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ANALYSIS OF PROCESS PARAMETERS FOR A SURFACE-GRINDING PROCESS BASED ON THE TAGUCHI METHOD

ANALIZA PROCESNIH PARAMETROV POSTOPKA BRUŠENJA POVRŠINE S TAGUCHIJEVO METODO

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In this study, the Taguchi method that is a powerful tool to design optimization for quality is used to find the optimum surface roughness in grinding operations. An orthogonal array, a signal-to-noise (S/N) ratio, and an analysis of variance (ANOVA) are employed to investigate the surface-roughness characteristics of AISI 1040 steel plates using EKR46K grinding wheels. Through this study, not only can the optimum surface roughness for grinding operations be obtained, but the main grinding parameters affecting the performance of grinding operations can also be found. Experimental results are provided to confirm the effectiveness of this approach. The results of this study showed that the depth of cut and the wheel speed have significant effects on the surface roughness, while the rate of feed has a lower effect on it.

Keywords: grinding, surface integrity, surface topography, surface roughness

V tej študiji je bila uporabljena Taguchijeva metoda kot močno orodje za določanje pogojev za doseganje optimalne hrapavosti pri brušenju. Za preiskavo značilnosti hrapavosti površine plošč iz jekla AISI 1040 pri uporabi brusnih kolutov EKR46K so bile uporabljene ortogonalna matrika, signal hrupa (S/N) in analiza variance (ANOVA). S to študijo je bilo mogoče dobiti optimalno hrapavost površine ter glavne parametre brušenja, ki vplivajo na zmogljivost brušenja. Na voljo so eksperimentalni rezultati, ki potrjujejo ta način. Rezultati študije kažejo, da imata globina brušenja in hitrost vrtenja brusnega koluta pomemben učinek na hrapavost površine. Hitrost podajanja pa ima manjši vpliv na hrapavost površine.

Ključne besede: brušenje, površinska integriteta, topografija površine, hrapavost površine

1 INTRODUCTION

Grinding is a manufacturing process with an unsteady process behavior, whose complex characteristics determine the technological output and the quality. An assessment of the grinding-process quality usually includes the micro-geometric quantities of the component. In order to predict the component behavior during the use or to control the grinding process, it is necessary to quantify surface roughness, which is one of the most critical quality constraints for the selection of grinding factors in a process planning. The process set-up often depends on the operator competence[1].

The quality of a surface generated by grinding determines many workpiece characteristics such as the minimum tolerances, the lubrication effectiveness and the component life, among others. A typical surface is characterized by clean cutting paths and plowed material to the sideway of some grooves. However, many other marks can be found, such as cracks produced by the thermal impact, back-transferred material and craters produced by a grain fracture[2,3].

The surface quality produced in surface grinding is influenced by various parameters such as[4,5]: *i.* wheel parameters – abrasives, grain size, grade, structure, binder, shape and dimension; *ii.* workpiece parameters – fracture mode, mechanical properties and chemical composition; *iii.* process parameters – wheel speed, depth of cut, table speed and dressing condition; *iv.* machine parameters – static and dynamic characteristics, spindle system, and table system.

Kwak[4] evaluated the effect of grinding parameters on the geometric error and optimum grinding conditions. Krajinik et al.[1] developed a second-order surface-roughness model using the central composite design technique. Hecker et al.[2] presented a prediction of the arithmetic mean surface roughness based on a probabilistic, undeformed, chip-thickness model for surface roughness in a grinding process. Gupta et al.[6] optimized grinding-process parameters using a numerical method. Tawakoli et al.[7] investigated the effects of a workpiece and grinding parameters on minimum quantity lubrication (MQL) and they compared the results with dry lubrication. Silva et al.[7–9] investigated the effects of grinding parameters on the ABNT 4340 steel using the MQL technique. Shaji et al.[5] analyzed the effects of process parameters and the mode of dressing on the force components and surface using the Taguchi experimental design method. Taguchi is the developer of the Taguchi method. He proposed that an engineering optimization of a process or product should be carried out with a three-step approach: i. system design, ii. parameter design, and iii. tolerance design[10,11].

