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OPTIMIZATION OF THE PROCESS PARAMETERS FOR SURFACE ROUGHNESS AND TOOL LIFE IN FACE MILLING USING THE TAGUCHI ANALYSIS

OPTIMIZACIJA PROCESNIH PARAMETROV GLEDE NA HRAPAVOST POVRŠINE IN TRAJNOSTNO DOBO ORODJA PRI ČELNEM REZKANJU Z UPORABO TAGUCHIJEVE ANALIZE

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In this study, the Taguchi method, which is a powerful tool to design quality optimization, is used to find the optimum surface roughness and tool life in milling operations. An orthogonal array, a signal-to-noise (*S/N*) ratio, and an analysis of variance (ANOVA) are employed to investigate the tool life and the surface-roughness characteristics of AISI D3 steel. Accordingly, the lowest surface roughness and the highest tool life were estimated to be 0.436 μm and 434.1 s, respectively and, finally, the Taguchi method allowed the optimization of the system for the verification of the tests.

Further, ANOVA analysis was revealed that the number of cutter insert was the most important parameter influencing the surface roughness with a 75.27 %, and cutting speed was the most important parameter influencing the tool life with a 95 %.

Keywords: material machinability, face milling, Taguchi method, optimization, experimental design

V tej študiji je bila uporabljena Taguchijeva metoda kot močno orodje za ugotavljanje razmer za doseganje optimalne hrapavosti in trajnostne dobe orodja pri rezkanju. Ortogonalna matrika, signal hrupa (*S/N*) in analiza variance (ANOVA) so bili uporabljeni za preiskavo zdržljivosti orodja in hrapavosti površine jekla AISI D3. Na podlagi rezultatov je bila ocenjena najmanjša hrapavost površine 0,436 μm in največja zdržljivost orodja 434,1 s, Taguchijeva metoda pa je omogočila optimizacijo sistema pri verifikaciji preizkusov.

Nadalje je ANOVA analiza odkrila, da je število rezalnih vložkov najbolj pomemben parameter, ki s 75,27 % vpliva na hrapavost površine, hitrost rezanja pa je najpomembnejši parameter, ki s 95 % vpliva na življenjsko dobo orodja.

Ključne besede: obdelovalnost materiala, čelno rezkanje, Taguchijeva metoda, optimizacija, načrtovanje preizkusov

1 INTRODUCTION

Basically, milling is one of the most commonly used chip removal operations in manufacturing processes and machined parts are usually utilized to assembly with other parts in aerospace, die, medical, automotive, defense industry and machine design as well as in manufacturing industries.[1] In addition to the cutting insert, the tool holder, workpiece material, cutting speed (V), feed rate (f), depth of cut (a) and number of milling cutting inserts are the most important cutting parameters that highly affect the performance characteristics such as tool life and surface roughness.

Generally, researchers have focused on the tool deformation, the effects of cutting-tool coatings and environmental conditions using a single insert. The costs of cutting tools are important to manufacturers. The cost factor causes lowering to the minimum level of an implementation with the least number of inserts. In contrast, the increase in the duration of the process is also a well-known factor.[2] The aim of this study is to find out the effects of the cutting parameters (the cutting speed, the feed rate and the number of cutting inserts) on the surface roughness and the tool life at high cutting speeds. The roughness of machined surface is an important quality indicator in machining processes and the various properties of machined parts such as corrosion, wear, friction, and heat transmission are also influenced by surface roughness.[3,4] Most of the process parameters like spindle speed, feed rate, number of insert, depth of cut, tool holder geometry, cutting insert geometry, tool material, cooling condition affect the tool life and surface roughness. Thus, it is difficult to define a general model for tool life and surface roughness.[5] Some statistical methods like Taguchi, Response Surface Methodology (RSM), desirability functional analysis, ANOVA and Grey Relational Analysis (GRA) have been applied for optimization and analysis of process parameters. The optimization using Taguchi method has revealed a unique and powerful optimization tool that differs from traditional applications.[6] For instance, Kivak et al.[7] studied the optimization of drilling parameters based on the Taguchi method to minimize the surface roughness (R_a) and thrust force (F_f). Their study showed that the cutting tool was the most significant parameter for the R_a. Moreover, the results of verification test demonstrated the Taguchi method for drilling operations was successful to obtain the better surface quality of the machined parts. Aslan et al.[8] evaluated the R_a and cutting-tool wear during the machining of AISI 4140 (63 HRC) steel with an experiment according to the Taguchi's L_{27} orthogonal array. From the ANOVA table, it was found out that tool wear is affected by cutting speed with 30 %. They suggested a 250 m/min cutting speed, a 0.25 mm depth of cut and a 0.05 mm/r feed rate to minimize the R_a value. Gunay and Yucel[9] investigated the R_a during the machining of high-alloy white cast iron with an experiment according to the Taguchi L_{18} orthogonal array. According to ANOVA data, they explained that the most important parameter was feed rate for Ni-Hard with 62 HRC although the cutting speed was the most important parameter for Ni - Hard with 50 HRC.

