INVESTIGATION OF CUTTING CONDITIONS INFLUENCE ON SURFACE ROUGHNESS DURING MQL MACHINING OF STEEL

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ABSTRACT
In the paper, the influence of the cutting conditions (cutting speed, feed, and depth of cut) during the machining of the cylindrical steel part on the surface roughness (average surface roughness-Ra) is analysed using experimental investigation. The material used in the full factorial experimental investigation was C45 steel, a diameter of 50 mm, machined on a conventional lathe POTISJE ADA 501M. Cooling and lubrication were realised by means of JOOM MQL system model J-T2X-012-2K-T, from Daido Metal, which supplies a cutting zone with oil-on-water droplets average size of 100 microns and with an oil film thickness of 1000 Å. Carbide inserts SNMG 120408-MA Grade US735 MITSUBISHI were used as cutting tools. The results of the experiment show that cutting speed is the most influential factor in surface roughness. Increasing cutting speed, the surface roughness decreases. This factor seems to be the only one that is statistically significant. Feed is the second strongest factor followed by the depth of cut. Both are statistically insignificant for 0.05 level of significance (95% reliability). The linear regression model is, by appropriate mathematical operation, transformed, coded, and decoded into the exponential model. The model is represented by diagrams given at the end of the work.

1. INTRODUCTION

Design of Experiment (DoE) is a powerful tool for achieving significant improvements in product quality and process efficiency. The methodology is not used only in engineering problems but also in various spheres of science and sociological studies. The basic parts of experiment planning, known as key steps of DoE, are [1]:

- **Setting objectives** - define the task of the experiment, scope, and materials, setting goals of the experiment, etc.
- **Selecting process variables** - process variables include both inputs and outputs - i.e., influential factors and responses.
- **Selecting an experimental design** - the choice of an experimental design depends on the objectives of the experiment and the number of influential factors investigated.
- **Association of treatments** - it is necessary to determine how to associate treatments with units (coded or uncoded), whereby only one of the treatments can be applied to each unit,
- **Conducting an experiment** - the experiment is performed according to the previously defined plan matrix,

Analysis and conclusions - obtained results are analyzed and conclusions are drawn.

In a statistical experiment, the influence of one or more factors on a certain phenomenon is observed. These factors are called controlled factors.

The observed phenomenon can also be influenced by random factors called uncontrolled or experimental errors [2]. To draw concrete conclusions from an experiment, it is

necessary to plan the performance of the experiment in a certain way and at the same time examine the conditions under which it is possible to reduce the experimental error. A well-planned experiment allows us to obtain clear interpretations and avoid complicated analyses, and a poorly planned experiment gives us wrong conclusions about a process.
In this case, Regression Analysis will be used as an investigation methodology to find out the functional relationship between input and output data. Regression analysis helps to quantitatively express the dependence between variables [3].

2. EXPERIMENTAL SETUP

In this study, the influence of cutting condition parameters, cutting speed expressed through the number of revolutions per minute n (rpm), feed rate f (mm/rev), and depth of cut d (mm), on average surface roughness Ra (microns) will be considered. The test was made on one cylindrical C45 steel rod, in which is incised 10 groves that enable easier distinction between experimental runs (Fig 1.).

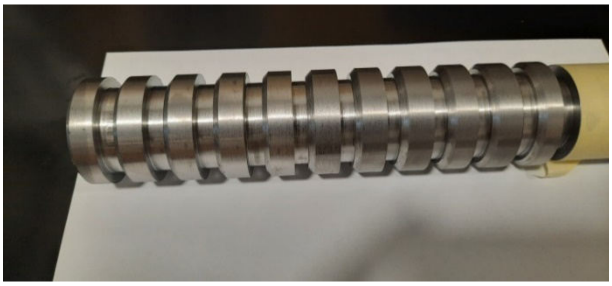


Figure 1. Cylindrical steel rod with 11 ribs

Every rib is used for one experiment with different cutting conditions. Machining is performed on the conventional lathe POTISJE type ADA PA 501M, in the laboratory LORAM, Faculty of Mechanical Engineering in Zenica.

Figure 2. Conventional lathe POTISJE type ADA PA 501M

For the purposes of the experiment, a medium-level of MQL lubrication system (Water 17.5 ml/min, Oil 30 cc/hour) was used (Fig. 3). MQL is the process of applying small amounts of high-quality lubricant directly to the cutting tool/work piece interface instead of using traditional flood coolants. MQL minimizes environmental impact by significantly reducing fluid usage and eliminating the need for coolant treatment and disposal. A flow rate in the range of 50–500 ml/hour is commonly applied for most industrial applications [4]. Due to the low consumption of cutting fluids, MQL is considered an environmentally friendly cooling technique.

