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ORIGINAL ARTICLE

Optimization of the dressing operation using load cells and the Taguchi method in the centerless grinding process

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Abstract The finishing processes of industrial components use grinding due to the elevated quality generated by this method. Centerless grinding is among the main manufacturing processes due to its high flexibility, accuracy, and great volume of production that is necessary in modern industry. However, the dressing operation has been a pronounced bottleneck in the centerless grinding process due to the time lost to make the corrections in the grinding wheel. This work presents an optimization of the dressing operation in centerless grinding using load cells and the Taguchi method. The experimental tests were carried out on the shop floor of a manufacturer of shock absorbers. The input parameters were the depth of dressing, the feed rate of dressing, the diameter of the grinding wheel, and the speed of the regulating wheel. The responses were the surface roughness, the roundness error, and the dressing force. The results show that the dressing time was reduced, generating an increase in machine productivity, the surface roughness of the work pieces was reduced with an improvement in quality, and the dressing force was proportional to the depth of dressing.

Keywords Dressing force · Centerless grinding · Taguchi method · Surface roughness · Load cell

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1 Introduction

The constant search by the consumer for new products with quality and low prices has forced companies to develop accurate technologies for the shop floor that do not increase the costs of production. According to Quintana and Ciurana [1], an improper technology, wrong machine selection, and inaccurate choice of process parameters can negatively affect productivity, precision, and flexibility, excluding products from the market. Gopalakrishnan et al. [2] affirm that machine tools are important for discrete production manufacturing if the machine tools are considered to be adapted to the new technologies. Based on this, production must be focused on attempting to deliver increased levels of quality and take into account production system parameters.

A simple change of culture on the shop floor can decrease the cost of production, since trial-and-error strategies can generate great losses and most of them do not effectively deal with the issue of increasing production. Anosike and Zhang [3] affirm that the major problem for manufacturers is responding quickly and effectively to unpredictable changes in the global market with efficient production strategies. The authors suggest an integrated decision system where a platform can plan and control, and the decisions can be considered at the same time as the system reconfiguration.

Several authors have proposed systems that allow for the integration of machine operator knowledge and the self-learning of productive systems. This system was a control algorithm for milling process, the FUZZY logic applied to the precision machining-oriented CNC, and the cost of the model based on multiple regression analyses are some of the strategies developed for increasing production, minimizing setup time, and definitions based on the information from the control of the machining process [1, 4].

Modern industries need to find new techniques for the monitoring of processes, latest equipment, and for encouraging their employees to carry out studies aimed at reducing costs, improving processes and products. Machining is the main productive process in the manufacturing sector. There is no industrial component that has not gone through a machining process. Turning, drilling, milling and grinding are the most common processes in production and each has away to control the cutting parameters. The quality of an industrial product depends on the type of machining process and the more quality is required for a product, the more complex is the process.

Grinding is a complex machining process that depends generally on the ability and knowledge of the operators. According to Koepfer [5], grinding is the metal working process that is most associated with a "black art" and much of this myth is perpetuated by a general lack of understanding of the fundamentals that make grinding applications successful. Thus, an exact setup has direct influence on product quality, because the stability of grinding processes is very sensitive to the setup conditions.

Among all grinding process, centerless grinding is the most complex process for establishing an optimal setup. According to Kim et al. [6], the main tasks of operators in grinding are to set up a machine properly so that it dresses the grinding wheel in the proper interval, and to adjust other grinding conditions such as cutting speed and feed rate. In addition, the setup of the regulating wheel and the blade are other complex parameters that can interfere in the process. According to Wu et al. [7], the function of the regulating wheel and the blade in conventional centerless grinding is to align the part into the grinding gap. Furthermore, the operator should carry out the dressing operation not only to avoid the occurrence of abnormalities but also to enable high efficiency production.

Dressing is a complex operation that demands a long time, which can vary according to the dimension of the grinding wheel. The aim of dressing is to sharpen and regularize the grinding wheel shape, and to clean the impurities coming from the chips. The cost involved in the dressing operation can compromise the process because of the need for machine, and consequently, production shut downs. Klocke and Linke [8] affirm that the dressing operation changes the working behavior of the grinding wheel, the Young's modulus, and the effective hardness of the grinding layer.

The quality of products manufactured by the centerless grinding process, therefore, is linked directly to the dressing operation. Pavel et al. [9] claim that the new electrolytic in-process dressing (ELID) method has attracted special interest recently not only because it cuts dressing times through in-process dressing, but also because on-line dressing, with a subsequent time reduction, becomes possible.

For this reason, the study of the dressing operation is very important, particularly for the grinding process on the shop floor, where machine shut downs represent an increase in costs and decrease in production. This work, therefore, focuses on the optimization of dressing with a load cell in centerless grinding aiming to improve the production process. The Taguchi method was applied to identify the most important factors in centerless grinding and to delimit the cost variations for each product quality setup parameter.

