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PARAMETER SCREENING IN LONGITUDINAL TURNING OF C45E STEEL FOR SURFACE ROUGHNESS ANALYSIS

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Abstract
Parameter screening refers to the identification of the most important controllable factors with respect to a given performance characteristic of a given system/process. In this study, Plackett-Burman design was applied in order to identify the factors that significantly affect surface roughness in longitudinal turning of C45E steel. The experiment involved realization of geometric Plackett-Burman design with eight trials and two replicates. Six turning controllable factors were considered in the design matrix (depth of cut, feed rate, cutting speed, insert nose radius, minor cutting edge angle and cooling/lubrication condition) and were varied at two levels. Analysis of the obtained results has shown that factors differently affect surface roughness and that their influences are in accordance with known theoretical knowledge. It was also observed that three factors have statistically significant impact on the machining quality, i.e., arithmetic surface roughness. These results can be considered as the first step for further experimental investigation of significant factors and their possible interactions effects.

Keywords: turning, design of experiments, Plackett-Burman design, surface roughness, C45E steel.

INTRODUCTION

Turning technology represents one of the oldest production technologies which, due to its favourable cutting mechanics and good trade-off between productivity, quality, and production costs, still plays significant role in today's modern industry. In the turning process single point cutting tool with defined geometry removes material from the rotating workpiece in the form of chips. The process mechanics is very complex and highly nonlinear and is governed by a number of controllable and non-controllable parameters, as well as their interactions. The turning process can be regarded as a specific tribo-mechanical system consisting of five basic groups: workpiece, cutting tool, cutting conditions, interface, and machine tool. This production system demands applications of contemporary technical knowledge, engineering, and technical skills, as well as appropriate scientific methods and approaches for its more efficient usage in given production conditions with specified requirements. One of the most popular scientific approaches for the analysis, modelling and optimization of industrial systems considers the application of design of experiments (DOE). Along with basic knowledge of statistics and physics of the process being studied, DOE provides many opportunities including: parameter screening, development of empirical models, optimization of processes/systems, multi-objective optimization, determination of robust conditions for process implementation, hypothesis testing and evaluation of alternative solutions, etc. As a rule, the first step in analysing complex industrial processes (or systems) involves the application of low resolution experimental designs, such as Plackett-Burman and fractional factorial designs, for parameter screening. The aim would be to analyse large set of controllable factors and identify a small number of factors that significantly affect the considered process performances (related to quality, productivity, costs, etc.).

In previous years, Plackett-Burman designs were applied in different industrial systems, such as electro-discharge machining (EDM) [1], plasma cutting process [2], stir casting [3], micro dry wire electrical discharge machining process (µDWEDM) [4], laser assisted machining (LAM) [5], ultrashort-pulsed laser technology for development of micro structured cutting tools [6], wood-chipping [7], die-sinking EDM [8], intermediate-wave infrared drying (IWIR) [9], laboratory quality assurance [10], etc. Likewise, fractional factorial designs were applied for analysis of milling [11, 12], wire electrochemical turning process [13], turning [14], WEDM [15], sculptured surface machining [16], laser cutting [17], etc.

Since machined surface texture has a significant effect on properties of the manufactured part, models for predicting the surface roughness values in turning are often required. In general, these models contain a geometric factor related to the insert nose radius, while the feed rate dominates as a kinematic factor. They usually predict the roughness values of R_a and R_t, as these are the most common industry requirements for roughness for manufactured parts [18]. Starting from the best-known surface roughness model proposed by Shaw and Crowell [19] a number of models, having different number of constitutive terms, were proposed for surface roughness prediction.

In order to get better picture about influential controllable factors which significantly affect surface roughness in longitudinal turning of C45E steel, this study uses Plackett-Burman design for assessment of six factors, including depth of cut, feed rate, cutting speed, insert nose radius, minor cutting edge angle and cooling/lubrication condition. The experimental investigation was performed by the application of geometric Plackett-Burman design with eight trials and two replicates. By using the acquired measurement data of arithmetic mean roughness values, the quantitative and qualitative analysis of the effects of the selected factors was performed.

