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Comparison between mathematical models for roughness obtained in test machine and in industrial machine in semifinish honing processes

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Abstract

In the present work second order mathematical models for semifinish honing are presented for average roughness Ra as a function of abrasive stone characteristics and honing parameters. Several tests were performed in both a test machine and in an industrial machine. Results from both machines were compared. Although roughness depends on the five variables studied (grain size, density, pressure, linear speed and tangential speed) in both cases, most important factors are grain size and pressure. It is possible to use the model for the test machine in the industrial machine, in a way that only a few tests will be performed in the industrial machine in order to translate the model.

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Keywords: honing; semifinish; roughness; design of experiments; mathematical models

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1. Introduction

Many variables influence surface roughness in honing processes, for example type of bond, type of abrasive, grain size of abrasive, pressure of the honing head, speed of the honing head, etc. [1]. Several authors have obtained mathematical models for roughness in honing processes. For example, Troglio et al. employed three-level design of experiments with grain size of abrasive, oil and workpiece material as factors and average roughness Ra and Rk-

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family parameters as responses [2]. Kanthababu et al. used three-level design of experiments with rotation speed, linear speed, pressure and honing time as variables, and different roughness parameters (Rk, Rpk, Rvk, Mr1, Mr2) as responses [3].

In a previous paper, mathematical models were presented for both average roughness Ra and material removal rate Qm in the rough honing process [4]. Two-level design of experiments was employed. Main variables affecting roughness were grain size and density of abrasive while main variables influencing material removal rate were grain size of abrasive and pressure of honing stones on the workpieces' surface.

In honing processes, it is usual to perform successive operations, each time with finer grain in order to achieve a smooth surface. Moreover, some vertical machines provided with three honing heads allow three honing operations in the same cylinder [5]. Since behavior of the honing process is different depending on grain size, in the present work research was divided into three types of experiments, related to rough honing, semifinish honing and finish honing respectively. In the present paper, second order statistical models were obtained from surface response design of experiments for surface roughness in semifinish processes. Tests were performed both in a test and in an industrial machine, and results from both machines were compared. Five variables were considered: grain size of abrasive (Gs), density of abrasive (De), linear speed (Vl), tangential speed (Vt) and pressure of the honing stones on the workpieces' surface (Pr).

2. Materials and methods

Cubic boron nitride (CBN) stones were chosen with metallic bond. Both a horizontal test machine (Fig. 1) and an industrial vertical machine (Fig. 2) were used in honing experiments.

Fig. 1. Horizontal test machine.

Fig. 2. Vertical industrial machine.

Steel St-52 cylinders of 80 mm interior diameter were honed. Length of cylinders was 100 mm in the test machine and 390 mm in the industrial machine.

Roughness was measured by means of a Hommel W5 roughness meter. A special tooling was built that allowed measuring 9 points along a diametral circumference in the interior surface of cylinders (Fig. 3), according to a previously defined methodology [6]. Roughness was measured 50 mm away from the cylinder's end in the test machine and 190 mm away from the cylinder's end in the industrial machine.

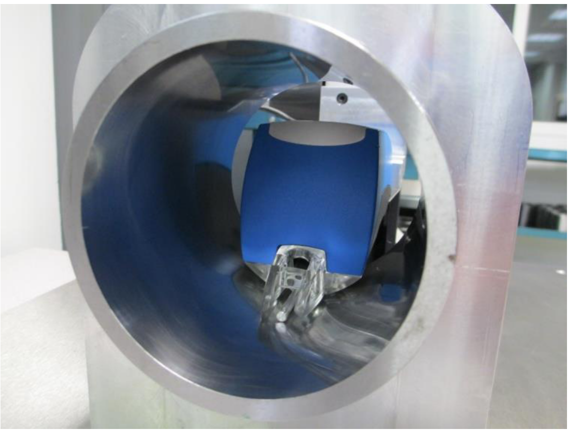


Fig. 3. Roughness meter and tooling used for measuring roughness.

