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Statistical analysis of surface roughness by design of experiments in hard turning

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1. Introduction

Finish hard turning is an emerging machining process which enables manufacturers to machine hardened materials having hardness greater than 45 HRC using a single point polycrystalline cubic boron nitride (PCBN commonly Known as CBN) or ceramic cutting tool without any aid of cutting fluid on a rigid lathe or turning center. This process has become a normal practice in industry because it increased productivity and reduced energy consumption [1, 2]. The surface roughness of machined parts is a significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength. The quality of the surface is a factor of importance in the evaluation of machine tool productivity. Hence it is important to achieve a consistent tolerance and surface finish. When surface finish becomes the main criteria in the quality control department. The productivity of the metal cutting operation is limited by the surface quality. Recent investigation by El-Baradie [3] and Bandyopadhyay [4] have shown that increasing the cutting speed can help to maximize productivity and, at the same time, it improves surface quality. According to Gorlenko [5] and Thomas [6], surface finish can be characterized by various parameters. The various roughness height parameters such as average roughness *Ra*, smoothening depth *Rp*, root mean square *Rq*, and maximum peak-to-valleyheight R_t can be closely correlated. Albrecht [7] investigated the effect of speed, feed, depth of cut and nose radius on the surface finish of a steel work-piece. Ansell and Taylor [8] have studied the effect of tool material on the surface finish of a cast-iron work-piece. Chandiramani and Cook [9] in their investigation on the effect of varying cutting speeds on the surface finish found an intermediate region of deterioration on surface finish due to the formation of built up edge. Karmaker [10], however, did not observe this in a study with ceramic tools.

The present study uses average roughness *Ra* and R_t for the characterization of surface roughness takes into account the simultaneous variation of the cutting variables and predicts the machining response (the surface roughness). The statistical method used in this analysis is known as response surface methodology which is a combination of the design of experiments and regression analysis and statistical inferences. The meaning of factorial design is that each complete test or replications of all the possible combinations of the levels of the factors are investigated [11]. Using residual mean square (RMS) and 3^3 factorial design of experiment, mathematical model of surface roughness as a function of feed rate, cutting speed and quadratic effect of cutting speed, have been developed with 95% confidence level. These model equations have been used to develop surface roughness 3D.

2. Experimental procedure

2.1. Processes and materials

The material used in the experiment was steel (42 CD 4), in the form of round bar 70 mm diameter and 370 mm length. The chemical composition is as follows: 0.42% C; 0.25% Si; 0.08% Mn; 0.018% S; 0.013% P; 0.021% Ni; 0.022% Cu; 1.08% Cr; 0.004% V; 0.209% Mo; 96.95% Fe. It is hardened to 54 HRC. The cutting insert used is a mixed ceramic (CC650), removable of square form with eight cutting edges and having designation SNGA 120408 T01020. It was clamped onto a tool holder ISO designation PSBNR2525K12. Combination of the insert and the tool holder resulted in negative rake angle γ = -6°, clearance angle α = 6°, negative cutting edge, inclination angle λ = -6°, and cutting edge angle Kr = 75° [12]. The lathe used for machining operation is Tos TRENCIN, Model SN40C spindle power 6.6 KW. A Surf test 301 Mitutoyo roughness meter was selected to measure different criteria of surface roughness (arithmetic average of absolute roughness *Ra* and maximum height of the profile R_t as shown in Fig. 1.

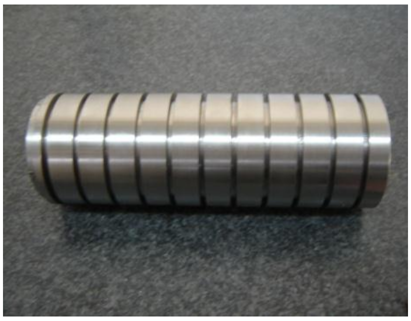

Fig. 1 The material used

Three levels were defined for each cutting variable as given in Table 1.