Neseli et al.[10] studied the influence of the tool geometry on the surface finish when turning the AISI 1040 steel with an Al_2O_3/TiC tool using the response-surface methodology (RSM). Their results indicated that the tool-nose radius was the dominant factor for the surface roughness with a 51.45 % contribution to the total variability of the model.

Asilturk and Akkus[11] applied the Taguchi method to minimize the surface roughness, which is R_a and R_z, in turning of hardened AISI 4140 steel (51 HRC) using coated carbide tools. In addition, their study explored the effects of the cutting speed, the feed rate and the depth of cut on the responses. From the ANOVA analysis, it was determined that the feed rate was the most significant parameter on results. Further, it was seen that the optimum machining parameters for R_a and R_z were different. Kacal and Gulesin[12] optimized the machining parameters for the finish turning of austempered cast iron (GJS-400-15). Their experimental investigation was conducted based on Taguchi's L_{18} orthogonal array. Statistical analysis, which was ANOVA, demonstrated that feed rate is the most important factor with 69.5 % for surface roughness (R_a). In addition, they identified the best machining parameters for R_a to be: an austempering temperature of 290 °C, a ceramic tool, a cutting speed of 800 m/min and a feed rate of 0.05 mm/r.

Sarikaya and Gullu[13] studied the Taguchi design and a response-surface-methodology-based analysis of the machining parameters for CNC turning under MQL. It was found that the most effective parameter for the surface roughness is the feed rate. In addition, the cooling conditions also significantly affect the surface roughness. Kadirvel and Hariharan[14] investigated the optimization of the die-sinking micro-edm process for multiple performance characteristics using the Taguchi-based grey relational analysis. Their study indicated that, on the basis of a confirmation test, the improvement in the performance characteristics was found to be as follows: MRR 3.86 %, TWR 4.20 % and SR 3.51 %. Kivak[15] investigated the Taguchi-method-based optimization of drilling parameters when drilling the AISI 316 steel with a PVD monolayer- and multilayer-coated HSS drills. The analysis results revealed that the feed rate was the dominant factor affecting the surface roughness and the cutting speed was the dominant factor affecting the flank wear. Koklu[16] investigated the influence of the process parameters and the mechanical properties of aluminum alloys on the burr height and the surface roughness in dry drilling using the Taguchi method. The analysis of variance and Taguchi techniques were applied in order to determine the effects of the drilling parameters.

The literature survey demonstrates that traditional experimental design procedures are too complicated and not easy to use. A large number of experimental tasks have to be performed when the number of process parameters increases. The Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments for solving this problem.[11]

The purpose of this study is to obtain the optimum milling parameters (the cutting speed, the feed rate, the number of cutting inserts) for the minimum surface roughness and the maximum tool life during the milling of AISI D3 steel. The Taguchi parameter-design approach was employed to achieve these goals. Moreover, a statistical analysis (ANOVA) was carried out to see which machining parameter is statistically significant. Finally, confirmation tests were conducted using the optimum cutting conditions determined with the Taguchi optimization method.

2 EXPERIMENTAL PROCEDURE

2.1 Milling experiments

In this study, AISI D3 cold-work tool steel was used as the workpiece material. This steel type is used in many manufacturing industries such as the ones manufacturing cold-extrusion and drilling moulds, mould plates, powder-metallurgy kits, ceramic shaping moulds and cold punches. The dimensions of the workpiece were 100 mm × 48 mm × 300 mm. The chemical composition of the work material is as follows: 1.938 % C; 0.37 % Si; 0.22 % Mn; 10.66 % Cr; 0.22 % Ni; 0.135 % V; 0.062 % W; 0.07 % Cu; 85.82 % Fe. The milling tests were performed using a Johnford VMC 550 model, a three-axis CNC vertical machine centre, equipped with the maximum spindle speed of 8000 r/min and a 10 kW drive motor. The values of process parameters were selected from the manufacturer's handbook recommended and the preliminary experiments for the tested material. Process parameters and their levels are shown in **Table 1**. In all the experiments, the depth of cut was determined as 1 mm. The experiments were carried out under dry cutting conditions. To protect these experiment conditions for each test, a new cutting insert was used for each experi-

Table 1: Chosen factors and their levels
Tabela 1: Izbrani faktorji in njihovi nivoji

Symbol	Cutting parameter	Levels for surface roughness			Levels for tool life		
		1	2	3	1	2	3
A	Cutting speed, *V*/(m/min)	80	120	180	416	500	600
B	Feed rate, *f*/(mm/r)	0.08	0.12	0.18	0.08	0.1	0.125
C	Number of cutting inserts, *z*	1	3	6	1	3	6

Table 2: Standard tool holder and cutting insert
Tabela 2: Standardno držalo orodja in rezalnega vložka

Standard tool holder					Standard cutting insert			
ASX445-080A06R					SEMT13T3AGSN-JM			
D/mm	*d*/mm	*L*/mm	*Z*	a_a/mm	D_1/mm)	S_1/mm)	F_1/mm)	R_e/mm
80	27	50	6	6	13.4	3.97	1.9	1.5

ment. The flowchart for the optimization of the milling parameters is shown in **Figure 1**. In the milling experiments, the coated carbide inserts manufactured by Mitsubishi Carbide were used. Based on the ISO description, they create a SEMT 13T3AGSN tool geometry and a JM-chip-breaker form. In the experiments, the ASX445-080A06R model of the tool holder was used. The geometry of the cutting tool is shown in **Figure 2**. The geometric features of the tools are listed **Table 2**.

