International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.11 No.10, pp 321-332, 2018

Approximation of An Experimental Model Obtained in A Testing Machine for use in an Industrial Production Machine.

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Abstract : Design of experiments (DOE) is a powerful tool that allows performing the modeling and analysis of the influence of factors of the process on the specified variables, which are often called response variables. Being a systematic procedure to analyze the effect of the response variables, and the controllable factors that are modified during the execution of the experiment.Within the different strategies of the design of experiments, the factorial design is one of the most widely used. The problem with factorial designs is a large number of experiments that may be necessary.It is not convenient to perform the tests of experimental designs in an industrial machine, because it is more difficult to control and measure the variables accurately and in an agile way. Moreover, if an industrial machine has to be used, it is not feasible to perform a large number of trials, because it would be necessary to interrupt production.Therefore it was decided to conduct an investigation in which experimental models were obtained in a testing machine that was specially developed for that purpose. Later, data were collected from an industrial machine that performed the same process, and with the same machining conditions. The problem to be solved is to what extent the models obtained in the testing machine can be adjusted or not to predict the process in industrial machines.A study was done by means of regression analysis of the correlation between the valuesobtained in the test machine and those obtained in the industrial machine. It was observed that the trends of roughness parameters given by the models obtained in the testing machine are similar to those obtained in the industrial process. For this reason it is feasible to adapt the models obtained in the testing machine for the industrial machine.

Keywords : Honing, design of experiments, surface roughness, material removal rate, regression analisys.

1. Introduction

Abrasive machining processes are, among the traditional types of machining processes, one of the most

Milton F. Coba Salcedo *et al* /International Journal of ChemTech Research, 2018,11(10): 321-332.

DOI= http://dx.doi.org/10.20902/IJCTR.2018.111040

complexes to model. This is due to the randomness that introduces in its analysis the effect of having different cutting points, on the work surface, points with different sizes, shapes, orientations, etc,[1]. Due to the complexity of developing an analytical model based on the mechanics of the honing process, which also takes into account the critical parameters of the process, it is necessary to obtain models empirically from the design of experiments[2,3].

The technique of designing experiments is a powerful work tool that allows the modeling and analysis of the influence of certain process factors on the specified variables, which are often referred to as response variables. As it is a systematic procedure, it allows the analysis of the effect on the response variables of the controllable factors that are modified during the execution of the experiment[4].

The design of experiments is divided into three stages: definition of the experiment, design, and analysis. Within the design of experiments, there are several strategies of experimentation, being the factorial design the most widely used. The factorial design consists of carrying out the experimentation crossing the levels of the different factors with all the possible combinations, which allows comparing the different observations of the response variable in a statistically homogeneous way. The factorial design also makes it possible to quantify the value of the interaction between the different factors[5].

The problem with factorial designs is the high number of experiments that may be necessary. To study k factors, each with p levels, pk tests would be needed. This problem is solved in two different ways; one is by using a fractionated factorial design, which reduces the number of experiments, or by using only two levels of experimentation, which is the strategy used in this research. This type of experiment is known as factorial design 2k, in which the interrelationship of the different factors is studied and quantified using two levels of experimentation for each of the factors, which allows the number of experiments to be carried out to be reduced[4,5].

It is not convenient to perform experimental design tests on an industrial machine, as it is more difficult to control and measure the variables in a precise. On the other hand, if an industrial production machine has to be used, it is not feasible to carry out a large number of tests, as it would be necessary to interrupt production. It was therefore decided to carry out all the tests on the honing machine. The problem to be solved is to what extent the models obtained in the testing machine can be adjusted or not to predict the process in industrial machines.

Production data from an industrial honing machine and samples of the corresponding machined cylinders have been collected to measure their roughness. The values of the process factors, tool and machine characteristics used in each case are available. A range of values has been chosen for the process in the industrial machine, similar to that used to obtain the models in the testing machine.

With the models obtained in the honing testing machine and the values of the process factors or variables (Abrasive stone, Density of the abrasive grain, Tangencial Speed, Axial speed, Pressure) used for machining in the industrial machine, the values of the roughness and material removal rate are calculated and then compared with the values obtained and measured for the same conditions in the machining in the industrial machine.

A study is made by means of regression analysis of the correlation between the values obtained with the models and those obtained in the industrial machine, and it is observed that the tendencies of the roughness values given by the models obtained in the testing machine are similar to the tendencies of the experimental values obtained in the industrial process and that it is feasible to adapt the models obtained in the testing machine for the industrial machine.

Therefore, based on the results of the correlation study of each model, the corresponding adaptation of the model of the testing machine is carried out to obtain an adapted model valid for its application in the industrial machine.

