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IMPROVING THE SURFACE ROUGHNESS AT LONGITUDINAL TURNING USING THE DIFFERENT OPTIMIZATION METHODS

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Original scientific paper

Determination of optimal machining parameters is a continuous engineering task whose goals are to reduce the production costs and to achieve the desired product quality. Hence, this paper presents and discusses different optimization methods to determine the optimal values of cutting speed, feed and depth of cut with the purpose of improving the surface roughness obtained in the finish longitudinal turning operation. Two experimental plans, one based on the conventional rotatable central composite design and the other based on the orthogonal arrays and signal-to-noise ratio were carried out on the practical case. By using these plans, different optimization methods, namely analytical, classical mathematical, Taguchi and artificial neural networks were performed and the results of optimal cutting parameters obtained with these methods were compared. Finally, the features, the merits and the limitations of the presented optimization methods were discussed.

Key words: *longitudinal turning, optimization methods, surface roughness*

Poboljšanje hrapavosti površine kod uzdužnog tokarenja uporabom različitih metoda optimiranja

Izvorni znanstveni članak

Određivanje optimalnih parametara obrade je kontinuirani inženjerski zadatak čiji su glavni ciljevi sniziti troškove proizvodnje i postići željenu kvalitetu proizvoda. Stoga se u ovom radu predstavljaju i diskutiraju različite metode za optimiranje brzine rezanja, posmaka i dubine rezanja u svrhu poboljšanja hrapavosti površine koja se dobiva završnom operacijom uzdužnog tokarenja. Na praktičnom su primjeru provedena dva plana pokusa, jedan temeljen na konvencionalnom centralnom kompozicijskom planu i drugi temeljen na ortogonalnim nizovima i omjeru signala i šuma. Uporabom ovih planova provedene su različite metode optimiranja i to analitička, klasična matematička, Taguchijeva i umjetne neuronske mreže, a dobiveni rezultati optimalnih parametara rezanja su uspoređeni. Zaključno, diskutiraju se značajke, prednosti i ograničenja predstavljenih metoda optimiranja.

Ključne riječi: *hrapavost površine, metode optimiranja, uzdužno tokarenje*

1 Introduction
Uvod

There are two main practical problems that engineers face in a manufacturing process. The first is to determine the values of the process parameters that will yield the desired product quality (meet technical specifications) and the second is to maximize manufacturing system performance using the available resources. The decisions made by manufacturing engineers are based not only on their experience and expertise but also on conventions regarding the phenomena that take place during processing. In the machining field, many of these phenomena are highly complex and interact with a large number of factors, thus preventing high process performance from being attained. To overcome these problems, the researchers propose models which try to simulate the conditions during machining and establish cause and affect relationships between various factors and desired product characteristics [1].

Surface roughness is a widely used index of product quality and in most cases a technical requirement for mechanical products. Achieving the desired surface quality is of great importance for the functional behaviour of a part. On the other hand, the process dependent nature of the surface roughness formation mechanism along with the numerous uncontrollable factors that influence pertinent phenomena, make a straightforward solution almost impossible, Figure 1. The most common strategy involves the selection of conservative process parameters, which neither guarantees the achievement of the desired surface finish nor attains high metal removal rates. Optimal surface roughness is necessary because of improvement of corrosion resistance, tribology attributes and aesthetic appearance. Exceedingly low surface roughness requires additional expenses of production. Therefore selection of optimal cutting parameters is necessary in order to achieve optimal values of surface roughness [2].

The aim of this study is to present and discuss the different optimization approaches and strategies in order to improve the surface roughness based on the experimental research of finish longitudinal turning [3].

2 Experimental Procedure
Eksperimentalni postupak

In order to establish the correlation between the cutting parameters and the surface roughness in the mathematical model form, machining issues were incorporated with different cutting conditions, aiming at simulating them for the surface roughness.

2.1 Machining Conditions
Uvjeti obrade

The longitudinal turning experiments were carried out on lathe machine "Georg Fisher NDM-16" at Production Engineering Institute of the University of Maribor. Test samples were carbon steel bars Ck45 (DIN 17006) with 100 mm in diameter and 380 mm in length. Experiments were carried out by the external machining turning tool with the holder mark DDJNL 3225P15 and the coated inserts type DNMG 150608-PM4025 under dry cutting conditions. The tool geometry was: rake angle 17°, clearance angle 5°, main cutting edge 93° with nose radius 0,8 mm. The experiments have been carried out by using rotatable central composite design with five levels (coded by: –1,6817; –1; 0; +1 and

