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DESIGN OF EXPERIMENT'S APPLICATION IN THE OPTIMIZATION OF MILLING PROCESS

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This paper examines the influence of cutting parameters on surface roughness of steel workpiece. The experiments have been carried out in accordance with a design of experiments (DOE). Equation for the surface roughness, as a function of cutting parameters, has been obtained by means of regression analysis. To obtain the minimal value of surface roughness, the equation optimizing was performed by using partial derivations and solving system of equations. The Taguchi method, with orthogonal arrays and signal to noise ratio, has been used to analyse impact of various cutting parameters on surface roughness and to find optimal levels of the cutting parameters. The comparison of results obtained by means of the response surface method and the Taguchi method was performed.

Key words: face milling, surface roughness, design of experiments, regression analysis, Taguchi method

Primjena plana pokusa u optimizaciji procesa glodanja. U radu je istraživana kvaliteta obrađene površine čeličnog obratka pri različitim parametrima obrade. Pokusi su izvedeni sukladno odabranom planu pokusa. Regresijskom analizom dobivena je jednadžba hrapavosti obrađene površine u ovisnosti o parametrima obrade. U cilju dobivanja minimalne hrapavosti obrađene površine obavljeno je optimiranje jednadžbe parcijalnim deriviranjem i rješavanjem sustava jednadžbi. Taguchijeva metoda s ortogonalnim nizovima i omjerom signala i šuma korištena je za analizu utjecaja parametara obrade na hrapavost površine te pronalaženje optimalne razine parametara. Na kraju su uspoređeni rezultati dobiveni metodom odzivne površine i Taguchijeve metode.

Ključne riječi: čeono glodanje, hrapavost obrađene površine, plan pokusa, regresijska analiza, Taguchijeva metoda

INTRODUCTION

Surface roughness is the characteristic of surface which describes the surface quality, with regard to machining. Machining accuracy is realized by selected cutting operations, which have limited capability of attaining the required surface roughness. Following modern production requests and technologic-economic analysis of processing operations, during the designing process, it is necessary to determine optimal cutting parameters in order to achieve minimal expenses or minimal production time. In their research, researchers have applied many statistical methods for prediction of optimal cutting parameters [1-4].

The subject of this study is to analyse dependence of surface roughness on three cutting parameters in face milling (cutting speed v_c, feed rate f_z and depth of cut a_p). In this work the response surface method (RSM) based on the rotatable central composite design (RCCD) has been used together with an analysis of variance (ANOVA) and regression analysis (RA). To obtain the minimal value of surface roughness, the surface roughness equation has been optimized by finding the partial derivations and solving the system of equations. A comparison of results obtained by means of the Taguchi method with the regression model was carried out. The Taguchi method, based on orthogonal arrays, has been used also for determining the influence of particular cutting parameters.

CONDITIONS OF EXPERIMENT

The face milling experiments were carried out on vertical machining center VC560, produced by Spinner, by using a face mill Helido S845 F45SX D063-05-22-R16 and inserts with eight helical right-hand cutting edges, S845 SXMU 1606ADTR-MM.

Test samples made of steel St 52-3, with dimensions 230 x 100 x 100 mm were prepared to remove rust, grooves and all damages from the top surface that was to be machined.

The surface roughness were measured by SJ301 instrument, produced by Mitutoyo.

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APPLICATION OF ROTATABLE CENTRAL COMPOSITE DESIGN (RCCD)

Design of experiment (DOE) was achieved using the rotatable central composite design (RCCD). The RCCD models response using the empirical second-order polynomial:

$$y = b_0 + \sum_{i=0}^{k} b_i \cdot X_i + \sum_{1\le i<j}^{k} b_{ij} \cdot X_i \cdot X_j + \sum_{i=1}^{k} b_{ii} \cdot x_i^2 \quad (1)$$

where:

– b_0, b_i, b_{ij} and b_{ii} are regression coefficients,
– X_i, X_j are the coded values of input factors.

The required number of experimental points for RCCD is determined by using expression:

$$N = 2^k + 2k + n_0 = n_k + n_\alpha + n_0 \quad (2)$$

where:

– k is the number of parameters,
– n_0 is the repeated design number on the average level,
– n_α is the design number on central axes.

