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APPLICATION OF TAGUCHI AND ANOVA METHODS IN SELECTION OF PROCESS PARAMETERS FOR SURFACE ROUGHNESS IN PRECISION TURNING OF TITANIUM

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Summary

The objective of this study is the selection of cutting data (such as v_c, f, a_p) and tool materials (PCD, ceramic, CBN and carbide cutting tools) in order to improve the surface roughness in precision turning operation of parts made of pure titanium (GRADE 2). Machining parameters and tool materials are considered as input parameters. The surface roughness is selected as the process output measure of performance. A Taguchi approach is employed to gather experimental data. Then, based on signal-to-noise (S/N) ratio, the best sets of cutting parameters and tool materials specifications have been determined.

Keywords: precision turning, Taguchi method, surface roughness

Dobór warunków procesu toczenia precyzyjnego tytanu metodą Taguchi i ANOVA uwzględniającej parametry chropowatości powierzchni

Streszczenie

W artykule przedstawiono dobór warunków procesu toczenia (v_c, f, a_p) oraz materiału narzędzia (ostrze z PKD, ceramiki, CBN, węglików spiekanych) do obróbki precyzyjnej elementów z czystego tytanu (GRADE 2), z uwzględnieniem kryterium chropowatości powierzchni. Warunki procesu obróbki i materiał ostrza są wejściowe, natomiast wybrane parametry chropowatości stanowią parametry wyjściowe. Badania doświadczalne prowadzono, wykorzystując metodę Taguchi. Określenie wartości proporcji intensywności sygnału (S) i szumu (N) było podstawą doboru parametrów procesu skrawania oraz materiału narzędzia.

Słowa kluczowe: toczenie precyzyjne, metoda Taguchi, chropowatość powierzchni

1. Introduction

Rapid technical development is connected with the constant need of new construction materials with new features. However, practical usage of these materials is strictly connected with their production and treatment methods. Therefore, it is needless to say that searching for new technologies is as important as developing the older ones.

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Nowadays, the most common method of shaping miniature parts and their surface layer is precision machining [1].

Modern material removal processes, especially for materials which are hard to machine, are expected to keep high end-product quality and reliability, to have high performance ratio, to deal with economic issues and to be more and more enviromentally friendly. As there are more and more products made of hard-machinable materials such as titanium or nickel alloys or special ceramics, there is an urge need to find new and more effective machining methods [1-3].

Since few years, there has been an increasing need for micro-scale components in such fields of industry as automotive, aviation, electronics etc. It stimulates the development of micro-machining processes such as micro-turning or micro-milling.

The required accuracy (in 4 to 6th grade) and surface quality (Ra = 0.5 to 2 μm) is obtained by using the appropriate treatment technology [4].

Titanium and titanium alloys are extremely difficult to cut material. It can be explained by the physical, chemical, and mechanical properties of the metal. Titanium and titanium alloys have low thermal conductivity and high chemical reactivity with many cutting tool materials. Its low thermal conductivity increases temperature at the cutting edge of a tool. Additionally, the low modulus of elasticity of titanium alloys and its high strength at elevated temperature impair its machinability [5-19].

Titanium owing a relatively low modulus of elasticity presents more “springiness” than steel. Slender parts tend to deflect under tool pressures, causing chatter, tool rubbing, and tolerance problems. The entire system should be very rigid and the tool should be properly shaped (very sharp).

The next important feature of titanium and titanium alloys is a complete absence of “built-up edge”, which causes a high shearing angle (the lack of a stationary mass of metal ahead of the cutting tool). This causes a thin chip to contact with a relatively small area on the cutting tool face and results in high bearing loads per unit area. The high bearing force, combined with the friction developed by the chip results in a great increase in heat on a much localized portion of the cutting tool.

Titanium and titanium alloys are generally used for components, which require the greatest reliability and therefore the surface integrity must be maintained. Machined surface characteristics such as a surface roughness and form as well as a sub-surface characteristics such as a residual stress, a granular plastic flow orientation and surface defects (porosity, micro-cracks, etc.) are important in determining the functional performance of machined components. The quality of surfaces of machined components is determined by the surface finish and integrity obtained after machining [5-19].

In literature, Response Surface Methodology (RSM) has been used by some researchers for the analysis and prediction of the surface roughness. However, few researchers have applied a Taguchi approach to cross examine the impact of individual factors and factor interactions, although the Taguchi method is relatively simple and can be used for optimizing different production stages with few experimental runs. The aim of the present study is, therefore, to investigate the surface roughness in precision turning of pure titanium (Grade 2) with the aid of a Taguchi design of experiment, using (PCD, ceramic, CBN and carbide cutting tools under various cutting conditions. Then, based on a signal-to-noise (S/N) ratio, the best sets of cutting parameters and tool materials specifications has been determined. Using these parameters values, the surface roughness of titanium parts may be minimized.

