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Application of the Method of Planned Experiment for the Evaluation of the Surface Roughness Parameter Ra

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The basic process of acquiring new knowledge is trial/experiment. We can define an experiment as a certain process that we prepare, organize and plan in order to know the object under investigation. Each experiment requires a multifaceted activity associated with professional knowledge, preparation of material security, especially security with measuring devices and measurement methods for determining the correct (objective) measured values. Planning experiments and analyzing the obtained results are important stages in revealing the nature and course of the technological process. With the planned experiment, we try to create such conditions that the range of experiments is as small as possible, but the volume and form of information are of the highest quality. The article presents the method of the planned experiment and its use in industrial practice. The mentioned methodology of the planned experiment is applied to the calculation of the mean arithmetic value of the surface roughness Ra depending on the cutting parameters. The advantage of this method is that it increases the accuracy of the obtained results, but mainly reduces the number of performed attempts.

Keywords: Planned Experiment, Cutting Parameters, Surface Roughness

1 Introduction

Currently, experiments are increasingly using mathematical statistics and mathematical processing of the obtained values with the use of computer technology in order to obtain maximum information at minimum costs. These mathematical-statistical methods have thus become an integral part of solving everyday technical tasks. The starting point for the use of mathematical methods is a mathematical description. However, how is it possible to describe complex engineering objects and technological processes, such as a machine tool or the calculation of optimal technology, by means of mathematics? It is clear from experience that engineering objects and technological processes can always be broken down into simpler and more elementary ones until we get ones that we can already describe mathematically. Thus, we can consider each studied object or phenomenon as a system, which is defined as a collection of elements and relationships between them. Engineering objects and technological processes mostly belong to complex multi-factor systems. Currently, we know two methods of knowing objects and processes, namely analysis and synthesis. When analysing complex engineering systems and objects, we proceed by breaking them down into simpler parts, which we subject to examination, testing and comparison. During the synthesis, we evaluate simple parts and by combining them we get an objective evaluation of the investigated object and process. In addition, great emphasis is also placed on quality, because its continuous improvement results in increasing not only the economic level, but also the future of the entire production process. Here, too, it is confirmed that various mathematical and statistical methods are used to measure and evaluate the level of quality, which are currently widely used in almost all scientific disciplines. One such method is the planned experiment method, which primarily reduces material and time requirements [1,2,3].

2 Planned experiment

We can define an experiment as a process that we prepare, organize and plan in order to know the object under investigation. The essence of this activity in the experiment is measurement, the goal of which is to obtain objective (correct), quantitative characteristics of the measured object. Processing of the obtained set of measured values, i.e. the evaluation of the monitored parameter is obtained as a result of the experiment in a mathematical, graphic, or tabular evaluation. Each experiment requires a multifaceted activity associated with professional knowledge, preparation of material security, especially security with measuring devices and measurement methods for determining the correct (objective) measured values. In the experimental method of learning, we can proceed in the classic way (complete, 100%) of finding the relationship between input factors and output parameter or use a planned experiment [4,5,6].

In the classical method, we apply a combination of the influence of all input factors on the output parameter. In the classical or complete method, we enter by changing one factor in a certain range with constant values of the other input factors. We repeat this procedure by changing the other factors in the required range, which is very demanding from the time and material point of view when determining the resulting dependence. This method requires an enormous number of trials and is therefore not widely used in practice [7,8].

The second method, which has a significantly greater use in experimental research, is the method of planning experiments. This method of trial planning is characterized by the fact that it increases the efficiency and improves the organization of experimental research. By the plan of the experiment we understand the determination of the number of experimental factors, their levels and their combinations. This powerful tool is used to monitor and study the factors or parameters affecting the process under study. It makes it possible to classify factors into significant and less significant, taking into account the surrounding conditions, which are mostly an integral part of the process. At the same time, it makes it possible to obtain information about the mutual influence of individual factors at the input, and thus actually get to know the whole process better. With the planned experiment, we try to create such conditions that the scope of the experiments is as small as possible, but the volume and form of information are of the highest quality. The plan of the experiment determines the number of trials from which the experiment is composed, the conditions under which the individual trials will take place and the order of the trials. The advantage of this method is that it increases the accuracy of the obtained results, which can be expressed by easily interpretable mathematical relationships, further reduces the number of necessary attempts and increases the reliability of the results. The method of the planned experiment is widely used in research and industrial practice, and thus has become an integral part of any demanding experimental research [9,10,11].

Experiments that contain all possible combinations of all levels and all factors are called full factorial experiments. If the number of factors is (k) and the number of levels of each of them is (p), then the number of combinations (N) in a full factorial experiment corresponds to the number of trials and the relationship applies:

$$N = p^k [-] \tag{1}$$

Where:

N…Number of combination [-],

p^k…Plan of the form [-].