Table 1

Attribution of the levels to the factors

Attribution of the levels to the factors			
Level	*Vc*, m/min	*f*, mm/rev	a_p, mm
1 Low	90	0.08	0.15
2 Medium	125	0.12	0.30
3 High	200	0.16	0.45

The variable levels were chosen within the intervals recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 27 tests.

2.2. Response surface methodology

The response surface methodology (RSM) is an empirical modelling approach for determining the relationship between various process parameters and the responses with the various desired criteria, by means of which we can further search the significance of these process parameters on the coupled responses. It is a sequential experimentation strategy for building and optimizing the empirical model. Therefore, RSM is a collection of mathematical and statistical procedures that are useful for the modelling and the analysis of problems in which a response of demand is affected by several variables and the objective is to optimize this response.

In this paper, cutting speed, feed rate, depth of cut have been considered as the process parameters and the surface roughness *Ra* and R_t are taken as the response variable. Surface roughness,

$$Y = F\ (Vc, f, a_p) + e_{ij} \tag{1}$$

where *Y* is the desired response and *F* is the response surface, e_{ij} is the residual.

3. Data analysis and discussion of results

The plan of tests was developed aiming at determining the relation between the influence of the cutting speed *Vc*, feed rate *f* and depth of cut a_p and the roughness parameters *Ra* and R_t Table 2. The statistical treatment of the data was made into two phases. The first one concerned the analysis of variance and the effects of the factors and of the interactions.

Table 2

Design layout and experimental results

Run	Coded			Actual factors			Response variables	
	X_1	X_2	X_3	*Vc*, m/min	*f*, mm/rev	a_p, mm	*Ra*, µm	R_t, µm
1	-1	-1	1	90	0.08	0.45	0.32	2.16
2	1	0	1	200	0.12	0.45	0.33	1.75
3	-1	0	0	90	0.12	0.30	0.67	3.45
4	-1	0	-1	90	0.12	0.15	0.33	2.25
5	-1	-1	-1	90	0.08	0.15	0.31	2.16
6	1	1	0	200	0.16	0.30	0.87	4.30
7	1	-1	0	200	0.08	0.30	0.22	2.0
8	0	-1	0	125	0.08	0.30	0.38	2.30
9	-1	1	1	90	0.16	0.45	1.09	4.83
10	0	-1	1	125	0.08	0.45	0.29	1.70
11	-1	1	-1	90	0.16	0.15	1.05	4.53
12	0	1	0	125	0.16	0.30	0.58	3.35
13	1	-1	1	200	0.08	0.45	0.24	1.75
14	1	-1	-1	200	0.08	0.15	0.29	2.20
15	1	1	-1	200	0.16	0.15	0.72	3.56
16	1	0	-1	200	0.12	0.15	0.34	2.23
17	-1	0	1	90	0.12	0.45	0.74	3.56
18	0	0	0	125	0.12	0.30	0.40	2.80
19	0	-1	-1	125	0.08	0.15	0.39	2.25
20	1	0	0	200	0.12	0.30	0.27	2.0
21	1	1	1	200	0.16	0.45	0.89	4.20
22	0	0	1	125	0.12	0.45	0.35	2.76
23	0	1	-1	125	0.16	0.15	0.44	2.80
24	-1	-1	0	90	0.08	0.30	0.20	1.90
25	0	0	-1	125	0.12	0.15	0.42	2.30
26	0	1	1	125	0.16	0.45	0.52	3.15
27	-1	1	0	90	0.16	0.30	1.06	5.03

The second one allowed the correlation between the parameters to be obtained. Afterwards, using of response surface optimization helps to identify the combination of input variable setting (cutting parameters) that jointly optimize the surface roughness value.

3.1. Variance analysis and effects of the factors

An analysis of data variance with arithmetic average roughness *Ra* and with maximum peak-to-valley height R_t was made with the objective of analyzing the influence of cutting speed *Vc*, feed rate *f* and depth of cut a_p on the total variance of the results.

