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Investigations on the Influence of Processing Conditions on Grinding Process

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Abstract — This paper details an in-depth assessment of the effect of processing conditions on the performance of grinding process. The experimental data was collected based on the design of Taguchi L_{18} fractional factorial mixed level scheme. In addition to the standard processing conditions in grinding, viz. number of passes, depth of cut and work speed; duty ratio and voltage were introduced in this comprehensive analysis. Five process outputs chosen: material removal rate (MRR), surface roughness, surface hardness, normal grinding force and tangential grinding force. The results of the investigation showed that MRR is significantly controlled by work speed, duty ratio and depth of cut. The MRR increases linearly with work speed, and the resulting improvement was observed to be 26%. The surface roughness decreases with an increase in number of passes as well as the voltage. The hardness increases linearly with the depth of cut. A decrease in normal force (F_n) with voltage is observed. All the normal probability plots for the five process output indicate linear relationship between probability and residuals.

Keywords — Electrolytic Grinding, Processing conditions, Taguchi array, Parametric analysis, Controlling factor and Normal probability plot.

I. INTRODUCTION

Grinding processes are used to smooth or improve surface finish quality. Grinding is a complex, material- removal process with a great number of influencing factors, which are non-linear, interdependent and difficult to quantify [1-5]. To maximize the surface quality, the selection of grinding parameters is vital; the vibration and surface roughness is chiefly affected by the selection of grinding parameters. So many factors influence the grinding process that a reproducible workpiece quality is rarely, if ever, achieved. Although many efforts have been made to predict the parameters of the grinding process, many difficulties remain because abrasive processes are dynamic in nature unlike turning and milling processes, as the cutting edges of the grinding wheel are not uniform and act differently on the workpiece at each grinding [1]. To predict the parameters of the grinding process, it is necessary to quantify surface roughness, which is one of the most critical quality constraints for the selection of grinding parameters in process planning. Cylindrical grinding is an essential process for final machining of components requiring smooth surfaces and precise tolerances. Although widely used in industry, grinding remains perhaps the least understood of all machining processes [2]. The major operating input parameters that influence the output responses, metal removal rate, surface roughness, surface damage, and tool wear, etc. are (i) wheel parameters: abrasives, grain size, grade, structure, binder, shape and dimension, etc. (ii) Work piece parameters: fracture mode, mechanical properties and chemical composition, etc. (iii) Process parameters: work speed, depth of cut, feed rate, dressing condition, etc. (iv) machine parameters: static and dynamic Characteristics, spindle system, and table system, etc. The knowledge is mainly in the form of physical and empirical models which describe various aspects of grinding process [2-8]. A software package has been developed which integrates these various models to simulate what happens during cylindrical grinding processes. Predictions from this simulation are further analyzed by calibration with actual data. It involves several variables such as depth of cut, work speed, feed rate, grit size, type of abrasive, chemical composition of wheel, etc. An assessment of the grinding-process quality usually includes the micro-geometric quantities of the component [3]. In order to predict the component behavior during the use or to control the grinding process, it is necessary to quantify surface roughness, which is one of the most critical quality constraints for the selection of grinding factors in a process planning. The empirical conditions having restricted range of validity are conventionally used in practice because grinding process involves many uncontrollable parameters [4]. So the ground surface quality with these conditions is not reliable or acceptable in any specific situation. To achieve the required surface quality in a specific situation, process parameters can be determined through a series of experimental runs [5]. But, that may be a time-consuming and expensive method and also it cannot determine the exact optimum because of restricted experiments. Taguchi and response surface methodologies can conveniently optimize the grinding parameters with several experimental runs well designed [6]. Many investigations have been carried out to understand relationship between grinding conditions and their influence on machining. Existing techniques employed to deal with the selection of grinding conditions can be classified as follows: i) data retrieval methods, ii) process model methods, iii) artificial intelligence (AI) methods. The data retrieval method uses a database of cutting conditions either as suggested in the hand book or gathered from the industrial field [7]. Though computerized machine ability database systems are available for turning, drilling and milling, only few covers grinding. The process models for grinding, both physical and empirical models, contribute significantly to the understanding of the process. However, as many uncontrolled parameters are involved in the grinding process, physical models cannot have a comprehensive definition and empirical models have restricted range of validity [3]. So, the process models are not reliable in practice. AI methods include rule based reasoning; care based reasoning, artificial neural networks, hybrid systems, etc. Each of these methods has its own limitations in giving a comprehensive and precise relationship between the grinding variables and the grinding behavior in a specific situation. To achieve the required quality requirements in a specific situation, operating parameters are often determined with the aid of grinding tests [8]. If more number of parameters are there the conventional testing methods are time consuming and expensive. Here lies the importance of the Taguchi methods for the design of experiments. Krishna and Rao [1] proposed a scatter search based optimization approach to optimize the grinding parameters of wheel speed, workpiece speed, and depth of dressing and lead of dressing using a multi-objective function model with a weighted approach for the surface grinding process. Habib [2] developed a comprehensive mathematical model for correlating the interactive and higher order influences of various electrical discharge machining parameters through RSM, utilizing relevant experimental data as obtained through experimentation. Another important work was presented by Agarval and Rao [3] about grinding parameter optimization. As a result of their study, a new analytical surface roughness model was developed on the basis of the stochastic nature of the grinding process, governed mainly by the random geometry and the random distribution of cutting edges on the wheel surface having random grain protrusion heights. Malkin [4] investigated the process monitoring and studied various grinding aspects such as cutting mechanisms, the specific energy and the interrelationship of the parameters. His research showed that the grinding process had very complex cutting mechanisms and that replicability of results was difficult to obtain under the same grinding conditions. Shaji [5] reported a study on the Taguchi method for evaluating process parameters in surface grinding with graphite as a lubricant. They analyzed the effect of the grinding parameters (wheel speed, table speed, depth of cut and the dressing mode) on the surface finish and the grinding force. Kwak [6] showed that the various grinding parameters caused a geometric error generated during the surface grinding, using the Taguchi method, and that the geometric error could be predicted by means of the response surface method. Usually, the equation for predicting cutting time is unknown during the early stages of cutting operations. Jeang [7] studied to determine the optimal cutting parameters required to minimize the cutting time while maintaining an acceptable quality level. He formulated an objective function using a software, with assistance from the statistical method and response surface methodology. Results showed the statistical method in cooperation with the optimal solutions found from mathematical programming can also be used as references for the possibility of robust design improvements. Babu [8] has applied grey relational analysis for optimization of grinding process. In their work, measurements were done for i) material removal rate, ii) surface roughness, iii) hardness, iv) normal force and v) tangential force. Elaborate analyses of grinding data to evaluate the effect of processing conditions on grinding process, have not been investigated so far. Therefore, the objective of this work is to apply statistical techniques to evaluate the grinding process as a function of the processing conditions.