In technical practice, plans of the form 2^k are most often used, 3^k are used less often.

3 Experimental material

In technical practice, two types of chrome steel are most often used for the production of rolling bearings, namely 14 109 (100Cr6) and 14 209 (100CrMn6). Rolling bearings are an important structural element and form an irreplaceable part of most machines and equipment. In the field of mechanical engineering, they have a specific structure and higher and higher demands are placed on them, such as accuracy, reliability, safety, low noise and weight, but above all efficiency. For this reason and the quality of the bearing production, heat-treated bearing steel 14 209.4 (100CrMn6) with a workpiece diameter of 50 mm was chosen for the experimental research. The measurement was carried out during external longitudinal turning without the use of process fluid with a replaceable cutting plate type 2NU-CNGA 120408 BNX 20 without coating on a universal lathe SUI 40 x 1000 with continuous speed control and a KISTLER 5006 dynamometer, which is in Fig.1. In addition to the above, measurements of cutting forces were also carried out in this experiment, but they are not included in this article. For this reason, a KISTLER 5006 dynamometer was also used for the selected turning technology.

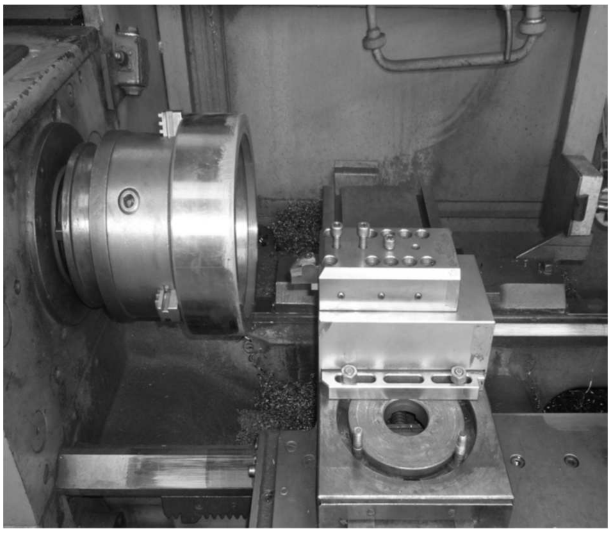

Fig. 1 *A view of the clamped workpiece with a KISTLER dynamometer on a lathe SUI 40*

The selected cutting material with basic characteristic data for the selected type of replaceable cutting plate is listed in Tab. 1.

Tab. 1 *Interchangeable cutting plates used in experimental measurement*

Cutting plate BNX 20	Coating type	Percentage volume of KNB grains	KNB grain size	Binder
	**Without coating**	**65-70**	**1 μm**	**TiN**

4 Experimental procedure of the planned experiment method

The most used and evaluated surface roughness parameter in technical practice is the Ra value, i.e. mean arithmetic deviation of the profile. The stated planned experiment is an attempt to use in the identification of the basic technological parameter depending on the cutting factors.

The size of the mean arithmetic deviation of the Ra profile is mainly influenced by the cutting parameters. The influence of cutting parameters, i.e., we can write the cutting speed (v_c), depth of cut (a_p) and feed (f) in the form of an equation:

$$Ra=C_{Ra}\cdot v_c^{b_1}\cdot a_p^{b_2}\cdot f^{b_3} \qquad (2)$$

Where:

C_{Ra}…A constant that determines the dimensional homogeneity of the regression function [-],

b_1, b_2, b_3…Exponents expressing the influence of individual variables Ra [-],

v_c…Cutting speed [m.min^{-1}],

a_p…Depth of cut [mm],

f…Feed [mm].

The experimental evaluation of the mean arithmetic deviation of the Ra profile was carried out using the method of statistical planning of the experiment. To find out the influence of cutting parameters on the evaluated roughness parameter Ra, a two-level plan was used, i.e., $N = 2^k$. In our case, this means $N = 2^3 = 8$. The matrix used to determine the two-level plan is shown in Tab. 2. Three factors with two levels were chosen to determine the influence of the mentioned factors on surface roughness. Level -1 represents the code designation of the lower level of the variable and level +1 represents the code designation of the upper level of the variable.

Tab. 2 *Monitored factors and their designation*

A variable quantity	Code designation	Level of variation (u_{x_i})	
		-1	**+1**
Cutting speed v_c (m.min^{-1})	x_1	**75**	**250**
Depth of cut a_p (mm)	x_2	**0.25**	**1**
Feed f (mm)	x_3	**0.051**	**0.102**

The experimental measurement of the surface roughness after turning on the bearing steel was carried out using the MITUTOYO SURFTEST SJ 301 device, which independently evaluated the roughness characteristics Ra. The measured values of roughness Ra are shown in Tab. 3.