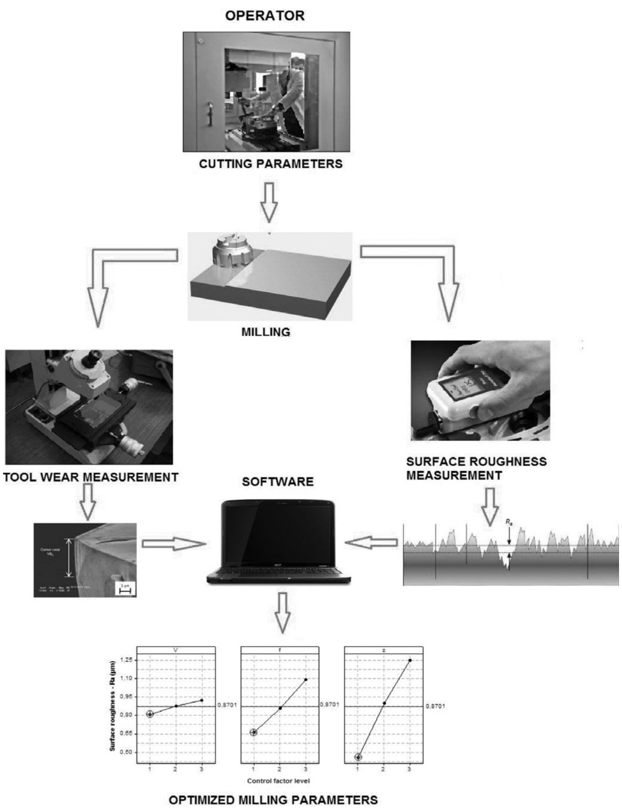

Figure 1: Flowchart for optimization of milling parameters
Slika 1: Diagram poteka optimizacije parametrov rezkanja

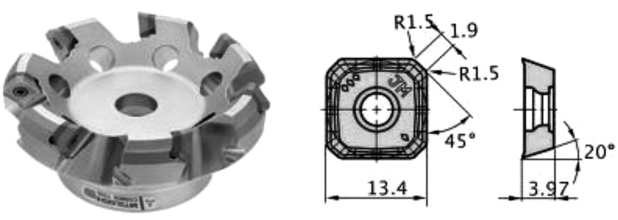

Figure 2: Cutting tool employed in the experiments
Slika 2: Rezalno orodje, uporabljeno pri preizkusih

2.2 Measurements

One of the most important quality indicators of the machined parts is surface roughness or surface quality. According to the standard, the average surface roughness is defined as R_a. In present work, R_a was determined by using a Mahr Perthometer M1 with a cut-off length of 0.8 mm and a sampling length of 5 mm based on ISO 4287 standard. It was considered by measuring the mean of the three roughness results performed from different locations on the workpiece.

Generally, the cutting tool-wear occurs in combination with the predominant wear mode, dependent upon the cutting parameters, cooling/lubrication conditions, workpiece material, cutting tool material and the tool insert geometry. The forms of the cutting-tool wear,

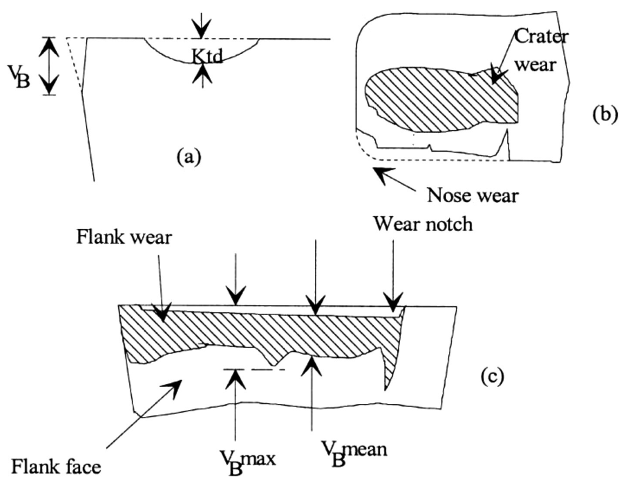

Figure 3: Conventional features of tool-wear measurements[17]
Slika 3: Običajne meritve obrabe orodja[17]

often expressed as the principal types of the tool wear are nose, flank, notch and crater wear types, and **Figure 3** shows how these wear features are usually measured.[17] In the present work, tool deformations were measured and investigated using a Mitutoyo light microscope with a 0.001 mm sensitivity and a capability of magnifying 5 to 10 fold. The experiments revealed that the notch wear was observed during the machining at high cutting speeds. The determination of the machining time was based on ISO 2688-1. When determining the tool life, VB_{max} was taken as 1 mm. The flank wear on the cutting tools was periodically measured and recorded to determine the tool life.