Tables 3 and 4 show the results of the ANOVA with the arithmetic average roughness *Ra* and maximum peak-to-valley height R_t, respectively.

This analysis was carried out for a 5% significance level, i.e. for a 95% confidence level. The last column of the previous table shows the percentage of each factor contribution *P* on the total variation, thus indicating the degree of influence on the result.

After analyzing Table 3, it may be observed that the feed rate factors $P = 57.49\%$, the cutting speed $P = 5.35\%$ and the interaction effect of cutting speed

(P = 8.89%) have great influence on the obtained roughness.

Analyzing Table 4, it may also be observed that the feed rate factors P = 61.67%, cutting speed P = 5.10% and interaction effect of cutting speed P = 5.10% also have considerable influence on the surface roughness, especially the feed rate factor. It should be noticed that the error associated to the ANOVA table for the *Ra* was approximately 21.34 and 17.92% for the R_t.

Using ANOVA to make this comparison requires several assumptions to be satisfied. The assumptions underlying the analysis of variance tell the residuals are determined by evaluating the following equation [13]:

$$e_{ij} = y_{ij} - \acute{y}_{ij} \quad (2)$$

Table 3

Analysis of variance for *Ra*

Source	DF	SeqSS	AdjMS	F-Value	P	Cont%
Vc	1	0.10384	0.14600	6.00	0.020	5.35
f	1	1.11502	0.04256	1.75	0.000	57.49
a_p	1	0.01280	0.00120	0.05	0.524	0.66
$Vc*Vc$	1	0.17246	0.17246	7.08	0.016	8.89
$f*f$	1	0.09459	0.09459	3.88	0.065	4.87
a_p*a_p	1	0.00439	0.00359	0.15	0.706	0.23
$Vc*f$	1	0.00235	0.00235	0.10	0.760	0.12
$Vc*a_p$	1	0.00536	0.00536	0.22	0.645	0.27
$f*a_p$	1	0.01541	0.01541	0.63	0.437	0.79
Error	17	0.41394	0.02435			21.34
Total	26	1.93934				100

Table 4

Analysis of variance for R_t

Source	DF	SeqSS	AdjMS	F-Value	P	Cont%
Vc	1	1.3235	0.9350	3.42	0.018	5.10
f	1	16	0.5379	1.97	0.000	61.67
a_p	1	0.1247	0.2132	0.78	0.616	0.48
$Vc*Vc$	1	1.3246	1.3246	4.84	0.042	5.10
$f*f$	1	1.2060	1.2060	4.41	0.051	4.64
a_p*a_p	1	0.3953	0.3953	1.45	0.246	1.52
$Vc*f$	1	0.1999	0.0791	0.29	0.598	0.30
$Vc*a_p$	1	0.2927	0.2927	1.07	0.315	1.12
$f*a_p$	1	0.4370	0.4370	1.60	0.223	1.68
Error	17	4.6502	0.2735			17.92
Total	26	25.9424				100

When e_{ij} is the residual, $\acute{y}_{ij}$ is the fitted value. A check of the normality assumption may be made by constructing the normal probability plot of the residuals. If the underlying error distribution is normal, this plot will resemble a straight line see Figs. 2 and 3. Since the p-value is larger than 0.05, it is concluded that normal assumption is valid. The other two assumptions are shown valid by means of plot of residuals versus fitted values. This plot is illustrated in Figs. 4 and 5 The structure less distribution of dots above and below the abscissa (fitted values) shows that the errors are independently distributed and the variance is constant [14]. Figs. 6 and 7 draws plot of main factor effects on the arithmetic average roughness *Ra* and maximum peak–to-valley height R_t. This plot is used to visualize the relation between factors and output response. Since the most significant factor which varies *Ra*, R_t during this process is the feed rate.