2. Materials and Methods

2.1. Input parameters of the experiment design

From the literature review on the state of the art of the honing process[6-8], and in collaboration with experts in the machining of the inner wall of hydraulic cylinders, and with manufacturers of industrial honing machines, the most important parameters or process factors in the honing operation were established: Abrasive type, abrasive density, abrasive grain size, linear speed, tangential speed, honing angle which is a function of speeds, working pressure, workpiece material and lubricant.

In principle, with the help of the experts in the process, parameters have been estimated that will remain fixed during the experiment. We have worked with only one material for the part, the most common steel used in the manufacture of cylinders, St-52 steel, and the type of material has been kept as a variable of fixed influence. Likewise, since the most widely used type of abrasive is CBN[8,9], it has been determined that this variable would also be adjusted. The coolant used has also remained fixed. The honing angle, which is a relationship between linear velocity and tangential velocity, is considered implicit in the above variables as described in[10,11].

Among the response variables are those related to the surface quality of the part and those related to the productivity of the process. The first group contains the basic roughness parameters. Table 1 shows the roughness parameters considered and which are extensively described in international standards[12-14].

Table 1. Surface Roughness Parameters.

Roughness Parameters	Roughness *Ra*, µm Roughness *Rt*, µm Roughness *Rq*, µm

Table 2. Productivity parameters process

Material remove rate	*Qm*, cm/min

The parameter or variable used to evaluate the productivity of the machining process is the rate of material removed, which corresponds to the volume of material removed per unit time and per unit of abrasive stone surface area, Qm = cm3/(cm2xmin) = cm/min[15]. Table 2.

The testing machine has all the necessary sensors to accurately measure and display the variables and factors involved in the honing process. It has a PLC for its control and automation system and a SCADA control system that allows visualizing the functions of interest in an agile way. Figure 1.

Figure 1. Honing test machine.

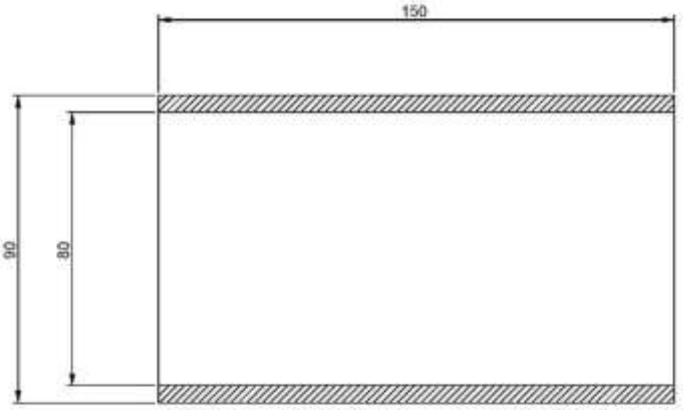

Figure 2. Honing test cilynder.

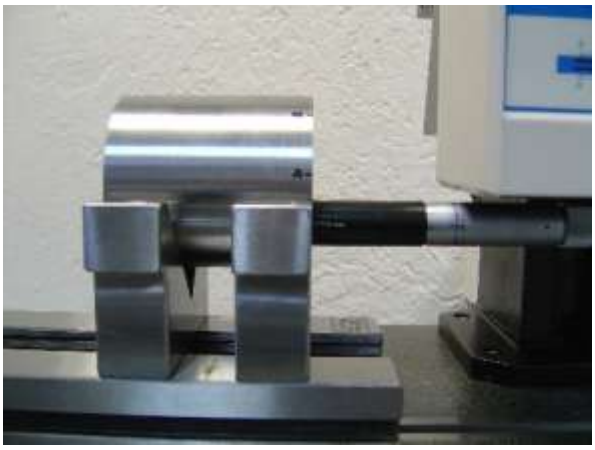

Figure 3. Measure roughness.

It can be seen in Figure 2 that the dimensions of the specimen used in the experiments, in the testing machine.

The specimen is 80 millimetres inside diameter and 150 millimetres long.

Figure 3 shows the process of measuring the roughness inside a specimen.

2.2. Experimental Analysis

In this experiment, a two-level 25 factorial design has been used. For the analysis of the results, the significance test level is set to 0.05 (p-value), and any response above this value is considered to be of little significance for the current analysis. In addition, the importance of each main and cross factor and the estimation of the p coefficients for the elimination of non-significant effects has been taken into account, with the aim of proposing a reduced model. The coefficients for the reduced model, the ANOVA variance analysis table and the corresponding adjustment coefficient have been determined. This estimates the quality of the regression performed for the reduced model.

As for the graphical tools for the analysis, the Pareto diagram has been taken into account for the standardized effects. Curvature analysis is also done in the ANOVA variance analysis. A response surface analysis is performed to study the effect of nonlinear interactions on the models. The model is proposed, both for the factorial analysis, linear model, and for the response surface, second-order model, and the selected models are validated.