In this study the wheel speed (*V*), the rate of feed (*F*) and the depth of cut (*D*) were selected as variable parameters. Other process parameters were fixed. The above parameters of grinding were analyzed and optimized with the Taguchi method using the experimentally obtained surface-roughness (Ra) results. Confirmation experiments were conducted at the optimum level to verify the effectiveness of the Taguchi approach.

2 EXPERIMENTAL STUDIES

Commercial AISI 1040 steel plates with the dimensions of 10 mm × 60 mm × 100 mm were used as the workpiece material. The grinding experiments were carried out on a grinding machine as shown in **Figure 1** using EKR46K grinding wheels.

The intense heat generated during the grinding due to a relatively high friction impairs the workpiece quality by inducing thermal damage. Therefore, the cooling and lubrication play a decisive role in grinding. In this study, a cutting fluid was used as a coolant in order to cool the workpiece and, hence, to prevent the thermal damage of the workpiece.

The initial grinding parameters were selected as follows: the wheel speed (*V*) of 1000 r/min; the feed rate (*F*) of 25 m/min and the depth of cut (*D*) of 0.10 mm. A feasible space for the grinding parameters was defined on the basis of the reference[12]. These parameters were further defined as follows: the wheel speed in the range of 1000–2 000 r/min, the feed rate in the range of 20–30 m/min, and the depth of cut in the range of 0.05–0.15 mm. Also, during the grinding operation the workpieces were cooled using cutting fluids. In the grinding parameter design, three levels of grinding parameters were selected as shown in **Table 1**. The surface roughness of grinded workpices was recorded as the R_a value with the ISO class-3-type, surface-roughness tester.

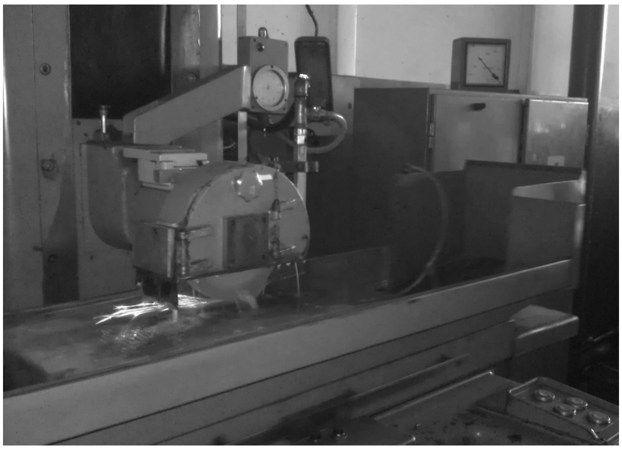

Figure 1: Experimental grinding machine
Slika 1: Eksperimentalni brusilni stroj

Table 1: Grinding parameters and their levels
Tabela 1: Parametri pri brušenju in njihove ravni

Symbol	Grinding parameter	Unit	*Level 1*	*Level 2*	*Level 3*
V	Wheel speed	r/min	1000	1500[a]	2000
F	Rate of feed	m/min	20	25[a]	30
D	Depth of cut	mm	0.05	0.10[a]	0.15

a: initial grinding parameters

3 RESULTS AND DISCUSSION

To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between the design parameters that need to be made to determine which level is better and, specifically, how much better it is. For example, a four-level design parameter counts for three degrees of freedom[11]. The degrees of freedom (V_f) associated with the interaction between two design parameters are given by the product of the degrees of freedom for the two design parameters. In this study, the interaction between the grinding parameters is neglected. Therefore, there are eight degrees of freedom (V_f = 9 –1= 8) owing to there being three grinding parameters (such as the wheel speed, the rate of feed and the depth of cut) of the grinding operations. Once the required degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than, or at least equal to, those for the design parameters. In this study, an L_9 orthogonal array with four columns and nine rows was used. This array has eight degrees of freedom and it can handle three-level design parameters. Each grinding parameter is assigned to a column, having nine grinding-parameter combinations available. Therefore, only nine experiments are required to study the entire parameter space using the L_9 orthogonal array. The experimental layout for the three grinding parameters using the L_9 orthogonal array is shown in **Table 2**. Since the L_9 orthogonal array has four columns, one column of the array is left empty for the error of the experiments; orthogonality is not lost by keeping one column of the array empty[11]. To increase the sensitivity of the results

Table 2: Experimental layout of the L_9 orthogonal array
Tabela 2: Eksperimentalna postavitev ortogonalne matrike L_9

Experiment number	Grinding parameter level		
	V/(r/min) Wheel speed	*F*/(m/min) Rate of feed	*D*/mm Depth of cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

each experiment in the L_9 orthogonal array was repeated three times.

