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An Experimental and Statistical Investigation on Shape Error in Interrupted Grinding

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Abstract

In this paper, the effect of grinding parameters (grain size, depth of cut, table speed and cutting width) on the shape error in the interrupted surface of GS-C25 material were experimentally and statistically investigated by using Taguchi method. A square geometry was cut into and removed from block samples by wire electrical discharge machine to provide an interrupted grinding material. After interrupted surface grinding experiments, shape error was measured by means of 3-dimensional optical measuring system with a strong light source. The Taguchi optimization approach, the analysis of variance, and linear regression analyses were employed to analyze the effect of grinding parameters. The statistical analysis of experimental data was performed using the Minitab 15 software. The optimization results show that the optimal combination for less shape error to use fine grinding wheel, lower depth of cut and width of cut and middle table speed have been given the best results. A linear mathematical model for the shape error was established between grain size of wheel, depth of cut, table speed and width of cut.

Keywords: Shape error, Interrupted grinding, Taguchi method

INTRODUCTION

Grinding is a finishing process, broadly used in manufacturing of components requiring fine tolerances, good surface finish and higher dimensional and geometrical accuracy. An understanding of the metal cutting processes is required when the aim is to increase the dimensional accuracy and the surface integrity of a machined part. To enhance product dimensional accuracy, the influence of heat partition on the deformation of the machined workpiece and the cutting force must be understood [1-3].

Compared with other material removal processes as an example of turning, milling and boring, the grinding process is more complex and more difficult to control. In addition to the static parameters of the grinding machine tool, there are many dynamic factors that contribute to the resulting dimensional accuracy. The errors in products are usually expressed as shape, waviness, or roughness errors. Shape errors are related to the operation itself and are caused by an undercut or overcut, cutting force, thermal deformation, deflection, wear, chatter, vibration and the plastic deformation of the grinding wheel. The ability of manual grinding to diminish such shape errors is limited because shape errors are often undetectable by the human eye [4, 5].

Several researchers have investigated the geometrical error of the workpiece and pointed out that the thermal deformation causes a serious concavity on the ground profile [6-11]. Kwak [12], Kwak and Kim [13] evaluated the effect of grinding parameters on geometric error and to minimize the geometric error has determined the optimal grinding conditions. Ohmori et al. [14] investigated the deformation behaviors of the sintered SiC workpiece during the grinding process. They have indicated that, the maximum value of the profile deformation is about 0.33µm. Sosa et al. [15] studied shape distortion, residual stress and surface roughness of thin ductile iron plates of different nodule count. They concluded that, sample distortion consisted in a longitudinally oriented curvature, of concave shape on the ground side.

The literature related to machining inaccuracy, resulting from surface grinding, mostly focused on errors resulted from heat. Errors in grinding process are influenced by not only heat but also grinding force. However, a very few published works are available on the effect of grinding parameters on shape error in interrupted grinding. The main goal of this research is to determine the effects of grain size, depth of cut, table speed and cutting width on shape error in interrupted grinding of GS-C25 cast steel. For interrupted grinding of the cast steel material, 50x50 mm square geometry removed from the block by using CNC wire electrical discharge machine to prepare samples. Taguchi's technique, the analysis of variance, and linear regression analyses were used to accomplish the objective.

MATERIALS AND METHOD

Grinding wheel and material

Universal grinding machine with an aluminum oxide grinding wheel was employed to perform a series of experiments in the current work. Table 1 shows the characteristics of the grinding wheel. The selection was made based on the wide industrial application of these grinding wheels. Four grinding wheels used in the experiments have different grain size namely 36, 46, 60 and 80 mesh. Before each grinding experiment,

Table 1 Characteristics of the grinding wheel

Grinding Parameters	
Grinding wheel type	350 × 40 × 127 TS 291 EKR 36, 46, 60, 80 K6 Aluminum oxide
Wheel grain size	36, 46, 60, 80
Hardness of wheel	K
Wheel grain texture	6
Wheel bond type	K
Wheel sharpening time	2 min
Diameter of the grinding wheel	350 mm
Grinding wheel width	40 mm
Inner diameter of the grinding wheel	127 mm

Table 2 Chemical composition and mechanical properties of GS-C25 cast steel

Chemical composition (wt %)	C = 0.18-0.23; Si = <0.60; Mn = 0.50-1.20; P = <0.020; S = <0.015
Mechanical properties	Tensile strength: 420–600MPa; yield strength: 240MPa; % elongation: 22; hardness: 130-170 HB

the grinding wheel was dressed using a single-point diamond dresser to produce a sharp and clean wheel surface. During the grinding process, a water-soluble machining fluid was used as a coolant.