The factors that have been defined above (velocities, pressure, abrasive grain, etc.) are expected to be statistically significant in factor analysis, as they are the fundamental process factors in honing machining. The number of factors considered in the factorial design is 5. In Table 3, can see the work intervals of each of the factors.

Table 3. Machining parameters.

	-1	**0**	**1**
Abrasive stone *(Gst) (FEPA)*	46	91	181
Density abrasive stone *(D) (FEPA)*	30	50	75
Axial speed *(m/min.) (VL)*	16	24	32
Tangencial speed *(m/min) (VT)*	25,15	37,70	50,25
Pressure *(N/cm^2) (P)*	300	450	600

The intermediate point is used to study the behavior of the relationship, whether it is linear, quadratic, etc. If a full 2k factorial design is performed for five factors at least 32 experiments are required. If replications are to be made, the number of experiments will increase by a multiple of 32. In this experimental design, central points and points centered on the faces, axial or star, have also been used to study the non-linear effects of interactions, known as curvature.

2.3. Equations proposed for process modeling in the testing machine

Once the models have been analyzed, it has been determined that the quadratic models obtained from the response surface analysis of the experimental designs in the honing machine are the ones that have shown the best behavior to predict the values of the response variables, surface roughness and material removal rate, in the honing. Table 4.

For the response surface analysis, the adjusted coefficient of determination is indicated by R2(adj).

Table 4. Models proposed for modeling by response surface analysis.

Experimental Models	**R^2 (adj)**
Arithmetic mean deviation of the assessed profile $Ra = -4,02476 + 0,01277717*Gst + 0,0666409*D + 0,10822*VT + 0,00182761*P - 0,000504091*D^2 - 0,00140027*VT^2 - 0,0000781722*Gst*D - 0,00008747*Gst*VT + 0,0000116715*Gst*P - 0,0000248841*D*P$	91,54 %
Total height of the profile $Rt = -37,6997 + 0,106556*Gst - 0,00602182*D + 1,405953*VT + 0,065211*P - 0,019388*VT^2 - 0,0000762325*P^2 - 0,000659129*Gst*D - 0,00070063*Gst*VT + 0,0000712811*Gst*P + 0,00022512*VT*P$	93,33 %
Root mean square deviation of the assessed profile $Rq = -9,046564 + 0,00911113*Gst + 0,0932068*D + 0,25222695*VT + 0,0131101*P + 0,0000267326*Gst^2 - 0,000771453*D^2 - 0,00325184*VT^2 - 0,00001312*P^2 - 0,00012929*Gst*D - 0,00013367*Gst*VT + 0,0000208751*Gst*P - 0,0000238163*D*P$	94,23 %
Material remove rate $Qm = 0,0440808 + 0,00257505*Gst - 0,000354681*D - 0,0305642*VT + 0,00190542*P - 0,0000086558*Gst^2 + 0,000350721*VT^2 - 0,0000024055*P^2 + 0,00000087432*Gst*P + 0,0000117108*VT*P$	83,97 %

3. Adjustment of The Experimental Models of the Testing Machine to an Industrial Honing Machine

For the process of adapting the models of the testing machine, tests were carried out on an industrial honing machine. Eighteen tubes were machined with honing, with six different conditions, i.e., three replicas for each condition. The ranges of the process parameters or factors used (Gst, D, VT, VL, P) were defined within the similar range for which the models were defined in the testing machine. The material of the tubes is St-52 steel; the length is 607 mm. The abrasive stones used were CBN, the tubes were machined with three different types of abrasive grit size, the grit density in the binder is 50 (FEPA standard)[16].

In Table 5, the general test conditions and the working ranges chosen for the tests on the industrial production machine can be seen.

Table 5. Process parameter values for the industrial honing machine.

Experiment	**Gst (FEPA)**	**P (N/cm^2)**	**D (FEPA)**	**VT (m/min)**	**VL (m/min)**
1.1.1	181	440	50	34	32
1.1.2	181	440	50	34	32
1.1.3	181	440	50	34	32
1.2.1	91	440	50	34	32
1.2.2	91	440	50	34	32
1.2.3	91	440	50	34	32
1.3.1	46	440	50	34	32
1.3.2	46	440	50	34	32
1.3.3	46	440	50	34	32
2.1.1	181	440	50	34	20
2.1.2	181	440	50	34	20
2.1.3	181	440	50	34	20
2.2.1	91	440	50	34	20
2.2.2	91	440	50	34	20
2.2.3	91	440	50	34	20
2.3.1	46	440	50	34	20
2.3.2	46	440	50	34	20
2.3.3	46	440	50	34	20

Table 6. Roughness values obtained with the models of the testing machine.