2. Experimental

2.1. Taguchi experiment: design and analisis

Traditional experimental design procedures are too complicated, very expensive and not easy to use. A large number of experimental works has to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments. Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process [20-24]. The greatest advantage of this method is saving of effort in conducting experiments; saving experimental time, reducing costs, and discovering significant factors quickly. The steps applied for Taguchi optimization in this study are presented in Figure 1.

2.2. Machining conditions and experimental design

The material used in this work was a pure titanium, Ti (Grade 2). Table 1 shows the chemical composition (wt. %) of titanium. The thermal and mechanical properties of the material are shown in Table 2 and 3 respectively.

The test sample was prepared in the form of shaft, 28 mm diameter with separated parts. The cutting tools types used in the experiments are listed in Table 4.

Turning tests were carried out on a Masterturn 400 with different cutting speeds, feed, depth of cut and cutting tools; in accordance with the Taguchi experiment design. The lathe equipped with variable spindle speed from 1 to 3000 rpm, and a 7.5 kW motor drive was used for the tests.

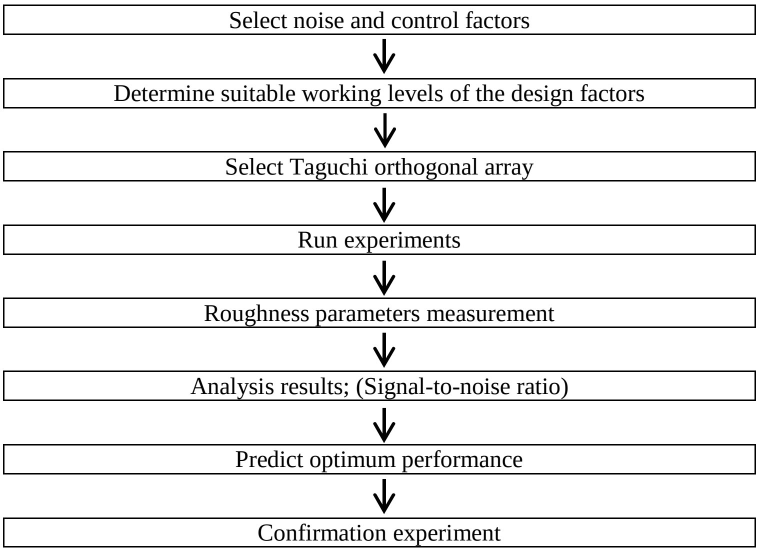

Fig. 1. Taguchi design procedure [20-24]

Table 1. Chemical Composition of Ti – Grade 2

Element	**Content, wt. %**
Carbon	0.10
Iron	0.20
Hydrogen	0.015
Nitrogen	0.03
Oxygen	0.25
Other, total	0.30
Ti	98.885

Table 2. Mechanical properties of Ti – Grade 2

Proporties	
Tensile Strength, Ultimate	344 MPa
Tensile Strength, Yield	276 – 448 MPa
Modulus of Elasticity	103 GPa
Shear Modulus	45 GPa
Hardness	200 HB
Poisson ratio	0.37

Table 3. Physical and thermal properties of Ti – Grade 2

Proporties	
Density	4.51 g/cm^3
Thermal conductivity	16.4 W/mK
Heat capacity	0.523 J/g C

Table 4. Geometry of the cutting edge

Types of cutting tools	**Tool designation**	**Tool holder**	**Geometry**
Polycrystalline diamond (PCD)	CNMA 120404 ID5	DCLNR 2020 K12	$\alpha_o = 6^o$; $\gamma_o = 1^o$; $\kappa_r = 95°$
Carbide insert	CNGP120408 H13A		$\alpha_o = 6^o$; $\gamma_o = 5^o$; $\kappa_r = 95°$
CBN insert	CNGA120408S01030AWH 7015		$\alpha_o = 6^o$; $\gamma_o = –6^o$; $\kappa_r = 95°$
Ceramic insert	CNGA 120408T IS8		$\alpha_o = 6^o$; $\gamma_o = –6^o$; $\kappa_r = 95°$

Taguchi methods which combine the experiment design theory and the quality loss function concept have been used in developing robust designs of products and processes and in solving some taxing problems of manufacturing [1, 13, 14, 16, 19]. The degrees of freedom for four parameters in each of four levels were calculated as follows: degree of Freedom (DOF) = number of levels -1 (1). For each factor DOF equals to:

For (A); DOF = 4 – 1 = 3
For (B); DOF = 4 – 1 = 3
For (C); DOF = 4 – 1 = 3
For (D); DOF = 4 – 1 = 3

In this research 16 experiments were conducted at different parameters. Taguchi L_{16} orthogonal array was used, which has sixteen rows corresponding to the number of tests, with four columns at four levels. For the process parameters in precision turning, four factors, each at four levels were taken into account, as shown in Table 5.