The Taguchi method is an important tool to carry out experiments meanly because it provides a low number of experiments. The methodology uses an orthogonal array and also tries to minimize the effects of the factors out of control. According to Asiltürk and Akkus [10], the basic philosophy behind the Taguchi method is to ensure the quality in the design phase. Abrasive processes are very difficult to evaluate due to the use of complex tool geometry. The grits have an indefinite shape that modifies during the cutting process due to breaking, pull out, flattening. Furthermore, uncontrollable factors, such as burnishing, increase of cutting efforts, and vibrations, can occur during grinding and not be perceived immediately.

Thus, the Taguchi method has a wide range of applications in machining processes. Huang et al. [11] used the Taguchi method to optimize the polishing of ceramic blocks. The polishing of brittle materials is intricate and parameters such as polishing time, load, rotational speed, diamond size, and concentration, have great influence on the process. According to the authors, the Taguchi method allowed the definition of the three main failure mechanisms: cracks, deep pits, and fracture during the process. Palanikumar [12] used the Taguchi method to minimize the surface roughness in machining glass fiber reinforced polymers (GFRP). The results showed that the optimal combination of machining parameters can be obtained using the Taguchi method to provide the requirements for the machining of GFRP composites.

According to Lin [13], the traditional experimental design methods are too complex and difficult to use. They imply that a large number of experiments have to be carried out when the number of machining parameter increase. Their development becomes unfeasible on the factory floor due to the costs, and the great time wasted. Based on this, the main factors that generate variations should be determined and checked under laboratory conditions. Kilickap [14] affirms that the Taguchi method can decrease the experimental time, reducing costs, and find out significant factors in a shorter time period. Based on this, the effect of the dressing operation on surface roughness, roundness error, and circularity error on the grinding of stems of shock absorbers using the Taguchi method and analysis of variance is evaluated in the present study.

Table 1 Experimental factors

Symbol	Cutting parameters	−1	0	+1
A	Speed of regulating wheel (rpm)	51	63	75
B	Diameter of grinding wheel (mm)	425	517	609.6
C	Feed rate of dresser (mm/rev)	84	104	124
D	Depth of dressing (mm)	0.042	0.084	0.126

2 Methodology

2.1 Experimental tests

The tests were carried out on the factory floor of a manufacturer of shock absorbers. The machine tool used was a centerless grinding model Twin Grip 350-20 with 50 HP of main motor power manufactured by Cincinnati. The speed of the regulating wheel, feed rate of the dresser, and the depth of dressing were the parameters used to define the time of the dressing operation. The speed of the regulating wheel defines the through-feed rate of the work piece and the cycle time. To reach the optimum cycle time and get the best finishing with low surface roughness and roundness, the through-feed rate depends on the topography of the grinding wheel. Table 1 shows the input parameters used in the experimental tests with their respective levels. The levels were chosen based on the accuracy of the grinder machine and technical specifications of the components.

The responses used in the tests were the surface roughness and the roundness of the work pieces, which are important technical data on the quality of the product. The dressing force was monitored using a load cell model HBS C2 with a limit of 1 kN. Figure 1 shows the assembly of the system on the dressing set. The surface roughness (R_z) was measured using a surface tester SJ-401 manufactured by Mitutoyo™ and the roundness error was controlled using a three-dimensional measuring machine.

Figure 2 shows the assembly of the system used for data acquisition in the monitoring of the dressing force. The load cell recorded the analogical signal in millivolts that was sent and converted this to volt in the multimeter. The signal converter was used to change the signal from analogical to digital. Thus, the signal recorded by the load cell could be analyzed directly on the computer using the specific software of the signal converter.

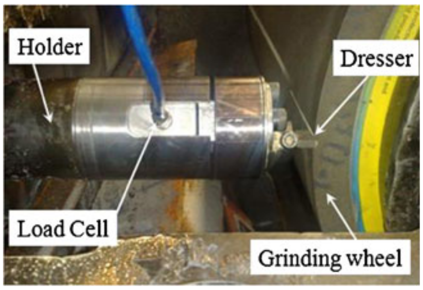


Fig. 1 Detail of the assembly of the load cell on the dresser

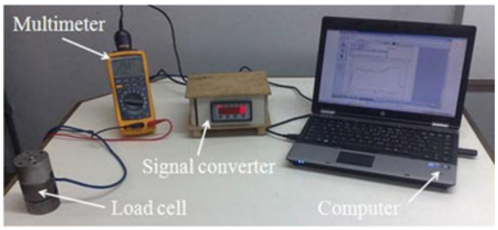


Fig. 2 System used for data acquisition

Through-feed centerless grinding has several parameters that need to be controlled on the factory floor before the startup of production. The aim of this study was to find the best group of parameters; for this reason, the values of Table 1 were used as input variables and the values of Table 2 were kept constant to strategically optimize the process. The monitoring of dressing according to the input parameters of Table 1, therefore, was carried out during the dressing operations of the grinding wheel.