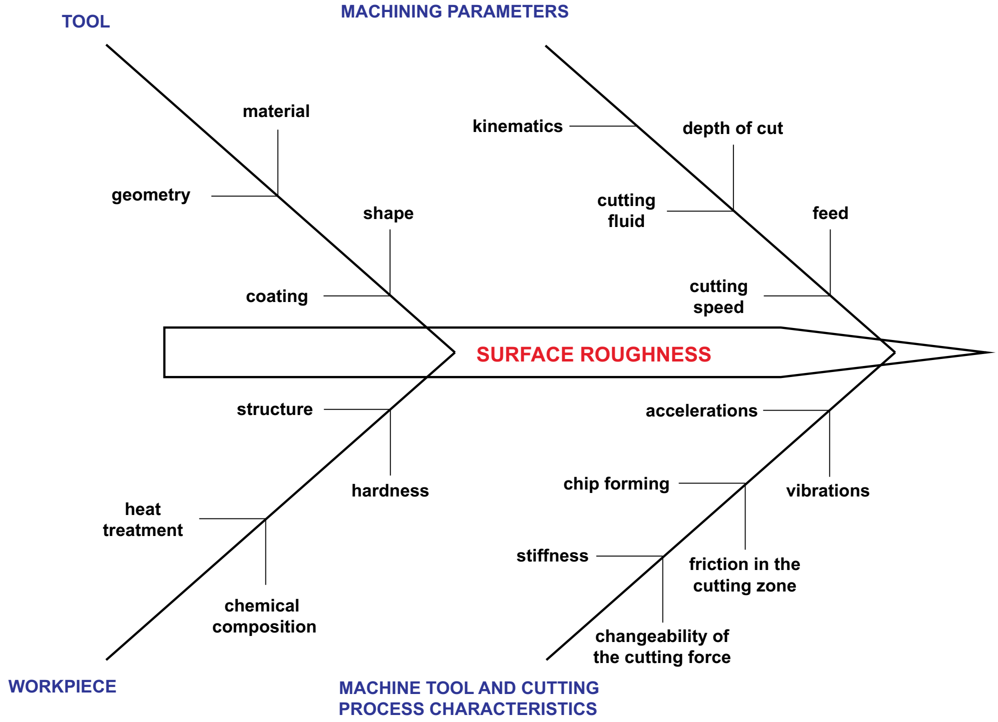

Figure 1 *Influential parameters on the surface roughness* [3]
Slika 1. *Utjecajni parametri na hrapavost površine* [3]

+1,6817) and orthogonal arrays with three levels (coded by: 1; 2 and 3) of three main cutting parameters, namely, cutting speed v_c, feed f and depth of cut a_p, Tab. 1 [3]. Before each cut, the insert was changed to eliminate the effect of tool wear.

Surface roughness measurements were performed with Surftest Mitutoyo SJ-201P.

2.2 Experimental Plans and Results
Eksperimentalni planovi i rezultati

To obtain the mathematical model that describes the effect of influential factors on surface roughness, the rotatable central composite design has been used together with an analysis of variance and multiple regression analysis. Accordingly, the required number of experimental points is $N = 2^3 + 6 + 6 = 20$, Tab. 2. There are eight experiments (3 factors on two levels, 2^3) with added 6 star points and centre point (average level) repeated 6 times to calculate pure error.

Parameters design is the key step in the Taguchi method to achieve reliable results without increasing the experimental costs. To study the entire space of parameters with a small number of experiments, Taguchi method uses a special design of orthogonal arrays where the experimental results are transformed into the signal-to-noise ratio, i.e. S/N ratio, as the measure of the quality characteristic deviating from the desired value. Tab. 3 shows that the experimental plan has three levels and an appropriate orthogonal array with notation L9 (3^4) was chosen [3].

The necessary number of test runs is nine, which represents big advantage since the number of tests is reduced in relation to the rotatable central composite design of experiments. Experimental results, together with their transformations into signal-to-noise ratios are given in Tab. 3.