Table 5. Precision turning parameters

Parameter	**Code**	**Levels**			
		1	**2**	**3**	**4**
Cutting tools	A	PCD insert	CBN insert	Ceramic insert	Carbide insert
Depth of cut, a_p, mm	B	0.05	0.075	0.1	0.125
Feed rate, f, mm/rev	C	0.038	0.048	0.058	0.077
Cutting speed, v_c, m/min	D	75	100	125	150

Data experiment results and S/N ratio for parameters *Sa*, *Sz* are presented in the form of orthogonal array L_{16} (Tab. 6). The researcher collects data by 16 conditions. Each condition will be determined by the factors. For instance the first condition is identified by the kind of cutting tools at PCD insert, depth of cut at 0.05 mm, feed rate at 0.038 mm/rev, cutting speed at 75 mm/min as well.

Table 6. L_{16} (4^4) Orthogonal Array, Experiment results and S/N ratio

Experiment Number	**Cutting parameter level**				***Sa***	**S/N ratio, dB for *Sa***	***Sz***	**S/N ratio, dB for *Sz***
	A	**B**	**C**	**D**				
	Types of Cutting tools	**Depth of cut a_p, mm**	**Feed rate *f*, mm/rev**	**Cutting speed v_c, m/min**				
1	*PCD insert* (Level 1) assigned a numerical value [1]	0.05 (Level 1)	0.038 (Level 1)	75 (Level 1)	0.226	12.918	5.73	-15.163
2		0.075 (Level 2)	0.048 (Level 2)	100 (Level 2)	0.218	13.231	2.21	-6.888
3		0.1 (Level 3)	0.058 (Level 3)	125 (Level 3)	0.235	12.579	2.32	-7.310
4		0.125 (Level 4)	0.077 (Level 4)	150 (Level 4)	0.201	13.936	1.89	-5.529
5	*CBN insert* (Level 2) assigned a numerical value [2]	0.05 (Level 1)	0.048 (Level 2)	125 (Level 3)	0.398	8.002	4.82	-13.661
6		0.075 (Level 2)	0.038 (Level 1)	150 (Level 4)	0.444	7.052	6.75	-16.586
7		0.1 (Level 3)	0.077 (Level 4)	75 (Level 1)	0.583	4.687	13.4	-22.542
8		0.125 (Level 4)	0.058 (Level 3)	75 (Level 1)	0.444	7.052	16	-24.082
9	*Ceramic insert* (Level 3) assigned a numerical value [3]	0.05 (Level 1)	0.058 (Level 3)	150 (Level 4)	0.637	3.917	6.26	-15.931
10		0.075 (Level 2)	0.077 (Level 4)	125 (Level 3)	0.601	4.423	14.4	-23.167
11		0.1 (Level 3)	0.038 (Level 1)	100 (Level 2)	0.231	12.728	4.21	-12.486
12		0.125 (Level 4)	0.048 (Level 2)	75 (Level 1)	0.634	3.958	5.82	-15.298
13	*Carbide insert* (Level 4) assigned a numerical value [4]	0.05 (Level 1)	0.077 (Level 4)	100 (Level 2)	0.622	4.124	2.91	-9.278
14		0.075 (Level 2)	0.058 (Level 3)	75 (Level 1)	0.401	7.937	2.19	-6.809
15		0.1 (Level 3)	0.048 (Level 2)	150 (Level 4)	0.31	10.173	3.94	-11.910
16		0.125 (Level 4)	0.038	125	0.296	10.574	2.38	-7.532

The surface roughness of the work piece was carried out using the measuring system of Taylor Hobson. To visualize surface test measurements TalyMap program was used. In the study, measurements of the surface topography of the selected parameters in the following conditions: sampling length (cut-off, λ_c) lr = 0.8 mm, number of sections 5, evaluation length ln = 4 mm, the number of registered Nx = 1000, sampling step Δx = 1 μm, stylus tip radius r_{tip} = 2 μm, the speed of the stylus v_{os} = 1 mm/s, the size of the surface on which the measurements of topography 1x1, number of sections 100, the interval of measurements roughness of 0.1 mm and Gaussian filter was applied. The measurements were repeated three times for statistical purposes.