2.2 The experimental design using the Taguchi method

The Taguchi method is a philosophy that enables the drastic reduction of the number of tests. The technique is based on the orthogonal array and also minimizes the effects of the factors out of control that can have influence on the tests. The most important stage of the test design lies in the selection of control factors [15]. According to Park [16], as many factors as possible should be included to identify non important variables at the earliest opportunity.

In the Taguchi method the signal-to-noise (S/N) ratio is applied as the quality characteristic to determine the correct choice. The S/N ratio is used as a measurable value instead of standard deviation because as the mean decreases, the

Table 2 Fixed parameters used in the tests

Parameter	Value
Number of steps in each dressing operation	1
“hw” height (difference between the center of the work piece and the center of the grinding wheel)	1 mm
Speed of the grinding wheel	1,200 rpm
G ratio	0.881
Removal specific rate	1.375 mm^3/mm/s
Overlap rate “Ud”	116.5
Equivalent diameter	12.165 mm
Tangential speed of the grinding wheel (Vs)	38.264 m/s

Table 3 Experimental results and S/N ratios values for roundness error and surface roughness R_z

Experimental number	A	B	C	D	Roundness error	R_z	Roundness for S/N ratios	R_z for S/N ratios
1	51	425.0	84	0.042	0.0047	0.81	46.5580	1.83030
2	51	425.0	104	0.084	0.0070	0.69	43.0980	3.22302
3	51	425.0	124	0.126	0.0055	0.61	45.1927	4.29340
4	51	517.0	84	0.084	0.0042	0.89	47.5350	1.01220
5	51	517.0	104	0.126	0.0045	0.59	46.9357	4.58296
7	51	517.0	124	0.042	0.0057	0.79	44.8825	2.04746
8	51	609.6	84	0.126	0.0052	0.61	45.6799	4.29340
9	51	609.6	104	0.042	0.0047	0.71	46.5580	2.97483
10	51	609.6	124	0.084	0.0052	0.80	45.6799	1.93820
11	63	425.0	84	0.042	0.0059	0.89	44.5830	1.01220
12	63	425.0	104	0.084	0.0059	0.79	44.5830	2.04746
13	63	425.0	124	0.126	0.0076	0.62	42.3837	4.15217
14	63	517.0	84	0.084	0.0054	0.67	45.3521	3.47850
15	63	517.0	104	0.126	0.0054	0.61	45.3521	4.29340
16	63	517.0	124	0.042	0.0050	0.75	46.0206	2.49877
17	63	609.6	84	0.126	0.0049	0.65	46.1961	3.74173
18	63	609.6	104	0.042	0.0036	0.89	48.8739	1.01220
19	63	609.6	124	0.084	0.0045	0.72	46.9357	2.85335
20	75	425.0	84	0.042	0.0091	0.79	40.8192	2.04746
21	75	425.0	104	0.084	0.0081	1.00	41.8303	0.00000
22	75	425.0	124	0.126	0.0065	0.56	43.7417	5.03624
23	75	517.0	84	0.084	0.0086	0.75	41.3100	2.49877
24	75	517.0	104	0.126	0.0059	0.63	44.5830	4.01319
25	75	517.0	124	0.042	0.0063	0.73	44.0132	2.73354
26	75	609.6	104	0.042	0.0040	0.87	47.9588	1.20961
27	75	609.6	124	0.084	0.0058	0.56	44.7314	5.03624

standard deviation also decreases, and the opposite can also occur. According to Kim [17], the use of the Taguchi method implies that the engineering systems have production factors that can be manipulated, and these can be divided into three categories.

The first category corresponds to the control factors, which affect the process variability that can be measured by the S/N ratio. The second are the signal factors, which do not influence the S/N ratio or process mean. Finally, there are the factors that do not affect the S/N ratio or process

Table 4 Analysis of Variance for S/N ratios — R_z factor

ANOVA	df	Sum of square	Mean square	F	P
Speed of regulating wheel	2	0.2068	0.1034	0.21	0.818
Diameter	2	1.0124	0.5062	1.02	0.417
Feed Rate	2	3.4153	1.7076	3.42	0.102
Depth of dressing	2	28.3078	14.1539	28.39	0.001
Speed of regulating wheel × Diameter	4	3.6174	0.9044	1.81	0.245
Speed of regulating wheel × Feed rate	4	9.2658	2.3164	4.65	0.048
Speed of regulating wheel × Depth of dressing	4	1.8497	0.4624	0.93	0.506
Diameter × Feed rate	4	2.0816	0.5204	0.58	0.690
Diameter × Depth of dressing	4	3.5356	0.8839	0.98	0.483
Feed rate × Depth of dressing	4	2.5388	0.6347	0.70	0.617
Residual error	4	2.9918	0.4986		
R^2	94.1 %				