Coordinate α is determined by expression:

$$\alpha = (2^k)^{1/2} \quad (3)$$

RCCD of experiment demands for measurements to be performed on 8 observed conditions (3 factors on two levels, 2^3), 6 observed conditions on the average level of input factors and 6 observed conditions on central axes, what makes total of 20 observed conditions. The theory of design of experiments and mathematical-statistical analysis use coded values of input factors of milling process. The coded values of three independent input factors obtain value of five levels, from -1,682 to +1,682.

Considering material of workpiece and tool producer recommendations for cutting parameters, Table 1 has been created, for 3-factor design of experiments.

Table 1. **Physical and coded values of input factors for second order design of experiments.**

Input factors						
Coded values	Levels	-1,682	-1	0	1	1,682
Physical values	$X_1 = v_c$ m/min	140	150	165	180	190
	$X_2 = f_z$ mm/tooth	0,20	0,24	0,30	0,36	0,40
	$X_3 = a_p$ mm	0,82	1,30	2,00	2,70	3,18

ANOVA and RA have been performed using software Design Expert 6.0. Measurements of surface roughness have been presented in Table 2. By applying regression analysis the values of coefficients of multiple regression have been assessed. The mathematical model, which describes the effect of influential factors on surface roughness, has also been obtained:

$$\begin{aligned} Ra = {} & 4{,}9271 - 0{,}0574 \cdot v_c + 1{,}1808 \cdot f_z - 0{,}0273 \cdot a_p \\ & + 1{,}78035 \cdot 10^{-4} \cdot v_c^2 + 11{,}6182 \cdot f_z^2 + 0{,}031243 \cdot a_p^2 - \\ & - 0{,}025 \cdot v_c \cdot f_z - 4{,}7619 \cdot 10^{-4} \cdot v_c \cdot a_p + 0{,}29762 \cdot f_z \cdot a_p \end{aligned} \quad (4)$$

where:

– v_c is cutting speed, m/min,
– f_z is feed rate, mm/tooth,
– a_p is depth of cut, mm.

Table 2. **Results of surface roughness examination according to multifactor second order design**

Number of experiment	Factors			Ra /µm
	X_1	X_2	X_3	
1.	0	0	0	0,57
2.	1	1	1	0,88
3.	1,682	0	0	0,45
4.	1	-1	-1	0,28
5.	0	0	0	0,48
6.	-1	-1	1	0,47
7.	0	0	-1,682	0,42
8.	0	0	0	0,50
9.	0	0	0	0,59
10.	-1,682	0	0	0,92
11.	0	0	1,682	0,81
12.	1	1	-1	0,77
13.	-1	1	1	1,10
14.	1	-1	1	0,34
15.	0	-1,682	0	0,23
16.	0	0	0	0,60
17.	0	1,682	0	1,15
18.	-1	1	-1	0,97
19.	0	0	0	0,62
20.	-1	-1	-1	0,39

Analysis of results and optimization of influencing parameters

The analysis of variance and the regression analysis indicate:

– variables which affect *Ra*, and are significant for mathematical model are: cutting speed v_c, feed rate f_z, depth of cut a_p, square of cutting speed v_c^2 and square of feed rate f_z^2,
– feed rate f_z has the most significant influence on surface roughness,
– variable a_p^2, the interactions of cutting speed and feed rate $v_c \cdot f_z$, cutting speed and depth of cut $v_c \cdot a_p$, and feed rate and depth of cut $f_z \cdot a_p$ do not significantly affect surface roughness, so they can be excluded from mathematical model,
– standard deviation is 0,067,

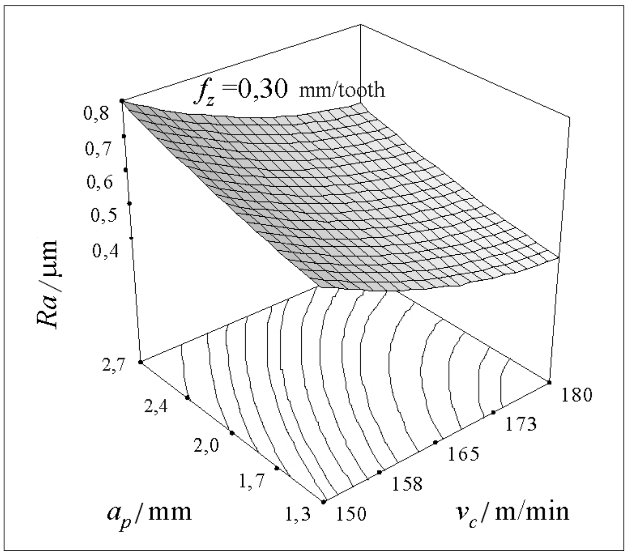

Figure 1. Influence of depth of cut and cutting speed on surface roughness at constant feed rate, f_z = 0,30mm/tooth