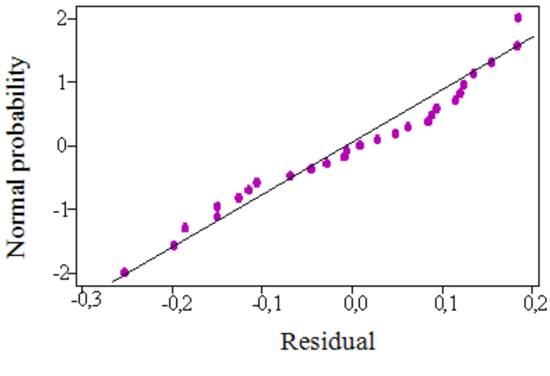

Fig. 2 Normal probability plot of residuals for surface roughness *Ra* data

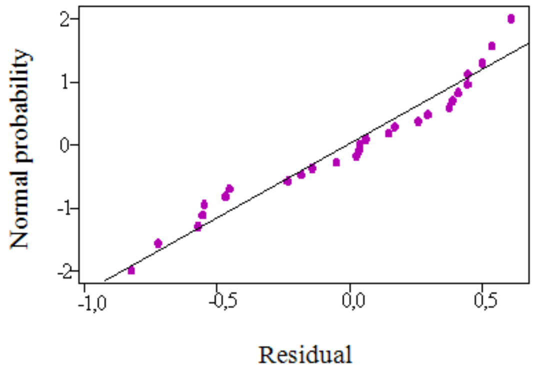

Fig. 3 Normal probability plot of residuals for surface roughness R_t data

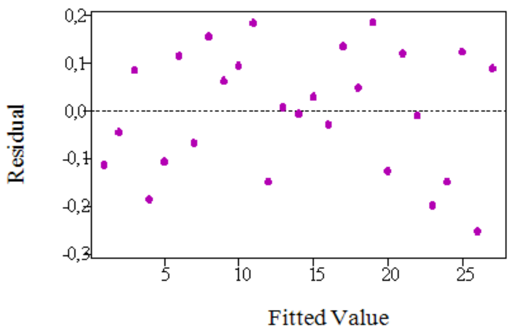

Fig. 4 Plot of residuals *vs*, fitted values for surface roughness *Ra* data

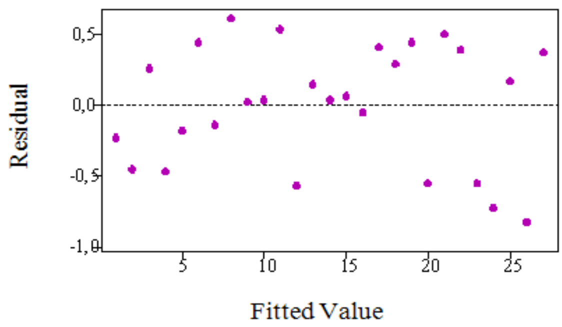

Fig. 5 Plot of residuals vs, fitted values for surface roughness R_t data

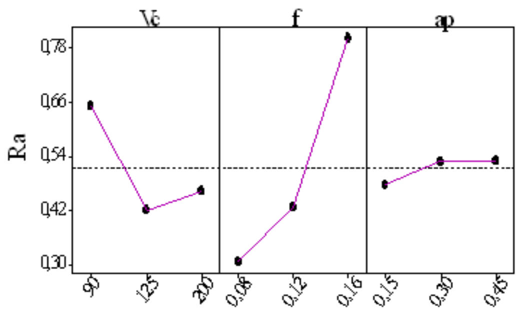

Fig. 6 Main factor plot: averages for *Ra*

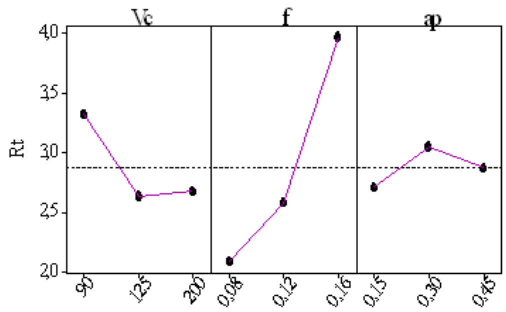

Fig. 7 Main factor plots: averages for R_t

2. Correlation

The correlation between the factors (cutting speed, feed rate and depth of cut) and the measured roughness parameters *Ra* and R_t were obtained by regression (response surface methodology). The obtained equations were as follows

