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Multi-Objective Optimization of Material Removal Rate and Tool Wear in Rough Honing Processes

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Abstract: This study focuses on obtaining regression models for material removal rate and tool wear in rough honing processes. For this purpose, experimental tests were carried out according to a central composite design of experiments. Five different parameters were varied: grain size or particle size of abrasive, density of abrasive or abrasive concentration, pressure of the stones against the cylinder internal surface, tangential speed (in this case, corresponding to the rotation speed of the cylinder), and linear speed of the honing head. In addition, multi-objective optimization was carried out with the aim of maximizing the material removal rate and minimizing tool wear. The results show that, within the range studied, the material removal rate depends mainly on tangential speed, followed by grain size and pressure. Tool wear is directly influenced by density of abrasive, followed by pressure, tangential speed, and grain size. According to the multi-objective optimization, if the two responses are given the same importance, it is recommended that high grain size, high density, high tangential speed, and low pressure be selected. Linear speed has less influence on both responses studied. If the material removal rate is considered to be more preponderant than tool wear, then the same values should be considered, except for high pressure. If tool wear is preponderant, then lower grain size of 128 (ISO 6106) should be selected, and lower tangential speed of approximately 166 min^{-1}. The other variables, density and pressure, would not change significantly from the first situation.

Keywords: honing; material removal rate; tool wear; regression models; multi-objective optimization

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1. Introduction

In the honing process, material is removed from the internal surface of cylinders by means of abrasive stones, which are attached to a honing head. The stones are made of abrasive material and bond. Different grain sizes (GS) or particle sizes of abrasive can be used, as well as different densities or abrasive concentrations (DE). The stones are expanded against the workpiece surface in order to apply a certain pressure (PR) on the workpiece surface. Usually, the honing head combines alternate linear movement (which provides linear speed VL) and rotation movement (which provides tangential speed VT) [1] (Figure 1). This creates a cross-hatched pattern that favors oil flow [2,3]. Wong and Tung stated that half of the losses in a combustion engine are produced in the piston-cylinder interface [4]. The friction coefficient between the piston ring and cylinder liner, as well as oil consumption, depend on the surface topography of the parts [5,6]. Thus, it is essential to obtain an appropriate surface finish, which can be achieved through the honing and plateau honing processes [7]. The honing process, in addition, provides high dimensional precision [8] and requires different stages in order to achieve the final surface finish [9]. In the rough honing phase, one of the main requirements is to maximize the material removal rate, which is related to the productivity of the process, while minimizing tool wear, which will lead to lower tool costs.

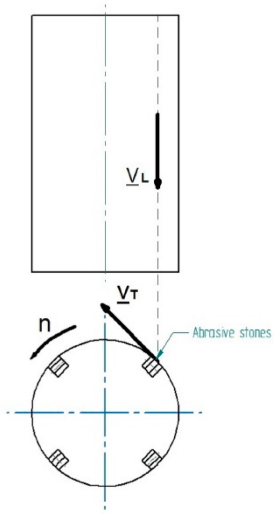

Figure 1. Schematic of the honing process: VL is linear speed of the honing head, VT is tangential speed (corresponding to the rotation speed n of the cylinder). In this example, the honing head is provided with 4 abrasive stones.

Regression models are often used to study and analyze machining processes. As for honing, Troglio [10], for instance, used factorial design with variables such as grain size, lubricating oil, and workpiece material, and average roughness Ra and parameters of the Rk family (Abbott-Firestone curve) as responses. Kanthababu et al. [11] investigated the effect of rotation speed, linear speed, pressure, honing time, and plateau-honing time on roughness parameters of the Rk family. Tang et al. [12] used gray relational analysis with response surface methodology (GRA-RSM) to model average roughness Ra. They found that average grain size was the most influential factor on roughness, followed by depth, tangential speed, and reciprocating speed.

