COMPARISON OF THE METHODS FOR PARAMETERS SIGNIFICANCE EVALUATION ON THE BASIS OF ROLLER BURNISHING PROCESS

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ABSTRACT

In the work the chosen methods for evaluation of a significance of controllable parameters in technological process results are compared. The task was realized on the basis of roller burnishing process of turned shaft made of 1.503 steel. The methods, which are compared are: a $2^3$ full factorial design and a Shainin method. Considered controllable parameters were: rate of feed, force of roller pressure and spindle rotation speed. Experiments conducted to minimize roughness ($R_a$ parameter) after treatment, in case of the $2^3$ full factorial design, enable to obtain a formula after relatively labor-intensive calculations. In case of the Shainin method it was possible to obtain faster approximate results comparable with these obtained using the $2^3$ full factorial design.

KEY WORDS
experiment planning, Shainin method, full factorial design

INTRODUCTION

Burnishing treatment is a kind of finishing treatment, which relays on, in technological applications, a surface cold plastic deformation. It is performed in order to obtain a great smoothness of treated surface and also for strain hardening. Application of adequate burnishing tools makes shape increase and dimensional accuracy also possible.

One of the more often applied burnishing methods is a roller burnishing. Optimal selection of roller burnishing process parameters allows to obtain required roughness [El-Tayeb et al., 2009; Hamadache et al., 2006].

Surface roughness has a big significance on machine parts matching. Depending on exploitation conditions, an optimal value of roughness, when wear of elements is minimum, exists. Roughness value has also an influence on corrosion and fatigue resistance, and electric and heat conduction. Optimal parameters selection for a certain roller burnishing process is therefore important for many reasons. Evaluation of significance of controllable parameters is a first stage of optimization. Evaluation of parameters significance can be done with the use of various methods [Hamrol, 2008; Korzyński, 2006; Gryna et al., 2007; Tanco et al., 2008; Anderson and Whitcomb, 2000]. Some of them base on statistics, others don't dictate so formalized procedure. An interesting question remains if all of them lead to the same conclusions. To answer the question, even partially, comparative analysis with the use of the two methods was conducted. The analysed methods allowing to evaluate a significance of process parameters were: the $2^3$ two-level, full factorial design based on statistics [Korzyński, 2006] and the Shainin method, which doesn't
dictate so formalized procedure [Hamrol, 2008; Jiju and Ho Yuen Cheng, 2003]. The Full factorial design and the Shainin methods are still applied in industry [Tanco et al., 2008; Jiju and Ho Yuen Cheng 2003; Jiju, 1999; Thomas and Jiju, 2004]. But there is little information concerning comparison of the two methods [Tanco et al., 2008; Thomas and Jiju, 2006]. Because of this reason, comparison of the methods is scientifically desirable. This is also valuable in ascertaining the usefulness of each approach. The aim of the analysis was to determine the influence of roller burnishing process parameters on process results and to find out if the results of the analysis conducted with both methods are the same.

The analysis was made on shafts 28.5 mn in diameter made of 1.503 steel. Input roughness defined by $R_a$ parameter was 5 μm after turning. Measurements of roughness were made using profile measurement gauge Surtronic 3 on sampling length equal 0,8 mm and measuring length equal 4 mm. For each treatment variant three measurements were made to measure the roughness. Arithmetic average from the measured values was treated as the element's roughness after treatment.

The paper is organized as follows. In section 2 an analysis of a significance of roller burnishing process parameters with the full factorial design method is reported. In section 3 an analysis of significance of process parameters with the use of the Shainin method is presented. Next, the results obtained from both methods are compared. The goal of this work was to compare the methods parameters significance evaluation on example of chosen manufacturing processes.

### Analysis of Significance of Process Parameters with the Usage of the $2^3$ Full Factorial Design

In the experiment the following controllable parameters were determined: rate of feed, spindle rotation speed and force of roller pressure on burnishing surface (Figure 1).

Values of parameters were set at two levels each, as it is presented in table 1. Eight experiments were conducted. Parameters in these experiments were set according to table 2. Following the procedure, variability units and central values of process parameters were set. Next, the parameters were encoded (Table 2).