Exp.	**Ra (µm) Real**	**Rt (µm) Real**	**Rq (µm) Real**	**Qm (cm/min) Real**	**Ra(µm) Model**	**Rt (µm) Model**	**Rq (µm) Model**	**Qm (cm/min) Model**
1.1.1	1,727	15,446	2,235	0,134	2,382	19,378	3,401	0,193
1.1.2	1,949	15,456	2,500	0,163	2,382	19,378	3,401	0,193
1.1.3	1,855	15,910	2,394	0,154	2,382	19,378	3,401	0,193
1.2.1	0,809	8,011	1,063	0,112	1,390	12,075	2,091	0,138
1.2.2	0,740	7,783	0,979	0,105	1,390	12,075	2,091	0,138
1.2.3	0,840	8,540	1,096	0,084	1,390	12,075	2,091	0,138
1.3.1	0,364	3,977	0,491	0,035	0,893	8,424	1,598	0,058
1.3.2	0,342	3,824	0,454	0,039	0,893	8,424	1,598	0,058
1.3.3	0,355	3,485	0,468	0,037	0,893	8,424	1,598	0,058
2.1.1	1,778	16,844	2,306	0,149	2,382	19,378	3,401	0,193
2.1.2	1,735	15,034	2,211	0,154	2,382	19,378	3,401	0,193
2.1.3	1,701	15,257	2,148	0,149	2,382	19,378	3,401	0,193
2.2.1	0,773	6,879	0,992	0,109	1,390	12,075	2,091	0,138
2.2.2	0,748	6,808	0,968	0,108	1,390	12,075	2,091	0,138
2.2.3	0,798	7,926	1,018	0,097	1,390	12,075	2,091	0,138
2.3.1	0,456	5,335	0,615	0,038	0,893	8,424	1,598	0,058
2.3.2	0,439	5,120	0,567	0,034	0,893	8,424	1,598	0,058
2.3.3	0,429	4,661	0,570	0,040	0,893	8,424	1,598	0,058

The results of the tests on the industrial machine are shown, the measured roughness parameters and the material removal rate, as well as the values that have been predicted with the models of the testing machine, Table 6.

When comparing the values of the roughness parameter Ra obtained in the industrial machine with those obtained with the Ra model of the testing machine, it can be observed that there is a clear difference between the values of the output variables obtained in the industrial machine with respect to the values obtained with the experimental models of the testing machine. This difference is normal, as the models have been obtained with a different machine. In Figure 4, it is observed that although there is a difference between the values, the model conveniently predicts the behavior or trend of surface roughness in the industrial machine.

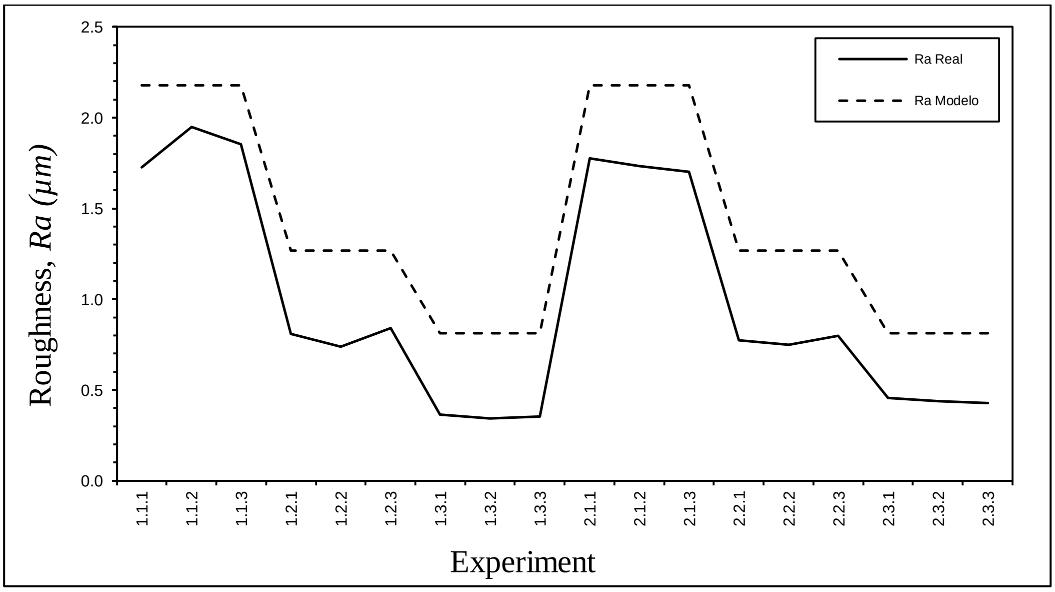

Figure 4. Comparison for the *Ra* parameter of the actual values obtained in the industrial machine vs. the values obtained by the model of the testing machine.

