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OPTIMIZATION OF CUTTING CONDITIONS FOR SURFACE ROUGHNESS BASED ON ORTHOGONAL ARRAYS

Zoran Jurkovic
Faculty of Engineering,
University of Rijeka
Vukovarska 58, Rijeka
Croatia

Miran Brezocnik
Faculty of Mechanical Engineering,
University of Maribor
Smetanova ulica 17, Maribor
Slovenia

Milenko Sekulic
Faculty of Technical Sciences, University of Novi Sad
Trg Dositeja Obradovica 6, Novi Sad
Serbia

ABSTRACT
Determination of optimal machining parameters by using optimization techniques is continuous engineering task with the main aim to reduce the production cost and achieve desired product quality. Hence, this paper presents optimization approach to determine optimal values of cutting speed, feed and depth of cut with the purpose of improving the surface roughness obtained in turning operation. To achieve this, two experimental plans have been carried out based on the factorial design of experiments and the orthogonal arrays. By using these plans, the classical mathematical optimization was performed according to response model of the surface roughness as well as the Taguchi approach. Furthermore, the experimental verification of optimal cutting parameters with their influences on the surface roughness was done.
Keywords: Turning, Surface roughness, Optimization, Orthogonal arrays

1. INTRODUCTION
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 effect 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 almost impossible a straightforward solution, see Figure 1. 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, 3]. The aim of this work is to present and discuss the different

optimization approaches and strategies in order to improve surface roughness based on experimental research of longitudinal turning [2].

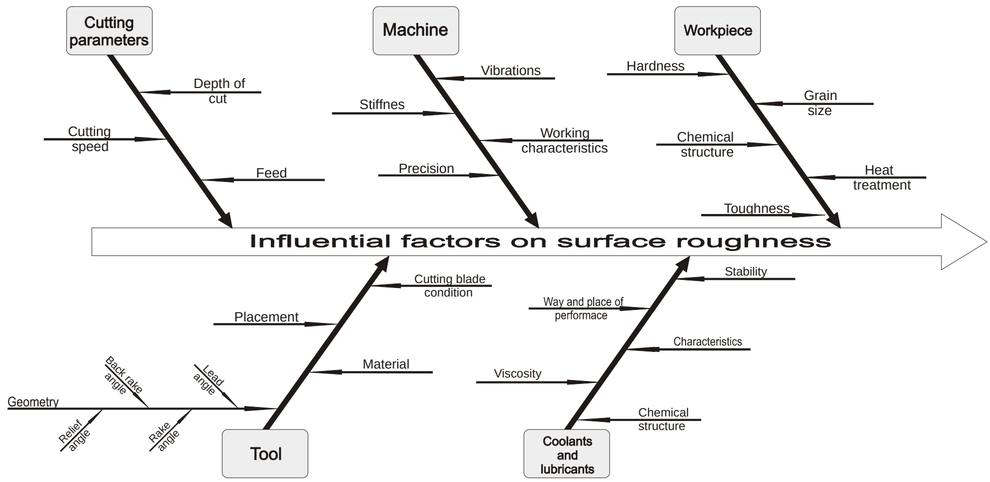

Figure1. Ishikawa diagram - influential parameters on surface roughness [3]

2. EXPERIMENTAL SETUP AND RESULTS

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

2.1. Machining conditions

Experimental researches were performed on lathe machine "Georg Fisher NDM-16" at Production Engineering Institute University of Maribor. Materials used in the tests were carbon steel bars DIN Ck45 with 100 mm diameter and 380 mm length. Experiments were carried out by external machining turning tool with holder mark DDJNL 3225P15 and 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. Before each cut, the insert was changed to eliminate the effect of tool wear.

2.2. Experimental plans and results

Surface roughness measurements were performed with Surftest Mitutoyo SJ-201P with possibilities to measure surface roughness parameters (R_a, R_t, R_q, R_z). The paper presents optimization approaches relating to determine optimal values of cutting speed, feed and depth of cut with the purpose to improve surface roughness obtained by turning operation. To achieve this, it has been carried out two experimental plans based on factorial design of experiment and orthogonal array. By using these plans it was performed classical mathematical optimization, according to response model of surface roughness, and the Taguchi approach (Table 1), respectively. The influence of the cutting parameters (v_c, f, a_p) on the arithmetic average roughness (R_a) values were presented in Table 1.

3. OPTIMIZATION METHODS

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. To select the cutting parameters properly, there are numbers of optimization techniques and some of them are presented in papers [2, 4, 5]. The optimum cutting parameters, in this case will be determined by the different optimization approaches, classical mathematical based on experimental obtained model, analytical based on literature known equation and Taguchi approach with the objective to improve surface roughness.

