increasing the feed per tooth, being greater than those in the X-axis direction. This is due to the fact that there is a significant component of chipping force in the Z-axis direction for a 45° cutter angle of engagement.



a)



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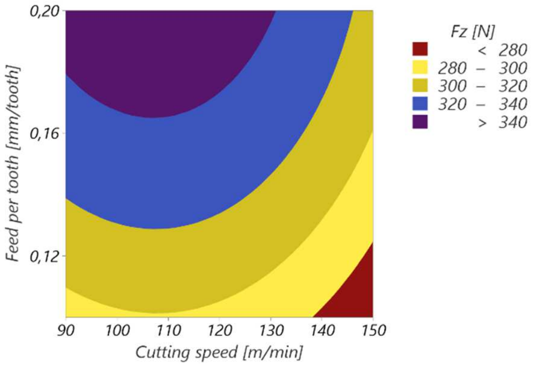

c)

Fig.15. Response surface for values of maximum cutting forces along the Z-axis as a function of cutting speed and feed per tooth for:
a) axial depth of cut of 1 mm,
b) axial depth of cut of 1.5 mm and
c) axial depth of cut of 2 mm.

The maximum cutting forces in the Z-axis direction are in the range of cutting speeds 100-120 m/min and for a feed per tooth of 0.2 mm/tooth for each cutting depth used. At higher cutting speeds the forces are found to be lower, which is due to rapid chip initiation at the impact between the edge of the removable insert and the workpiece.

5. CONCLUSION

This study presents findings of research on the face milling process with a modular milling cutter with removable carbide inserts with AlTiCrN coatings, of a hard steel 55NiCrMoV7 with a hardness of 46 HRC.

It is shown how the three-dimensional measurement of the cutting forces is carried out and how they evolve along the process. For the stability range of the cutting process, associated with the full engagement of the cutter in the cutting operation, a detailed analysis of the cutting forces was carried out, showing differences between the maximum values of the maximum cutting forces in the three directions and on each of the five cutter teeth.

We determined the equations describing the dependence of cutting forces on the parameters of the cutting conditions by using a face-centered composite experimental design and multivariable regression analysis. Using the equations obtained in this way and the response surface method, the main dependencies of the cutting force on the parameters of the cutting conditions were identified. Thus, it was found that:

(1) cutting forces increase with increasing cutting depth;

(2) cutting forces increase in all three measurement directions with increasing tooth feed;

(3) relatively low cutting forces are obtained for higher cutting speeds, which is due to rapid chip initiation.

The results obtained can be used in industry and research to study the influence of cutting parameters on the process forces in the face milling of hard metals.

Research can be continued by correlating the evolution of cutting forces with process temperatures and numerical simulation of the cutting process to optimise it.

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Studiul forțelor de așchiere la frezarea plan-frontală a unui oțel dur

Oțelurile dure sunt des utilizate în industria ștanțelor și matrițelor, dar și în alte industrii, cum sunt industria de automobile sau industria navală. Aceste tipuri de oțeluri au anumite dificultăți la prelucrarea lor prin așchiere, motiv pentru care aceste aspecte trebuie analizate şi înțelese pentru a stabili corect sculele așchietoare, dispozitivele tehnologice utilizate și parametrii tehnologici utilizați. În lucrare sunt analizate forțele de proces pentru frezarea plan-frontală a oțelului dur 55NiCrMoV7. Se utilizează un dispozitiv elastic cu mărci tensometrice pentru măsurarea forțelor de așchiere pe trei direcții și este implementat un plan experimental de tip factorial compus cu fețe centrate, în care sunt variate adâncimea de așchiere, avansul pe dinte și viteza de așchiere.

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