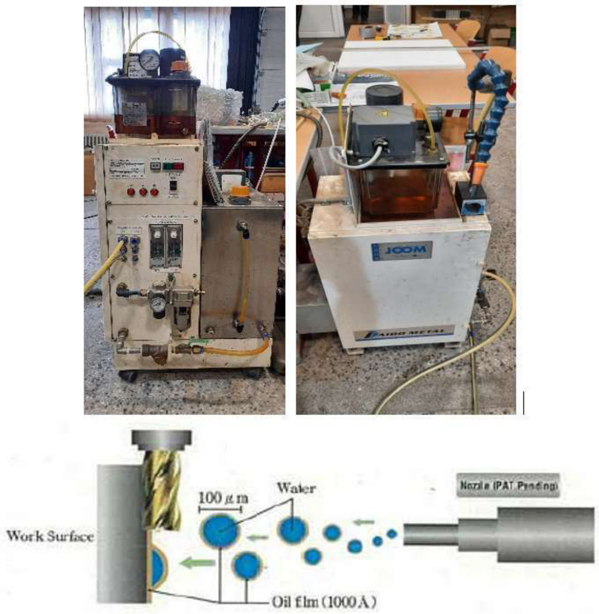


Figure 3. JOOM MQL system

Water and oil levels were kept constant throughout all experiments. Machining is performed with a replaceable cutting insert (carbide grade) type SNMG 120408-MAUS735, manufactured by MITSUBISHI. Cutting conditions were set up according to the cutting insert's producer recommendations.

Figure 4. Replaceable cutting insert type SNMG 120408-MAUS735

A full factorial design with k = 3 factors on 2 levels was applied. The number of runs is:

$$N = 2^k + n_0 = 2^3 + 3 = 11 \tag{1}$$

where n_0 is the number of replicates in the central point.
The primary goal has been to define cutting conditions that produce the best results of Ra factor – values of surface roughness. The specified experimental limits are given in Table 1.:

Table 1. The values of factor levels and cutting conditions

Factors	Factor levels	Cutting speed *n (rpm)*	Feed, *s (mm/rev)*	Depth of cut *d(mm)*
		X_1	X_2	X_3
Upper level	+1	910	0,196	1,5
Central point	0	600	0,124	1
Lower level	-1	265	0,049	0,5

Experimental runs have been randomized and are presented in Table 2. Roughness measuring was performed on a 3D Measuring system MicroCadMahr device for contactless measuring. The measurement was performed at 3 different points on rib circumference, rotated for 120 deg. Results were processed by *MarSurf XR20 V1-21.1* software.

Table 2. Plan of experiment with measuring results for parameter Ra

Exp. point N	Plan matrix				Measurement results Ra (µm)				
	X_0	Number of revolutions	Feed	Cutting depth	Measurements			Raaverage	
		X_1	X_2	X_3	I	II	III	y	ln(y)
1.	1	1	1	1	3,8	4,8	4,7	4,4	1,49
2.	1	-1	1	1	4,4	4,6	4,8	4,6	1,53
3.	1	1	-1	1	3,6	3,3	2,7	3,2	1,16
4.	1	-1	-1	1	4,7	4,3	4	4,3	1,47
5.	1	1	1	-1	3,6	4,3	4,6	4,2	1,43
6.	1	-1	1	-1	5	5,3	5,5	5,3	1,66
7.	1	1	-1	-1	3,9	4,2	4,2	4,1	1,41
8.	1	-1	-1	-1	5,5	4,4	4,9	4,9	1,60
9.	1	0	0	0	3,9	4,1	3,4	3,8	1,34
10.	1	0	0	0	4,1	4,4	4,6	4,4	1,47
11.	1	0	0	0	4,6	4,5	3,7	4,3	1,45

3. ANALYSIS OF RESULTS

Analysis of results was performed by Data Analysis Tool Pack from the Microsoft Excel software package [6]. It has been shown the analysis for the case given in Table 2. It has been assumed that the exponential function is a possible description of relations between parameters and cutting conditions:

$$Ra = C \cdot n^x \cdot f^y \cdot d^z \ldots \qquad (2)$$

where:

- C is constant and x, y, and z, are the exponents.
- n is the number of revolutions, [rpm];
- f is feed rate, [mm/rev];
- d is the depth of cut, [mm].

As mentioned, appropriate statistical processing of data will be performed using *MS Excel* [5,7]. In the case of data shown in Table 2, data processing generates the following output:

Table 3. Regression analysis from MS Excel

Regression Statistics	
Multiple R	0,8529
R Square	0,7275
Adjusted R Square	0,6108
Standard Error	0,0816
Observations	11

Table 3.1 ANOVA table

ANOVA	df	SS	MS	F	Significance F
Regression	3	0,12	0,04	6,232	0,0217
Residual	7	0,04	0,00		
Total	10	0,17			

Table 3.2 Coefficients values and its significance

	Coefficients	Standard Error	t-Stat	P-value
Intercept	1,4545	0,024	59,05	1,05E-10
X1	-0,0949	0,028	-3,28	0,013
X2	0,0584	0,028	2,022	0,082
X3	-0,0563	0,028	-1,95	0,0920