Experiments were conducted following a central composite design, thus allowing the estimation of linear and quadratic effects (both interactions and pure quadratic terms) [7]. Specifically, a 2^{5-1} was used as factorial design for the five studied factors. Axial points were located on the faces of the cube. A set of 6 center points was also included. Each run was replicated, thus having a total of 64 runs. Table 1 shows low and high level for each of the factors. It should be noticed that selected levels are not exactly the same for the test machine and the industrial machine, as they had to be adapted to be able to hone all cylinders in both machines.

Table 1. Ranges of variables employed

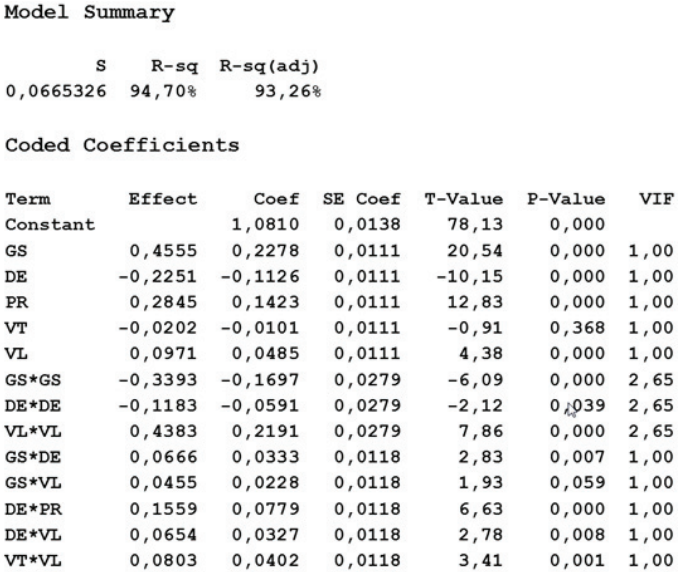
Variable	Test machine	Industrial machine
Gs (FEPA 61)[8]	46-76	46-76
De (ISO 6104)[9]	15-45	15-45
Pr (N/cm^2)	400-700	400-700
Vt (m/min)	30-50	15-35
Vl (m/min)	20-40	15-25

3. Results

Data were analyzed with Minitab 17 statistical software [10]. The best possible model using Ra as response for both the test machine and the industrial machine was computed using a least squares regression procedure. The model for the test machine is:

$$Ra = 0{,}481 + 0{,}0982\,Gs - 0{,}02636\,De - 0{,}000091\,Pr - 0{,}01305\,Vt - 0{,}1585\,Vl - 0{,}000754\,Gs^2 - 0{,}000263\,De^2 + 0{,}002191\,Vl^2 + 0{,}000148\,Gs \cdot De + 0{,}000152\,Gs \cdot Vl + 0{,}000035\,De \cdot Pr + 0{,}000218\,De \cdot Vl + 0{,}000402\,Vt \cdot Vl$$

Fig. 4 shows the Minitab output for this model, with p-values for assessing coefficient significance and the standard deviation of residuals (S) and coefficient of determination (R^2).