3. Results and analysis of experiment

3.1. Analysis of the S/N Ratio

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristics and the term 'noise' represents the undesirable value for the output characteristics. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available, depending on the type of characteristics: lower is better (LB), nominal is the best (NB), or higher is better (HB) [13]. Smaller is better S/N ratio was used in this study, because lower parameters of surface roughness (*Ra* and *Rz*) were desirable.

Quality characteristics of the smaller is better is calculated according to the following equation:

$$\eta = -10 \times \log_{10} [(1/n) \times \Sigma(y_i^2)] \tag{1}$$

where n is the number of measurements in a trial/row and y_i is the measured value in a run/row. The S/N ratio values were listed in Table 6 for parameters of surface roughness (*Sa* and *Sz*). Table 7 shows the response table for S/N ratio of *Sa* for "smaller is better" obtained for different parameter levels.

Table 7. Response table for Signal to Noise Ratios of *Sa*

Level	**Types of Cutting tools**	**Depth of cut a_p, mm**	**Feed rate f, mm/rev**	**Cutting speed v_c, m/min**
1	PCD insert	7.240	**10.818**	7.375
2	CBN insert	8.161	8.841	**9.284**
3	Ceramic insert	**10.041**	7.871	8.894
4	Carbide insert	8.880	6.792	8.770
Delta	–	2.801	4.026	1.909
Rank	1	3	2	4

The analysis of S/N ratio of *Sa* revealed, that the first factor that causes parameter *Sa* to be great is the type of the cutting tool, its feed rate, depth of cut and cutting speed as latest factors, respectively. Table 8 shows the response table for S/N ratio of *Sz* for “smaller is better” obtained for different parameter levels. The analysis of S/N ratio of *Sz* found, that the first factor that causes parameter *Sz* to be great is the type of the cutting tool, its feed rate, cutting speed and depth of cut as latest factors, respectively. After that, the analysis is made to determine suitable factor of each main factor from S/N ratio, as shown in Figure 2 and 3.

Table 8. Response table for Signal to Noise Ratios of S_z

Level	**Types of cutting tools**	**Depth of cut a_p, mm**	**Feed rate *f*, mm/rev**	**Cutting speed v_c, m/min**
1	**-8.722**	-13.508	-12.942	-14.953
2	-19.218	-13.363	**-11.939**	-13.183
3	-16.721	-13.562	-13.533	-12.917
4	-8.882	**-13.110**	-15.129	**-12.489**
Delta	10.495	0.451	3.190	2.464
Rank	1	4	2	3

From the S/N ratio analysis (Fig. 2 and 3) the optimal machining conditions were 100 m/min cutting speed (level 2), 0.038 mm/rev feed rate (level 1), 0.1 mm depth of cut (level 3), PCD cutting tools (level 1) for parameter *Sa*. 150 m/min cutting speed (level 4), 0.048 mm/rev feed rate (level 2), 0.125 mm depth of cut (level 4), PCD cutting tools (level 1) for parameter *Sz*. respectively.

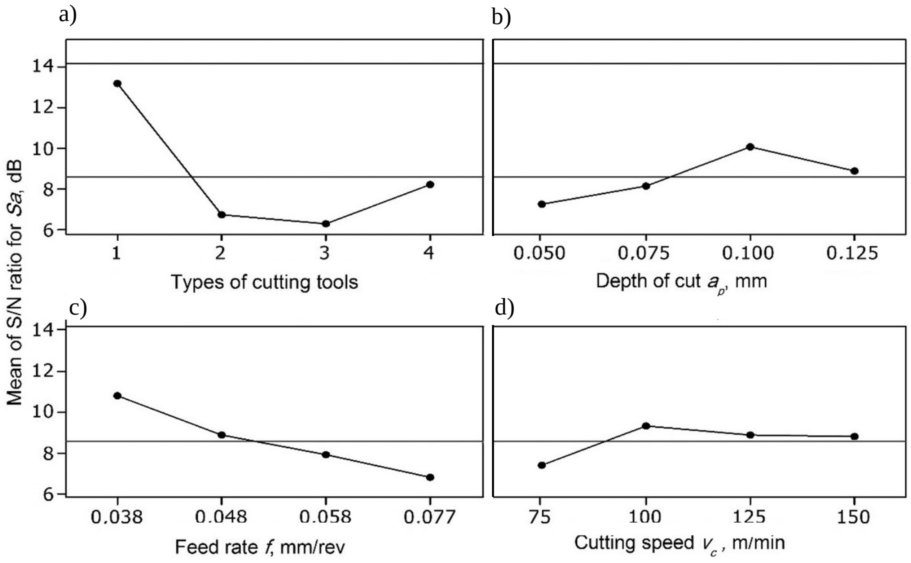

Fig. 2. S/N ratio values for parameter *Sa*: a) types of cutting tools, b) depth of cut, c) feed rate, d) cutting speed