$$Ra = 2.16714 - 13.5420f - 1.93.10^{-2}\ Vc + 6.6.10^{-5}\ Vc^2$$

$$R_t = 6.79063 - 48.1415f - 4.8.10^{-2}\ Vc + 1.82.10^{-4}\ Vc^2$$

Table 5

Table of coefficients for regression analysis. Response *Ra*

Predictor	Coefficient	SE coefficient	*T*	*P*
Constant	2.16714	0.9076	2.39	0.029
Vc	-0.0193565	0.007905	-2.45	0.025
f	-13.5420	10.24	-1.32	0.000
*Vc**Vc*	0.000065	0.000025	2.66	0.016

Table 6

ANOVA table for the fitted models *Ra*

Source	DF	Seq SS	Adj MS	F-Value	*P*	Remarks
Regression	9	1.52540	0.169489	6.96	0.000	Significant
Residual error	17	0.41394	0.024349			
Total	26	1.93934				
R^2						78.7%
R^2 adjusted						67.4%

Table 7

Table of coefficients for regression analysis. Response *Ra*

Predictor	Coefficient	SE coefficient	*T*	*P*
Constant	6.79063	3.042	2.23	0.000
Vc	-0.04898	0.0265	-1.85	0.018
f	-48.1415	34.33	-1.40	0.000
*Vc**Vc*	0.000182	0.000083	2.20	0.042

Table 8

ANOVA table for the fitted models *Ra*

Source	DF	Seq SS	Adj MS	F-Value	*P*	Remarks
Regression	9	21.2922	2.36580	8.65	0.000	Significant
Residual	17	4.6502	0.27354			
Total	26	25.9424				
R^2						82.1%
R^2 adjusted						72.6%

The statistical significances of the fitted quadratic model for the arithmetic average roughness (*Ra*) and with maximum peak-to-valley height (R_t) were evaluated by the F-test of ANOVA in Tables 6-8. Values of "Prob. > F for the term of models are less than 0.05, this indicates the obtained models are considered to be statistically significant. Which is desirable as it demonstrates that the term in the model have a significant effect on the responses. The other important coefficient R^2, When R^2 approaches to unity, the good the response model fits the actul data Tables 6-8.

Analysis of variance was derived to examine the null hypothesis for the regression that is presented in Tables 6-8. The result indicates that the estimated model by the regression procedure is significant at the α-level of 0.05. The R^2 (R-squared) amount was calculated to check the goodness of fit. The R^2 value with the arithmetic average roughness Ra and maximun peak-to-valley height R_t indicates that the predictors explain 78.7%, and 82.1% of the response variation, respectively. Adjusted R^2 for the number of predictors *Ra* and R_t in the models were 67.4% and 72.6% respectively.

4. Surface plots

A graphical analysis was done on the observed values using Minitab software. The response surface plots obtained for each process parameter with respect to the cutting parameters based on the response surface methodology is being presented. Fig. 8 shows the estimated response surface plots of surface roughness *Ra* and R_t for the cutting parameters (namely cutting speed, feed rate, depth of cut)