![Figure 1. Diagram of roller burnishing process](image)

1 – roller, 2 – shaft, $f$ – rate of feed, $P$ – force of roller pressure, $n$ – spindle rotation speed of shaft, $n_r$ – spindle rotation speed of roller

Source: Authors elaboration.

Parameters were encoded as follows:

- $x_1$ – force of roller pressure [kG] (1kG = 9,81N) – symbol „$P$“,
- $x_2$ – rate of feed [mm] – symbol „$f$“,
- $x_3$ – spindle rotation speed [rpm] – symbol „$n$“, Simultaneously the following assumptions were made:

- $r$ – number of replications – 3,
- $N$ – number of experiments – 8,
- $\alpha$ – established significance level – 0.05.

In the further part of this paper calculations made in accordance with the methodology described in the literature are presented.

Values of parameters for roller burnishing process (Table 1) were chosen on the basis of preliminary experiments.

In table 2, values of roughness parameter $R_a$ after treatment, its averaged values and measuring errors for each of the eight conducted experiments are presented.

Values of measuring errors variance are calculated according to the following formula:

$$S^2(y)_i = \frac{1}{r-1} \sum_{i=1}^{r} (y_i - \overline{y}_i)^2$$

(1)

Repeatability of the experimental conditions was evaluated according to the $2^3$ full factorial design procedure. Next, the regression coefficients were calculated and their significance was verified. Finally, the adequacy of obtained formula was checked.

Calculated coefficients of regression equation were as follows:
### Table 1.
VALUES OF BURNISHING PROCESS PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Force of roller pressure [kg]</th>
<th>Rate of feed [rpm]</th>
<th>Spindle rotation speed [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{max}}$</td>
<td>$P_{\text{min}}$</td>
<td>$f_{\text{max}}$</td>
</tr>
<tr>
<td>Input values of parameters</td>
<td>120</td>
<td>60</td>
<td>0.22</td>
</tr>
<tr>
<td>Variability units</td>
<td>$\Delta x_1 = (P_{\text{max}} - P_{\text{min}})/2 = 30$</td>
<td>$\Delta x_2 = (f_{\text{max}} - f_{\text{min}})/2 = 0.086$</td>
<td>$\Delta x_3 = (n_{\text{max}} - n_{\text{min}})/2 = 37.5$</td>
</tr>
<tr>
<td>Central values</td>
<td>$\hat{x}_1 = (x_1 - \bar{x}<em>1)/\Delta x_1 = (P - x</em>{10})/\Delta x_1 = (P - 90)/30$</td>
<td>$\hat{x}_2 = (x_2 - \bar{x}<em>2)/\Delta x_2 = (f - x</em>{20})/\Delta x_2 = (f - 0.134)/0.086$</td>
<td>$\hat{x}_3 = (x_3 - \bar{x}<em>3)/\Delta x_3 = (n - x</em>{30})/\Delta x_3 = (n - 62.5)/37.5$</td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

### Table 2.
THE 2^3 TWO-LEVEL, FULL FACTORIAL DESIGN TABLE WITH RESULTS OF THE CALCULATIONS

<table>
<thead>
<tr>
<th>$N^*$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$Y_1$</th>
<th>$Y_2$</th>
<th>$Y_3$</th>
<th>$Y$</th>
<th>$S^2(y_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>1.28</td>
<td>2.62</td>
<td>2.66</td>
<td>2.19</td>
<td>0.617</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-2.24</td>
<td>2.2</td>
<td>1.28</td>
<td>1.91</td>
<td>0.295</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>2.48</td>
<td>2.6</td>
<td>2.38</td>
<td>2.49</td>
<td>0.012</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>1.22</td>
<td>2.62</td>
<td>2.06</td>
<td>1.97</td>
<td>0.497</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>2.72</td>
<td>2.44</td>
<td>1.62</td>
<td>2.26</td>
<td>0.327</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
<td>0.78</td>
<td>0.82</td>
<td>0.80</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>1.36</td>
<td>2.34</td>
<td>2.08</td>
<td>1.93</td>
<td>0.258</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.94</td>
<td>0.64</td>
<td>0.69</td>
<td>0.051</td>
</tr>
</tbody>
</table>