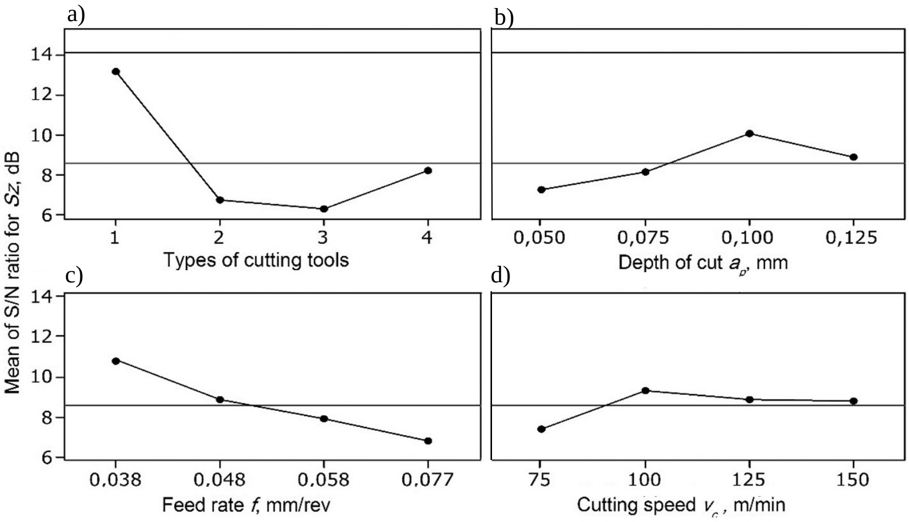

Fig. 3. S/N ratio values for parameter *Sz*: a) types of cutting tools, b) depth of cut, c) feed rate, d) cutting speed

3.2. Analysis of Variance (ANOVA)

ANOVA is a statistically based objective decision-making tool for detecting any differences in the average performance of groups of items tested. ANOVA helps in testing the significance of all main factors and their interactions by comparing the mean square against an estimate of the experimental errors at specific confidence levels. First, the total sum of squared deviations Seq SS from the total mean *Sa* i *Sz* ratio n_m can be calculated as:

$$\text{Seq SS} = \sum_{i=1}^{n}(n_i - n_m)^2 \tag{2}$$

where *n* is the number of experiments in the orthogonal array and n_i is the mean *Sa* or *Sz* for the experiment. The percentage contribution P can be calculated as:

$$P\% = \frac{Seq\,SS_D}{Seq\,SS_T} \tag{3}$$

where Seq SS_D is the sum of the squared deviations. The ANOVA results are illustrated in Table 9 for *Sa* and in Table 10 for *Sz*. Statistically, there is a tool called an F test, named after Fisher [15] to see which design parameters have a significant effect on the quality characteristic.

In the analysis the F-ratio is a ratio of the mean square error to the residual error and is traditionally used to determine the significance of a factor. The

P-value reports the significance level (suitable and unsuitable) in Table 9 and 10. Percent (%) is defined as the significance rate of the process parameters on the parameters Sa and Sz. The percent numbers decipt, that the applied types of cutting tools, feed rate, depth of cut and cutting speed have significant effects on *Sa*. It can observed from Table 9 that the applied types of cutting tools (A), feed rate (C), depth of cut (B) and cutting speed (D) affect the Sa rate by 50.75%, 20.57%, 8.50% and 4.22% in the precision turning of pure titanium (Grade 2), respectively. A confirmation of the experimental design was necessary in order to verify the optimum cutting conditions.

Table 9. Analysis of Variance for *Sa* using Adjusted SS for Tests

Source	**DF**	**Seq SS**	**Adj MS**	**F**	**P, %**
Types of Cutting tools	3	0.21074	0.07025	3.18	50.75
Depth of cut a_p	3	0.03531	0.01177	0.53	8.50
Feed rate f	3	0.08543	0.02848	1.29	20.57
Cutting speed v_c	3	0.01752	0.00584	0.26	4.22
Error	3	0.06627	0.02209	–	15.96
Total	15	0.41527	–	–	100

Table 10. Analysis of Variance for *Sz* using Adjusted SS for Tests

Source	**DF**	**Seq SS**	**Adj MS**	**F**	**P, %**
Types of Cutting tools	3	157.82	52.61	1.52	49.81
Depth of cut a_p	3	6.24	2.08	0.06	1.97
Feed rate f	3	39.44	13.15	0.38	12.45
Cutting speed v_c	3	9.53	3.18	0.09	3.01
Error	3	103.80	34.60	–	32.76
Total	15	316.83	–	–	100

3.3. Development of Response Surface Model

The analysis with Taguchi method mentioned above is an analysis only for the main factors that affect parameters *Sa* and *Sz* without any consideration of correlation between factors. Therefore the researcher has performed Response Surface Regression in the analysis of correlation between factors.

