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ISSN 0543-5846
METABK 50(1) 17-20 (2011)
UDC – UDK 621.914.2:621.9.015:658.511=111

ROTATABLE CENTRAL COMPOSITE DESIGN OF EXPERIMENTS VERSUS TAGUCHI METHOD IN THE OPTIMIZATION OF TURNING

Received – Prispjelo: 2009-11-24
Accepted – Prihvaćeno: 2010-06-06
Original Scientific Paper – Izvorni znanstveni rad

This paper examines the influence of cutting parameters, namely cutting speed, feed and depth of cut on the tangential component of cutting force in the rough longitudinal turning operation. Two experimental plans, one based on the common rotatable central composite design and the other based on the Taguchi method with orthogonal arrays and signal-to-noise ratio, have been used to analyse impact of cutting parameters on the tangential component of cutting force and to find optimal level of the cutting parameters. The comparison of results obtained by given experimental plans was performed. Finally, the features, the merits and the limitations of the presented optimisation approaches were discussed.

Key words: longitudinal turning, cutting force, rotatable central composite design of experiments, Taguchi method

Centralni kompozicijski plan pokusa nasuprot Taguchijevoj metodi u optimizaciji tokarenja. U radu se istražuje utjecaj parametara rezanja i to brzine rezanja, posmaka i dubine rezanja na tangencijalnu komponentu sile rezanja kod grubog uzdužnog tokarenja. Dva plana pokusa, jedan temeljen na uobičajenom centralnom kompozicijskom planu i drugi temeljen na Taguchijevoj metodi s ortogonalnim nizovima i omjerom signala i šuma, korištena su za analizu utjecaja parametara rezanja na tangencijalnu komponentu sile rezanja te za pronalaženje optimalne razine parametara. Rezultati dobiveni pomoću oba plana pokusa su uspoređeni. Zaključno, diskutiraju se značajke, prednosti i ograničenja predstavljenih optimizacijskih pristupa.

Ključne riječi: uzdužno tokarenje, sila rezanja, centralni kompozicijski plan pokusa, Taguchijeva metoda

INTRODUCTION

Many manufactured products require machining at some stage of their production sequence. Generally, machining ranges from relatively rough cleaning of castings to high-precision micromachining of mechanical components that require narrow tolerances.

It is estimated that of all machining processes about 40% pertain to turning. Turning is the most common way for processing rotational (symmetrical or non-symmetrical, round or non-round) surfaces with single-point cutting tool [1].

Cutting force is the basic indicator of cutting process behaviour. Having knowledge of the cutting force function, the rational construction and economical efficiency of production systems, the optimization of machining process and the development of particular concepts for adaptively controlled manufacturing systems are ensured [2].

The aim of this research is to analyse dependence of the tangential component of cutting force F_c on three cutting parameters, namely the cutting speed v_c, the feed f and the depth of cut a_p, in the rough longitudinal turning operation and to find optimal level of the parameters. Two different experimental plans have been used: the rotatable central composite design and the Taguchi method. A comparison of results obtained by given experimental plans was carried out. Based on this comparison, valuable remarks about presented optimisation approaches are pointed out in the conclusion of this study.

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CONDITIONS OF THE EXPERIMENTS

The rough 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 DIN Ck45 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 the rotatable central composite design with five levels (coded by: – 1,6817; – 1; 0; + 1 and + 1,6817) and the orthogonal arrays with three levels (coded by: 1; 2

Table 1 **Physical and coded values of cutting parameters for designs of experiments**

Symbol	Parameters / Levels	Lowest	Low	Centre	High	Highest
	Coding – classical experimental design	– 1,6817	– 1	0	+ 1	+ 1,6817
A	Cutting speed (m/min) $X_1 = v_c$	266	300	350	400	434
B	Feed (mm/rev.) $X_2 = f$	0,23	0,3	0,4	0,5	0,57
C	Depth of cut (mm) $X_3 = a_p$	1	1,5	2,25	3	3,5
	Coding – orthogonal array	-	1	2	3	-

and 3) of three cutting parameters (Table 1) [3]. Before each cut, the insert was changed to eliminate the effect of tool wear.

The tangential component of cutting force was measured utilizing force transducer KISTLER (Type: 9257 A).