Experimental results were transformed into a signal-to-noise (S/N) ratio. There are three categories of quality characteristics, i.e., the-lower-the-better, the higher-the-better, and the-nominal-the-better. In the present study the-lower-the-better quality characteristic was selected for the surface roughness. The loss function of the-lower-the-better quality characteristics can be expressed as[13]:

$$L_j = \frac{1}{n}\sum_{k=1}^{n} y_i^2 \tag{1}$$

$$\eta_j = -10 \lg L_j \tag{2}$$

where n is the number of tests, y_i is the experimental value of the i^{th} quality characteristic, L_j is the overall loss function and η_j is the S/N ratio. **Table 3** shows the average experimental results for the surface roughness and the corresponding S/N ratio using equations (1) and (2).

Table 3: Experimental results for the surface roughness and S/N ratio
Tabela 3: Eksperimentalno izmerjena hrapavost površine in razmerje S/N

Experi-ment number	Process parameters			R_a (μm)	S/N ratio (dB)
	V (r/min)	F (m/min)	D (mm)		
1	1000	20	0.05	0.22	13.15
2	1000	25	0.10	0.32	9.90
3	1000	30	0.15	0.56	5.04
4	1500	20	0.10	0.28	11.06
5	1500	25	0.15	0.30	10.46
6	1500	30	0.05	0.20	13.98
7	2000	20	0.15	0.48	6.38
8	2000	25	0.05	0.38	8.40
9	2000	30	0.10	0.40	7.96

Since the experimental design is orthogonal, it is then possible to separate out the effect of each grinding parameter at different levels[11,13]. The mean S/N ratio for each level of the grinding parameters is summarized in an S/N response table for the surface roughness. In addition, the total mean S/N ratio for the nine experiments is also calculated and listed in **Table 4**.

As shown in equations (1) and (2), from the view point of the-lower-the-better quality characteristic, a greater S/N ratio corresponds to a smaller variance of the output characteristic around the desired value. As indicated in **Figure 2**, the optimum parameters for the grinding of the AISI 1040 steel become the wheel speed at level 2, the feed rate at level 1 and the depth of cut at level 1 and therefore the combination of parameters is $V_2F_1D_1$.

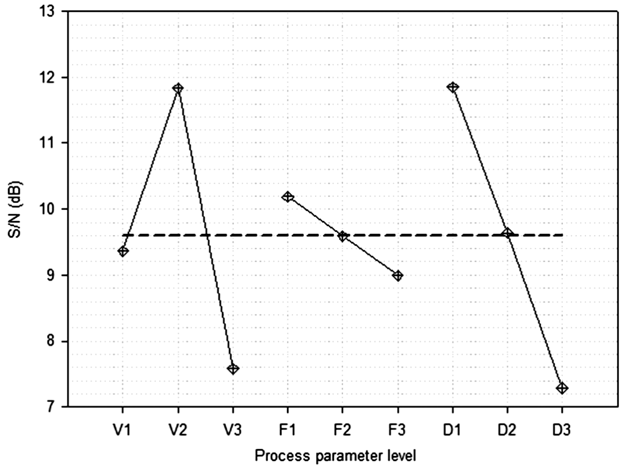

Figure 2: S/N graph for the surface roughness
Slika 2: S/N-graf za hrapavost površine