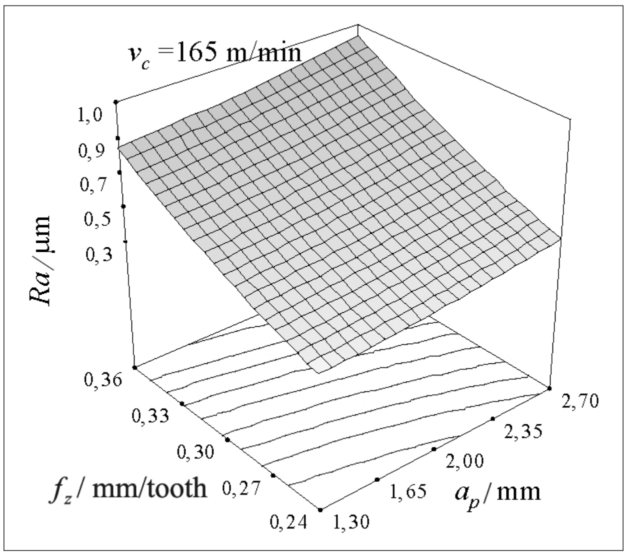

Figure 2. Influence of feed rate and depth of cut on surface roughness at constant cutting speed, v_c = 165 m/min

– coefficient of determination is R^2=0,9678, which means that the model is representative, because it clarifies 96,78 % of deviations, which are the result of variable's influence.

Optimal cutting parameters for minimal surface roughness, have been analitically achieved. The necessary condition for existing of extreme value is that partial derivation of equation (4), per every undependent variable, has zero value. When the Sylvester's criterion has been met (second derivation per every independent variable is greater than zero), then this extreme is minimal value of the function presented with expression (4).

Optimal cutting parameters for minimal value of surface roughness are:

v_c=171 m/min, f_z=0,12 mm/tooth, a_p=1,18 mm.

Figures 1, 2 and 3 show the dependence of surface roughness on the two factors which combine, whereas the value of the third factor is constant and has the mean value.

APPLICATION OF ROBUST DESIGN OF EXPERIMENT: TAGUCHI METHOD

The Taguchi's design of experiments uses orthogonal arrays, the basic characteristics of which is balance, i.e. both balance of elements of columns and balance between the columns. This means that every factor appears on the same number of levels and that every factor on any level will be in all combinations with other factors. The number of input factors, as in the RCCD, is three, but the levels of input factors have been changed. In the design of experiments based on othogonal array L9 (3^4), three levels have been used. The necessary number of

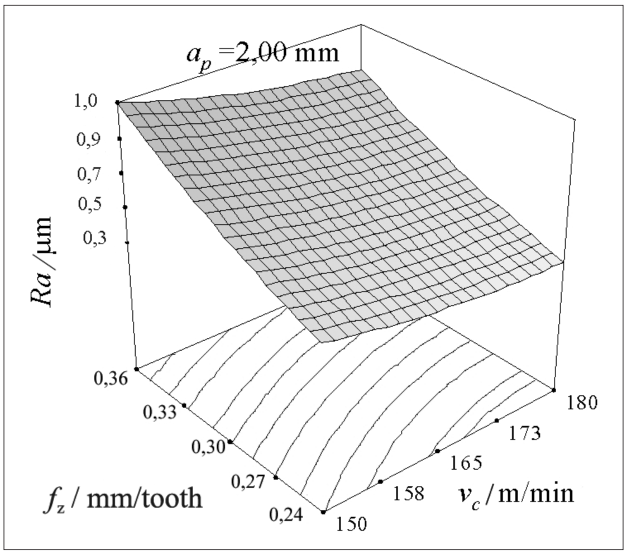

Figure 3. Influence of feed rate and cutting speed on surface roughness at constant depth of cut, a_p = 2,00 mm

test runs is nine, which represents big advantage since the number of tests is reduced in relation to RCCD. Robust design and experimental results, together with result transformations into signal-to-noise ratio are given in Table 3.