Different authors have studied the material removal rate in the honing processes. For example, Bell et al. investigated the effect of pressure and grit size on material removal rate, tool wear, and roughness of steel cylinders. They found that the stone pressure influenced material removal rates significantly [13]. Szabo performed honing experiments on cast iron material, in which cutting speed, tool pressure and machining time were varied. He observed that the tool pressure increased the material removal rate. He found values between 0.015 and 0.020 mm/s (0.090 and 0.120 cm/min) when using cubic boron nitride (cBN) stones [14]. Vrac et al. varied circumferential or tangential speed, axial speed, pressure, and crossing angle using diamond abrasive stones in rough honing. They observed that honing speed influences the roughness-material removal rate dependence, especially for coarser-grained tools. They reported similar material removal rates, between 0.015 and 0.021 mm/s (0.090 and 0.124 cm/min) [15]. More recently, the same authors [16] varied cutting speed and specific pressure in honing experiments with diamond abrasive stones. They obtained exponential models for maximum peak height Rp, productivity, and specific volume productivity. They found that cutting speed was the most influential factor on productivity, followed by specific pressure. A previous work about rough honing with cBN stones, in which grain size and density of abrasive were varied, reported material removal rate values of up to 0.36 cm/min [17]. In the electrochemical honing process, Shaikh and Jain obtained material removal rates up to 0.68 mm^3/s, with voltage and rotary speed as the main influential parameters [18]. In the magnetic-assisted abrasive honing process, Chohan reported MRR values up to 0.03 g/min. using iron oxide abrasives [19].

In different machining processes, for instance, milling, it is usual to employ regression models to obtain mathematical models that relate process parameters to responses related to surface finish and productivity [20]. However, in the literature, not many studies are known that analyze the influence of honing parameters on tool wear. For example, Bell et al. observed that the stone pressure influences tool wear in honing processes [13]. Cabanettes et al. studied the evolution of areal roughness parameters with tool wear when honing motor blocks. They found that the most useful parameters for this purpose are Spk, Sk, Ssc, and a tailor-made parameter describing the plateau coverage [21]. They reported that as the tool wears down, the plateau and peaks become rougher, with sharper asperities. In rough honing with diamond stones, Vrac et al. observed that higher honing speed produces more heat at the working area, and this leads to higher grain stress and fall-out of grains from the abrasive stones [15]. In a previous work about rough honing with cBN stones, tool wear values up to 0.0008 cm^3/min were reported [17].

Regarding multi-objective optimization of honing processes, Nguyen et al. optimized both surface roughness and machining time in finishing honing [22], by means of response surface and genetic algorithms. Optimal values corresponded to tangential speed of 36 m/min, linear speed of 9.5 m/min, and grain size of 220. Lawrence et al. optimized different roughness parameters and honing angles in rough, finishing, and plateau honing processes by means of Taguchi design and Gray-relational analysis [23]. For example, in rough honing, recommended values for the process parameters were rotational speed of 37 m/min, oscillatory speed of 19 m/min, pressure of 700 kPa, and honing time of 300 s. However, tool wear has scarcely been used in the optimization of honing processes and can be quite significant in rough honing processes, in which the highest material removal rates are achieved.

As a general trend, in abrasive machining processes an increase in productivity, i.e., higher material removal rate, leads to an increase of tool wear. Tool wear can produce deviations in the dimensional quality of the parts [24] as well as deviations in roughness values [21]. Thus, it is important to ensure relatively high productivity without compromising the quality of the parts. The main objectives of this study are to model and to simultaneously optimize the material removal rate and tool wear in rough honing processes. First, the main variables affecting the performance of the honing process were selected. Experimental tests were then performed and regression models were sought. The models were simplified, removing the less significant factors. Finally, a multi-objective optimization is proposed involving the two questions studied, in which the material removal rate is to be maximized while tool wear is minimized.

2. Materials and Methods

In this paper, different honing tests were carried out first, according to a full factorial design of experiments. Liner regression models were obtained, which were later simplified using the stepwise selection method. Multi-objective optimization was then performed, in order to simultaneously minimize the material removal rate and tool wear.