2.3 Control factors and orthogonal array

The cutting speed V (m/min), feed rate f (mm/r) and number of cutting inserts (z) were selected as the control factors for the surface-roughness and tool-life values, and their levels were determined as shown in **Table 1**. The orthogonal array (OA) enables an effective tool to conduct the test with the small number of studies in the Taguchi experimental method. The total degree-of-freedom (DF_T) is the basis of orthogonal array for experimental design.[18] In present work, because there are three control factors and three levels, the DF_T is given as twenty-six. In order to make the performance comparisons between control factors and its different combinations, an OA having at least nine or twenty-seven test trials (DF_T + 1) shoud be selected. Therefore, the standard L_{27} (3^3) OA is selected for the study and the surface-roughness and tool-life values are measured via the experimental design for each combination of the control factors. Determination of the quality characteristics of the measured control factors is provided by the *S/N* ratios.

3 RESULTS AND DISCUSSIONS

3.1 Analysis of the signal-to-noise (S/N) ratio

With the Taguchi method we used the signal-to-noise (*S/N*) ratio as the quality characteristic of choice. In milling operations, a lower surface roughness and larger tool life are indications of a better performance. Therefore, in order to obtain the optimum machining performance, the smaller-the-better (Equation 1) and larger-the-better (Equation 2) ratios were selected for the minimum surface roughness and maximum tool life, respectively:

Table 3: Experimental results, means and corresponding *S/N* ratios
Tabela 3: Eksperimentalni rezultati, povprečja in ustrezna razmerja *S/N*

Exp. No.	Cutting-parameter level			Measured surface roughness, R_a/µm	Calculated (*S/N*)/dB	Measured tool life, *T*/s	Calculated, (*S/N*)/dB
	A Cutting speed, *V*/(m/min)	B Feed rate, *f*/(mm/r)	C Number of inserts, *z*				
1	1	1	1	0.160	15.9176	435	52.7698
2	1	1	2	0.582	4.7015	426	52.5882
3	1	1	3	1.079	–0.6604	403	52.1061
4	1	2	1	0.383	8.3360	401	52.0629
5	1	2	2	0.784	2.1137	365	51.2459
6	1	2	3	1.194	–1.5401	338	50.5783
7	1	3	1	0.586	4.6420	369	51.3405
8	1	3	2	1.109	–0.8986	354	50.9801
9	1	3	3	1.400	–2.9226	328	50.3175
10	2	1	1	0.206	13.7227	266	48.4976
11	2	1	2	0.723	2.8172	236	47.4582
12	2	1	3	1.084	–0.7006	233	47.3471
13	2	2	1	0.456	6.8207	231	47.2722
14	2	2	2	0.869	1.2196	222	46.9271
15	2	2	3	1.261	–2.0143	193	45.7111
16	2	3	1	0.724	2.8052	216	46.6891
17	2	3	2	1.160	–1.2892	210	46.4444
18	2	3	3	1.409	–2.9782	167	44.4543
19	3	1	1	0.303	10.3711	118	41.4376
20	3	1	2	0.708	2.9993	110	40.8279
21	3	1	3	1.104	–0.8594	100	40.0000
22	3	2	1	0.552	5.1612	102	40.1720
23	3	2	2	0.945	0.4914	97	39.7354
24	3	2	3	1.290	–2.2118	86	38.6900
25	3	3	1	0.761	2.3723	97	39.7354
26	3	3	2	1.211	–1.6629	91	39.1808
27	3	3	3	1.449	–3.2214	82	38.2763

$$\text{Smaller–the–better: } \frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (1)$$

$$\text{Larger–the–better: } \frac{S}{N} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \quad (2)$$

Here, y_i is the ith measure of the experimental results in a run/row and n gives the number of measurements in each trial/row test.