The workpiece material used in this study was GS-C25 cast steel; the chemical composition and mechanical properties of the material are listed in Table 2. GS-C25 cast steel materials are used in valves which serve for transmitting and storing high temperature and pressurized liquids. The experimental cast workpiece dimensions having stress relieving treatment are 205x140x30 mm. Square (50x50 mm) shapes from each sample were removed by a CNC wire electrical discharge machine, to prepare the specimen and to provide the interrupted cutting conditions during grinding.

Measurement of shape error

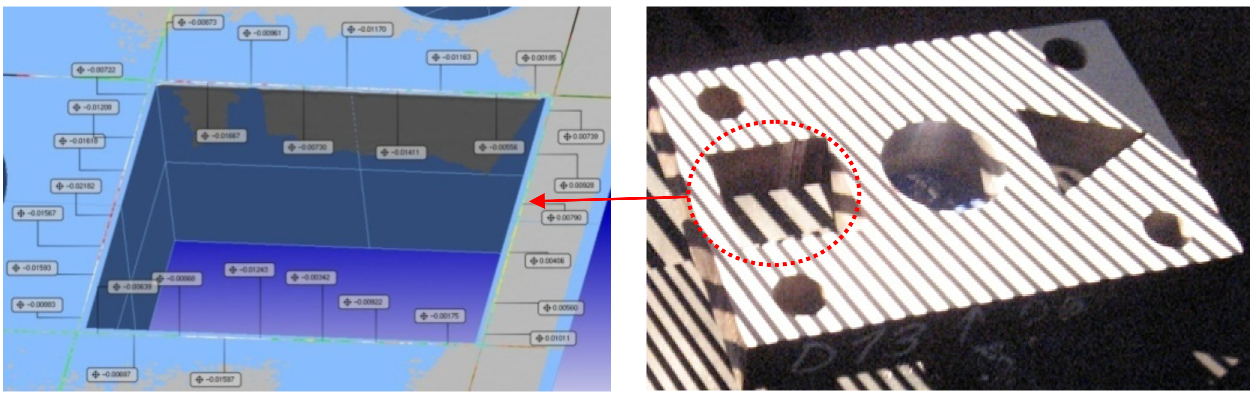
In order to measure the shape errors of parts, a Breuckmann opto TOP-HE coded structured light system was used. 3-dimensional optical measuring system with a strong light source drops on the fringes of different textural properties to the body. These coded lights on the surface of the body are deformed depending on the direction of the characteristic features of the object. Therefore, point cloud that contains information in the surface of the object is created. With the help of computer it is possible to measure the object' reference or surface' point cloud. Then, CAD modeling, an application of reverse engineering is possible with the help of the point cloud. The desired information is obtained from model with this data [16]. Fig. 1 shows the painted workpiece, projected fringe pattern and a typically example obtained by optical scanning.

Design of experiment and Taguchi technique

The most important mission to minimize the shape errors in grinding is the selection of appropriate grinding wheel and cutting parameters. Modeling and optimization are requirements for the control of any process to achieve improved product quality, high productivity and low cost. Nevertheless, because of the inherent complications of the grinding processes, its modeling and optimization still remains one of the most critical and difficult task for researchers and practitioners [17, 18].

The Taguchi approach has produced a unique, efficient, cost-effective, time-saving and powerful quality improvement discipline that differs from the traditional process. Since the product has a great impact on the life cycle, cost and quality of a component, the Taguchi design of experiment method (DOE) provides a design engineer with a systematic approach for determining the optimum design parameters to obtain the best performance at the lowest cost. Lately, it has been widely used to determine optimum parameters. The quality characteristics to be optimized are identified for any engineering optimization problem. Quality characteristics are systematically arranged as maximization, minimization, or normal criterion.

DOE is a statistical method used to investigate the effects of multiple factors simultaneously. This results in the effective experimental plan and produces a statistical analysis to determine easily what parameters are having the most influential effects on the final results. Then, the factors within the system may be grouped as signal factors, noise factors and control factors. Signal factors affecting the product's distinct and unique characteristics and performance will be determined. Noise factors are those uncontrollable variables that are either very difficult or uneconomical to control. Control factors are the specified parameters that the designer has to optimize to give least sensitivity of the response to the effect of noise factors. An orthogonal array is chosen based on the number of factors and levels of variations, and a loss function is then defined to



(a) (b)

Fig. 1 (a) An example obtained by optical scanning (b) painted workpiece calculate the deviation between the experimental and most wanted values. A quality characteristic determines the choice of the loss function The value of the overall loss function is further transferred into a signal to noise ratio (S/N) that is identified by η with units of decibels (dB). The best value of the identified parameter is predicted from the S/N curves. A statistical analysis of variance (ANOVA) is performed to see the percentage effect on the output response. At last, a verification test is conducted using the best set of chosen values of the identified variables; this final step is the utmost important in the DOE method [19-21].