Table 5 S/N Response for R_z

Level	A	B	C	D
1	2.911	2.627	2.706	1.930
2	2.788	3.018	2.595	2.454
3	3.001	3.055	3.399	4.316
Δ	0.214	0.428	0.804	2.386

mean. Considering the practical data, the mean value considered as a target may change drastically during the process development. Thus, nowadays there are two applications in which the concepts of S/N ratio are useful: the improvement of product quality through variability reduction and the improvement of measurements and control. Shetty et al. [18] affirm that the S/N ratio characteristics can be divided into three categories given by Eqs. 1, 2, and 3:

1. When the *nominal* is the best characteristic,

$$\frac{S}{N} = 10\log\frac{\bar{y}}{S_y^2} \tag{1}$$

2. When the *smaller* is the best characteristic,

$$\frac{S}{N} = -10\log\frac{1}{N}\left(\sum y^2\right) \tag{2}$$

3. When the *larger* is the best characteristic,

$$\frac{S}{N} = -\log\frac{1}{N}\left(\sum\frac{1}{y^2}\right) \tag{3}$$

Based on this, the engineering systems can manipulate production factors that can be divided into three categories; where $\bar{y}$ is the average of observed data, S_y^2 is the variation of y, n is the number of observations, and y is the observed data. Therefore, the best result can be considered the one where surface roughness and roundness error correspond to “the smaller is the best" scenario. In addition, the loss function was considered to be the difference between the experimental and desired values. Accordingly, the optimum cutting conditions required for the best surface roughness were obtained by using Eq. 1. Thereby, S/N ratios and level values were calculated by using Eq. 2, which corresponds to the smaller is the better scenario in the MINITAB™ 14. Thus, the Taguchi method and L27 orthogonal array were used to reduce the number of experimental tests. The design of experiments (DOE) and measured surface roughness and roundness error are shown in Table 3. The experiments were carried out with three replicates.

3 Analyzing and evaluating the results obtained using Taguchi method

3.1 Surface roughness analysis

The S/N ratio is the main criterion in the Taguchi method for experimental analysis. In this study the S/N ratio should have a maximum value to define the optimum cutting conditions according to Taguchi method. Thus, when the results of surface roughness are considered, it can observe that the best setup was found to be at the 5.03624 ratio, according to the L27 array in Table 3. The results of the experimental tests demonstrated, therefore, that two different setups should be chosen to obtain the best surface roughness and roundness error based on the lower values. Analyzing first

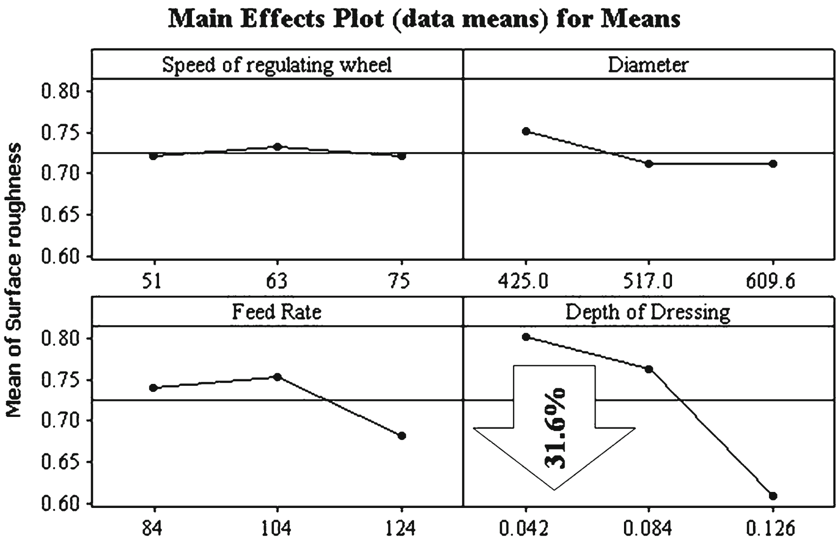
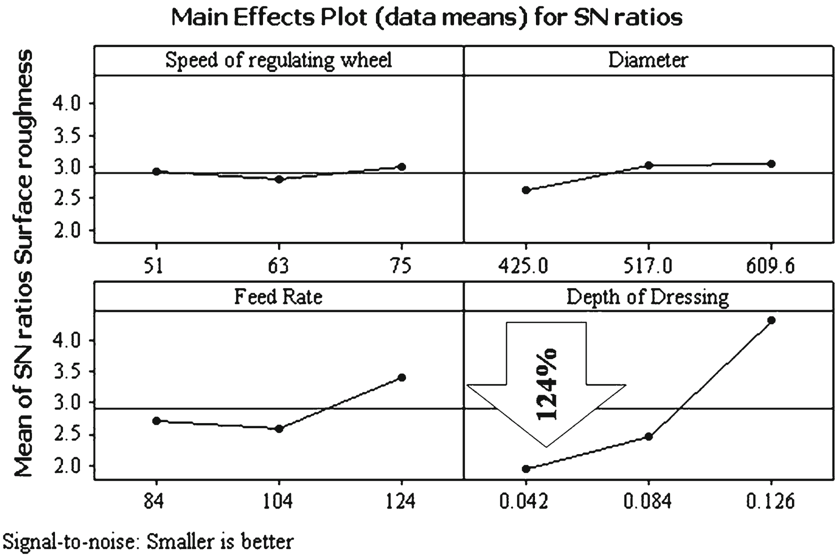