2.1. Honing Process

A horizontal honing test machine from Honingtec (Honingtec S.A., Els Hostalets de Balenyà, Spain) was used to perform the experiments (Figure 2).

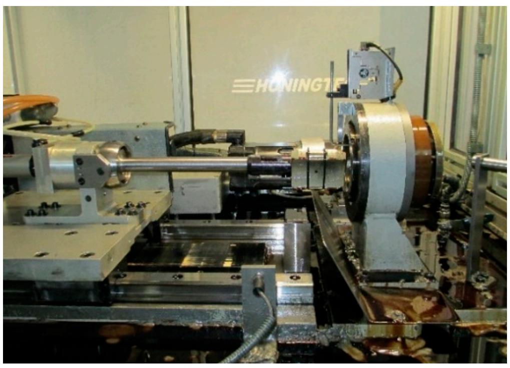

Figure 2. Honing test machine.

Cubic boron nitride (cBN) was used as an abrasive material, with metallic bond. In Figure 3, the honing head is observed, with one of the three honing stones.

Figure 3. Honing head provided with cBN abrasive stones.

Unlike most industrial machines, in the test machine the tangential speed is produced by the rotation of the part, while the head only has a reciprocate linear movement.

2.2. Design of Experiments

A complete factorial design with two levels was selected. Considering that the number of factors is 5, the number of experiments will be $2^5 = 32$ experiments. A central point was added to the design, with three replicates. Thus, the total number of experiments was 33.

Based on results obtained from previous studies [25,26], the variables of the honing process (factors) that most influence the outcome of the process were selected, along with their values. This defined the following five factors, which were the input variables of the statistical model:

1. GS: Grain size of the abrasive stone (ISO 6106 standard) [27];
2. DE: Density of the abrasive stone (ISO 6104 standard) [28];
3. VL: Linear speed of the stone with respect to the piece (m/min);
4. VT: Rotation speed of the workpiece (min^{-1});
5. PR: Working pressure (N/cm^2).

The selected levels for the five variables considered are shown in Table 1.

Table 1. Variables of the factorial design of experiments.

Variable	Low Level	High Level
GS (ISO 6106)	76	181
DE (ISO 6104)	30	75
VL (m/min)	20	32
VT (min^{-1})	80	180
PR (N/cm^2)	450	600

2.3. Determination of Material Removal Rate (Qm) and Tool Wear (Qp)

The two output variables of the models (answers) are defined as:

1. Qm (cm/min): Material removal rate
2. Qp (cm^3/min): Tool wear

The variable Qm is defined as the volume of material removed (cm^3) every minute (min) and per unit area of the abrasive wheel in cm^2. This parameter allows for evaluating whether the material start-up is optimal and calculating the machining time; Qm was calculated by measuring a part's initial and final diameter with an alexometer (Figure 4).

Figure 4. Alexometer used to measure the internal diameter of the cylinders.

The Qp response is a measure of the performance of abrasive wheels and is defined as the volume of material removed over the machining time. It allows for calculating the abrasive stone consumption. It was calculated from the measurement of the weight of the abrasive stones before and after each honing test on a Kern 440 scale (Figure 5).

Figure 5. Scale used to weigh the abrasive stones and tool holders.

2.4. Regression Models and Multi-Objective Optimization

Linear regression models with all the terms were obtained for each response by means of Minitab statistical software version 19 (Minitab LLC, State College, PA, USA). Reduced models were then obtained from the application of backward stepwise regression, in which each step gradually eliminated the less significant terms from the model.

Multi-objective optimization was performed by means of the desirability function method [29]. The material removal rate Qm is to be maximized, whereas tool wear Qp is to be minimized.

3. Results and Discussion

The results of the experiments are shown in Table 2.