Experimental design and optimization

The aim of the experimental research is to explore the influence of wheel and grinding parameters on shape error in interrupted square geometry. Whit this aim in mind a number of experiments was conducted. Grain size of wheel (M), depth of cut (D), feed rate (V) and cutting width (W) were selected as independent parameters to be used in the experiments. The basic stage for achieving the herein above target the wheel and grinding parameters are selected, and the suitable orthogonal array (L_{16}) is established. Grinding parameters and their levels used in this experimental study were given Table 3. Table 4 presents L_{16} orthogonal array, grinding condition, the experimentally measured shape error (SE) values, and S/N ratio for square geometry. For statistical analysis of the experimental data, Minitab 15 software was utilized.

Table 3 Process parameters and their levels

Symbol	Grinding parameters	Levels			
		1	2	3	4
M	Grain size (Mesh)	36	46	60	80
D	Depth of cut (µm)	10	25	40	55
V	Table speed (m/min)	18	22	26	30
W	Width of cut (mm)	1	2	3	4

Table 4 Taguchi design matrix, shape error values and S/N ratio for square geometry

Exp. No.	Coded factors				Actual factors				Response	
	X_1	X_2	X_3	X_4	*M*	*D*	*V*	*W*	SE (µm)	S/N (dB)
1	1	1	1	1	36	10	18	1	18.20	-25.201
2	1	2	2	2	36	25	22	2	21.32	-26.576
3	1	3	3	3	36	40	26	3	29.11	-29.281
4	1	4	4	4	36	55	30	4	31.08	-29.850
5	2	1	2	3	46	10	22	3	19.49	-25.796
6	2	2	1	4	46	25	18	4	25.15	-28.011
7	2	3	4	1	46	40	30	1	22.67	-27.109
8	2	4	3	2	46	55	26	2	26.41	-28.435
9	3	1	3	4	60	10	26	4	22.78	-27.151
10	3	2	4	3	60	25	30	3	25.27	-28.052
11	3	3	1	2	60	40	18	2	21.74	-26.745
12	3	4	2	1	60	55	22	1	20.45	-26.214
13	4	1	4	2	80	10	30	2	18.50	-25.343
14	4	2	3	1	80	25	26	1	19.22	-25.675
15	4	3	2	4	80	40	22	4	19.87	-25.964
16	4	4	1	3	80	55	18	3	21.66	-26.713

RESULTS

Effect of grinding condition on shape error

The shape error of each workpiece is measured from the surface. The measurement of 30 points was taken from the scanned geometry. Here, the largest data was chosen as the shape error. Table 5 presented the mean S/N ratio each level of the factors studied at four levels for the shape error. On the other hand smaller the better quality characteristic for shape error should be taken for obtaining optimal grinding performance. Lower shape error is always preferred. It can be seen from Table 5 that, using 80 mesh grain size resulted in less shape error than among all the four level considered. As can be seen from response table for signal to noise ratios, the smaller the better value for the depth of cut is 10 µm rather than 25, 40 and 55 µm. As regards the table speed, level 2 (22 m/min) generates less shape error than among all the four level. Finally, the preference values for width of cut are 1 mm rather than 2, 3, and 4 mm.

Response table results show that depth of cut is the most influential factor, closely followed by the grain size of wheel. Width of cut and table speed are situated on the third and fourth stage of this arrangement. And also maximum S/N response value at each level gave the minimum shape error. Optimum level is obtained by selection of appropriate values in the wheel and grinding parameters in order to minimize the shape error square geometries. $M_4D_1V_2W_1$ is the best arrangement of parameters for achieving the minimum shape error in square geometry.

Table 5 Response table for signal to noise ratios

Level	Grain size	Depth of cut	Table speed	Width of cut
1	-27.73	-25.87*	-26.67	-26.05*
2	-27.34	-27.08	-26.14*	-26.77
3	-27.04	-27.27	-27.64	-27.46
4	-25.92*	-27.80	-27.59	-27.74
Δ	1.80	1.93	1.50	1.69
Rank	2	1	4	3

*Optimum Level
Δ: Difference between maximum and minimum shape error response value

Table 6 ANOVA results for shape error

Factor	DF	SS	V	F	%
M	3	55.403	18.468	16.99	25.77
D	3	56.026	18.675	17.18	26.06
V	3	50.052	16.684	15.35	23.28
W	3	50.229	16.743	15.41	23.37
Error	3	3.260	1.087	-	1.52
Total	15	214.970	-	-	100