The *S/N* ratios for the surface roughness and tool life were calculated using Equations 1 and 2, as shown in **Table 3**. The milling parameters were divided by considering different levels and possible effects, according to the selected orthogonal array. According to the experimental results, the mean of the surface roughness was 0.8701 μm and its mean *S/N* ratio was 2.353 dB. The mean value of tool life and its mean *S/N* ratio were also calculated as 232.4 s, and 46.031 dB, respectively. Further, the effects of input parameters on the responses can be analyzed with help of *S/N* ratios. These effects are defined and evaluated according to the total mean values of the experimental-trial results or *S/N* ratios. The minimum surface-roughness and the maximum tool-life values can be calculated from the total mean values of the experimental-trial results for the surface roughness and tool life. An important requirement when calculating the optimum points is to identify the optimum levels of machining parameters. They were defined by assessing different levels of the input parameters, based on the results from combinations produced by the OA. The levels of the control factors were determined for both the surface roughness and tool life, presented in **Table 4**, and *S/N* graphics of these levels were used for the evaluation (**Figures 4** and **5**). As shown in **Figure 4**, the surface roughness is found to be minimal at low cutting speed and feed rate and the minimum number of cutting inserts. The surface roughness increases with a rise in the cutting speed for a given value of the feed rate. Since the temperature increases between the tool material and the workpiece material through the friction under higher cutting speed, the cut chips by the cutting tool stick over the cutting insert with help of the high temperature.[19] Therefore, the surface roughness increases during the experiments at higher cutting speeds. The increased feed rate and number of cutting inserts lead to vibration, generating more heat and, thereby, a higher surface roughness occurs.[20] The tool life based on the wear value of VB_{max} = 1 mm for all the experiments is drawn. According to **Figure 5**, the longest tool life was obtained at the lowest values of the cutting speed, feed rate and number of cutters. When **Figure 5** is evaluated, it is possible to observe that an increased number of cutting inserts leads to a decreased tool life. This can be explained with the cutting temperature and the vibrations generated at the tool/chip contact when the number of cutting inserts is increased. It is known that a high cutting temperature occurs in the primary deformation zone

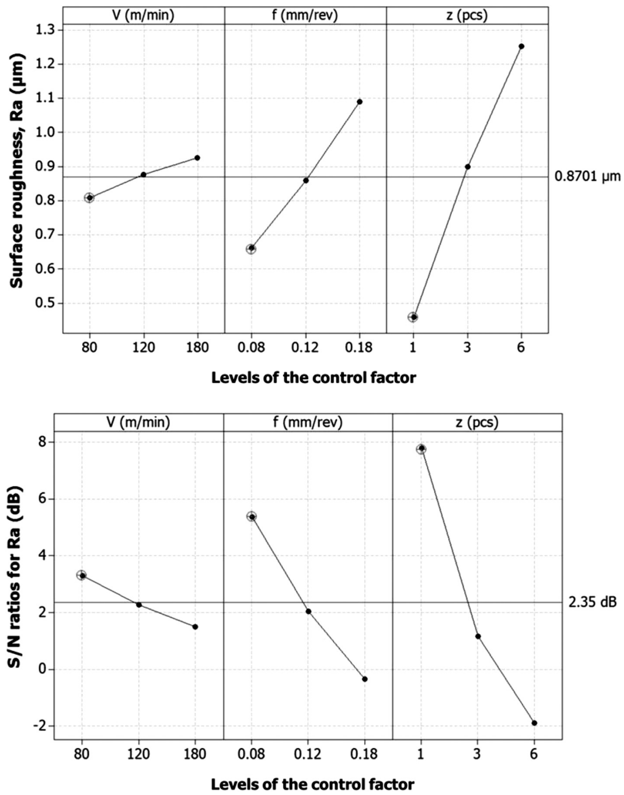

Figure 4: Main effects plot of the factors and *S/N* graph for the surface roughness
Slika 4: Prikaz glavnih faktorjev in odvisnost *S/N* od hrapavosti površine

Table 4: Response table for *S/N* ratios (dB) and means
Tabela 4: Tabela odzivov (dB) za različna razmerja *S/N* in za različna sredstva

Control factors	Surface roughness (R_a)				Tool life (T)			
	Level 1	Level 2	Level 3	Delta	Level 1	Level 2	Level 3	Delta
S/N ratios								
A	3.30	2.26	1.49	1.80	51.55	46.76	39.78	11.77
B	5.37	2.04	–0.35	5.72	47.00	45.82	45.27	1.73
C	7.79	1.16	–1.90	9.69	46.66	46.15	45.28	1.39
Means								
A	0.81	0.88	0.92	0.12	379.89	219.33	98.11	281.78
B	0.66	0.86	1.09	0.43	258.56	226.11	212.67	45.89
C	0.46	0.90	1.25	0.79	248.33	234.56	214.44	33.89