Fig. 3 Graph of the means of surface roughness (R_z)

Fig. 4 Graph of S/N ratios for surface roughness (R_z)



the surface roughness, the ideal setup corresponds to the use of elevated speeds for the regulating wheel, a high feed rate for the dresser, and high depth of dressing at the lowest diameter. However, considering the analysis of variance for the S/N ratios in Table 4, one can observe that only the depth of dressing has significance for the surface roughness according to the *P* value.

The use of a high depth of dressing for the dresser provides a high pull out and great rate of break of grits. Consequently, the topography of the grinding wheel shows a great number of sharp grits after the dressing operation. Thus, the use of a high depth of dressing not only satisfactorily corrects the grinding wheel topography but also provides a great number of sharper grits. This can be confirmed by the results of Table 5, which show the average S/N ratio for every level of the experiment. The depth of dressing is the parameter that has the highest variance considering the different values of the S/N ratio ranging from maximum and minimum. Thus, the claim that the depth of dressing is the most important input parameter on surface roughness can be supported.

Table 6 Analysis of variance for S/N ratios – Roundness error factor

ANOVA	df	Sum of square	Mean square	F	P
Speed of regulating wheel	2	22.042	11.021	7.88	0.021
Diameter	2	34.379	17.190	12.29	0.008
Feed rate	2	3.094	1.547	1.11	0.390
Depth of dressing	2	4.737	2.369	1.69	0.261
Speed of regulating wheel × Diameter	4	9.818	4.454	1.75	0.256
Speed of regulating wheel × Feed rate	4	11.417	2.854	2.04	0.208
Speed of regulating wheel × Depth of dressing	4	7.035	1.759	1.26	0.381
Diameter × Feed rate	4	1.733	0.433	0.31	0.859
Diameter × Depth of dressing	4	11.968	2.9921	2.17	0.189
Feed rate × Depth of dressing	4	7.211	1.8028	1.31	0.365
Residual error	4	8.393	1.399		
R^2	91.7 %				

Figure 3 plots the principal effects for the means, and Fig. 4 shows the main effect plot for the S/N ratios considering the results for surface roughness R_z. One can observe that the decrease of surface roughness corresponded to a 31.6 % change in the depth of dressing, from 0.042 to 0.126 mm.

The other input parameters were on average and had no influence on the surface roughness. When analyzing the S/N ratio, the increase of ratios was of 48.3 %. Based on the Taguchi prediction, therefore, the larger difference between the S/N ratio values will have a more significant effect on surface roughness, R_z.

The grinding wheels are composite materials formed by grits and bonds, and their hardness and efficiency are based on the thermal treatment that improves the physical characteristics. Thus, one can support that the lowest diameter has a superior quality considering the physical properties. Furthermore, one should bear in mind that the surface roughness tends to vary depending upon grinding wheel wear, and that the best group of parts is found in the set with the lowest

Table 7 S/N response for roundness error

Level	A	B	C	D
1	45.79	43.64	44.79	45.59
2	45.59	45.11	45.53	44.56
3	43.78	46.41	44.84	45.01
Δ	2.01	2.76	0.74	1.02