EXPERIMENTAL SETUP AND MEASUREMENTS

The workpiece material used in the experiment was C45E steel (AISI 1045, Ck 45 DIN 17200). C45E steel is unalloyed medium carbon steel that has good machinability, high tensile properties, and moderate wear resistance. The experimental units used in machining trials were in the form of bar pre-machined to diameter of 72 mm. The cutting tool is a toolholder CORUN PCLNR 3225P 12 (cutting edge angle of $\kappa = 95°$, minor cutting edge angle of $\kappa_1 = 5°$, rake angle of $\gamma_{oh} = -6°$, and inclination angle of $\lambda = -6°$) with CORUN CNMM 120404 insert for medium to rough machining: rake angle of $\gamma_{oi} = 22°$, nose radius $r_\varepsilon = 0.4$ mm, and grade of 4025 (coated carbide), and CORUN CNMM 120408 insert for medium to rough machining: rake angle of $\gamma_{oi} = 22°$, nose radius $r_\varepsilon = 0.8$ mm, and grade of 4025 (coated carbide). Minor cutting edge angle of $\kappa_1 = 25°$ is achieved by rotating the tool post. The experimental setup for machining is given in Fig. 1.

During machining, either tough or brittle material behaviour, which has a large effect on chip formation, can be realized by varying the amount and direction of stress, governed by the feed velocity, cutting speed, depth of cut, and tool normal rake angle, tool cutting edge angle and tool cutting edge inclination [20]. In the present experimental investigation, cutting regimes corresponding to trials 7 and 8 produced unfavourable continuous snarled chips (Fig. 1). Boron oil, as a multi-purpose cutting and metal working oil, was used in wet cooling/lubrication conditions.

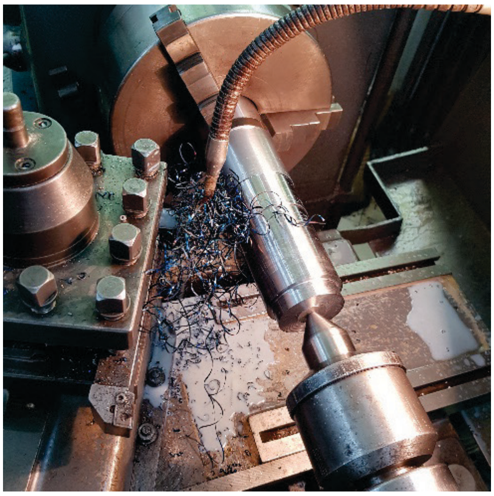

Fig. 1. *Experimental setup (minor cutting edge angle of κ_1 = 25° is achieved by rotating the tool post)*

Universal lathe machine POTISJE PA-C 30 with the motor power of 11 kW was used to perform the experiment in laboratory conditions. In this experiment, longitudinal turning trials were performed in order to screen several turning parameters and determine their quantitative and qualitative effects on the resulting surface roughness. To this aim, a geometric Plackett-Burman screening design was applied, which enables screening of up to seven factors by conducting only eight experimental trials [21]. This design is equivalent to the 2^{7-4} fractional factorial design having resolution III. In such designs the estimations of the main effects are not confounded with any other main effects, but are confounded with the effects of two-factorial interactions. The application of such designs can be justified if one deals with a number of factors and if one can assume that higher order factorial interactions are not important.

Cutting parameter ranges and levels were selected considering machining handbooks, machine tool characteristics, recommended cutting conditions for the insert, workpiece diameter, and previous experience. Factors with their names, labels, and values on low level (-1) and high level (+1) are shown in Table 1. Factor combinations, based on the Plackett-Burman design, are given in Table 2.

Table 1. *Factors and levels*

Factor	**Unit**	**Label**	**Low level (-1)**	**High level (+1)**
Depth of cut, a_p	mm	A	1	2
Feed rate, f	mm/rev	B	0.107	0.196
Cutting speed, v	m/min	C	167	206
Insert nose radius, r_ε	mm	D	0.4	0.8
Minor cutting edge angle, κ_1	°	E	5	25
Cooling/lubrication conditions	-	F	dry	wet

Table 2. *Tested cutting regimes*

Trial	**A**	**B**	**C**	**D**	**E**	**F**
1	+1	-1	-1	+1	-1	+1
2	+1	+1	-1	-1	+1	-1
3	+1	+1	+1	-1	-1	+1
4	-1	+1	+1	+1	-1	-1
5	+1	-1	+1	+1	+1	-1
6	-1	+1	-1	+1	+1	+1
7	-1	-1	+1	-1	+1	+1
8	-1	-1	-1	-1	-1	-1
Number of replicates = 2, degrees of freedom of the experiment = 16						

In order to reduce the effect of uncontrolled variation and improve statistical accuracy of the experiment in terms of main effect estimates, two replicates were performed in the experiment, making a total of 16 experimental trials. In addition, to avoid any bias in the experiment, which may result from the effects of some extraneous unknown factors, all experimental trials were performed in a completely randomized order. The same principle was adopted when assigning experimental units to cutting regimes. All other factors that could affect the outcome of the experiment were kept constant.