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Model Summary

        S    R-sq  R-sq(adj)
0,0665326  94,70%     93,26%

Coded Coefficients

Term        Effect     Coef  SE Coef  T-Value  P-Value   VIF
Constant             1,0810   0,0138    78,13    0,000
GS          0,4555   0,2278   0,0111    20,54    0,000  1,00
DE         -0,2251  -0,1126   0,0111   -10,15    0,000  1,00
PR          0,2845   0,1423   0,0111    12,83    0,000  1,00
VT         -0,0202  -0,0101   0,0111    -0,91    0,368  1,00
VL          0,0971   0,0485   0,0111     4,38    0,000  1,00
GS*GS      -0,3393  -0,1697   0,0279    -6,09    0,000  2,65
DE*DE      -0,1183  -0,0591   0,0279    -2,12    0,039  2,65
VL*VL       0,4383   0,2191   0,0279     7,86    0,000  2,65
GS*DE       0,0666   0,0333   0,0118     2,83    0,007  1,00
GS*VL       0,0455   0,0228   0,0118     1,93    0,059  1,00
DE*PR       0,1559   0,0779   0,0118     6,63    0,000  1,00
DE*VL       0,0654   0,0327   0,0118     2,78    0,008  1,00
VT*VL       0,0803   0,0402   0,0118     3,41    0,001  1,00
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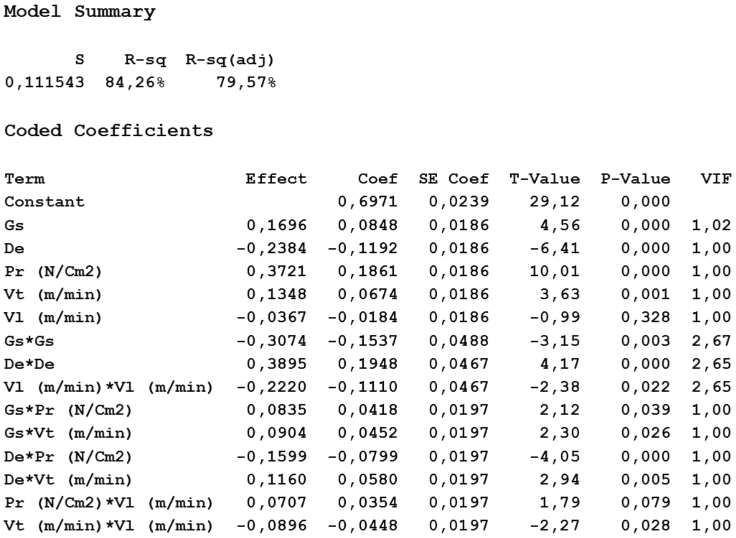
Fig. 4. Minitab output showing significant effects for Ra in the test machine

The model for the industrial machine is:

$$Ra = -2{,}869 + 0{,}0712\,Gs - 0{,}0500\,De + 0{,}000231\,Pr - 0{,}0053\,Vt + 0{,}1704\,Vl - 0{,}000683\,Gs^2 + 0{,}000866\,De^2 - 0{,}00444\,Vl^2 + 0{,}000019\,Gs\cdot Pr + 0{,}000301\,Gs\cdot Vt - 0{,}000036\,De\cdot Pr + 0{,}000387\,De\cdot Vt + 0{,}000047\,Pr\cdot Vl - 0{,}000896\,Vt\cdot Vl$$

Fig. 5 shows the Minitab output for the industrial machine model.



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Model Summary

       S    R-sq  R-sq(adj)
0,111543  84,26%     79,57%

Coded Coefficients

Term                      Effect     Coef  SE Coef  T-Value  P-Value   VIF
Constant                           0,6971   0,0239    29,12    0,000
Gs                        0,1696   0,0848   0,0186     4,56    0,000  1,02
De                       -0,2384  -0,1192   0,0186    -6,41    0,000  1,00
Pr (N/Cm2)                0,3721   0,1861   0,0186    10,01    0,000  1,00
Vt (m/min)                0,1348   0,0674   0,0186     3,63    0,001  1,00
Vl (m/min)               -0,0367  -0,0184   0,0186    -0,99    0,328  1,00
Gs*Gs                    -0,3074  -0,1537   0,0488    -3,15    0,003  2,67
De*De                     0,3895   0,1948   0,0467     4,17    0,000  2,65
Vl (m/min)*Vl (m/min)    -0,2220  -0,1110   0,0467    -2,38    0,022  2,65
Gs*Pr (N/Cm2)             0,0835   0,0418   0,0197     2,12    0,039  1,00
Gs*Vt (m/min)             0,0904   0,0452   0,0197     2,30    0,026  1,00
De*Pr (N/Cm2)            -0,1599  -0,0799   0,0197    -4,05    0,000  1,00
De*Vt (m/min)             0,1160   0,0580   0,0197     2,94    0,005  1,00
Pr (N/Cm2)*Vl (m/min)     0,0707   0,0354   0,0197     1,79    0,079  1,00
Vt (m/min)*Vl (m/min)    -0,0896  -0,0448   0,0197    -2,27    0,028  1,00
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Fig. 5. Minitab output showing significant effects for Ra in the industrial machine