The above analysis revealed that contour plots of parameters *Sa* are curves (Fig. 4). Therefore, the mathematical model suitable for predicting the suitable value is the Quadratics model (equation (4)) by considering the Full Quadratics model as shown in equation (5) (parameter *Sa*) and equation (6) (parameter *Sz*). The coefficients of factors that affect response value are as shown in Table 11.

$$y = b_o + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + \\ + b_{44}x_4^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{14}x_1x_4 + b_{23}x_3x_3 + b_{24}x_2x_4 + b_{34}x_3x_4 \qquad (4)$$

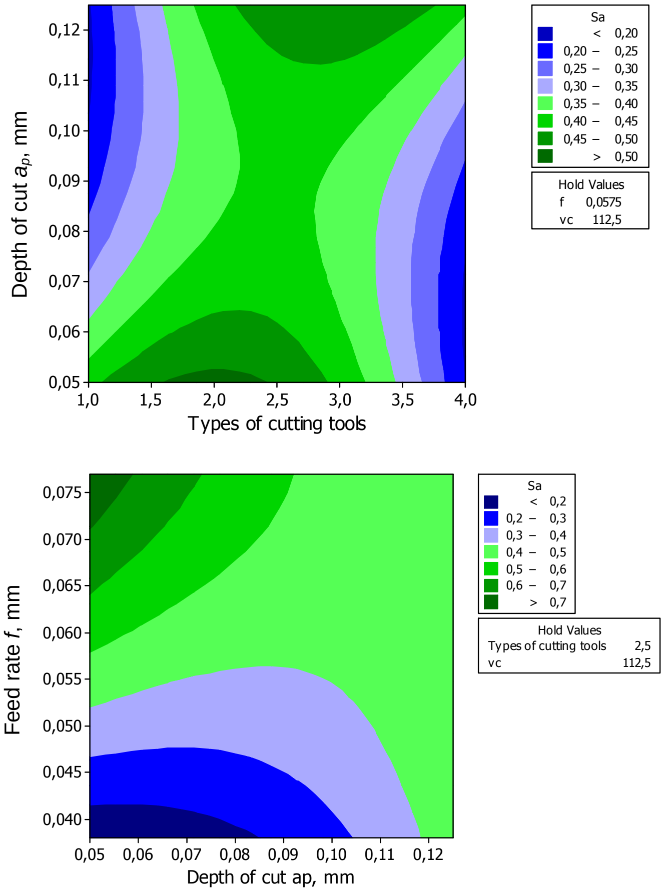

Fig. 4. Sample contour plots of parameter *Sa*

With the above coefficients of factors that affect response value the mathematical equation can be built as follows:

Mathematical model for forecasting parameter *Sa*:

$$\boldsymbol{Sa} = 0.128697+0.086009*\textit{Types of cutting tools}-0.57116*a_p+ +38.0591*f-0.02034*v_c-0.07921*\textit{Types of cutting tools}^2+ +56.9252*a_p^2-114.843*f^2+0.00012*v_c^2+2.01841*\textit{Types of cutting tools}*a_p+3.79478*\textit{Types of cutting tools}*f-7.76\text{E-}04*\textit{Types of cutting tools}*v_c -230.907*a_p*f-0.01161*a_p*v_c-0.0548*f*v_c \quad (5)$$

Where types of cutting tools are 1, 2, 3, 4.

Table 11. Coefficients of factors that affect response value

Parameters	**Coef for Sa**	**Coef for Sz**
Constant	0.128697	–14.8875
Types of cutting tools	0.086009	35.8353
a_p	–0.57116	–694.914
f	38.0591	4499.99
v_c	–0.02034	–1.98477
Types of cutting tools Types of cutting tools*	–0.07921	–10.4595
a_p*a_p	56.9252	407.426
f*f	–114.843	–23584
vc*vc	0.00012	0.004536
*Types of cutting tools**a_p	2.01841	66.5592
*Types of cutting tools*f*	3.79478	70.6766
*Types of cutting tools**v_c	–7.76E-04	0.027693
a_p*f	–230.907	–15892.3
a_p*v_c	–0.01161	12.381
$f*v_c$	–0.0548	–3.13643

Mathematical model for forecasting parameter *Sz*:

$$\boldsymbol{Sz} = -14.8875+35.8353*\text{ Types of cutting tools } -694.914*a_p+4499.99*f- \\ -1.98477*v_c-10.4595*\text{ Types of cutting tools}^2+407.427*a_p^2 -23584*f^2 \\ +0.004536*v_c^2 +66.5592*\text{ Types of cutting tools}*a_p+ \\ +70.6766*\text{ Types of cutting tools*f} + 0.027693*\text{ Types of cutting tools}*v_c \\ -15892.3*\ a_p*f +12.381*\ a_p*v_c -3.13643*\ f*v_c \tag{6}$$

Where types of cutting tools are 1, 2, 3, 4.