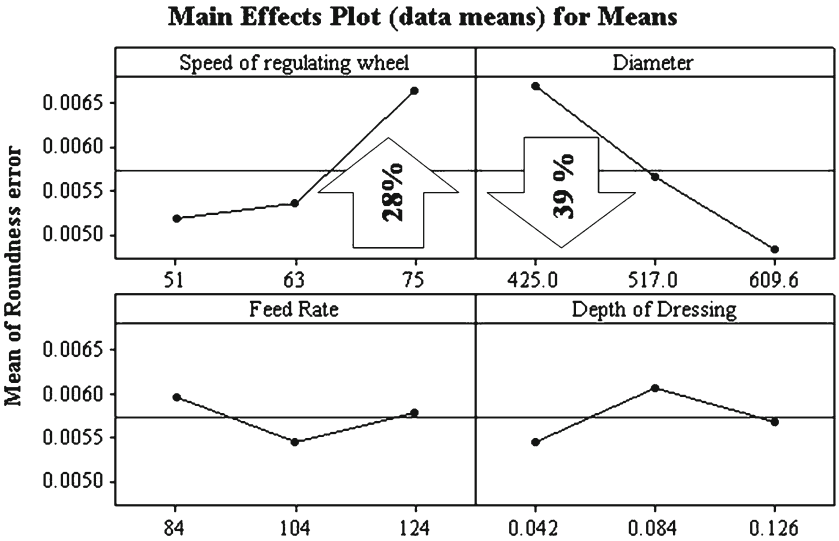


Fig. 5 Graph for the mean of the roundness error

diameters. Thus, it should be emphasized that the best surface roughness occurred only when the diameter reached the final value of 425 mm.

3.2 Roundness error analysis

According to the Taguchi method, the S/N ratio should have a maximum value to define the optimum cutting conditions. Thus, in Table 3, one can observe that the highest S/N ratio for roundness error was found to be the 48.8739 ratio for the 27 array. The analysis of data in Table 3 shows that the optimization of the grinding process, when roundness error is considered, can be obtained using average values for the speed of the regulating wheel and the feed rate for dresser, but with a lower depth of dressing with a higher diameter. It is noteworthy that, in contrast to what was observed for surface roughness, the highest diameter generated the lowest roundness error. Considering the analysis of variance for the S/N ratios in Table 6, one can observe that the speed of the regulating wheel and the diameter have a significant effect on roundness error. According to the data, it can be affirmed that the smaller *P* value implies a greater significance on the response.

The roundness error corresponds to a solid formed by several sets of two circles that are used as reference. This way, one circle is drawn outside the roundness profile to enclose it in its entirety, and a second circle is drawn inside the roundness profile to inscribe the profile. Based on this, the roundness error can be defined as the difference between the radius of each of those two circles, and simultaneously, the group of predefined circles measured in the axial length. Considering that the work piece is in contact with the regulating wheel during the entire grinding process in the grinding gap, the diameter and speed of the regulating wheel are the main factors to have a significant effect on roundness error. The speed of the regulating wheel provides a movement in the axial direction that displaces the work piece into the grinding gap.

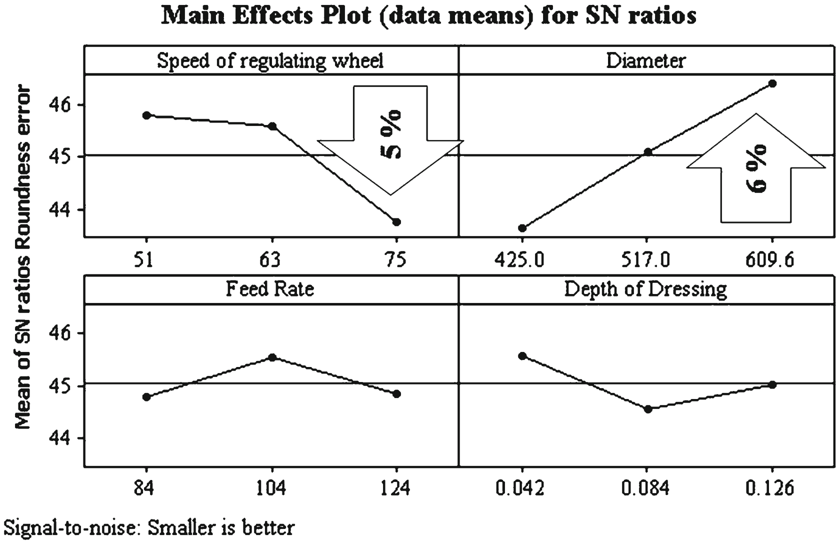


Fig. 6 Graphic of S/N ratios of roundness error

Table 8 Experimental results and S/N values for tangential and radial force

Experiment number	C	D	Tangential force	Radial force	Tangential force for S/N ratios	Radial force for S/N ratios
1	124	0.126	56.8	241.178	−35.0870	−47.6468
2	84	0.126	51.4	279.300	−34.2193	−48.9214
3	104	0.126	53.7	294.000	−34.5995	−49.3669
4	124	0.084	37.2	107.800	−31.4109	−40.6524
5	84	0.084	31.3	127.400	−29.9109	−42.1034
6	104	0.084	30.4	127.400	−29.6575	−42.1034
7	124	0.042	11.1	39.200	−20.9065	−31.8657
8	84	0.042	10.2	9.800	−20.1720	−19.8245
9	104	0.042	12.3	19.600	-21.7981	−25.8451

At this point, it is important to try to understand the influence of the input parameters on roundness error. The use of a higher diameter generated more accuracy and rigidity due to the greater mass of the grinding wheel. Furthermore, average values for the speed of the regulating wheel keep vibrations of the work piece in the grinding gap at a low level. Thus, a higher diameter and an average speed of the regulating wheel constitute the most important factors for the optimization of roundness error.