The highest material removal rate values of 0.743 cm/min corresponds to experiment 28, obtained with high grain size, high density, low linear speed, high rotation speed, and high pressure. The lowest material removal rate of 0.106 cm/min corresponds to experiment 4, with high grain size, high density, low linear speed, low rotation speed, and low pressure.

The highest tool wear was reported in experiment 30, with high grain size, low density, high linear speed, high rotation speed, and high pressure. The lowest tool wear was obtained in experiment 23, with low grain size, high density, high linear speed, low rotation speed, and high pressure. Tool wear is usually low when honing steel parts with cBN stones.

Table 2. Qm and Qp results for the different experiments.

Experiment	GS (ISO 6106)	DE	VL ($m \cdot min^{-1}$)	VT (min^{-1})	PR (N/cm^2)	Qm Exper. (cm/min)	Qp Exper. (cm^3/min)
1	76	30	20	80	450	0.130	0.008
2	181	30	20	80	450	0.311	0.059
3	76	75	20	80	450	0.249	0.011
4	181	75	20	80	450	0.106	0.003
5	76	30	32	80	450	0.134	0.008
6	181	30	32	80	450	0.258	0.032
7	76	75	32	80	450	0.207	0.015
8	181	75	32	80	450	0.150	0.003
9	76	30	20	180	450	0.336	0.054
10	181	30	20	180	450	0.493	0.071
11	76	75	20	180	450	0.367	0.010
12	181	75	20	180	450	0.660	0.015
13	76	30	32	180	450	0.290	0.019
14	181	30	32	180	450	0.489	0.084
15	76	75	32	180	450	0.415	0.023
16	181	75	32	180	450	0.386	0.016
17	76	30	20	80	600	0.237	0.034
18	181	30	20	80	600	0.303	0.087
19	76	75	20	80	600	0.286	0.024
20	181	75	20	80	600	0.405	0.039
21	76	30	32	80	600	0.191	0.027
22	181	30	32	80	600	0.291	0.032
23	76	75	32	80	600	0.277	0.010
24	181	75	32	80	600	0.394	0.035
25	76	30	20	180	600	0.383	0.061
26	181	30	20	180	600	0.500	0.078
27	76	75	20	180	600	0.371	0.028
28	181	75	20	180	600	0.743	0.065
29	76	30	32	180	600	0.539	0.106
30	181	30	32	180	600	0.565	0.122
31	76	75	32	180	600	0.423	0.031
32	181	75	32	180	600	0.538	0.024
33	126	50	26	130	525	0.399	0.045

3.1. Linear Model for Qm

The reduced regression model for material removal rate is as follows (Equation (1)):

$$Qm = -0.236 - 0.000104\ GS + 0.001094\ VT + 0.000610\ PR + 0.000009\ GS \cdot VT \quad (1)$$

Parameter R^2-adj is 74.82%.

Figure 6 corresponds to the main effects plot for Qm.

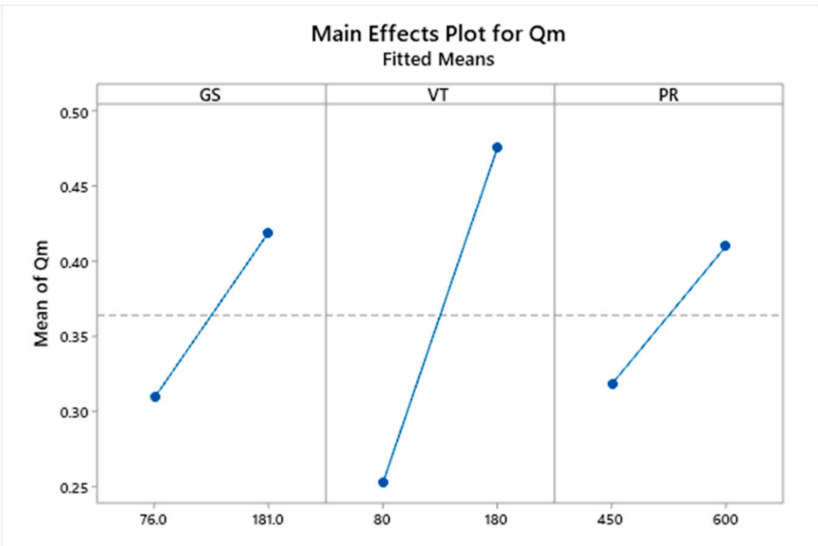

Figure 6. Main effects plot for material removal rate Qm.