Both models were validated based on an analysis of residuals, which show no dependence, no heteroscedasticity and no departure from normality. The lack of fit tests based on the pure error give high p-values (above 10%), showing that the models accurately fit the collected data.

All five variables (Gs, De, Pr, Vt and Vl) appear in each of the models, so all factors affect the response Ra, to some extent, in both the test and industrial machines. A relative importance index has been computed for each of the factors in the model [11]. The relative importance index (RII) for factor x_i is computed using the expression in Equation 1:

$$RII = \left(R^2_{y(x_1,\ldots,x_p)} - R^2_{y(x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_p)} \middle/ R^2_{y(x_1,\ldots,x_p)} \right) \cdot 100 \qquad (1)$$

Where $R^2_{y(x_1,\ldots,x_p)}$ is the coefficient of determination of the full model and $R^2_{y(x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_p)}$ is the coefficient of determination of the model where all terms having x_i have been removed. This difference, divided by a normalizing factor and expressed as a percentage, shows the relative importance of factor x_i. Once the RII for each of the factors is computed, results are rescaled so that the total sum is 100%.

Fig. 6 summarizes the relative importance of all five factors (Gs, De, Pr, Vt and Vl) for both the test machine and the industrial machine. Grain size of abrasive (Gs), pressure of the honing stones on the workpieces' surface (Pr) and density of abrasive (De) are the most important factors, followed by a great distance by the speeds (Vl and Vt). The relative importance is swapped for Gs and Pr in both machines: Gs is the most important in the test machine, whereas Pr is the most important in the industrial machine.

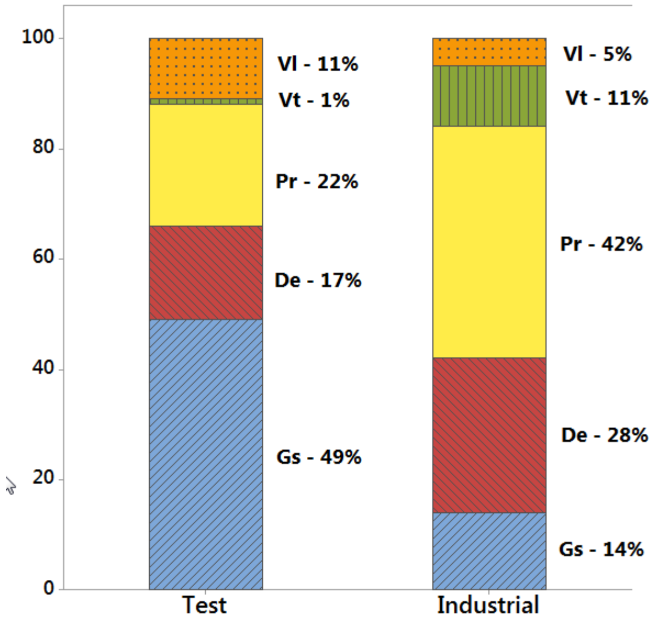

Fig. 6. Relative importance of factors for the test and the industrial machines

The surface response of Ra as graphically depicted from the models has been represented, placing the most important factors in the axes (Gs, Pr and De). Using Gs and Pr as independent variables, Fig. 7 shows the surface for the test machine, and Fig. 8 depicts the surface for the industrial machine. Using Pr and De as independent variables, Figs. 9 and 10 show the surface for the test and industrial machines, respectively. All factors not represented in the axes are kept at its middle value for this graphical representation.

