Prediction of material removal rate in turning using Response Surface Method

I Stănășel¹, F S Blaga¹, T Buidoș¹, F Corb¹

Faculty of Managerial and Technological Engineering, University of Oradea, Romania

stanasel@uoradea.ro

Abstract. Obtaining quality products at low costs is the main objective of any company. As a result, the efficiency of the production processes is sought by identifying a favorable combination of all the factors that influence the respective process. With regard to metal cutting, the Material Removal Rate (MRR) is an important factor affecting machining time. The paper makes a study to highlight the influence of cutting parameters on material removal rate using Response Surface Method (RSM). Using analysis of variance (ANOVA), you may identify the significant factors of the process and determine a second-order regression model that takes into account both main effects but also and the interactions between factors. It also presents the possibility of optimization of cutting parameters for streamlining the turning process.

1. Introduction

Obtaining a product in economic conditions largely depends on the manufacturing technology. This must ensure that products of appropriate quality are obtained at low cost and high productivity. Within companies, there are continuous changes, which aim is to improve the functional performances of products or manufacturing processes. Therefore, research is needed to establish a relationship that will lead to the optimization of the parameters of the new technological process. In the case of products obtained by cutting processing, production costs are influenced by several factors, including material rate removal.

The optimization of the material removal rate is of great importance in the conditions of large-scale manufacturing. This aspect is noticed by many researchers who propose different methods for adjusting the parameters in order to optimize the cutting process.

The paper [1] investigates by an experimental procedure the optimum process parameters for optimization of material removal rate and tool wear while turning of hardened AISI 52100 steel under dry cutting conditions using Taguchi method. The importance of parameters is studied by using ANOVA. The authors [2] studied the machinability of mild steel in the turning process by using a conventional lathe machine. Two parameters, like tool rake angle and feed, are varied to investigate their effect. The material removal rate is studied, taking into account two variable parameters like tool rake angle and feed. The techniques Taguchi and ANOVA were used to reduce machining time and also the power during processing. Article [3] describes a combined mathematical, graphical method in order to adjust material removal rate in pocket milling operations but with reduction of tooling cost, machining vibration, noise and also to increase surface finish. The authors [4] presents the effect of the spindle speed, feed rate and depth of cut in dry turning of grey cast iron FG 260 in a computer numericaly controled lathe. In order to study the material removal rate the process parameters were varied and were investigated optimum conditions for higher MRR, being used Taguchi method, analysis of variance, multivariable linear regression (MVLR). In [5] is shown an approach of Taguchi method with the aim

of optimizing the MRR for an EMCO Concept Turning center, by variation of cutting parameters speed, feed and depth of cut. The study gives a predictive model to determine MRR by combining machining parameters, and it was proposed the optimal solution for increasing efficiency of the machining process.

A method for establishing the relationship between parameters influencing a particular process is the method of factorial experiments. The Response Surface Method is an empirical method that allows the determination of a relationship between different parameters and the response of a process. This method is based on mathematical and statistical calculations. It is used to model and optimize the processes in which the answer depends on several variables.

The paper presents the use of Response Surface Method (RSM) in order to estimate the material removal rate according to the cutting parameters of the turning process and proposes a method of optimizing them over the ranges of values.

2. Material and method

Usually, the influence of different factors is studied one by one at a time, to explore a phenomenon. This means changing the values of the studied factor, and observing the behavior of the process, while all other factors are kept constant. In this way, relations of connection and curves of variation are highlighted, which represent only partially the studied phenomenon, since the interactions between factors are not taken into account. The material for which the study was carried out is Al 7075.