3 Optimization Methods
Metode optimiranja

The optimisation of machining processes is essential for the achievement of high responsiveness of production, which provides a preliminary basis for survival in today's dynamic market conditions. The ratio between costs and quality of products in each production stage has to be carefully monitored and immediate corrective actions have to be taken in the case of deviation from the desired trend [4]. To select the cutting parameters properly, there are numbers of optimization techniques and some of them are

Table 1 *Physical and coded values of cutting parameters for designs of experiments*
Tablica 1. *Fizikalne i kodirane vrijednosti parametara rezanja za planove pokusa*

Symbol	Parameters / Levels	Lowest	Low	Centre	High	Highest
	Coding – classical experimental design	–1,6817	–1	0	+1	+1,6817
A	Cutting speed $X_1 = v_c$ (m/min)	366	400	450	500	534
B	Feed $X_2 = f$ (mm/rev.)	0,066	0,1	0,15	0,2	0,234
C	Depth of cut $X_3 = a_p$ (mm)	0,13	0,4	0,8	1,2	1,47
	Coding – orthogonal array	-	1	2	3	-

Table 2 *Average surface roughness (Ra) results for rotatable central composite design of experiments*
Tablica 2. *Rezultati prosječne hrapavosti površine (Ra) za centralni kompozicijski plan pokusa*

Test No.	Coded factors			Ra/μm
	X_1	X_2	X_3	
1.	–1	–1	–1	0,77
2.	1	–1	–1	0,80
3.	–1	1	–1	1,70
4.	1	1	–1	1,67
5.	–1	–1	1	1,11
6.	1	–1	1	1,19
7.	–1	1	1	2,14
8.	1	1	1	1,77
9.	0	0	0	1,26
10.	0	0	0	1,30
11.	0	0	0	1,29
12.	0	0	0	1,28
13.	0	0	0	1,27
14.	0	0	0	1,28
15.	–1,682	0	0	1,37
16.	1,682	0	0	1,31
17.	0	–1,682	0	1,21
18.	0	1,682	0	2,32
19.	0	0	–1,682	1,17
20.	0	0	1,682	1,13

Table 3 *Orthogonal array L9 (3^4) with average surface roughness (Ra) results and calculated S/N ratios*
Tablica 3. *Ortogonalni niz L9 (3^4) s rezultatima prosječne hrapavosti površine (Ra) i izračunatim S/N omjerima*

Test No.	A	B	C	D experimental error	Ra/μm	S/N ratio
1.	1	1	1	1	0,77	2,306
2.	1	2	2	2	1,33	–2,503
3.	1	3	3	3	2,14	–6,595
4.	2	1	2	3	1,11	–0,887
5.	2	2	3	1	1,13	–1,037
6.	2	3	1	2	2,01	– 6,07
7.	3	1	3	2	1,19	– 1,487
8.	3	2	1	3	1,05	– 0,452
9.	3	3	2	1	1,93	– 5,715

shown in Fig. 2 [3, 5, 6, 7].

In this study the optimum cutting parameters will be determined by the different optimization methods: analytical based on the literature known equation, classical mathematical based on the experimental model, Taguchi and artificial neural networks with the objective to improve surface roughness.

3.1 Conventional Methods
Konvencionalne metode

According to conventional approaches to the optimization of cutting parameters, two methods are described in this paper: analytical study (AS) and classical mathematical analysis (CMA).

AS is based on literature known analytical model (1) as suggested in [8]. Due to the particular geometry of lathe machining, there is a direct relationship between turning parameters and the roughness of the machined surfaces. To calculate the theoretical arithmetic average roughness (Ra_t), the following equation is used:

$$Ra_t \approx \frac{32 f^2}{r_\varepsilon}. \tag{1}$$

On the other hand, in CMA the optimization of cutting parameters is carried out by finding the partial derivations of the experimentally obtained mathematical model and solving the system of equations. Surface roughness model of finish turning based on the rotatable central composite design (Tab. 2), as the function of cutting speed v_c, feed f and depth of cut a_p, has the following polynomial form:

$$\begin{aligned} Ra &= 2{,}706 - 0{,}00614 v_c - 16{,}98 f - 1{,}5175 a_p + \\ &+ 0{,}0132 v_c f + 0{,}0054 v_c a_p + 20{,}45 f a_p - \\ &- 0{,}048 v_c f a_p + 0{,}56 \cdot 10^{-5} v_c^2 + 65{,}6 f^2 - 0{,}325 a_p^2. \end{aligned} \tag{2}$$

The necessary condition for existing of extreme value is that partial derivation of equation (2), per every independent variable, has zero value. When the Sylvester's criterion has been met (second derivation per every independent variable is greater than zero), then this extreme is minimal value of the function presented with expression (2).