$x_i$ – encoded parameter; $y$ – averaged roughness parameter $R_\alpha$ after treatment; $y_i$ – next roughness measurement for given experiment variant; $S^2(y_i)$ – variance of measuring errors

Source: Authors elaboration.

\[
\begin{aligned}
\sum_{i=1}^{N} x_{0i} y_i &= 1.778 \\
\sum_{i=1}^{N} x_{1i} y_i &= 0.358 \\
\sum_{i=1}^{N} x_{2i} y_i &= 0.010 \\
\sum_{i=1}^{N} x_{3i} y_i &= 0.437
\end{aligned}
\]

Next, using Cochran test, repeatability of experimental conditions was evaluated. Value of G coefficient and degree of freedom numbers were as follows:

\[
\begin{aligned}
b_0 &= \frac{1}{N} \sum_{i=1}^{N} x_{0i} y_i = 1.778 \\
b_1 &= \frac{1}{N} \sum_{i=1}^{N} x_{1i} y_i = 0.358 \\
b_2 &= \frac{1}{N} \sum_{i=1}^{N} x_{2i} y_i = 0.010 \\
b_3 &= \frac{1}{N} \sum_{i=1}^{N} x_{3i} y_i = 0.437
\end{aligned}
\]

\[
\begin{aligned}
f_1 &= N = 8 \\
f_2 &= r - 1 = 3 - 1 = 2
\end{aligned}
\]

On that basis the critical value of G coefficient was defined:

\[
G_{kr} = G_{(0.05,8,2)} = 0.5157
\]

\[
G < G_{kr}, \text{ so experiments were conducted with a satisfactory repeatability.}
\]

\[
G = \frac{S^2(y)_{\text{max}}}{\sum_{i=1}^{N} S^2(y_i)} = 0.242
\]

Next, a significance of regression coefficients was checked.
Because variance of measurement errors was:

\[ S^2(y) = \frac{1}{N} \sum_{i=1}^{N} S^2(y)_i = 0.1113, \]  
\[ (7) \]

and number of degree of freedom was:

\[ f = N (r - 1) = 8 (3 - 1) = 16 \]  
\[ (8) \]

then a critical value of \( t \) coefficient was:

\[ t_{kr} = t_{(0.05;16)} = 2.120 \]  
\[ (9) \]

and a critical value of coefficients of regression equation was:

\[ b_{kr} = t_{(a,f)} \sqrt{\frac{S^2(y)}{N_f}} = 0.1443 \]  
\[ (10) \]

On the basis of \( b_{kr} \) value a significance of coefficients of regression equation was verified:

\[
\begin{align*}
\hat{b}_0 > b_k : & \Rightarrow 1.778 > 0.1443 \Rightarrow \text{coefficient is significant} \\
\hat{b}_1 > b_k : & \Rightarrow 0.358 > 0.1443 \Rightarrow \text{coefficient is significant} \\
\hat{b}_2 < b_k : & \Rightarrow 0.010 < 0.1443 \Rightarrow \text{coefficient is insignificant} \\
\hat{b}_3 > b_k : & \Rightarrow 0.437 > 0.1443 \Rightarrow \text{coefficient is significant}
\end{align*}
\]  
\[ (11) \]

Encoded regression equation assumes a form as follows:

\[ y = b_0 + b_1 x_1 + b_3 x_3 \]  
\[ (12) \]

\[ y = 1.853 + 0.450 x_1 + 0.437 x_3 \]  
\[ (13) \]

Next, an adequacy of regression was evaluated. Using formula (13) the following was obtained:

\[ \begin{align*}
\hat{y}_1 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_2 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_3 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_4 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_5 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_6 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_7 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583 \\
\hat{y}_8 &= b_0 + b_1 x_1 + b_3 x_3 = 1.778 + 0.358 + 0.437 = 2.583
\end{align*} \]  
\[ (14) \]