It is observed that three main variables affect material removal rate: grain size, tangential speed, and pressure. Specifically, high tangential speed, high grain size, and high pressure lead to high material removal rate Qm.

Figure 7 depicts the interaction plot for Qm.

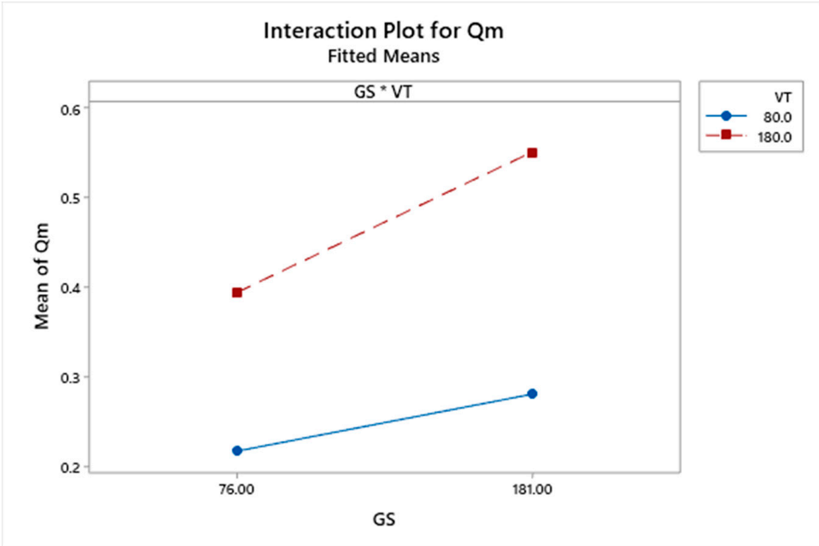

Figure 7. Interaction plot for material removal rate Qm.

The interaction between grain size and tangential speed is the most significant. The effect of grain size on material removal rate is more important when considering high speed of 180 min^{-1} than low speed of 80 min^{-1}. However, in both cases higher grain size leads to a higher material removal rate.

Figure 8 shows the Pareto chart of the standardized effects, with a significance level $\alpha = 0.1$. In the chart, bars crossing the red line are considered to be statistically significant. The red number is the t value corresponding to a $(1–\alpha/2)$ quantile of a t-distribution that has the same degrees of freedom as error.

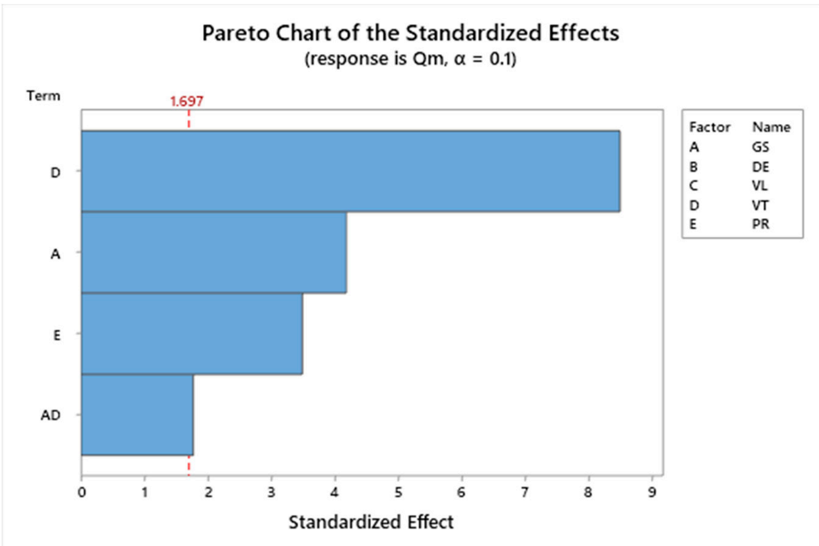

Figure 8. Pareto chart of the standardized effects for material removal rate Qm.