Tab. 3 *Two-level experiment plan of measured and calculated values*

N	v_c (m.min^{-1})	u_{x_1}	a_p (mm)	u_{x_2}	f (mm)	u_{x_3}	**Ra_i (μm)**					$\bar{y}_i=\frac{\sum Ra_i}{5}$	**log y_i**
							1	2	3	4	5		
1	75	-	0.25	-	0.051	-	0.38	0.39	0.40	0.41	0.40	0.396	-0.402
2	75	-	0.25	-	0.102	+	0.49	0.49	0.52	0.51	0.53	0.508	-0.294
3	75	-	1	+	0.051	-	0.51	0.51	0.58	0.58	0.60	0.556	-0.254
4	75	-	1	+	0.102	+	0.73	0.79	0.81	0.79	0.80	0.784	-0.105
5	250	+	0.25	-	0.051	-	0.43	0.38	0.39	0.41	0.43	0.408	-0.389
6	250	+	0.25	-	0.102	+	0.72	0.66	0.68	0.68	0.59	0.666	-0.176
7	250	+	1	+	0.051	-	0.42	0.42	0.48	0.47	0.43	0.444	-0.352
8	250	+	1	+	0.102	+	0.81	0.77	0.79	0.79	0.79	0.79	-0.102

For the mathematical expression of the influence of cutting speed (v_c), depth of cut (a_p) and feed (f) on the surface roughness parameter Ra, a model of the linear form of multiple regression was used for the measured values, which has the basic form:

$$y=b_0+\sum_{i=1}^{k} b_i \cdot x_i \tag{3}$$

Where:

b_0…Arithmetic mean of the measured logarithmic values [-],

b_i…Arithmetic mean from a two-level plan [-],

x_i…Coded cutting parameter [-].

$$b_0=\frac{\sum \bar{y}_i}{n} \tag{4}$$

$$b_i=\frac{u_{x_i} \sum y_i}{n} \tag{5}$$

Where:

n… Number of measurements [-].

By introducing a logarithmic transformation, equation (2) is linearized to the form:

$$\log Ra=\log C_{Ra}+b_1 \log v_c+b_2 \log a_p+b_3 \log f \tag{6}$$

The dependence of roughness Ra on cutting conditions is expressed using a polynomial, where x_1 is cutting speed (v_c), x_2 is depth of cut (a_p), x_3 is feed (f) in the form:

$$Ra=b_0+b_1 \cdot x_1+b_2 \cdot x_2+b_3 \cdot x_3 \tag{7}$$

Calculation of mean logarithmic values of factors:

$$\log v_{c\ str}=\frac{\log v_{c_{max}}+\log v_{c_{min}}}{2} \tag{8}$$

$$\log a_{p\ str}=\frac{\log a_{p_{max}}+\log a_{p_{min}}}{2} \tag{9}$$

$$\log f_{str}=\frac{\log f_{max}+\log f_{min}}{2} \tag{10}$$

We will convert the individual factors to a logarithmic form:

$$x_1=\frac{\log v_c-\log v_{c_{str}}}{\log v_{c_{str}}-\log v_{c_{min}}} \tag{11}$$

$$x_2=\frac{\log a_p-\log a_{p_{str}}}{\log a_{p_{str}}-\log a_{p_{min}}} \tag{12}$$

$$x_3=\frac{\log f-\log f_{str}}{\log f_{str}-\log f_{min}} \tag{13}$$

Calculation of coefficients of the regression equation in coded form to the formula (4):

$$b_0=\frac{\sum \bar{y}_i}{n} \tag{14}$$

$$b_1=\frac{u_{x_1} \sum y_i}{n} \tag{15}$$

$$b_2=\frac{u_{x_2} \sum y_i}{n} \tag{16}$$

$$b_3=\frac{u_{x_3} \sum y_i}{n} \tag{17}$$

After substituting into equation (7) and modifying it, we get the resulting equation, which expresses the dependence of the valuable surface roughness parameter Ra on the cutting conditions in the form:

$$Ra=1.4733 \cdot v_c^{0.0305} \cdot a_p^{0.2474} \cdot f^{0.7839} \tag{18}$$

From the resulting equation (18) of the evaluated surface roughness parameter Ra, it follows that all cutting parameters affect the quality of the machined surface. The performed experiments showed that, of the cutting parameters, the feed rate (f) has the greatest influence on the mean arithmetic deviation of the Ra profile, followed by the depth of cut (a_p) and the cutting speed (v_c) has the least influence. Constructed graphic dependencies confirm that the results obtained in equation (18) are correct and point to the sequence of the influence of the cutting parameters on the evaluated surface roughness parameter Ra.