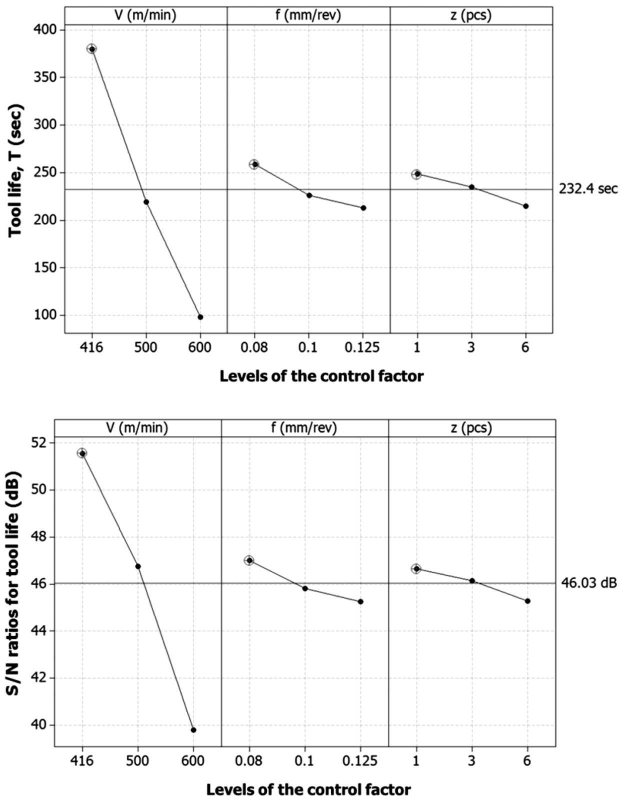

Figure 5: Main effects plot of the factors and *S/N* graph for the tool life
Slika 5: Prikaz glavnih faktorjev in odvisnost *S/N* od zdržljivosti orodja

with the increasing cutting speed. Thus, the wear mechanisms are accelerated and so the tool life is decreased.

The *S/N* ratios of the surface-roughness data obtained from the experimental work, later used to determine the optimum level of each variable, were calculated in **Table 3**. **Figure 4** illustrates the graphs of the *S/N* ratios that were calculated for the surface roughness. As mentioned above, the maximum value of the *S/N* ratios gives the optimum cutting conditions. Thus, the optimum combination for the R_a was determined as $A_1B_1C_1$ (A_1 = 80 m/min, B_1 = 0.08 mm/r, C_1 = 1 cutting insert). The *S/N* ratios for the tool-life data obtained from the experimental results were calculated in **Table 3**. **Figure 5** illustrates the graphs of the *S/N* ratios that were calculated for the tool life. The optimum combination for the tool life was determined as $A_1B_1C_1$ (A_1 = 416 m/min, B_1 = 0.08 mm/r, C_1 = 1 cutting insert).

3.2 Analysis of variance (ANOVA)

The Taguchi method was used for determining the optimum cutting conditions according to the *S/N* ratio, while the control-factor correlation with the experimental results was determined with the help of an analysis of variance (ANOVA). The analysis of variance (ANOVA) was employed through the Minitab 16.0 Program. **Table 5** shows the results of ANOVA for the surface roughness and tool life. In addition to the degree of freedom, the mean of squares (*MS*), the sum of squares (*SS*), the *F*-ratio, *P*-values and the contribution (*PCR*) associated with each factor were presented. This analysis was performed for a confidence level of 95 %. The importance of the input parameters in ANOVA analysis was identified by comparing the *F*-values of each input parameters. The *F*-value determined in the ANOVA table was compared with the value according to standard *F*-tables for a given statistical level of importance.[21] According to the ANOVA table, the *P*-value is effective for all three levels at the reliability level of 95 %, because the results for the surface roughness and tool life are lower than 0.05. As the results of the evaluation of the surface roughness, the percentage contributions of input parameters for *A*, *B* and *C* were determined as: (1.63, 21.96 and 75.27) %, respectively, and the error was 1.14 % (**Table 5**). Thus, it was found that the number of cutting inserts and the feed rate vary significantly more than the cutting speed regarding the surface roughness in milling the AISI D3 steel. The ANOVA table indicates that the variable most significantly affecting the surface-roughness value is the number of cutting inserts with 75.27 % of *PCR*. This result clearly shows the effects of the

Table 5: Results of ANOVA for responses
Tabela 5: Rezultati ANOVA-odzivov

Variation of source	Degree of freedom (*DF*)	Sum of squares (*SS*)	Mean of squares (*MS*)	*F*-ratio	*P*-value	Contribution (%)
Surface roughness (R_a)						
A	2	0.06141	0.03071	14.26	0.000	1.63
B	2	0.82931	0.41466	192.53	0.000	21.96
C	2	2.84270	1.42135	659.97	0.000	75.27
Error (*e*)	20	0.04307	0.00215			1.14
Total	26	3.77650				100
Tool life (*T*)						
A	2	359615	179807	975.62	0.000	95.00
B	2	10018	5009	27.18	0.000	2.65
C	2	5228	2614	14.18	0.000	1.38
Error (*e*)	20	3686	184			0.97
Total	26	378547				100

number of cutting inserts on the surface roughness in milling the AISI D3 steel whose vibration generated a higher frequency between the tool and the workpiece with the increasing number of cutting inserts. The other variable that has an effect on the R_a is the feed rate with 21.96 % of *PCR*. It is known that an increasing feed rate increases the chip volume removed per unit time.[7] Accordingly, **Table 5** shows that the percentage contributions of factors *A*, *B*, and *C* for the tool life are (95.00, 2.65 and 1.38) %, respectively, and the error is 0.97 %. Thus, **Table 5** indicates that the most effective variable for the tool life is the cutting speed (95.00 %). The feed rate and number of cutting inserts do not affect the tool life. In milling operations, the cutting speed is the most effective cutting parameter, reducing the tool life, because an increasing cutting speed increases the cutting temperature in the primary deformation zone. As a result of this situation, the wear mechanisms are accelerated.