The model of the appropriate parameters of *Sa* as the 4rd equation is the comparison between the real value and the forecasted value of the model by the parameter as shown in Table 12 as follows:

The information in Table 12 show the result of the comparison between actual value and forecasted value. The forecasted values of parameter *Sa* have the average error of only 0.015%.

4. Conclusion

Surface roughness is an important measure of performance in machining operations. This study investigates the overall effects of turning parameters (cutting speed. depth of cut and feed rate) and kind of cutting tool geometry specifications on surface roughness of Ti (Grade 2) parts. To model the process. Taguchi method has been employed for experimental tests. Then analysis of variance (ANOVA) and the response surface methodology was used to determine optimal values of input parameters to achieve the minimum surface roughness; as the process output characteristics. The optimal machining conditions were 100 m/min cutting speed (level 2), 0.038 mm/rev feed rate (level 1), 0.1 mm depth of cut (level 3), PCD cutting tools (level 1) for parameter *Sa*. 150 m/min cutting speed (level 4), 0.048 mm/rev feed rate (level 2), 0.125 mm depth of cut (level 4), PCD cutting tools (level 1) for parameter *Sz*, respectively.

Table 12. Comparison of actual value and forecasting value of parameter *Sa*

Experiment number	**Cutting parameter level**				***Sa***		
	A	**B**	**C**	**D**			
	Types of cutting tools	**Depth of cut a_p, mm**	**Feed rate *f*, mm/rev**	**Cutting speed v_c, m/min**	**Actual**	**Predicting**	**%Error**
1	PCD insert (Level 1) assigned a numerical value 1	0.05 (Level 1)	0.038 (Level 1)	75 (Level 1)	0.226	0.226	0.0315%
2		0.075 (Level 2)	0.048 (Level 2)	100 (Level 2)	0.218	0.218	2.3566%
3		0.1 (Level 3)	0.058 (Level 3)	125 (Level 3)	0.235	0.235	2.1829%
4		0.125 (Level 4)	0.077 (Level 4)	150 (Level 4)	0.201	0.201	0.0291%
5	CBN insert (Level 2) assigned a numerical value 2	0.05 (Level 1)	0.048 (Level 2)	125 (Level 3)	0.398	0.398	1.6642%
6		0.075 (Level 2)	0.038 (Level 1)	150 (Level 4)	0.444	0.444	0.5174%
7		0.1 (Level 3)	0.077 (Level 4)	75 (Level 1)	0.583	0.583	0.1246%
8		0.125 (Level 4)	0.058 (Level 3)	75 (Level 1)	0.444	0.444	1.1744%
9	Ceramic insert (Level 3) assigned a numerical value 3	0.05 (Level 1)	0.058 (Level 3)	150 (Level 4)	0.637	0.637	0.8131%
10		0.075 (Level 2)	0.077 (Level 4)	125 (Level 3)	0.601	0.601	0.3412%
11		0.1 (Level 3)	0.038 (Level 1)	100 (Level 2)	0.231	0.231	0.9118%
12		0.125 (Level 4)	0.048 (Level 2)	75 (Level 1)	0.634	0.634	0.8223%
13	Carbide insert (Level 4) assigned a numerical value 4	0.05 (Level 1)	0.077 (Level 4)	100 (Level 2)	0.622	0.622	0.4873%
14		0.075 (Level 2)	0.058 (Level 3)	75 (Level 1)	0.401	0.401	1.0730%
15		0.1 (Level 3)	0.048 (Level 2)	150 (Level 4)	0.31	0.31	1.8560%
16		0.125 (Level 4)	0.038	125	0.296	0.296	1.5401%

In addition the effects (in percent) of each these parameters on the output have been determined. It is shown that the kind of the cutting tool has the most significant effect on the surface roughness.

References

[1] J. GAWLIK, J. KRAJEWSKA, M. NIEMCZEWSKA-WÓJCIK: Precision machining of spherical ceramic parts. *Advances in Manufacturing Science and Technology*, **38**(2013)4, 19-30.

[2] S. PŁONKA: The influence of selected parameters of finish turning of copper on the surface roughness. *Advances in Manufacturing Science and Technology*, **31**(2007)4, 7-19.