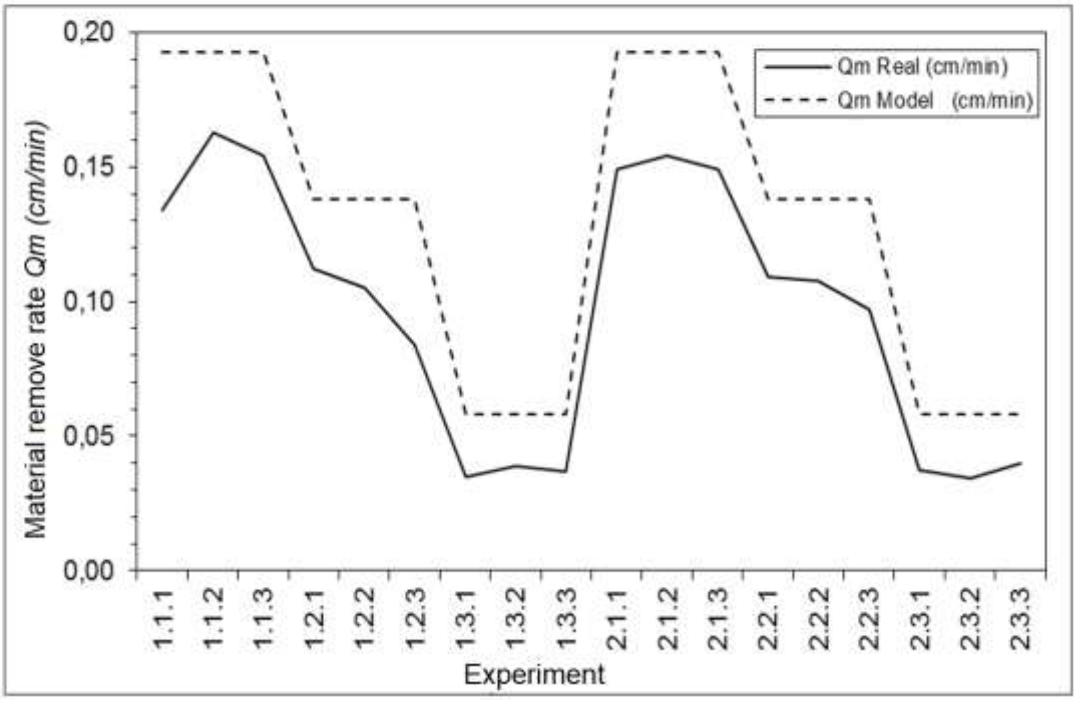

Figure 5. Comparison for the *Qm* parameter of the actual values obtained in the industrial machine vs. the values obtained by the model of the testing machine.

When comparing the values obtained for the parameter material removal rate Qm with the results obtained with the models of the testing machine, Figure 5, it is observed that the values obtained with the models of the testing machine are similar in their behavior or tendency to those obtained in the experimental tests on the industrial production machine.

3.1. Correlation analysis between the values of the industrial machine and those of the model of the testing machine

Regression analysis has been carried out to study the correlation between the values of the output variables for the different conditions of the industrial machine and the values obtained for the same conditions with the models obtained in the testing machine. Figures 6 and 7.

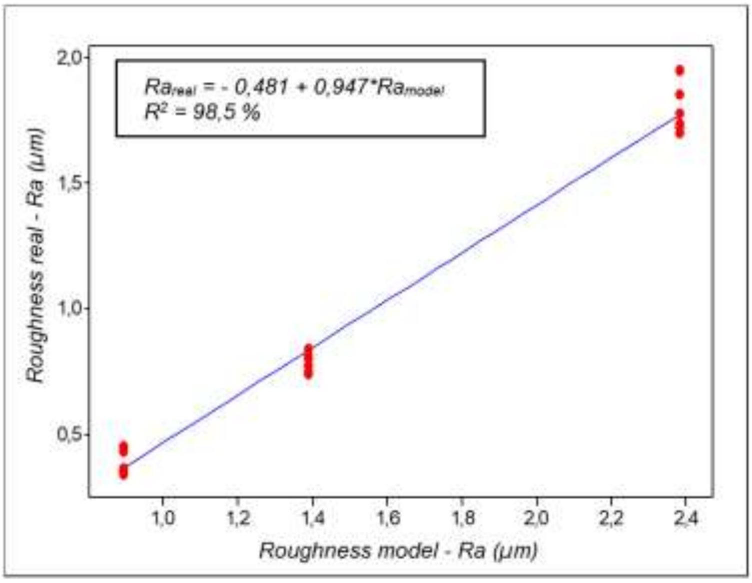

Figure 6. Correlation between the real roughness values *Ra* vs. the values obtained from the *Ra* model.