Table 7 shows the S/N response for roundness error with the diameter being the parameter that has the highest variance considering the different values for the S/N ratio between maximum and minimum. One can, therefore, support that the diameter is the most important input parameter for roundness error.

Figure 5 plots the principal effects for the means, and Fig. 6 shows the main effect plot for S/N ratios considering the results for roundness error. The graphs in Figs. 5 and 6 confirm that a larger S/N ratio for the input parameter has a great influence on the response. It can see that the decrease of roundness error corresponded to a 39 % change in the diameter, from 425 to 609.6 mm. The speed of the regulating wheel demonstrated an increase of 28 % when the speed was increased from 51 to 75 rpm. The other input parameters were on average and had no influence on the roundness error.

Table 9 Analysis of variance for S/N ratios — tangential and radial force

ANOVA	df	Sum of square	Mean square	F	P
Tangential force					
Feed rate	2	5.15	0.8440	25.336	0.000
Depth of dressing	2	8.29	0.9001	2.409	0.095
Feed rate × Depth of dressing	4	1.80	5.061	1.088	0.356
Residual error	4	2.82	4.27		
R^2	98.8 %				
Radial force					
Feed rate	2	7.69	5.84	8.14	0.001
Depth of dressing	2	3.98	1.35	4.40	0.000
Feed rate × Depth of dressing	4	5.52	0.51	5.84	0.094
Residual error	4	1.21	3.21		
R^2	98.4 %				

Analyzing the S/N ratio, one can state that the smaller S/N occurs when the speed of regulating wheel decreases 5 % and the diameter increases 6 %. Based on the Taguchi method, large differences between the S/N ratio values provide a more significant effect on the roundness error.

3.3 Dressing force analysis

To determine the radial and tangential force on the dresser during the dressing operation, the analysis was carried out using the Taguchi method and the L9 orthogonal array. The values for radial and tangential force are shown in Table 8. The results of the experimental tests demonstrated that the use of lower input parameters for depth of dressing and feed rate generated the highest S/N ratios. Thus, the choice of the highest S/N values caused the lowest forces on the dresser during the dressing operation. However, when the analysis of variance is taken into account for the S/N ratios, one can observe in Table 8 that the feed rate has a significant effect on two dressing efforts according to the *P* value. However,

Table 10 S/N Response for tangential and radial force

Level	Tangential force		Radial force	
	C	D	C	D
1	−28.10	−20.96	−35.95	−25.85
2	−28.69	−30.33	−39.11	−41.62
3	−29.13	−34.64	−40.05	−48.65
Δ	1.03	13.68	3.11	22.80

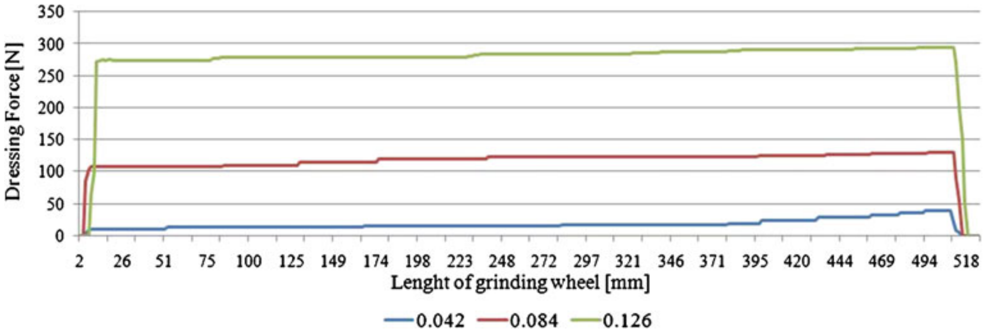


Fig. 7 Dressing force for the depths of dressing of 0.042, 0.084, and 0.126 mm

one can support that only the depth of dressing has a significant effect on radial effort. This result can be ascribed to the displacement of the dresser during the dressing operation. The dresser has several diamond tips encrusted in it, and its aim is to correct the topography of the grinding wheel with a scraping axial movement.