[3] P. PYTLAK: The influence of cutting parameters on the surface texture of 18CrMo4 hardened steel. *Advances in Manufacturing Science and Technology*, **35**(2011)1, 55-69.

[4] J. GAWLIK, W. ZĘBALA: Kształtowanie jakości wyrobów w obróbce precyzyjnej. *Mechanik*, (2011)12, 6-7.

[5] A.L. MANTLE, D.K. ASPINWALL: Surface integrity and fatigue life of turned gamma titanium aluminide. *J. Mater. Process. Tech.,* **72**(1997), 413-420.

[6] A.R. ZZAREENA, S.C. VELSHUIS: Tool wear mechanisms and tool life enhancement in ultra-precision machining of titanium. *J. Mater. Process. Tech.,* **212**(2012), 560-570.

[7] C.H. CHE-HARON, A. JAWID: The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V. *J. Mater. Process. Tech.,* **166**(2005), 188-192.

[8] C.H. CHE-HARON: Tool life and surface integrity in turning titanium alloy. *J. Mater. Proc. Tech.*, **118**(2001), 231-237.

[9] C. NIKOS TSOURVELOUDIS: Predictive modeling of the Ti-6Al-4V alloy surface roughness. *J. Intell. Robot Syst.,* **60**(2010), 513-530.

[10] E.O. EZUGWU et al.: Evaluation of the performance of CBN tools when turning Ti–6Al–4V alloy with high pressure coolant supplies. *Int. J. Machine Tools & Manufacture,* **45**(2005), 1009-1014.

[11] E.O. EZUGWU, J. BONNEY, Y. YAMANE: An overview of the machinability of aeroengine alloys. *J. Mater. Process. Tech.,* **134**(2003), 233-253.

[12] E.O. EZUGWU, Z.M. WANG: Titanium alloys and their machinability – a review. *J. Mater. Process. Tech.,* **68**(1997), 262-274.

[13] E.O. EZUGWU et al.: Surface integrity of finished turned Ti–6Al–4V alloy with PCD tools using conventional and high pressure coolant supplies. *Int. J. Mach. Tool. Manu.,* **47**(2007), 884-891.

[14] M.V. RIBEIRO, M.R.V. MOREIRA, J.R. FERREIRA: Optimization of titanium alloy (6Al-4V) machining. *J. Mater. Process. Tech.,* **144**(2002), 458-463.

[15] P.F. CHAUVY, C. MADORE, D. LANDOLT: Variable length scale analysis of surface topography: characterization of titanium surfaces for biomedical applications. *Surf. Coat. Tech.,* **110**(1998), 48-56.

[16] S. RAMESH, L. KARUNAMOORTHY, K. PALANIKUMAR: Measurement and analysis of surface roughness in turning of aerospace titanium alloy. *Measurement,* **45**(2012), 1266-1276.

[17] S.K. BHAUMIK, C. DIVAKAR, A.K. SINGH: Machining Ti-6Al-4V alloy with a wBN-cBN composite tool. *Mater. Design*, **16**(1995)4, 221-226.
[18] W. GRZESIK: A survey of current knowledge on machining titanium and its alloys. Proc. 5th International Scientific Conference Development of Metal cutting, Kosice 2005, 21-26.
[19] Z.A. ZOYA, R. KRISHNAMURTH: The performance of CBN tools in the machining of titanium alloys. *J. Mater. Process. Tech.*, **100**(2000), 80-86.
[20] A.R. MOTORCU: The optimization of machining parameters using the taguchi method for surface roughness of AISI 8660 Hardened Alloy Steel. *J. Mech. Eng. Sci.*, **56**(2010)6, 391-401.
[21] E. KURAM et al.: Optimization of the cutting fluids and parameters using Taguchi and ANOVA in milling. Proc. of the World Congress on Engineering, London 2010, 1-5.
[22] F. KOLAHAN, M. MANOOCHEHRI, A. HOSSEINI: Application of Taguchi method and ANOVA analysis for simultaneous optimization of machining parameters and tool geometry in turning. *Eng. Tech.*, **74**(2011), 82-85.
[23] K. CHOMSAMUTR, S. JONGPRASITHPORN: Optimization parameters of tool life model using the Taguchi approach and response surface methodology. *Int. J. Comput. Inf. Sci.*, **9**(2012) 3, 120-125.
[24] R.S. RAMA, G. PADMANABHAN: Application of Taguchi methods and ANOVA in optimization of process parameters for metal removal rate in electrochemical machining of Al/5%SiC composites. *Int. J. Eng. Res. Ap.*, **2**(2012)3, 192-197.

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