RESULTS OBTAINED BY ROTATABLE CENTRAL COMPOSITE DESIGN

The required number of experimental points is $N = 2^3 + 6 + 6 = 20$ (Table 2). There are eight factorial experiments (3 factors on two levels, 2^3) with added 6 star points and centre point (average level) repeated 6 times to calculate the pure error [4, 5]. That experimental plan enables to obtain the following second order polynomial model by applying multiple regression analysis:

$$\begin{aligned} F_c = {} & 187{,}937 + 1{,}847 v_c - 1970{,}77 f + \\ & + 10{,}418 a_p - 3{,}918 v_c f - 0{,}633 v_c a_p + \\ & + 1598 f a_p + 1{,}169 v_c f a_p - \\ & - 7{,}676 \cdot 10^{-5} v_c^2 + 4067{,}65 f^2 + 40{,}953 a_p^2 \end{aligned} \tag{1}$$

The analysis of variance and the multiple regression analysis indicate:

- variables which affect F_c, and are significant for mathematical model are: feed f, depth of cut a_p, square of feed f^2, square of depth of cut a_p^2 and the interaction of feed and depth of cut fa_p;
- depth of cut a_p affect F_c the most;
- variables v_c and v_c^2, the interactions of cutting speed and feed $v_c f$, cutting speed and depth of cut $v_c a_p$ and cutting speed with feed and depth of cut $v_c f a_p$ do not significantly affect F_c, so they can be excluded from mathematical model;
- coefficient of determination is very high, i.e. R^2 = 0,9961, which means that the model is representative, because it clarifies 99,61% of all deviations.

Figure 1 shows a contour plots obtained by the polynomial model (1).

To select the cutting parameters properly, there are numerous optimization methods [3, 5, 6, 7, 8, 9, 10]. In this study, optimal cutting parameters for the minimal tangential component of cutting force have been determined with GA (Genetic Algorithm) optimizer [8]. After genetic search with number of generations = 150, population = 200, crossover probability = 0,75 and mutation probability = 0,01, the founded optimal cutting parameters were: v_c = 300 m/min, f = 0,3 mm/rev. and a_p = 1,5 mm.

Table 2 **Results of F_c using the rotatable central composite design of experiments**

Test No.	Coded factors			Fc/N
	X_1	X_2	X_3	
1.	– 1	– 1	– 1	879,224
2.	1	– 1	– 1	894,327
3.	– 1	1	– 1	1436,299
4.	1	1	– 1	1408,114
5.	– 1	– 1	1	1754,215
6.	1	– 1	1	1726,937
7.	– 1	1	1	2896,122
8.	1	1	1	2860,663
9.	0	0	0	1677,149
10.	0	0	0	1672,771
11.	0	0	0	1679,359
12.	0	0	0	1678,825
13.	0	0	0	1675,829
14.	0	0	0	1678,223
15.	– 1,682	0	0	1697,504
16.	1,682	0	0	1683,361
17.	0	– 1,682	0	1002,763
18.	0	1,682	0	2609,254
19.	0	0	– 1,682	765,921
20.	0	0	1,682	2746,389

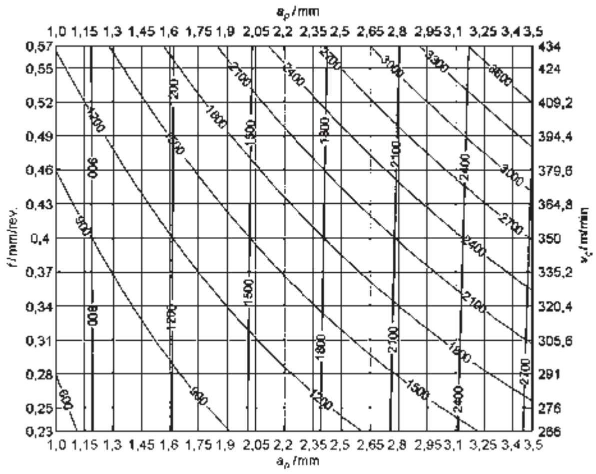

Figure 1 Contour plots obtained by the polynomial model (1) for v_c = 350 m/min and f = 0,4 mm/rev.

RESULTS OBTAINED BY TAGUCHI METHOD

Taguchi method [3, 7, 11] is used to determine optimal cutting parameters and to make a comparison with the results obtained with the rotatable central composite design of experiments. Parameters design is the key step in Taguchi method to achieve high quality without increasing cost. To solve this problem 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. Table 3 shows that the experimental plan has three levels and an appropriate orthogonal array with notation L9 (3^4) was chosen.

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 Table 3.