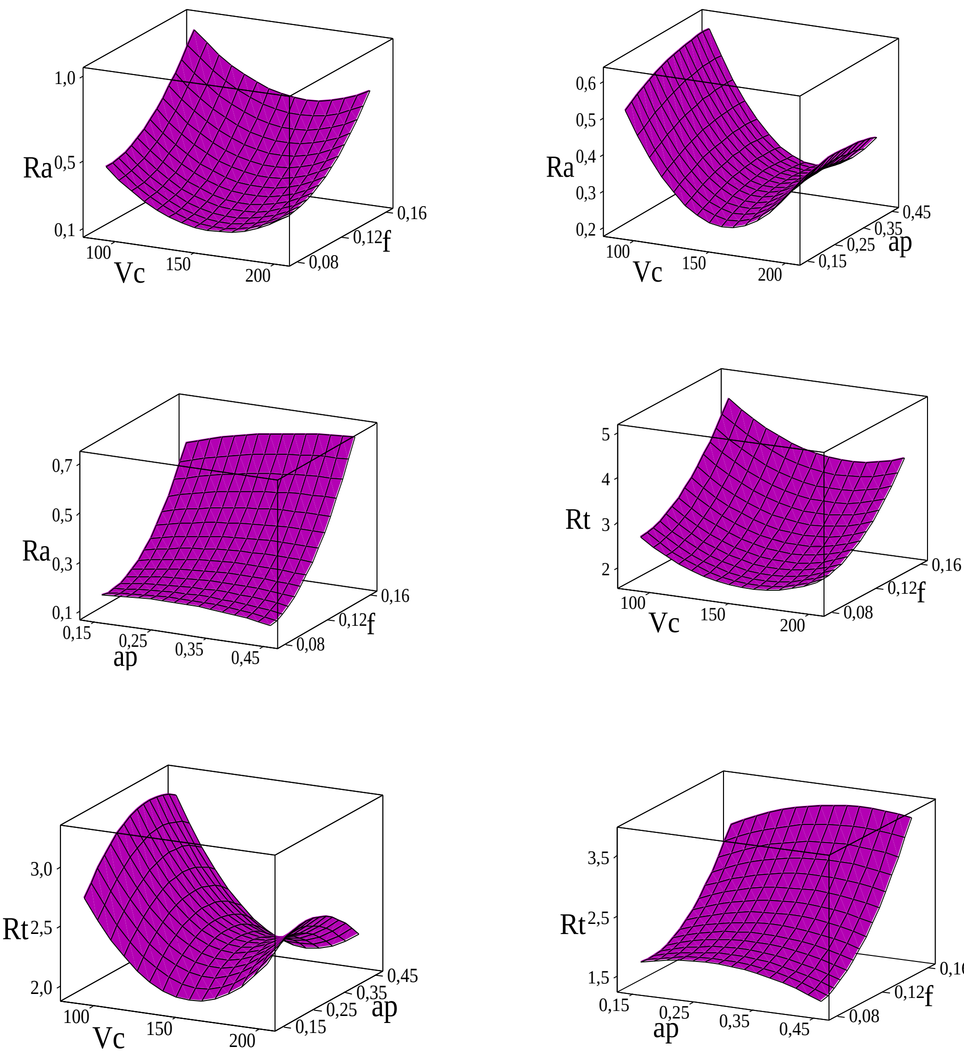

Fig. 8 The response surface plots of surface roughness according to change of cutting speed, feed rate, depth of cut

5. Response optimization

One of the main goals for the experiment is help investigate optimal values of cutting parameters, in order to obtain the desired value of the machined surface during the hard turning process.

The use of response surface optimization helps to identify the combination of input variable settings (machining parameters) that jointly optimize the surface roughness value during hard turning process. Joint optimization must satisfy the requirement for all the responses in the set. Optimization achievement is measured by the composite desirability which is the weighted geometric mean of the individual desirability is for the responses on a range from zero to one. One represents the ideal case. Zero indicates that one or more responses are out-side acceptable limits. Table 9 shows the RSM optimization results for the roughness parameters. The optimum cutting parameters obtained in Table 9 are found to be cutting speed of 160 m/min, feed rate of 0.08 mm/rev, cutting depth of 0.45 mm. The optimized surface roughness parameters are *Ra* = 0.05 μm, R_t = 1.37 μm.