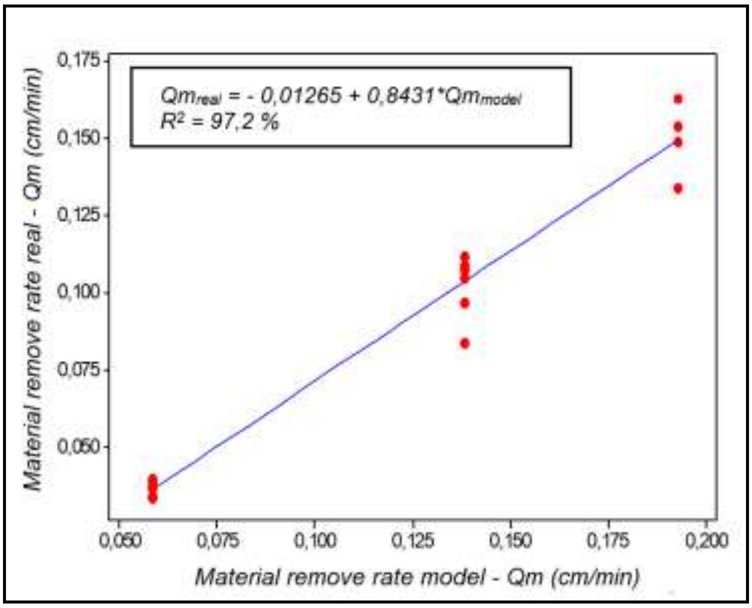

Figure 7. Correlation between the real values of *Qm* vs. the values obtained from the *Qm* model.

As can be seen in Figures 6 and 7, the values obtained with the model of the testing machine correlate very well with the roughness Ra values measured and the material removal rate Qm obtained with the industrial machine. The adjusted correlation coefficient is R2(adj) = 98,5 % and 97,2 % respectively. As can be seen, the correlation is good. This indicates that the adapted model would fit the data obtained in the industrial machine well.

In linear regression equations, Eq. 1, you have dependent variables and form-independent variables:

$$E[Y|X=x] = \beta1*x + \beta0 \qquad (1)$$

Where, $E[Y|X=x]$: Hope of the response variable Y when the predictor variable X is worth x:
X: Predictive variable
$\beta1$: Slope of the line
$\beta0$: Ordered at the origin

The expression $\beta1$ calculates the slope of the linear regression line. The expression $\beta0$ is the sample intercept, i.e. the value of Y when X is zero [3]. The final adapted models for the industrial production machine are shown in Table 8.

Table 8. Models adapted to the industrial honing machine.

Prediction models adapted to the industrial machine
Arithmetic mean deviation of the assessed profile $Ra = -0,481 + 0,947*(-4,02476 + 0,01277717*Gst + 0,0666409*D + 0,10822*VT + 0,00182761*P - 0,000504091*D^2 - 0,00140027*VT^2 - 0,0000781722*Gst*D - 0,00008747*Gst*VT + 0,0000116715*Gst*P - 0,0000248841*D*P)$
Total height of the profile $Rt = -4,55 + 1,037*(-37,6997 + 0,106556*Gst - 0,00602182*D + 1,405953*VT + 0,065211*P - 0,019388*VT^2 - 0,0000762325*P^2 - 0,000659129*Gst*D - 0,00070063*Gst*VT + 0,0000712811*Gst*P + 0,00022512*VT*P)$
Root mean square deviation of the assessed profile $Rq = -1,037 + 0,981*(-9,046564 + 0,00911113*Gst + 0,0932068*D + 0,25222695*VT + 0,0131101*P + 0,0000267326*Gst^2 - 0,000771453*D^2 - 0,00325184*VT^2 - 0,00001312*P^2 - 0,00012929*Gst*D - 0,00013367*Gst*VT + 0,0000208751*Gst*P - 0,0000238163*D*P)$
Material remove rate $Qm = -0,01265 + 0,8431*(0,0440808 + 0,00257505*Gst - 0,000354681*D - 0,0305642*VT + 0,00190542*P - 0,0000086558*Gst^2 + 0,000350721*VT^2 - 0,0000024055*P^2 + 0,00000087432*Gst*P + 0,0000117108*VT*P)$

Table 9. Roughness values vs. values obtained from the adapted models.