The figures clearly show the curvilinear – second order – nature of surface response for Ra. They also confirm that both models are very similar. In the case of Gs and Pr (Figs. 7 and 8), both surfaces have a roof tile shape with the same orientation. In the case of Pr and De (Figs. 9 and 10), the surfaces are basically planes with a slight curvature.

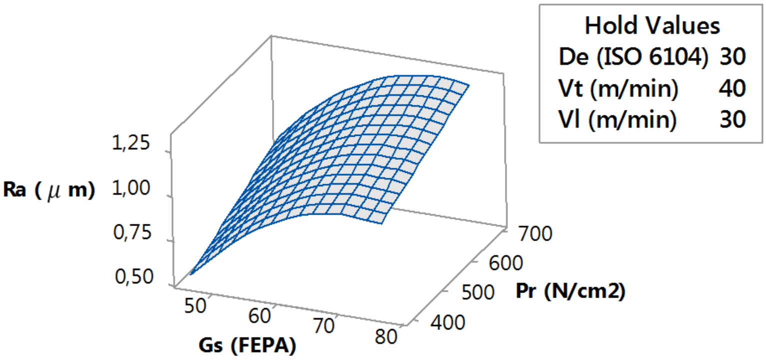

Fig. 7. Surface response for Ra for the test machine, placing Gs and Pr in the axes

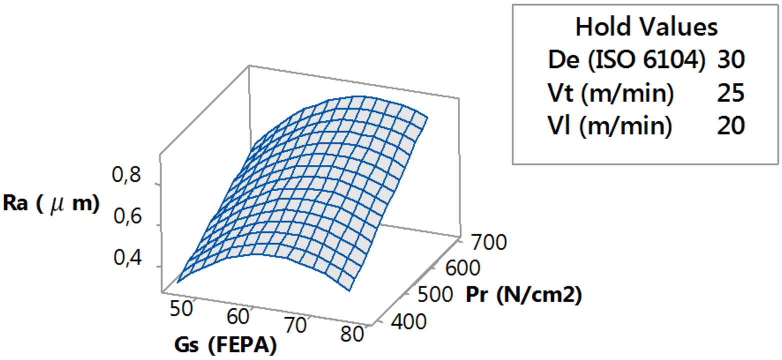

Fig. 8. Surface response for Ra for the industrial machine, placing Gs and Pr in the axes

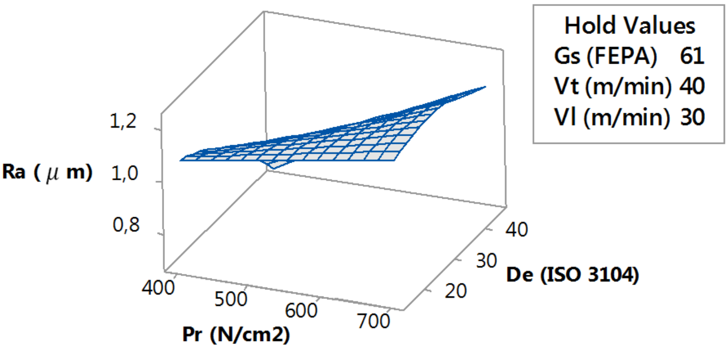

Fig. 9. Surface response for Ra for the test machine, placing Pr and De in the axes

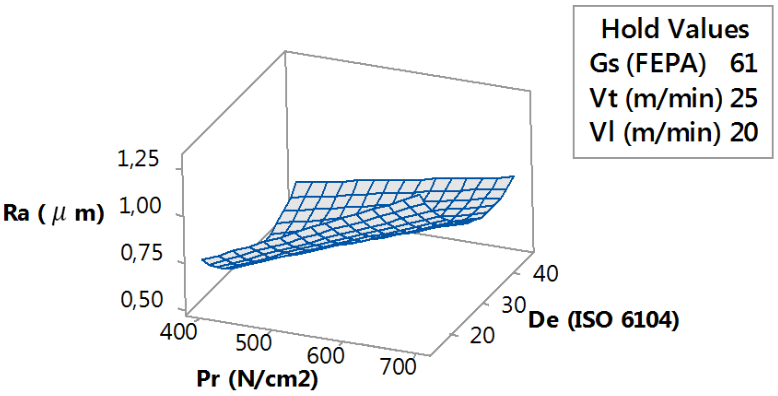

Fig.10. Surface response for Ra for the industrial machine, placing Pr and De in the axes