3.3 Verification experiments

In the last step of the Taguchi approach, the optimization was confirmed via verification tests then the determination of the parameter levels giving the optimum results. The verification-test results were obtained for the optimum parameter levels ($A_1B_1C_1$) of the surface roughness. Later, the calculation of the predicted minimum surface roughness R_{ap} from Equation 3, taking into consideration individual effects of factors *A*, *B*, *C* and their levels, is as follows:

$$R_{ap} = T_{Re} + (A_1 - T_{Re}) + (B_1 - T_{Re}) + (C_1 - T_{Re}) \quad (3)$$

where A_1 is the mean (0.81 μm) of the experimental trials at the first level of factor *A*. B_1 is the mean (0.66 μm) of the experimental trials at the first level of factor *B*. C_1 is the mean (0.46 μm) of the experimental trials at the first level of factor *C*. With Equation 3, the minimum surface roughness was calculated as 0.147 μm. As determined in **Figure 5**, *A*, *B*, *C* and their levels were used for the calculation of the predicted optimum tool life. The equation for the predicted optimum tool life is as follows:

$$T_p = T_T + (A_1 - T_T) + (B_1 - T_T) + (C_1 - T_T) \quad (4)$$

where *A*, *B* and *C* are the means (379.89, 258.56 and 248.33) s of the experimental trials at the optimum levels of these factors. With Equation 4, the maximum tool life was calculated as 441.67 s. The confidence interval (*CI*) was conducted to confirm the output parameters of the verification test. The *CI* for the estimated optimum results was calculated using the following equation:[22]

$$CI = \sqrt{F_{\alpha;1;Ve} \cdot V_{ep} \cdot \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \quad (5)$$

where, with respect to $F_{\alpha;1;Ve}$, *F* is the ratio of significant level α, α is the significance level, $1 - \alpha$ is the confidence level and V_e is the degree of freedom of the pooled error variance. V_{ep} is the pooled error variance, *r* is the number of repeated trials ($r\neq$), *N* is the total number of experimental trials, n_{eff} is the number of effective measured results defined as[22]:

$$n_{eff} = \frac{N}{1+b} \quad (6)$$

where *b* is total degress of freedom associated with items used in estimate.

In the present investigation, three verification tests (*r* = 3) were made to assess the performance of the experimental study used for the surface roughness at optimum parameters ($A_1B_1C_1$). The value of $F_{\alpha;1;Ve} = 4.30$ which has a 95 % confidence level for the surface roughness, was found with respect to the values of $\alpha = 0.05$ and $V_e = 20$, based on the look-up table. According to Equations 5 and 6, the confidence interval (*CI*) is calculated as 0.07. The result value of the confirmation test performed for the surface roughness is expected to be in the confidence interval of (0.147 ± 0.07) or (0.077 – 0.217) with a 95 % confidence level.

In the present work, the values of the surface roughness from the three confirmation tests performed with regard to the optimum levels ($A_1B_1C_1$) were measured as (0.159, 0.162 and 0.168) μm. As shown in **Table 6**, the mean of the measurements was 0.163 μm. The mean result of the confirmation tests in the optimum conditions is within the confidence interval (0.077 < 0.163 < 0.217). As the mean result falls within this limit, the experiment is considered satisfactory. The optimization of process parameters was achieved using the Taguchi method for the surface roughness at the confidence level of 95 %.

Three confirmation experiments were carried out under the optimum conditions ($A_1B_1C_1$) for the tool life. The value of $F_{\alpha;1;Ve} = 4.30$ which has a 95 % confidence level for the tool life, was found with respect to the values of $\alpha = 0.05$, and $V_e = 20$, based on the look-up table. According to Equations 5 and 6, the confidence interval (*CI*) is calculated as 21.4 s. The result value of the confirmation test performed for the tool life is expected to be in the confidence interval of (441.7 ± 21.4) or (420.3 – 463.1) with a 95 % confidence level. In this study, the values of the tool life from the three confirmation tests performed with regard to the optimum levels ($A_1B_1C_1$) were measured as (440.2, 436.4 and 425.7) s. As shown in **Table 7**, the mean of the measurements was 434.1 s. The mean result of the confirmation tests in the optimum condition is within the confidence interval (420.3 < 434.1 < 463.1). As the mean result falls within this limit, the experiment is considered satisfactory. The optimization of the process parameters was achieved using the Taguchi method for the tool life at the confidence level of 95 %. According to the optimum test and the predicted combination, the comparisons of the surface roughness and tool life, and the combinations

Table 6: Comparisons of surface roughness and tool life
Tabela 6: Primerjave hrapavosti površine in zdržljivosti orodja