Table 1. L_9 (3^4), with experimental results (average) and calculated signal-to-noise (S/N) ratios [2]

Trial №	A cutting speed v_c	B feed rate f	C depth of cut a_p	D experimental error	Experimental results, average R_a (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

3.1. Conventional approaches

According to conventional approaches, two methods are described in this paper: classical mathematical analysis (CMA) and analytical study (AS). In the CMA the optimization of cutting process parameters were carried out by derivation of the obtained mathematical model based on experimental research. In this particular case derivation of predicted mathematical model will be performed with the aim to find optimal cutting parameters (v_c, f, a_p) in relation to surface roughness. On the other hand, AS is based on literature known analytical models [6]. 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 maximum peak-to-valley height (R_{tt}) and theoretical arithmetic average roughness (R_{at}), the following equations were used:

$$R_{tt} \approx \frac{f^2}{8r_\varepsilon}\times 1000, \qquad R_{at} \approx \frac{0{,}032 f^2}{r_\varepsilon}\times 1000 \tag{1}$$

where f is the feed rate (mm/rev) and r_ε is the tool nose radius (mm).

Surface roughness model of finish turning based on the factorial design of experiment, as function of the cutting speed (v_c), feed rate (f) and depth of cut (a_p), has the following polynomial form:

$$\begin{aligned} R_a &= 2{,}706 - 0{,}00614 v_c - 16{,}98 f - 1{,}5175 a_p + 0{,}0132 v_c f + 0{,}0054 v_c a_p + \\ &+ 20{,}45 f a_p - 0{,}048 v_c f a_p + 0{,}0000056 v_c^2 + 65{,}6 f^2 - 0{,}325 a_p^2. \end{aligned} \tag{2}$$

In CMA the optimization of cutting process parameters was carried out by derivation of the obtained mathematical model (2).

3.2. Taguchi approach

In this paper optimization based on Taguchi approach [2, 7, 8] is used to achieve more efficient cutting parameters and to compare results obtained with other optimization techniques presented in this paper. Parameter design is the key step in the Taguchi approach to achieve high quality without increasing cost. To solve this problem Taguchi approach uses a special design of orthogonal arrays where the experimental results are transformed into the S/N ratio as the measure of the quality characteristic deviating from the desired value. Table 1 shows that the experimental plan has three levels and an appropriate Taguchi orthogonal array with notation L_9 (3^4) was chosen. The last column of parameters notation with D (Table 1) was used to estimate the experiment error. The right side of the table includes the average results (each trial has 3 samples) of the measured arithmetic average surface roughness (R_a) and the calculated signal-to-noise (S/N) ratio. The S/N ratio, as the yardstick for analysis of experimental results, is calculated according to the following equation:

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

where is: η – signal-to-noise ratio (S/N); n – number of repetitions of the experiment; y_i – measured value of quality characteristic. The above equation, which is used to calculate the S/N ratio, is in relation to the smaller-is-better quality characteristics, what in the particular case means minimization of arithmetic average roughness to achieve the desired surface roughness.

4. DETERMINATION OF OPTIMAL CUTTING PARAMETERS

Optimal cutting parameters and their influences on the surface roughness were analysed. According to the analysis of variance the most influence on the surface roughness has the feed rate with 77,65% of contribution and there are no significant influences of the cutting speed and the depth of cut. The experimental verification test was compared with the results of optimal turning parameters obtained with different optimization approaches, Table 2. That obtained prediction model (2) is the very good base for finding the optimal parameters which was verified with the confirmation test (Table 2). The presented optimization techniques give accurate results (as indicated by the confirmation test) with small deviation between each other, except the analytical method.

Table 2. The comparison of the optimal results obtained with different methods and confirmation test

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

5. CONCLUSION

In this paper an application of the different optimization approaches to find optimal cutting parameters is shown. The presented optimization techniques, classical and Taguchi, have its features, merits and limitations which is presented on the practical case. Hence, the following conclusions can be drawn: (i) Classical experimental design methods are 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 approach 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. (ii) On the other hand, the advantage of classical experimental design methods is possibility to obtain mathematical model which is powerful tool to predict response for any of input parameters value 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 approach, because optimal value have to be one of parameter levels. In addition, Taguchi approach is better for parameters with discrete values in contrast to classical optimization technique and continuous values. Finally, all optimization techniques presented here have potentiality (more or less) to improve initial process parameters or in study case the achievement of the desired surface roughness at longitudinal turning process.

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