As can be seen in Figure 8, the term that most influences material removal rate is tangential speed. This result is in accordance with the work by Vrac et al. [16], in which, as a general trend, the higher the cutting speed (the composition of radial and axial speed) the higher the material removal rate. Bai et al. [30] found that material removal rate increased with tangential speed, but also with linear speed, which has less influence in this work. Other influential factors in the material removal rate are grain size and pressure. The effect of grain size on the material removal rate was observed by Buj-Corral et al. [31], whereas the effect of pressure was reported by Bell et al. [13]. The higher the pressure exerted by the abrasive stones, the higher the material removal rate.

3.2. Linear Model for Qp

The reduced regression equation for tool wear is as follows (Equation (2)):

$$Qp = -0.1394 + 0.000458\ GS + 0.000824\ DE - 0.000286\ VL + 0.000586\ VT + 0.000157\ PR - 0.000005\ GS \cdot DE - 0.000007\ DE \cdot VT \quad (2)$$

Parameter R^2-adj is 71.38%.

Figure 9 shows the main effects plot for Qp.

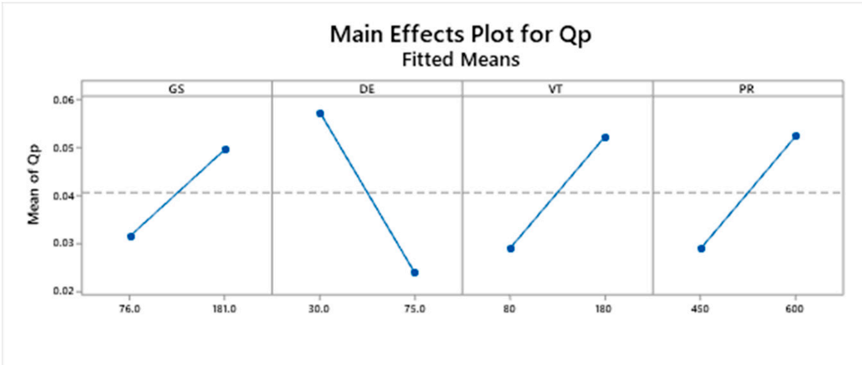

Figure 9. Main effects plot for tool wear Qp.

It can be seen from Figure 9 that linear speed does not significantly affect tool wear. Tool wear decreases with density, whereas it increases with pressure, tangential speed, and grain size.

Figure 10 depicts the interaction plot for Qp.