Comparison	Surface roughness			Tool life		
	Level	R_a/µm	(*S/N*)/dB	Level	*T*/s	(*S/N*)/dB
Initial combination	$A_2B_1C_2$	0.723	2.82	$A_2B_1C_2$	236	47.45
Optimum combination (Experiment)	$A_1B_1C_1$	0.163	15.9	$A_1B_1C_1$	434.1	52.74
Optimum combination (Prediction)	$A_1B_1C_1$	0.147	16.63	$A_1B_1C_1$	441.67	52.92

Table 7: Comparisons of experimental trials
Tabela 7: Primerjave eksperimentalnih poskusov

Comparison	Surface roughness			Tool life		
	Level	R_a/µm	Quality loss	Level	*T*/s	Quality loss
Initial combination	$A_2B_1C_2$	0.723	–	$A_2B_1C_2$	236	–
Optimum combination (Prediction)	$A_1B_1C_1$	0.147±0.07	–	$A_1B_1C_1$	434.1±21.4	
Optimum combination (Confirmation)	$A_1B_1C_1$	0.163	4.9 %	$A_1B_1C_1$	441.67	29.5 %

($A_2B_1C_2$) selected in the twenty-seven initial trials are given in **Table 6**. According to the comparison table, the surface roughness and tool life are reduced from 0.723 µm to 0.163 µm, and from 236 s to 434.1 s, respectively. The improved efficiency due to the optimum combination was increased for the surface roughness and tool life by up to 77.45 % ((0.723 – 0.163)/0.723) and by up to 45.63 % ((434.1 – 236)/434.1), respectively. The performance comparisons between the initial parameters and the optimum conditions are given in **Table 6**. In addition to, the quality losses are listed in **Table 7**.

The quality losses between the initial and optimum combinations for both the surface roughness and tool life are calculated as follows[18]:

$$\frac{L_{\mathrm{opt}}(y)}{L_{\mathrm{int}}(y)} \approx \left(\frac{1}{2}\right)^{\frac{\Delta_n}{3}} \tag{7}$$

where $L_{\mathrm{opt}}(y)$ and $L_{int}(y)$ are the optimum and initial combinations, respectively. Δ_n is the difference between the *S/N* ratios for the optimal and initial combinations. The differences between *S/N* ratios that can be used to evaluate the quality loss of the optimum combination for the surface roughness and tool life, were found to be 13.08 (Δ_n = 13.08 (= 15.9 – 2.82)) and 5.29 (Δ_n = 5.29 (52.74 – 47.45)), respectively. The quality loss was calculated as 0.049 using Equation 7 for the surface roughness. Thus, the quality loss of the surface roughness for the optimum combination is only 4.9 % of the initial combination. Therefore, the quality losses of the surface roughness were reduced to 95.1 % through the Taguchi application. The quality loss for the tool life was calculated as 0.295, using Equation 7. The quality loss of the tool life for the optimum combination is only 29.5 % of the initial combination. Consequently, the quality losses of the tool life were reduced to 70.5 % through the Taguchi method.

4 CONCLUSIONS

This study focuses on the Taguchi method used for investigating the influence of the cutting parameters on the surface roughness and tool life when face milling the AISI D3 steel. In the milling experiments, different levels of the cutting speed, the feed rate and the number of cutting inserts as the machining parameters are used under dry cooling conditions. The experimental results were evaluated using the analysis of the signal-to-noise ratio, the main effect graphs of means and ANOVA. The optimum operating parameters are determined using the Taguchi method. The results can be drawn as follows:

The optimum levels of the control factors providing a better surface roughness and tool life were: A_1 (the cutting speed, 80 m/min), B_1 (the feed rate, 0.08 mm/r), and C_1 (the number of cutting inserts, 1 insert), and A_1 (the cutting speed, 416 m/min), B_1 (the feed rate, 0.08 mm/r), C_1 (the number of cutting inserts, 1 insert), respectively.

The effects of the process parameters on the surface roughness and tool life were detected by ANOVA analysis. It was revealed that the number of cutting inserts the most important parameter influencing the surface roughness with 75.27 %. Further, cutting speed was the most important parameter influencing the tool life with 95 %.

Through the confirmation experiment, the surface roughness was obtained, with one of the initial combinations, as 0.723 µm, and the surface roughness was improved to 77.45 %. The tool life was obtained, with one of the initial combinations, as 236 s, and it was improved to 45.63 %. The quality losses for the surface roughness and the tool life determined from optimum points were calculated as 4.9 % and 29.5 %, respectively.

The confirmation-experiment results indicated that the observed values were within the calculated confidence interval (*CI*) for the confidence level of 95 %.

The present work demonstrates to industrial users how to apply the Taguchi parameter design for optimizing the machining performance with a minimum cost and time in milling the AISI D3 steel. Moreover, this study considered other factors (the cutting speed, the feed rate, the number of cutting inserts) to find how the control factors affect the surface roughness and tool life. Future works may be extend to analyzing the effects of some additional variables such as different tool holders, tool materials, workpiece materials and cooling conditions (wet, HPC, MQL, cryogenic, etc.).

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