Table 3 **Orthogonal array L9 (3^4) with experimental results and calculated *S/N* ratios**

Test No.	A v_c	B f	C a_p	F_c/N	*S/N* ratio
1.	1	1	1	879,224	– 58,886
2.*	1	2	2	1706,310	– 64,642
3.	1	3	3	2896,122	– 69,248
4.*	2	1	2	1260,859	– 62,014
5.*	2	2	3	2370,946	– 67,510
6.*	2	3	1	1415,452	– 63,020
7.	3	1	3	1726,937	– 64,746
8.*	3	2	1	1177,007	– 61,419
9.*	3	3	2	2177,104	– 66,758

* additionally performed experiments

For the minimal tangential component of cutting force, the solution is "smaller is better", and *S/N* ratio is determined according to the following equation:

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

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

Graphic analysis of experimental data obtained with Taguchi method, has been presented in Figure 2. The response graphs of the tangential component of cutting force F_c has been shown for all three control factors. The minimal F_c is achieved using the cutting parameters where *S/N* ratio is maximal. The influence of parameter on the output process variable is represented by the angle of inclination of the line which connects different parameter levels. It can be seen from the presented graphs that depth of cut has the greatest influence on the tangential component of cutting force, feed has a little bit smaller influence, and cutting speed has insignificant influence on the tangential component of cutting force.

The optimization of cutting parameters inside of offered factors levels, with regard to the criterion "smaller is better", gives the following combination of the cutting parameters which enables the minimal tangential component of cutting force: v_c = 300 m/min, f = 0,3 mm/rev. and a_p = 1,5 mm.

COMPARISON OF OBTAINED RESULTS

The presented optimisation approaches provide the same optimal values for the cutting parameters and give accurate results (as indicated by the confirmation test) with small deviation between each other, Table 4.

Table 4 **The comparison of the optimal results obtained with different plans and confirmation test**

	Optimal cutting parameters		Confirmation test
	Prediction model (1)	Taguchi method	
Level	A1B1C1	A1B1C1	A1B1C1
F_c/N	857,202	858,519	879,224

CONCLUSIONS

In this paper an application of two experimental plans to find optimal cutting parameters is shown. The presented optimization approaches, one based on the common rotatable central composite design of experi-

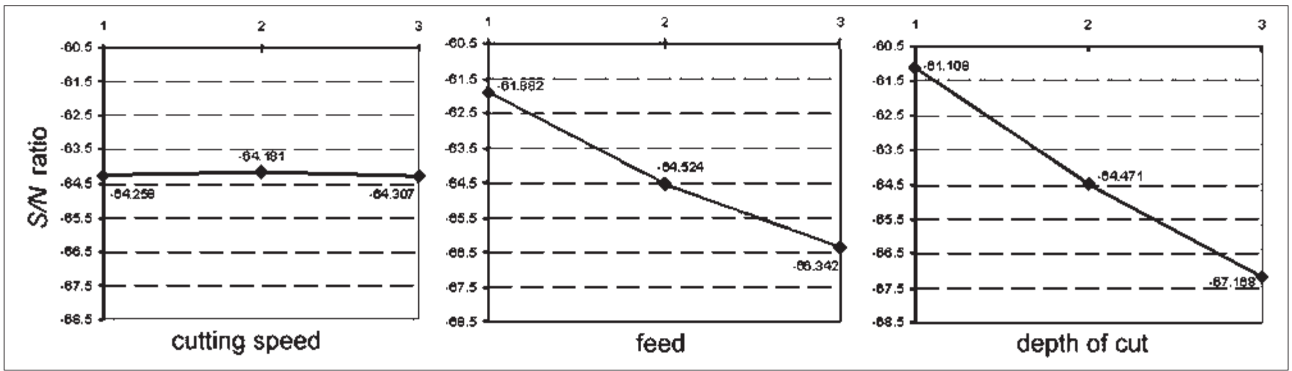

Figure 2 Influence of control factors on *S/N* ratio

ments, and the other based on the Taguchi method, have their features, merits and limitations which are presented on the practical case of the rough longitudinal turning operation.

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 description of state.

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

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Note: The responsible translator for English language is lecturer from Faculty of Engineering, University of Rijeka, Croatia.

List of Symbols:

depth of cut / mm	a_p
Tangential component of cutting force / N	F_c
Feed / mm/rev	f
Number of experiments	N
Number of replication	n
Signal-to-noise ratio	S/N
Coefficient of determination	R^2
Cutting speed / m/min	v_c