Surface roughness was adopted as a main quality criterion in this study. It was assessed in terms of the arithmetic mean roughness (R_a). Surface roughness measurements were performed at the Mahr MarSurf XR 1 roughness measuring station, using a skidless probe system BFW 250. The measurement conditions were chosen to meet the following roughness definition standards: reference length λ_c = 0.8 mm, number of repetitions of reference length n_r = 5, which means that the total test length is 5.6 mm, measurement profile R and results are passed through Gauss filter. The accuracy of the surface roughness measuring device is 0.001 µm.

RESULTS AND DISCUSSION

The quantitative and qualitative effects of the main factors on the response in the application of the Plackett-Burman experimental design can be determined as in the case of classical factorial experimental designs of 2^k type. In doing so, one should take into account the number of occurrences of the level of each factor in the experiment, as well as the number of experimental trial replicates [21]. Conducting statistical analysis helped in determining the main effects of individual factors on surface roughness, as shown in diagrams in Fig. 2.

From Fig. 2 it can be concluded that factors A, B, and E have a positive correlation with the resulting surface roughness, i.e., an increase in the depth of cut, feed rate and minor cutting edge angle increases surface roughness and vice versa. On the other hand, factors C, D and F have a negative correlation with surface roughness, i.e., with an increase in their values one could expect lower surface roughness (better surface finish).

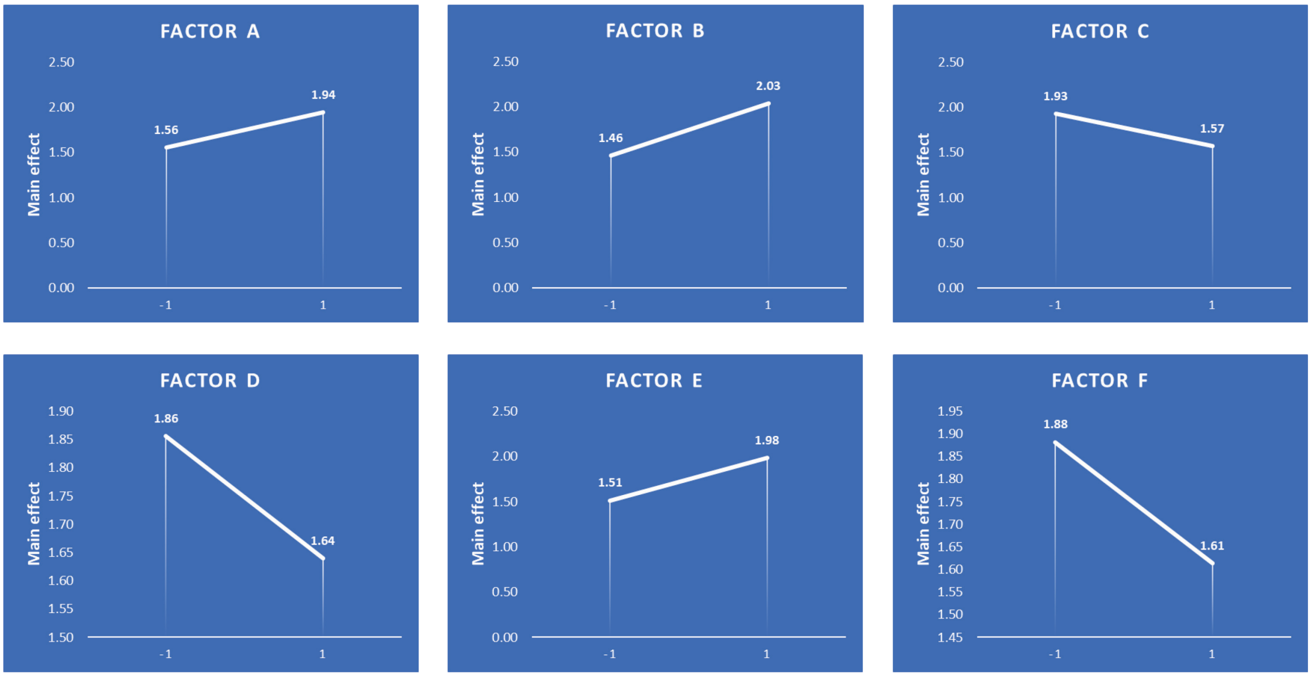

Fig. 2. *Main effects plots of turning parameters on surface roughness*

Considering the absolute values of the main effects it can be concluded that the factor B (feed rate), has the greatest effect on the surface roughness, while the smallest main effect on the change in surface roughness has the factor D (insert nose radius). This observation is quite interesting given that insert nose radius is a constitutive term in some derived analytical and empirical models for estimation of surface roughness in turning. Still, as would be expected from these models, an increase in insert nose radius results in better surface finish, and the same observation can be made in this case. Based on the conducted analysis one can derive the ranking order of factors, based on the absolute values of the main effects, in descending order as follows: B-E-A-C-F-D.