Exp.	**Gst (FEPA**	**P (N/cm^2**	**D (FEPA**	**VT (m/min**	**VL (m/min**	**Ra Real (µm)**	**Rt Real (µm)**	**Rq Real (µm)**	**Qm Rea (cm/min**	**Ra Model (µm)**	**Rt Model (µm)**	**Rq Model (µm)**	**Qm Model (cm/min**
1.1.1	181	440	50	34	32	1,727	15,446	2,235	0,134	1,775	15,603	2,297	0,150
1.1.2	181	440	50	34	32	1,949	15,456	2,500	0,163	1,775	15,603	2,297	0,150
1.1.3	181	440	50	34	32	1,855	15,910	2,394	0,154	1,775	15,603	2,297	0,150
1.2.1	91	440	50	34	32	0,809	8,011	1,063	0,112	0,835	8,008	1,011	0,104
1.2.2	91	440	50	34	32	0,740	7,783	0,979	0,105	0,835	8,008	1,011	0,104
1.2.3	91	440	50	34	32	0,840	8,540	1,096	0,084	0,835	8,008	1,011	0,104
1.3.1	46	440	50	34	32	0,364	3,977	0,491	0,035	0,365	4,211	0,528	0,037
1.3.2	46	440	50	34	32	0,342	3,824	0,454	0,039	0,365	4,211	0,528	0,037
1.3.3	46	440	50	34	32	0,355	3,485	0,468	0,037	0,365	4,211	0,528	0,037
2.1.1	181	440	50	34	20	1,778	16,844	2,306	0,149	1,775	15,603	2,297	0,150
2.1.2	181	440	50	34	20	1,735	15,034	2,211	0,154	1,775	15,603	2,297	0,150
2.1.3	181	440	50	34	20	1,701	15,257	2,148	0,149	1,775	15,603	2,297	0,150

2.2.1	91	440	50	34	20	0,773	6,879	0,992	0,109	0,835	8,008	1,011	0,104
2.2.2	91	440	50	34	20	0,748	6,808	0,968	0,108	0,835	8,008	1,011	0,104
2.2.3	91	440	50	34	20	0,798	7,926	1,018	0,097	0,835	8,008	1,011	0,104
2.3.1	46	440	50	34	20	0,456	5,335	0,615	0,038	0,365	4,211	0,528	0,037
2.3.2	46	440	50	34	20	0,439	5,120	0,567	0,034	0,365	4,211	0,528	0,037
2.3.3	46	440	50	34	20	0,429	4,661	0,570	0,040	0,365	4,211	0,528	0,037

The real Ra roughness values and those obtained with the adapted models are shown in Table 9, and the real Qm roughness values and those obtained with the adapted model.

3.2. Analysis of the adapted models

For Ra, and Qm, the values obtained in the industrial machine and the corresponding values obtained with the adapted models are compared, Figures 8 and 9.

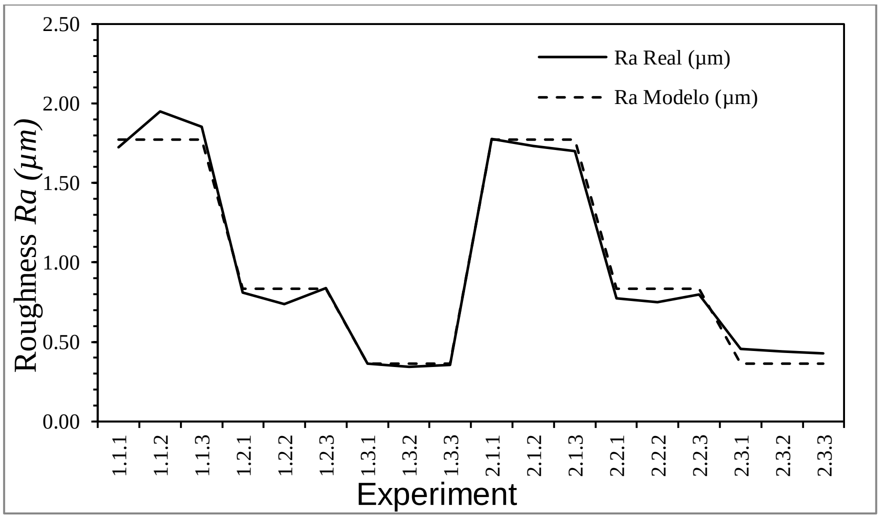

Figure 8. Comparison for *Ra* of the values obtained in the industrial machine vs. the values obtained using the adapted model.