The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the quality characteristic. This is accomplished by separating the total variability of the S/N ratios, which is measured with the sum of the squared deviations from the total mean S/N ratio, into contributions by each design parameter and the error. First, the total sum of squared deviations SS_{Total} from the total mean S/N ratio η_m can be calculated as[11,13]:

$$SS_{Total} = \sum_{i=1}^{n} (\eta_i - \eta_m)^2 \tag{3}$$

where η_i is the mean S/N ratio for the i^{th} experiment. Statistically, there is a tool called an F test named after Fisher[14] enabling us to see which design parameters have a significant effect on the quality characteristic. Normally, the change of the grinding parameter has a significant effect on the surface roughness when the F value is large. In performing the F test, the mean of squared deviations for each design parameter needs to be calculated. The mean of squared deviations is equal to the sum of squared deviations divided by the number of degrees of freedom associated with the design parameter. Then the F value for each design parameter is simply the ratio of the mean of squared deviations to

Table 4: S/N response table for grinding parameters
Tabela 4: Tabela odzivov S/N za različne parametre brušenja

Symbol	Grinding parameters	Mean S/N ratio (dB)			Total mean S/N (dB)	Maximum-Minimum
		Level 1	*Level 2*	*Level 3*		
V/(r/min)	Wheel speed	9.36	11.83	7.58	9.60	4.25
F/(m/min)	Rate of feed	10.19	9.59	8.99		1.20
D/mm	Depth of cut	11.85	9.64	7.29		4.56

Table 5: Results of ANOVA for the grinding parameters
Tabel 5: Rezultati za parametre brušenja ANOVA

Symbol	Grinding parameters	Degree of freedom	Sum of square	Mean square	*F*	Contribution (%)
V	Wheel speed	2	0.040	0.020	2.48	40
F	Rate of feed	2	0.009	0.003	0.40	9
D	Depth of cut	2	0.050	0.025	3.09	50
Error		2	0.001	0.003		1
Total		8	0.1			100

Table 6: Results of the confirmation experiment
Tabela 6: Rezultati potrditvenih preizkusov

	Initial grinding parameters	Optimum grinding parameters		Improvement of the S/N ratio (dB)
		Prediction	*Experiment*	
Level	$V_1F_1D_1$	$V_2F_1D_1$	$V_2F_1D_1$	0.68
R_a/μm	0.22	0.19	0.20	
S/N (dB)	13.15	14.69	13.83	

the mean of the squared error. **Table 5** shows the results of ANOVA for the grinding parameters.

It can be found that the depth of cut and the wheel speed have significant effects on the surface roughness. Increasing wheel speed and depth of cut increase the surface roughness. However, the change in the rate of feed has a lower effect on the surface roughness. In the present study, the contribution order of the studied grinding parameters for the surface roughness of the AISI 1040 steel is found to be as follows: the depth of cut (50 %), the wheel speed (40 %) and the rate of feed (9 %).

Once the optimum level of design parameters has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimum level of design parameters. The estimated S/N ratio $\hat{\eta}$ using the optimum level of design parameters can be calculated as:

$$\hat{\eta}=\eta_m+\sum_{i=1}^{j}(\eta_i^- -\eta_m)^2 \qquad (4)$$

where η_m is the total mean S/N ratio, η_i^- is the mean S/N ratio at the optimum level, and j is the number of the main design parameters that affect the quality characteristic. The estimated S/N ratio using the optimum grinding parameters for surface roughness can then be obtained and the corresponding surface roughness can also be calculated by using equations (1) and (2). **Table 6** shows a comparison of the predicted surface roughness with the actual surface roughness using the optimum grinding parameters. A close agreement between the predicted and actual surface roughness is observed.

The increase in the S/N ratios from the initial surface roughness to the optimum surface roughness is calculated as 0.68 dB.

The values given in **Table 6** were calculated with the Taghuchi method and experimentally verified.

4 CONCLUSIONS

In this study, an application and adaptation of the Taguchi optimization and quality-control method were established for the optimization of the surface roughness in a grinding process. The Taguchi method provides a systematic and efficient methodology with fewer experiments and trials. The experimental results obtained in this study showed that the depth of cut and the wheel speed have significant effects on the surface roughness. The rate of feed has a lower effect on the surface roughness. The contribution order of the grinding parameters including the depth of cut, the wheel speed and the rate of feed is 50 %, 40 % and 10 %, respectively. A change made to all the grinding parameters significantly changes the surface roughness. The optimum grinding-parameter combination for the AISI 1040 steel includes the wheel speed (*V*) of 1 500 r/min and the depth of cut (*D*) of 0.05mm.

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