In general case, in experimental designs, the F-test or p-value from ANOVA analysis are usually used to assess whether factors significantly influence the response. The F-value measures on how well the factors describe the variation in the mean of data. Higher F-value implies that the estimated factor effects are real since the factors are able to explain adequately the variation in the data especially related to its mean [4]. The significance diagram and the Pareto diagram can be used for the same purpose. Previously, it is necessary to choose the level of significance (α), for which values of 0.05 or 0.1 are most often used [21, 22]. Therefore, in the present experimental study, level of significance of α = 0.1 was considered.

In order to estimate F-values for each term in the model one needs to divide the factor variance with the error variance [23]. If the observed (calculated) value of F-ratio is higher than the critical F-value (tabulated value of F-ratio), there is a statistically significant effect of considered factor on the change in response value. In the present study, for the level of significance of $\alpha = 0.1$, $m = 1$ degrees of freedom for factors and $n = 9$ degrees of freedom for error, tabulated value of F-ratio is F = 3.36.

Fig. 3 shows the observed values of F-ratios for all factors. It is evident from the graph that factors A, B and E, that is, predominantly feed rate, minor cutting edge angle and depth of cut, respectively, statistically affect the change in surface roughness values. As argued by Rico et al. [24] the cutting edge angle may significantly affect the surface roughness due to the imperfect geometry of the insert. These authors observed the most significant effects of the cutting edge angle and feed rate on resulting surface roughness in turning of aluminum 1350.

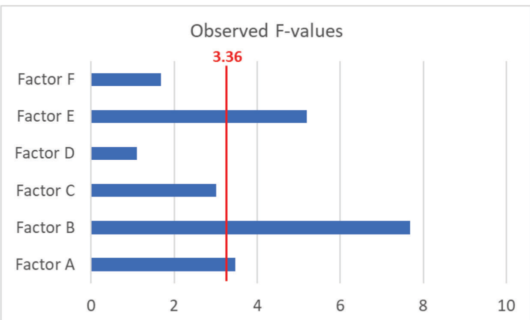

Fig. 3. *Assessment of statistical significance of considered factors*

The parameters that were identified as statistically significant can be further considered by using higher resolution designs such as full factorial designs, central composite designs or Box-Behnken designs. In that way, a more comprehensive analysis of the factor effects, as well as their interaction effects will be enabled. Moreover, determination of optimal combination of factor values for surface roughness minimization thorough development of mathematical models and application of certain optimization algorithms would be possible.

In the case it is necessary to predict surface roughness only considering main effects of factors, the following linear mathematical model, in the coded form, can be used:

$$R_a = 1.75 + 0.19 \cdot A + 0.29 \cdot B - 0.18 \cdot C - 0.11 \cdot D + 0.24 \cdot E - 0.13 \cdot F \qquad (1)$$

where R_a (μm) is arithmetic mean roughness, A = depth of cut, B = feed rate, C = cutting speed, D = insert nose radius, E = cutting edge angle and F = cooling/lubrication conditions.

CONCLUSION

Based on the experimental results of measuring the arithmetic mean surface roughness values in longitudinal turning of C45E steel, as well as the performed qualitative-quantitative analysis based on geometric Plackett-Burman design, it can be clearly seen that within a set of machining factors that are commonly considered in process planning, some have more pronounced effect and should be carefully considered. Statistical analysis of the experimentally obtained surface roughness values showed that, at level of significance of $\alpha = 0.1$, three factors (feed rate, minor cutting edge angle and depth of cut) significantly affect the considered response quality characteristic. Based on the conducted analysis, the most important parameters in longitudinal turning of C45E steel, regarding the resulting surface roughness, were identified. In addition, given that observed results are, to a great extent, in accordance with the well-known machining practice and theory, one can confirm the effectiveness of using Plackett-Burman design for factor screening of controllable factors in turning processes.

The results suggest that the best surface quality in longitudinal turning of C45E steel, i.e., the minimal value of surface roughness, can be expected under wet conditions when using low depth of cut, low feed rate, high cutting speed, larger insert nose radius and smaller minor cutting edge angle. However, having in mind that with relatively few experimental trials, such as in low resolution experimental designs, one cannot assess the possible factorial interactions, the scope of future research can be towards more detailed analysis of the factors identified as statistically significant.

If one considers a broader picture, the limitation of the study was that only arithmetic mean surface roughness was considered as performance characteristic.

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