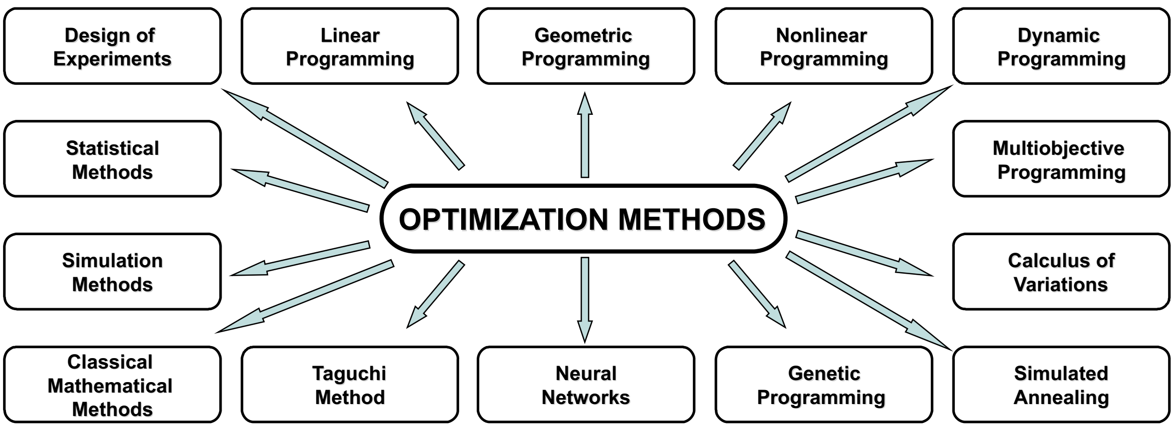

Figure 2 *Optimization methods*
Slika 2. *Metode optimiranja*

3.2 Taguchi Method
Taguchijeva metoda

An optimization based on the Taguchi approach [3, 6, 9] is used to achieve more efficient cutting parameters and to make a comparison with the results obtained with other methods presented in this paper.

In Tab. 3, the column of parameters marked with D was used to estimate the experimental error. The right side of the table includes the average results (each trial had 3 samples) of the measured arithmetic surface roughness *Ra* and the calculated signal-to-noise (*S*/*N*) ratio. For the minimal surface roughness, the solution is "smaller is better", and *S*/*N* ratio is determined according to the following equation:

$$S/N = -10 \cdot \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{\,2}\right), \tag{3}$$

where n is the number of replication and y_i is the measured value of output variable.

The minimal *Ra* is achieved using the cutting parameters where *S*/*N* ratio is maximal.

3.3 Artificial Neural Networks
Umjetne neuronske mreže

Over the past years, several technologies have been introduced to help engineers to analyze and design complex systems. One of these techniques is artificial neural networks (ANN) technology. ANN is a young discipline of science, but is necessary to respect the intenseness of its development [10, 11]. The purpose of the ANN application is the imitation of human thinking by the solution of a specific problem. Another advantage for the ANN application is the ability of its adaptation to the situation and environment changes.

The ANN technology has become very popular and is used in many fields. In the field of reliability assurance of machines and facilities it can be applied in technical diagnostics, which deals with the application of diagnostic equipments during the real processing. Also, using of ANN becomes a very useful optimization technique [12, 13], applicable in the process for optimization of cutting parameters in order to improve the process and product quality, surface roughness etc. Herein, the application of the hardware unit, based on neural network's computation approach during the data processing in experimental conditions, done in section 2.1, is shown. This hardware unit is "neurone" processor, as a part of automatic lathe machine. Programming of the "neurone" processor is done by software package Statistica [14], using ANN mode, based on previous research [15].

In this research, optimal cutting parameters and their influences on the surface roughness were analysed. According to the analysis of variance through implementation of the ANN optimization method using Statistica software as a tool, the feed has the greatest influence on the surface roughness with 77,65 % of contribution while the influences of the depth of cut and the cutting speed are much smaller.

The experimental verification test was compared with the results of optimal turning parameters obtained with different optimization methods, Tab. 4. The obtained prediction model (2) is a very good base for finding the optimal cutting parameters which was verified with the confirmation test (Tab. 4) and also with the contour graph, Fig. 3.

All of the presented optimisation methods provide the same optimal condition (A1B1C1 - No. 1): cutting speed, A1 = v_c = 400 m/min, feed, B1 = f = 0,1 mm/rev., and depth of cut, C1 = a_p = 0,4 mm. Furthermore, all optimization methods except the analytical one (which is expected), give accurate results (as indicated by the confirmation test in Tab. 4) with the small deviation between each other.

4 Conclusion
Zaključak

In this paper, the application of different optimization methods to find optimal cutting parameters is shown. The presented optimization methods, namely analytical, classical mathematical, Taguchi and artificial neural networks, have their features, merits and limitations which are presented on the practical case. Hence, the following conclusions can be made.