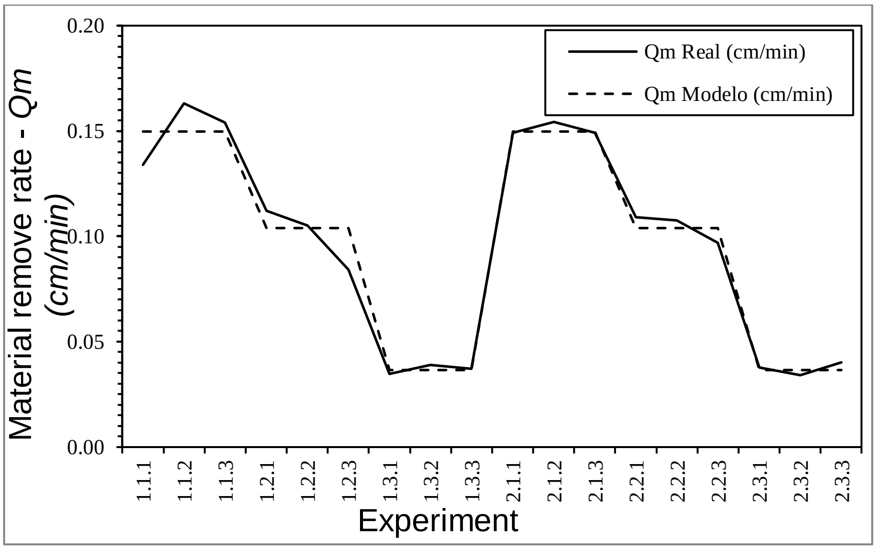

Figure 9. Comparison for *Qm* of the values obtained in the industrial machine vs. the values obtained by the adapted model

The results obtained with the adapted models are similar to those obtained with the industrial machine. Table 10 shows the relative error Eq. 2, between the values obtained with the industrial machine and those obtained with the different non-adapted and adapted models. It is observed that the difference between the values is considerably high. When the values obtained with the industrial machine are compared with the values obtained with the adapted models, there is a significant decrease in the relative error.

$$Relativeerror = \frac{Real - Teorico}{Real} x100 \qquad (2)$$

Table 10. Analysis of the values obtained with the model adapted to the industrial machine.

						Experimental roughness values testing machine *vs* Roughness values obtained with the model of the testing machine				**Experimental roughness obtained in the industrial machine *vs* Roughness values obtained with the model adaptation**			
Exp.	**Gst (FEPA)**	**P (N/cm2**	**D (FEPA)**	**VT (m/min)**	**VL (m/min)**	**(%) Err. Rel. Ra**	**(%) Err. Rel. Rt**	**(%) Err. Rel. Rq**	**(%) Err. Rel. Qm**	**(%) Err. Rel. Ra**	**(%) Err. Rel. Rt**	**(%) Err. Rel. Rq**	**(%) Err. Rel. Qm**
1.1.1	181	440	50	34	32	29,54	24,21	43,44	28,96	5,34	1,30	4,99	7,57
1.1.2	181	440	50	34	32								
1.1.3	181	440	50	34	32								
1.2.1	91	440	50	34	32	75,02	49,09	100,35	39,77	5,56	3,05	5,31	10,68
1.2.2	91	440	50	34	32								
1.2.3	91	440	50	34	32								
1.3.1	46	440	50	34	32	152,59	124,61	239,73	58,50	3,18	12,27	12,20	4,39
1.3.2	46	440	50	34	32								
1.3.3	46	440	50	34	32								
2.1.1	181	440	50	34	20	37,15	23,65	53,24	27,82	2,28	4,47	3,73	1,30
2.1.2	181	440	50	34	20								
2.1.3	181	440	50	34	20								
2.2.1	91	440	50	34	20	79,93	68,42	110,68	32,49	8,11	11,69	2,36	5,11
2.2.2	91	440	50	34	20								
2.2.3	91	440	50	34	20								
2.3.1	46	440	50	34	20	102,53	67,71	173,90	57,22	17,26	16,17	9,54	6,21
2.3.2	46	440	50	34	20								
2.3.3	46	440	50	34	20								

4. Conclusion

The experimental model obtained in the testing machine has been adapted to an industrial production machine. As a summary it can be concluded that:

To adapt the models, a linear regression of the values obtained with the model of the testing machine vs. the values obtained with the industrial machine is made and from this correlation, the regression equation is established. The values obtained with the regression model are then compared with the actual values measured, and the prediction is checked for accuracy.

Once the adaptation of the roughness models has been carried out, the reduction in the relative error between the values obtained with the adapted models and the values obtained with the industrial machine is very high, compared to the relative error that exists between the non-adapted model and the real values obtained in the industrial machine, which is considerably high. It is possible to predict values with an error rate between 1.3% and 17.26% for the roughness variables.

In the case of the adaptation of the stock removal rate model, it is observed that the error also presents a significant reduction with respect to the non-adapted model, being able to predict values with an error rate of between 1.3% and 10.68%.

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