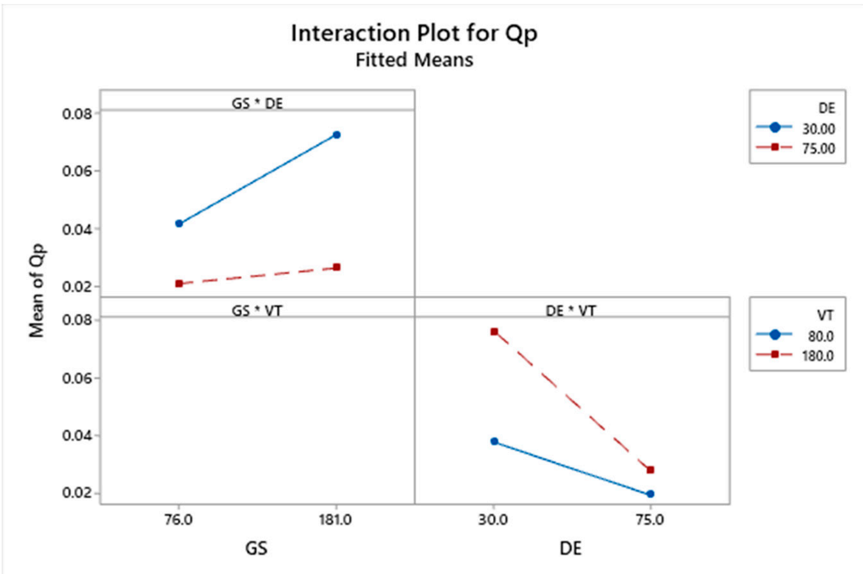

Figure 10. Interaction plot for tool wear Qp.

Figure 10 shows that the two interactions correspond to grain size–density and density–tangential speed. Regarding the GS·DE interaction, it is observed that tool wear increases substantially with grain size when low density is considered. When high density is considered, tool wear only increases slightly with grain size. As for the DE·VT interaction, tool wear has a higher value with low density for high tangential speed than for low tangential speed. In contrast, when high density is used, similar tool wear values are obtained regardless of the tangential speed used.

Figure 11 depicts the Pareto chart of the standardized effects, with a significance level $\alpha = 0.1$.

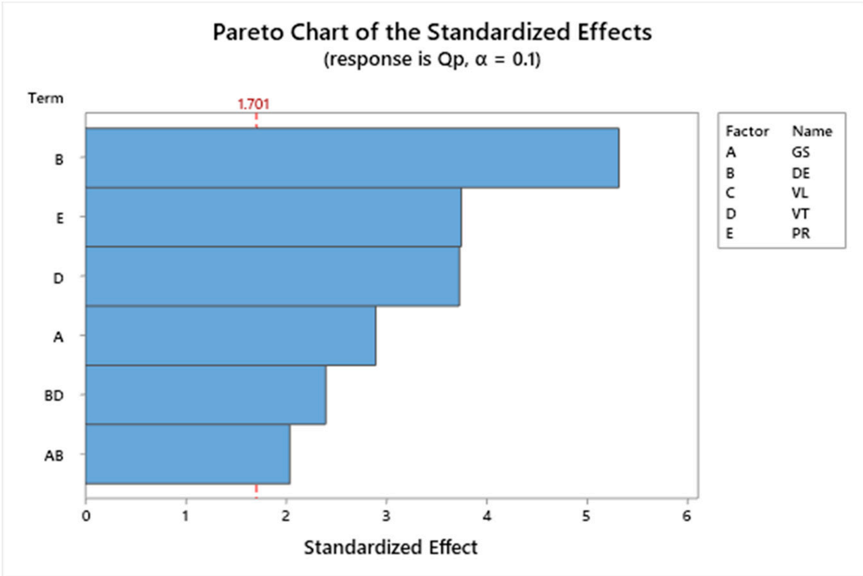

Figure 11. Pareto chart of the standardized effects for tool wear Qp.

The main term influencing tool wear is density, followed by pressure, tangential speed, and grain size. Linear speed is not significant in this case. The effect of pressure on tool wear was previously observed by Bell et al. [13]. The higher the pressure, the higher the tool wear.

3.3. Multi-Objective Optimization

The ultimate goal of this study is to optimize the process by maximizing the volume of machined material per time unit (Qm), which is related to productivity, while minimizing tool wear (Qp), which is related to tool cost.

In the desirability function method defined by Derringer and Suich [29], an importance value is assigned to each one of the selected responses. In this work, a first optimization step is made in which the same level of importance is defined for the two responses, namely material removal rate Qm and tool wear Qp. Two more optimization steps are then carried out, in which one of the responses is assigned an importance value that is ten times higher than the other one, thus highlighting the preponderance of one response over the other.

3.3.1. Optimization with the Same Importance Level for Qm and Qp

The results are presented in Table 3.