Than an adequacy variance equaled:

\[ S_{ad}^2(y) = \frac{1}{N} \sum_{i=1}^{N} \left( \bar{y}_i - \hat{y}_i \right)^2 = 0.3332 \]  
\[ (15) \]

where:

\[ k \]  
- number of components of regression equation after rejecting free components; 
\[ k = 2. \]
TABLE 3.
ANALYSIS PLAN IN THE SHAININ METHOD WITH SYSTEMATIC VARIATION OF FACTORS IN ROLLER BURNISHING PROCESS

<table>
<thead>
<tr>
<th>Parameter’s code</th>
<th>Description of a parameter</th>
<th>Theoretically unfavorable level (-)</th>
<th>Theoretically favorable level (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>Force of roller pressure – P [kg]</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>X₂</td>
<td>Rate of feed – f [rpm]</td>
<td>0.048</td>
<td>0.22</td>
</tr>
<tr>
<td>X₃</td>
<td>Spindle rotation speed – n [rpm]</td>
<td>25</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

TABLE 4.
RESULTS OF THE EXPERIMENTS

<table>
<thead>
<tr>
<th>Number of experiments (test)</th>
<th>Combination of parameters</th>
<th>Roughness of samples after treatment R₈ [μm]</th>
<th>Average roughness after treatment R₈ [μm]</th>
<th>Conclusions/Notices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X₁ X₂ X₃</td>
<td>1.84</td>
<td>1.78</td>
<td>Roughness for unfavorable factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X₁ X₂ X₃</td>
<td>0.28</td>
<td>0.23</td>
<td>Roughness for favorable factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>X₁ X₂ X₃</td>
<td>0.14</td>
<td>0.16</td>
<td>Significant roughness improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>X₁ X₂ X₃</td>
<td>0.30</td>
<td>0.31</td>
<td>Significant roughness improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>X₁ X₂ X₃</td>
<td>1.14</td>
<td>1.25</td>
<td>Roughness improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>X₁ X₂ X₃</td>
<td>0.28</td>
<td>0.32</td>
<td>Roughness improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>X₁ X₂ X₃</td>
<td>1.56</td>
<td>1.66</td>
<td>Significant roughness deterioration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>X₁ X₂ X₃</td>
<td>0.86</td>
<td>0.85</td>
<td>Significant roughness improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors elaboration.

FIGURE 2.
ILLUSTRATION OF THE RESULTS OF ROLLER BURNISHING PARAMETERS SIGNIFICANCE EVALUATION WITH THE SHAININ METHOD

Source: Authors elaboration.
On the basis of the presented results the following conclusions can be drawn:

- the strongest influence on surface roughness have factors: \(X_1\) (force of roller pressure) and \(X_3\) (spindle rotation speed),
- \(X_2\) (rate of feed) has also influence on roughness, but the influence is weaker than other parameters.

General conclusions concerning significance of certain input parameters are identical with the \(2^3\) two-level, full factorial design.

CONCLUSIONS

After the comparison of the \(2^3\) two-level, full factorial design and the Shainin method, it can be stated that each of them offers a possibility to evaluate a significance of roller burnishing process parameters. The Shainin method is less labour-intensive and time-consuming. Unfortunately results obtained with this method are not so precise as in the \(2^3\) full factorial design, where a mathematic formula and calculating procedure is based on statistics. The Shainin method is based on selective variation of process parameters and doesn't reject the parameters directly, but gives indications which parameters are less significant. In the analyzed case both methods indicate less significance of speed of feed in the established range of variability.

Choice of a method for significance evaluation and parameters choosing depends on the established assumptions and needs of a person who conducts an experiment.

Recommended further studies include:
- comparison of the full factorial design with other methods, which allow to evaluate a significance of process parameters (Taguchi method, Greaco-Latin square, Hyper-Graeco-Latin square),
- searching for fields of efficient applications for each of the mentioned methods on the example of specific manufacturing processes.

REFERENCES