Table 9

Response optimization for surface roughness parameters

Parameters	Goal	Optimum combination			Lower	Target	Upper	Predicted response
		Vc, m/min	*f*, mm/rev	a_p, mm				
Ra, μm	Minimum	160	0.08	0.45	0.22	0.22	1.09	0.05
R_t, μm	Minimum	160	0.08	0.45	1.70	1.70	5.03	5.03
Desirability = 1								
Composite desirability = 1								

6. Conclusion

1. Response surface methodology combined with the factorial design of experiment are useful techniques for surface roughness tests. Relatively, a small number of designed experiments are required to generate much useful information that is used to develop the predicting equations for surface roughness.

2. An analysis of variance (ANOVA) the feed rate is the cutting condition that has the highest physical as well statistical influence for the roughness parameters. Arithmetic average roughness was approximately 57.49% and 61.67% for the maximum peak-to-valley height. The cutting speed and depth of cut does not seen to have influence on the surface roughness parameters.

3. The surface roughness equation shows that the feed rate is the main influencing factor on the roughness.

4. The surface roughness 3D are useful in determining the optimum cutting conditions for a given surface roughness.

5. The using of the response surface optimization and composite desirability show that the optimal setting values of machining parameters are (*Vc* = 160 m/min, *f* = 0.08 mm/tr, a_p = 0.45 mm) for cutting speed, feed rate and depth of cut respectively.

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TEKINTO PAVIRŠIAUS ŠIURKŠTUMO STATISTINĖ ANALIZĖ EKSPERIMENTO PLANAVIMO METODU

R e z i u m ė

Šioje studijoje pateiktas bandymas ištirti pjovimo režimų (pjovimo greičio, pastūmos ir pjovimo gylio) įtaką paviršiaus šiurkštumui atliekant išbaigiamąjį jėginį 42CrMo4 plieno ruošinio tekinimą su AL_2O_3/Tic padengtu metalo keramikos įrankiu, kurio sudėtyje yra 70% Al_2O_3 ir 30% Tic. Pjovimo režimų (pjovimo greičio, pastūmos ir pjovimo gylio) ir apdirbimo metu pasiektų rezutatų (paviršiaus šiurkštumo) tarpusavio santykis yra modeliuojamas ir analizuojamas taikant paviršiaus reakcijos metodologiją. Pjovimo režimų įtaka apdirbimo parametrų kintamiesiems įvertinama pritaikant variantų analizės metodą (ANOVA). Kvadratinis paviršiaus reakcijos metodologijos modelis, susietas su atsako optimizavimo ir kompozicinio tinkamumo įvertinimo technika, buvo panaudotas apdirbimo parametrų optimalioms reikšmėms siekiamų tikslų (paviršiaus šiurkštumo) atžvilgiu rasti. Rezultatai rodo, kad pastūma yra pagrindinis veiksnys, lemiantis šiurkštumo parametrus Ra ir R_t – atitinkamai 57,49% ir 61,67%. Kvadratinis modelis geriausiai apibūdina paviršiaus šiurkštumo variacijas esant didžiausiai pastūmos ir nedidelei pjovimo greičio ir gylio įtakai.

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STATISTICAL ANALYSIS OF SURFACE ROUGHNESS BY DESIGN OF EXPERIMENTS IN HARD TURNING

S u m m a r y

In the present study, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness in finish hard turning of 42CrMo4 steel using coated mixed ceramics tool AL_2O_3/Tic which is approximately composed of 70% of Al_2O_3 and 30%of Tic. The relationship between cutting parameters (cutting speed, feed rate and depth of cut) and machining output variables (surface roughness) through the response surface methodology (RSM) are analysed and modelled. The combined effects of the cutting parameters on machining output variables are investigated while employing the analysis of variance (ANOVA). The quadratic model of RSM associated with response optimization technique and composite desirability was used to find optimum values of machining parameters with respect to objectives (surface roughness). The results show that the feed rate is the dominant contributor to the roughness parameters *Ra* and R_t accounting for 57.49% and 61.67%, respectively. A quadratic model best describes the variation of surface roughness with major contribution of feed rate, cutting speed and secondary contributions of interaction effect of cutting speed.

Keywords: hard turning, surface roughness, RMS, ANOVA.

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