If you know the parameters of cutting at turning: cutting depth (t, mm); feed (sr, mm / rot) and speed (n, rot/min), the relationship that expresses the amount of material removed is:

$$MRR = \pi \left(\frac{D_{med}}{2}\right) t \cdot s_r \cdot n \tag{1}$$

where:

$$D_{med} = \frac{d_i + d_{i+1}}{2}$$
(2)

MRR – material removal rate (mm³/min) D_{med} - average diameter of the work piece (mm) d_i – initial diameter (mm) d_{i+1} – actual diameter (mm) t – cutting depth (mm)

- s_r cutting feed rate (mm/rot)
- *n* cutting speed (rot/min).

From the point of view of the working mode, for the study of a process, the method of the factorial experiments involves identifying the influence factors and the response that characterizes the respective process. For each factor, the domain in which it takes values is defined, and the matrix for conducting experiments is also established. The objective of the experiment consists of determining the influence of factors xi on the answer function y and expressing it by the form:

$$y = f(x_1, x_2, \dots, x_k)$$
 (3)

The model obtained from the experiments is an empirical one, in which its statistical estimation replaces the real response function. The form of the empirical model is expressed by mathematical functions that can be polynomial, logarithmic, exponential etc. Usually, the polynomial form is the most used, due to the convenient possibilities for mathematical processing. Higher-order polynomials, most commonly of the second order, expressed by the general relationship, are usually used to describe the optimal:

$$y = b_0 + \sum_{j=1}^k b_j x_j + \sum_{j=1}^k b_{ij} x_j^2 + \sum_{i,j=1}^k b_{ij} x_i x_j + e$$
(4)

The aim of the experiments carried out was to obtain the necessary data to determine the coefficients of the presented model. The regression model resulting from the calculations does not cover the entire range of values that process influence factors may take, but it is satisfactory as an approximation for the field of studied values of influence factors.

Using the method of the factorial experiment, it is proposed to estimate the cutting parameters so as to obtain a high MRR, under the conditions of getting an appropriate quality of the surface. The range of factor variation is shown in Table 1.

Factor	Symbol	Units	Low	High
Curring Depth	t	mm	0.50	5.50
Feed	$\mathbf{s}_{\mathbf{r}}$	mm/rot	0.05	0.55
Speed	n	rot/min	200	2000

 Table 1. The level of cutting parameters.

3. Result and Discussion

The array of the experiment is presented in Table 2.

Run	A: Curring depth	B:Feed	C: Speed	Material removal rate
	mm	mm/rot	rot/min mm ³ /min	
1	5.5	0.05	2000	1727.88
2	2.75	0.54	1010	4711.92
3	5.4	0.275	1010	4711.92
4	0.625	0.345	1251.67	847.89
5	5.3	0.3	1914.6	9563.68
6	5.5	0.55	2000	19006.6
7	2.75	0.274707	1964	4661.16
8	3.425	0.3425	245	902.89
9	2.75	0.274707	1964	4661.16
10	3.425	0.06	1253	808.93
11	2.75	0.274707	1964	4661.16
12	0.5	0.05	1331.5	104.58
13	5.5	0.55	200	1900.66
14	2.75	0.54	1010	4711.92
15	0.5	0.05	200	15.71
16	3.65	0.05	200	114.67
17	0.5	0.55	2000	1727.88
18	5.4	0.275	1010	4711.92
19	2.75	0.54	1010	4711.92
20	0.5	0.363233	200	114.11

Table 2. The experimental array.

In Table 3 is presented the Analysis of Variance (ANOVA) of the experimental data. Fisher test (F-value) is 209.28, which means that the model is significant. The p value is 0.0001 < 0.05 (significance level), which indicates model terms are significant. As you can see in table 3, the significant terms of the model are A, B, C, AB, AC, BC, A², B², C². Also, p-value of the model showed that there is 0.01% chance that an F-value this large could occur due to noise. The coefficient of determination R² is 0.9947 indicates a strong correlation between the real model and the regression model. Adjusted R² has value 0.99, which means a good correlation of the model, depending on the number of significant variables. Predicted R² is 0.9774 indicating how well a regression model anticipates responses to new observations. The difference is less than 0.2, which shows a good correlation between Adjusted R² and Predicted R². Adeq. Precision measures the signal-to-noise ratio, the ratio value must be greater than 4. The values 57.866 shown a good signal, so the model can be used to navigate the design space.