Based on the models found for the test and industrial machines, predictions of Ra have been computed in those areas of experimentation that are common for both machines. Fig. 11 shows a comparison of expected Ra for each combination of factors (Gs, De, Pr, Vt and Vl). It should be noticed that the profile of the curves is very similar, and that the difference between both machines is basically a translation. This translation is more accused in some areas than in others. In those areas where De is low and Pr is high, or where De is high and Pr is low, the curves are much closer: this fact is coherent with the presence of interaction De·Pr in both models. When Gs is low the curves are closer than when is high, becoming then almost coincident.

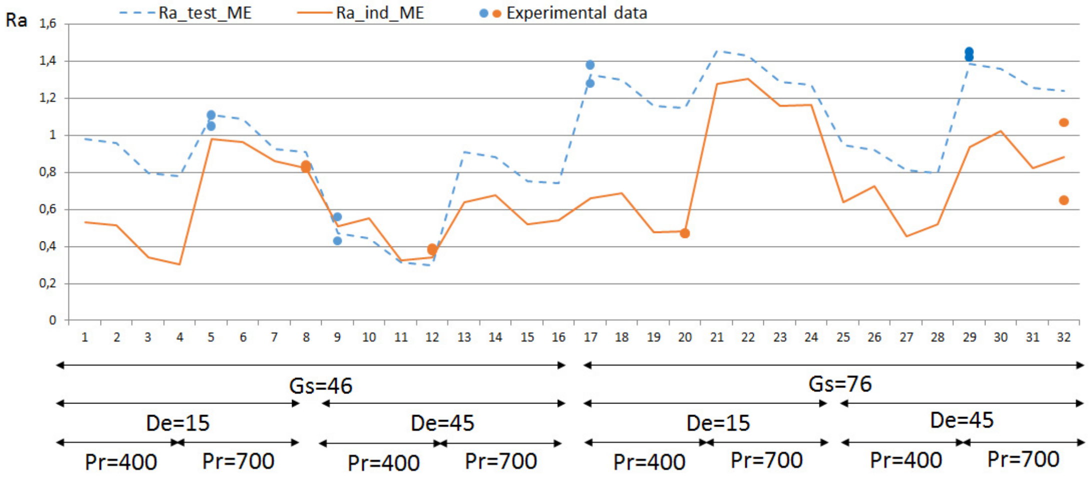

Fig. 11. Comparison of predictions for Ra in the test machine (Ra_test) and in the industrial machine (Ra_ind)

Similarities in the models for the test and the industrial machines, as highlighted in Figs. 7 to 11, make possible the use of the model for the test machine in the industrial machine, taking into account that a few tests should be done in order to discover the translation constant for each area. As possibilities of experimentation in a production context can be scarce, this option can be useful from a practical point of view.

4. Conclusions

Main conclusions of the present work are:

- In semifinish honing processes performed in a test machine, main factors influencing roughness were grain size and pressure, while in an industrial machine main factors were pressure and density of abrasive stones.
- Similar trends in roughness values were obtained in the test machine and in the industrial machine. However, at low pressure and low density, as well as at high pressure and high density, roughness obtained in the industrial machine was lower than that of the test machine.
- It was possible to obtain the mathematical model of the industrial machine from the mathematical model of the test machine by means of translation of roughness values. Only few tests will be necessary in the industrial machine to find the translation constants in different areas of the model.

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