Table 9 shows the analysis of variance for the S/N ratios for tangential and radial force. It can be inferred from data that feed rate has an influence on tangential and radial force due to its displacement direction. Analyzing the tangential force, the displacement of the dresser is based on the variation of the feed rate when the depth of dressing is fixed. Thus, higher feed rate values cause higher tangential and radial forces. During the dressing operation, the resultant vector is represented by a single vector that has the same effect as the two vectors (radial and tangential vector) when they are working at the same time. In the opposite situation, the radial force is influenced by the depth of dressing due to the displacement of the dresser in the radial direction.

Table 10 shows the S/N response for tangential and radial forces where the depth of dressing is the parameter that has the highest variance when the different S/N ratios between maximum and minimum are considered. It can therefore be supported that, when radial and tangential forces are considered, the depth of dressing is the most important input parameter.

The load cell used in the experiments was capable of monitoring the force in the tangential and radial direction. The depth of dressing is related directly to the dressing force. However, the dressing force generally is not monitored during the process because of the difficulty of assembling measurement devices. This work showed that it was possible to assemble a low-cost device for monitoring the dressing force. The device and the acquisition system developed allowed not only to know the dressing force, but also to better understand the grinding wheel profile.

Figure 7 shows the results for the dressing force with depths of dressing of 0.042, 0.084, and 0.126 mm, respectively. The acquisition system was capable of demonstrating the behavior of the dressing during the entire process. The dressing forces for the depths of dressing of 0.042, 0.084, and 126 mm were 39, 130, and 294 N. A short slope can be observed at the beginning and at the end of the process that corresponds to the chamfer of the grinding wheel that causes the work piece to enter the grinding gap.

However, an inclination occurred at the position of 377 mm associated with excess material for the depth of dressing of 0.042 mm. The same inclination occurred at the distance of 150 mm for the depths of dressing of 0.084 and 0.126 mm. This excess of material was investigated after the dressing operation and a misalignment of the bearings was found, explaining the difference of dressing force between the beginning and the end of dressing.

Figure 8 shows the dressing with the depth of 0.042 mm. A large peak of dressing force of 393 N can be observed. This peak occurred due to the problems with the dresser set. After the dressing with a depth of 0.042 mm, the dresser set was disassembled, and the ball bearings were worn and had a big clearance. Based on this, one can support that the monitoring of the dressing operation provides not only information on the grinding wheel surface but also allows performing diagnostics on the machine, such as clearances in the dresser set and misalignment of the grinding wheel bearings.

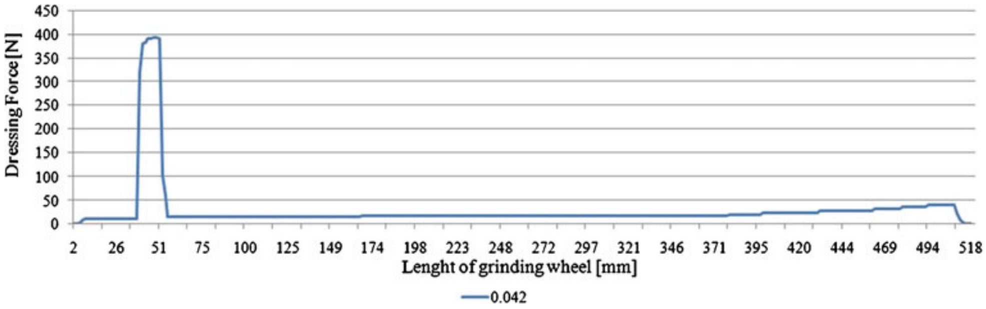


Fig. 8 Dressing force for depth of dressing of 0.042 with a failure of set dresser

4 Conclusions

According to the results, the following points are summarized:

- The best finishing with the lowest surface roughness was found for the setup using a higher speed of the regulating wheel, feed rate, and depth of dressing for the lowest grinding wheel diameter.
- The speed of the regulating wheel and the diameter of the grinding wheel showed an influence on roundness error, but the diameter was the most important factor for roundness error. The best setup, according to the S/N ratios, to optimize and minimize roundness error occurred with an average feed rate, mean speed of the regulating wheel, and lower depth of dressing for the highest diameter of the grinding wheel.
- The feed rate and depth of dressing have great influence on dressing operations. The use of higher depths of dressing caused higher tangential and radial forces, but the feed rate showed more influence on tangential and radial forces than depth of dressing.
- The use of load cells to monitor the dressing operation provides a perfect diagnostic tool, not only for grinding wheel topography, but also for monitoring and finding mechanical problems in the grinder device.
- Finally, the use of the Taguchi method provided a better understanding of the setup of the grinding process, indicating that, depending on the response variables, different setups can be necessary. However, the use of analysis of variance together with the Taguchi method allows the identification of the more significant input parameter and helps in the choice of the ideal setup.

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