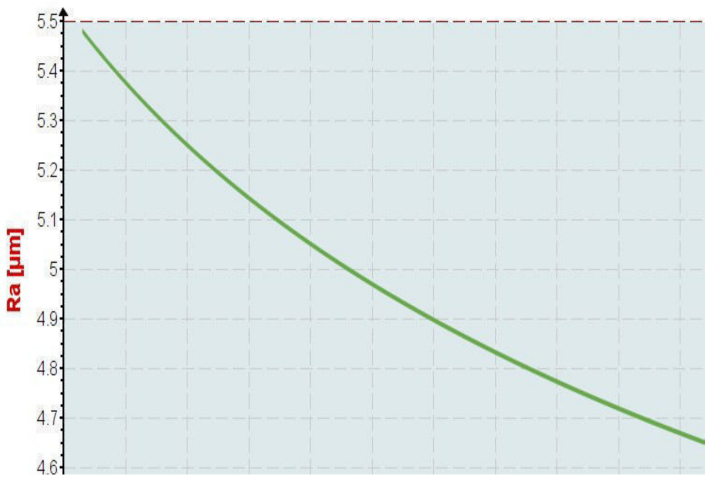
On the basis of these results, the linear regression model was obtained as follows:

$$y = 1,45455 - 0,09493 \cdot X_1 + 0,0584 \cdot X_2 - 0,05635 \cdot X_3 \quad \ldots (3)$$

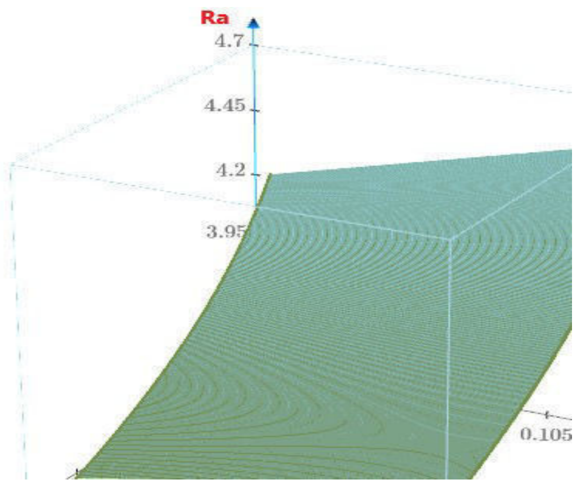
From the ANOVA table (Table 3), the given model adequately describes the analysed process. Also, only the number of revolutions, X_1, significantly influences the model (P-value less than 0.05, for 95% reliability). Transforming this model into natural coordinates gives:

$$Ra = 12,94 \cdot n^{-0,154} \cdot f^{0,0864} \cdot d^{-0,102} \quad (4)$$

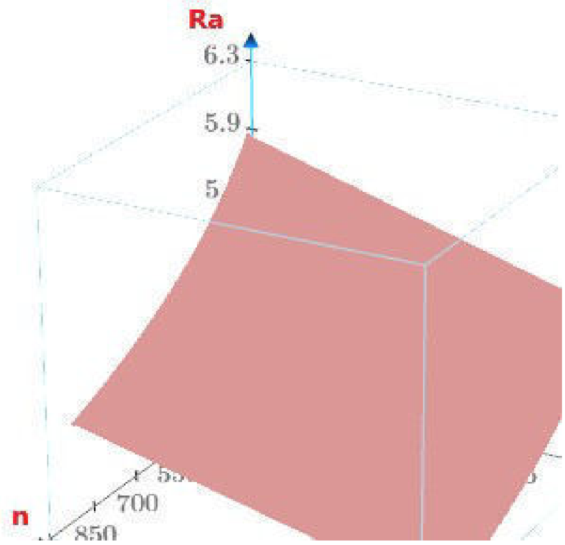
Figure 5 shows the graphical interpretation of obtained correlation in the case of the Ra surface roughness parameter. The first 2D Figure (5.1.) shows the function when statistically significant factors are included, in this case only n. In Figures 5.2 and 5.3 insignificant factors are also included to obtain 3D visualisation of its effect.
This 2D and 3D interpretation is obtained in the software MathCAD.



1) Ra = f (n)



2) Ra = f (n, f), d = const.



3) Ra = f (n, d), f = const.

Figure 5.Cutting conditions influence on average roughness Ra

4. CONCLUSION

Functional relationship between the input data *n*, *f*, *d*, and *Ra* factor as output is obtained by regression analysis.

This relationship is expressed through the mathematical model in the form of the equation (eq.4) that connects a dependent variable with independent variables quantity respecting appropriate assumptions and constraints.

As previously shown, the exponential model adequately describes the functional relationship between input and output data, as shown in the *ANOVA* table ($F > F_{tab}$ $F_{0.05,3,6} = 4.7571$, for $\alpha = 0,05$, $k = 3$, and $N-k-1 = 6$).

By analyzing individual factor significance, it can be stated that in this model, only cutting speed is a statistically significant factor. Increasing cutting speed (the number of revolutions), surface roughness is decreasing. The other two influential factors, feed, and depth of cut, are statistically insignificant under analysed experimental conditions and probability of 95%.

5. REFERENCES

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