Table 3. Multi-objective optimization considering the same level of importance for Qm and Qp.

GS (ISO 6106)	DE (ISO 6104)	VT (min^{-1})	PR (N/cm^2)	Qm (cm/min)	Qp (cm^3/min)	Composite Desirability
181	75	180	456.01	0.508232	0.0183842	0.741495

A composite desirability of 0.741 was obtained. In this case, in order to maximize Qm and to minimize Qp, the use of high grain size (181, ISO 6106), high density (75, ISO 6104), high tangential speed (180 min^{-1}), and low pressure (456.01 N/cm^2) is recommended. High grain size leads to a high material removal rate but also produced high tool wear. Density mainly influences tool wear, with high density corresponding to low tool wear.

High tangential speed leads to a high material removal rate, but also to high tool wear. Finally, low pressure leads to low tool wear but also reduces the material removal rate.

3.3.2. Optimization When Qm Is Preponderant

The results of the multi-objective optimization are presented in Table 4.

Table 4. Multi-objective optimization considering that Qm is preponderant.

GS (ISO 6106)	DE (ISO 6104)	VT (min^{-1})	PR (N/cm^2)	Qm (cm/min)	Qp (cm^3/min)	Composite Desirability
181	75	180	600	0.596095	0.0409946	0.760863

In this case, as grain size is assigned a higher importance value, high pressure (600 N/cm^2) should be selected, as it is related to high material removal rate. The other variables are kept in their high values: grain size 181 (ISO 6106), density 75 (ISO 6104), and tangential speed 180 min^{-1}. Composite desirability (0.761) is slightly higher.

3.3.3. Optimization When Qp Is Preponderant

The results are presented in Table 5.

Table 5. Multi-objective optimization considering that Qp is preponderant.

GS (ISO 6106)	DE (ISO 6104)	VT (min^{-1})	PR (N/cm^2)	Qm (cm/min)	Qp (cm^3/min)	Composite Desirability
128	75	165.9	450	0.394140	0.0135332	0.855239

In this case, as tool wear is assigned a higher importance value than tool wear, both lower grain size values of 128 and lower tangential speed values of 165.9 min^{-1} are recommended, as opposed to the results in Section 3.3.1. A low pressure value of 450 N/cm^2 is to be selected, which produces low tool wear. The highest composite desirability from the three cases studied (0.855) was obtained in this section. High density of 75 is recommended for the three cases studied, as it has less influence on the material removal rate but it ensures low tool wear.

4. Conclusions

In the present work, linear regression models were obtained for the material removal rate and tool wear in rough honing processes, considering five different variables: grain size, density of abrasive, pressure, linear speed, and tangential speed.

It was observed that the material removal rate depends mainly on tangential speed, grain size, and pressure, whereas tool wear depends on density, pressure, tangential speed, and grain size. Thus, tangential speed and grain size influence both the material removal rate and tool wear. Linear speed is not significant for either of the two responses considered.

Grain size, tangential speed, and pressure have opposite effects on the objective of maximizing the material removal rate and minimizing tool wear. Although high grain size, tangential speed, and pressure increase the material removal rate, they also increase tool wear. Thus, process parameters need to be carefully selected in order to simultaneously minimize both variables. According to multi-objective optimization, if the two responses are given the same importance value then high values should be selected for all variables except for pressure, which should be low. If the material removal rate is preponderant, then all variables are to be selected at their high values, including pressure. If tool wear is preponderant, then lower grain size and tangential speed values of 128 (ISO 6106) and 165.9 min^{-1}, respectively, should be chosen, while low pressure (450 N/cm^2) is considered. High density (75, ISO 6104) is recommended in all cases, which leads to low tool wear without significantly reducing the material removal rate.

This work will help to select appropriate honing conditions in rough honing processes, when high productivity and low tool costs are required. Future research will address the effects of the use of different abrasive and/or bond materials on material removal rate and tool wear.

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