Table 7 Result of the confirmation experiment for shape error (SE)

	Optimal grinding parameters	
	Estimated result	Confirmed result
Level	$M_4D_1V_2W_1$	$M_4D_1V_2W_1$
SE (µm)	11.925	12.10
S/N ratio (dB)	-22.962	-21.655

Analysis of Variance

The analysis of variance (ANOVA) technique on the experimental results was used to quantify the effect of the process parameters on the shape error. ANOVA test for significant differences between the controllable factors by comparing variances [22]. The variations due to all four factors and the error were investigated in this study. Table 6 shows the results of ANOVA analysis and indicates that grain size, depth of cut, table speed, and cutting width are significant (at the 95% confidence level) parameters influence the shape error. From Table 6, it can be seen that the depth of cut (26.06%), grain size (25.77%), cutting width (23.37%), and table speed (23.28%) have statistical and physical significance on the shape error.

Determination of optimal machining parameters for minimum shape error

In this study, the optimum levels of wheel and grinding parameters such as $M_4D_1V_2W_1$ for the minimum shape error were determined. Optimal conditions were not previously found between the experimental conditions. By means of the Minitab 15 software, the minimum shape error (SE=11.925 µm) can be predicted under the above-mentioned cutting conditions (Table 7). Then, as a result of verification experiments in the shape error, 12.10 µm was measured. However, this experimental shape error value (12.10 µm) is lower than other experimental shape error values (Table 4). Shape error in interrupted grinding is greatly decrease thought of the Taguchi approach.

Development of linear shape error mathematical modeling

In the present study, multiple regression analysis is performed to find out the relationship between grinding independent variables and shape error. Grain size of wheel, grinding depth, table speed and cutting width were considered as variables in the development of mathematical models for shape error. Shape error (SE) can be written as follows:

$$SE = f(M, D, V, W) \quad (1)$$

where *SE* is the desierd response anf *f* is the response function. The linear model of shape error can be written as follows:

$$SE = b_0 + b_1A + b_2B + b_3C + b_4D + \mathcal{E} \quad (2)$$

where b_0 is constant, b_1, b_2, b_3 and b_4 represent the coefficients and ε is the error. In this work, Eq. (2) can be rewritten according to the four variables in the coded form:

$$SE = b_0 + b_1M + b_2D + b_3V + b_4W + \mathcal{E} \quad (3)$$

The developed mathematical model for the estimation of the shape error (SE) in surface grinding is expressed in coded units as follows:

$$SE = 14.176 - 0.11159M + 0.10720D + 0.30438V + 1.5645W + \mathcal{E}$$
$$R^2 = 85.9\% \quad (4)$$

In multiple linear regression analysis, R^2 is the correlation coefficient (R^2>0.80) for the models, which indicate that there is a good agreement between the experimental data and created model. In this study, R^2 is found as 0.859 of the value which is larger than (0.8). As seen from this, the regression model for shape error matches fairly good the experimental data.

DISCUSSION

The value of shape error in the interrupted grinding in this study was from 18.20 to 31.08 µm. The shape error diminishes with increasing grain size of wheel, decreasing the depth of cut and width of cut. The ranking of the influence on shape error is grain size, depth of cut, table speed and width of cut (Table 5). When the shape error of the confirmed experiment and the estimated error were compared, it was found that there is a small difference between the estimated value and the confirmed value. This indicates that the predicted values were very close to the experimental results. The shape error according to various grinding conditions could be successfully predicted and minimized easily by using quadratic polinomial model.

CONCLUSION

The shape error in the interrupted surface grinding process was investigated both experimentally and the obtained results were modeled statistically. The lower is the better type of quality characteristic can be used for optimizing the grinding parameters. The depth of cut was the most influential controllable factor among the other grinding parameters to affect the shape error. The grain size of wheel was the second factor on the shape error followed by cutting width and table speed. The best parametric combination of the four control factors was obtained with wheel and grinding conditions such as grain size of wheel 80 (mesh), 10 µm depth of cut, 22 m/min table speed and 1 mm width of cut ($M_4D_1V_2W_1$). The percentage contribution of the depth of cut, grain size of wheel, width of cut, and table speed to the shape error are 26.06%, 25.77%, 23.37%, and 23.28%, respectively. The minimum shape error in the verification experiment results is reached 12.01 µm. The estimated and confirmed optimum values of S/N ratio were found to be -22.962 and -21.655 dB (11.925 and 12.10 µm, respectively). A linear model for the shape error was developed from the experimental data based on response surface methodology.

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