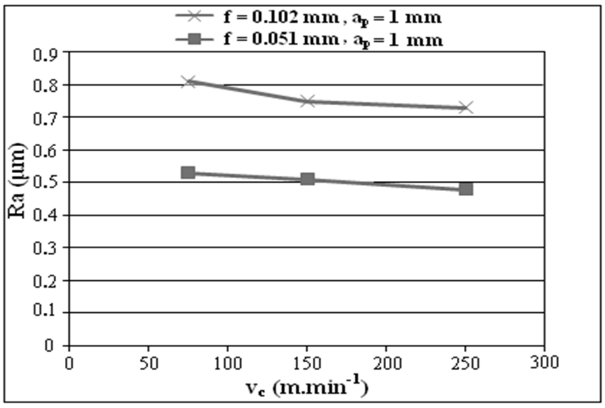

Fig. 2 *Graphical dependence of the Ra=f(v_c)*

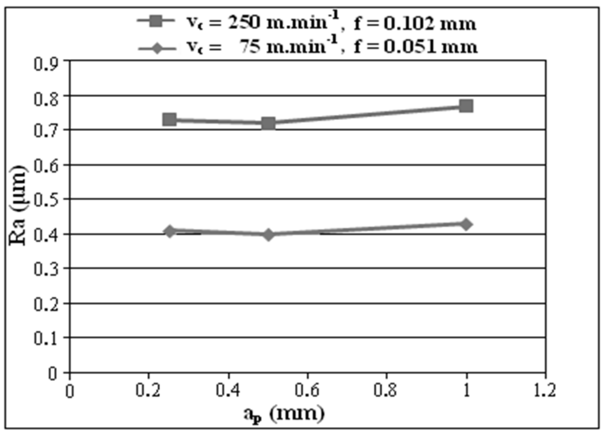

Fig. 3 *Graphical dependence of the Ra=f(a_p)*

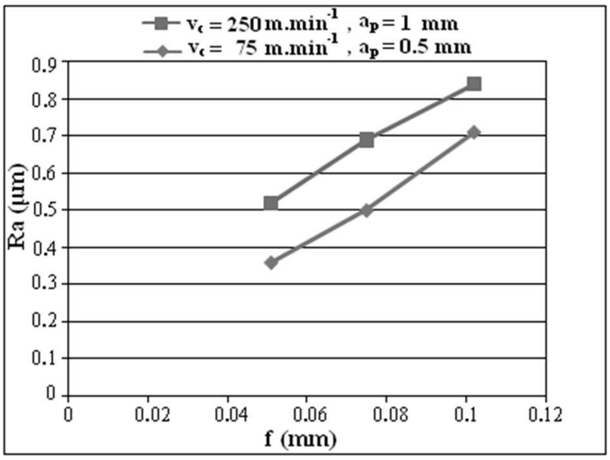

Fig. 4 *Graphical dependence of the Ra=f(f)*

5 Conclusion

Surface roughness is a very important criterion when assessing surface quality. It is one of the parameters that determine the applicability of any components within various structural units. The optimal choice of the surface character and compliance with the requirements for the character of the surface during the production of products affects not only the appearance of the individual components, but also the correct function, service life, price, and overall construction.

In technical practice, the mean arithmetic deviation of the profile is the most used and most evaluated parameter of surface roughness. Since the cutting parameters play an important role in creating the microgeometry of the surface, the presented article points to the analysis of the influence of the cutting parameters on the roughness of the machined surface.

Currently, various mathematical-statistical methods are used in the implementation of experiments, which have the task of reducing, above all, the material and time-consuming nature of the experiments. The article therefore presents the method of a planned experiment for the experimental evaluation of surface roughness during turning of bearing steel. Here, it was confirmed that in the field of verification of theoretical relationships, it is necessary to analyze the correctness of individual dependencies and the determination of given parameters for linear dependencies, which are highly dependent on input factors. These input factors are not only the cutting parameters, but also the constancy of the properties of the materials, cutting tools, machine tools, machining methods and the conditions of the performed experiments. A significant role in this stage is also played by the given subject (person), who influences the stated conditions of the experiment.

In conclusion, it can be concluded that:

- The results of the experiment, which were achieved using the planned experimental method applied to the calculation of the evaluated surface roughness parameter Ra, point to the simplicity and effectiveness of using this method in practice in the number of performed experiments.
- That experiment planning is one of the most effective tools of the pre-production phase. It is a kind of mathematical tool that allows manufacturers to quantify the importance of input factors that are initially among the most influential.
- According to the resulting equation (18), the evaluated surface roughness parameter, i.e. of the mean arithmetic deviation Ra, on the basis of the used method of the planned experiment, the theoretical starting points of the influence of cutting parameters on the quality of the machined surface were proven and confirmed in the following order: amount of feed (f), depth of cut (a_p), cutting speed (v_c).

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