Classical experimental design method, i.e. rotatable central composite design, is too complex and not easy to use. A large number of experiments have to be carried out especially 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 a small number of experiments. Furthermore, to obtain optimal value of process parameters the classical method needs the prediction model to be used for optimization procedure, which is not necessary for orthogonal arrays design. Also, the parameters value needs to be defined strictly numerical not as a description of state.

On the other hand, the advantage of classical experimental design method is a possibility to obtain mathematical model which is a powerful tool to predict response for any of the input parameters values within the experimental domain, and optimal values can be any of the parameters point i.e. parameters are continuous and can take any real value. This is impossible in the Taguchi method, because the optimal value has to be one of the parameter levels. In addition, the Taguchi method is better for parameters with discrete values in contrast to classical

Table 4 *Comparison of the optimal results obtained with different methods and confirmation test*
Tablica 4. *Usporedba optimalnih rezultata dobivenih različitim metodama i test potvrde*

	Initial parameters	Optimal cutting parameters			Confirmation test by ANN
		Analytical model (1)	Prediction model (2)	Taguchi method	
Level	A3B1C2	A1B1C1	A1B1C1	A1B1C1	A1B1C1
Surface roughness *Ra*/μm	1,07	0,40	0,887	0,862	0,77

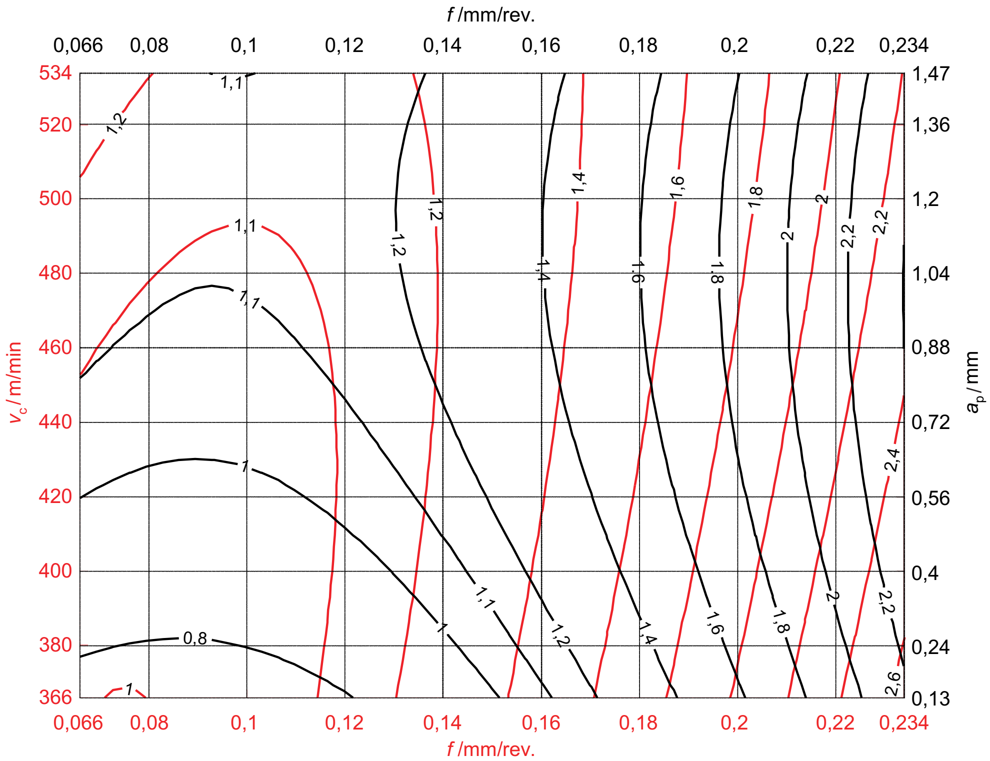

Figure 3 *Surface roughness contour graph obtained by polynomial model (2)*
Slika 3. *Konturni graf hrapavosti površine dobiven polinomskim modelom (2)*

optimization technique and continuous values.

All optimization methods presented herein have a potentiality (more or less) to improve the initial process parameters or in the study case the achievement of the desired surface roughness at longitudinal turning process, with high accuracy, which was clearly verified by the confirmation experiment.

The accuracy of network results depends on the amount of training models. By the training set of input-output data, the output value variation can be determined from the desired value. Also, to have a minimal difference between actual and desired value in the case of different output parameters the weights can be modified. The advantage of Statistica software is the support of automated creation, training and testing of neural networks: in this contribution, a neural network application in operating the determination of optimal cutting parameters to improve surface roughness based on different optimization methods.

5
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