The core criterion for analysis of experimental data is signal-to-noise ratio, i.e. ratio S/N [2]. For the minimal surface roughness, the solution is "smaller is better", ratio *S/N* is determined:

$$S / N = -10 \cdot \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (5)$$

where:
n – is the number of replication, y_i – measured value of output variable.

Table 3. **Robust design and results of experiment**

Input factors			
Levels	-1	0	1
$X_1=v_c$ / m/min	150	165	180
$X_2=f_z$ / mm/tooth	0,24	0,30	0,36
$X_3=a_p$ / mm	1,30	2,00	2,70

Nr	X_1	X_2	X_3	Ra/μm	*S/N*
1.	-1	-1	-1	0,39	1,71
2.*	-1	0	0	0,41	1,36
3.	-1	1	1	1,10	-7,16
4.*	0	-1	0	0,23	6,56
5.*	0	0	1	0,79	-4,23
6.*	0	1	-1	0,95	-5,86
7.	1	-1	1	0,34	2,97
8.*	1	0	-1	0,74	-3,51
9.*	1	1	0	0,78	-4,04

* - additonally performed experiments

Analysis of results

Influence of control factor on S/N ratio has been presented in Figure 4. The response graphic of surface roughness has been shown for all three control factors. The best surface quality is achieved using the cutting parameters where S/N ratio is maximal. Parameter influence on output process variable shows angle of inclination of the line which connects different parameter levels. It can be seen from the presented graphs that feed rate has the greatest influence on the surface roughness. Depth of cut has certain influence, and cutting speed has insignificant influence on surface roughness.

The optimization of cutting parameters inside of offered factors levels, with regard to criterion "smaller is better", gives the combination of control factors: X_1=0, X_2=-1, X_3=0. Namely, this combination of control factors, which is within the tested range, enables the lowest surface roughness. The S/N ratio under optimum conditions is 6,56.

CONCLUSIONS

Based on performed experiments and by comparing the test results acquired with RSM method and the Taguchi method, it can be concluded:

– Matemathical model, which exactly determines surface roughnes for certain cutting parameters has been obtained by means of response surface method and it enables a high quality analysis of experiments range as well as achieving of optimal exact values. On the other side there is the Taguchi method by means of which values of optimal parameters are obtained among control factor levels.
– The biggest advantage of the Taguchi method, in relation to response surface method, is the effectivness of robust design itself which can be seen through reliable results and reduced number of test runs, unlike the presented RCCD, which is with this research shown and confirmed.

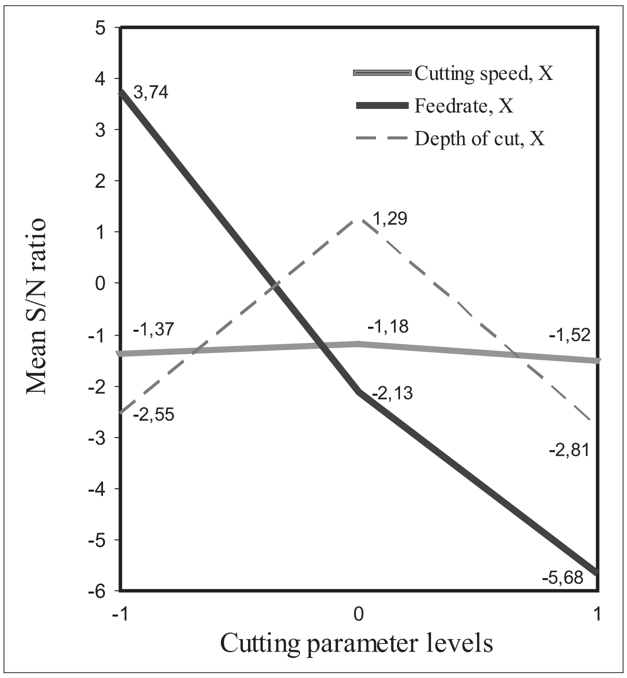

Figure 4. Influence of control factor on S/N ratio

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