Source	Sum of	df	Mean	F-value	p-value	
	Squares		Square			
Model	20849.91	9	2316.66	209.28	< 0.0001	significant
A-t	4862.07	1	4862.07	439.22	< 0.0001	
B-s	5171.58	1	5171.58	467.18	< 0.0001	
C-n	5062.15	1	5062.15	457.3	< 0.0001	
AB	957.21	1	957.21	86.47	< 0.0001	
AC	947.37	1	947.37	85.58	< 0.0001	
BC	853.11	1	853.11	77.07	< 0.0001	
A ²	372.66	1	372.66	33.67	0.0002	
B ²	364.77	1	364.77	32.95	0.0002	
C^2	310.62	1	310.62	28.06	0.0003	
Residual	110.7	10	11.07			
Lack of Fit	110.7	5	22.14			
Cor Total	20960.6	19				

Table 3. ANOVA for Quadratic model

Final equation in terms of actual factors is:

$$\sqrt{MRR} = -5.04448 + 5.62723 \cdot t + 55.1091 \cdot s + 0.0148941 \cdot n + 21.3868 \cdot t \cdot s + +0.00575621 \cdot t \cdot n + 0.0567796 \cdot s \cdot n - 1.54503 \cdot t^2 - 149.93 \cdot s^2 - 1.10669e^{-05} \cdot n^2$$
(5)

In figure 1 is shown the normal plot of residuals. Residues are distributed relatively evenly on a straight line in both positive and negative direction, which shows that the pattern is appropriate. In figure 2 is presented the Predicted vs Actual graph. As you can see, the estimated values with the regression model are placed very close to the line at 45 degree with the observed points, which shows a good correlation of the model with the observed data.









The amplitude of the effects of the cutting parameters on MRR over the studied range is shown in figure 3. It can be seen that the speed and the cutting depth have the most significant influence on the amount of removed material.



Figure 3. The effects of the cutting parameters on MRR.

a) – \sqrt{MRR} vs. speed ; b) - \sqrt{MRR} vs. cutting depth ; c) - \sqrt{MRR} vs. feed .

In Figure 4 is shown the response surface for material removal rate according to the cutting parameters. The regression model obtained by the factorial experiments offers the possibility of optimizing the process on the field of variation of the influence factors. In the case of finishing operations, it is possible to act in order to increase the quantity of material removed, in conditions of minimizing the working advance in order to obtain an adequate roughness on the processed surface. For this situation, in figure 5 the optimal solution t = 5.5 mm is presented; n = 2000rot / min; sr = 0.24 mm/rot; $\sqrt{MRR} = 0.8964$ (MRR = 8035.3296 mm³/min).





Figure 5. The optimal solution for minimum cutting feed and maximum material removal rate for studied interval.
a). Depth=5.5 [mm]; b). Feed=0.247 [mm/rot];
c). Speed=2000 [rot/min]; d). √MRR =0.8964

4. Conclusions

The use of factorial experiments allows the modelling of processes which depend on several variables. In this paper it was analyzed the influence of the parameters of the process of cutting at turning on the MRR. For experiments, an orthogonal matrix L20 was used. Using a second-order polynomial, the regression model was obtained, which was analyzed and the influence of the process parameters on the MRR, as well as the interactions between them were highlighted. From the analysis, it is observed that the feed and the cutting depth have the most significant influence on the material removed rate for the studied range. Based on the obtained model, the cutting parameters can be adjusted so that certain objectives corresponding to a specific purpose are met. For example, it is possible to optimize the maximum quantity of material removed, or the maximum quantity for an advance imposed in order to ensure an adequate roughness of the processed surface.

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