II. EXPERIMENTAL WORK

In this section, the experimental design, experimental procedure and selection of processing conditions are discussed.

Experimental design: Taguchi methods of experimental design provide a simple, efficient and systematic approach for the optimization of experimental designs for performance quality and cost. The traditional experimental design procedures focus on the average product or process performance characteristics. But the Taguchi method concentrates on the effect of variation on the product or process quality characteristics rather than on its averages. That is, the Taguchi's approach makes the product or process performance insensitive to variation to uncontrolled or noise factors. Taguchi recommends that this can be done by the proper design of parameters during the 'parameter design' phase of off-line quality control. He designed certain standard orthogonal arrays (OAs) by which simultaneous and independent evaluation of two or more parameters for their ability to affect the variability of a particular product or process characteristic can be done in a minimum number of tests. Subsequently, decision is made for the optimum combination of these parameters. The parameter design phase of the Taguchi method generally includes the following steps: (1) identify the objective of the experiment; (2) identify the quality characteristic (performance measure) and its measurement systems; (3) identify the factors that may influence the quality characteristic, their levels and possible interactions; (4) select the appropriate OA and assign the factors at their levels to the OA; (5) conduct the test described by the trials in the OA; (6) analysis of the experimental data using the signal-to-noise (S/N) ratio, factor effects and the ANOVA (analysis of variance) to see which factors are statistically significant and find the optimum levels of factors; (7) verification of the optimal design parameters through confirmation experiment.

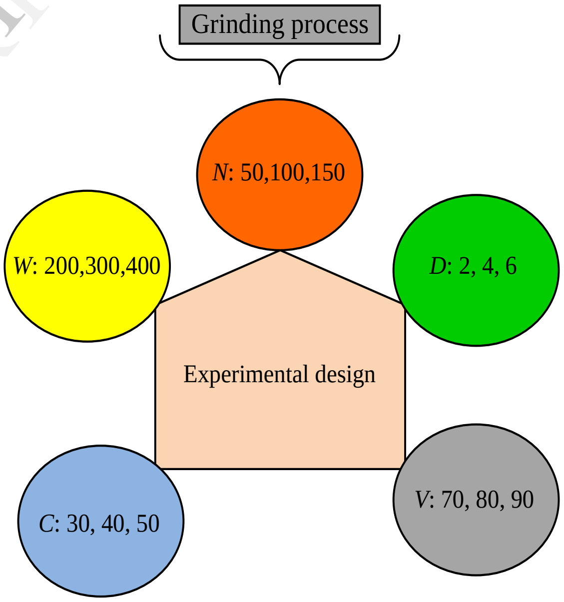

Fig. 1 The processing conditions for grinding process (parameters and their levels)

In this work, the processing parameters used were: i) number of pass (*N*), ii) work speed (*W*) in mm/min, iii) depth of cut (*D*) in µm, iv) current duty ratio (*C*) in % and v) voltage (*V*) in volts [8]. The parameters, their range and levels are presented in Fig. 1. A fractional factorial design was used based on the L_{18} orthogonal array.

Experimental procedure: A surface grinding machine was used for conducting the experiments. The electrode material was copper. The workpiece and dynamometer were assembled and set over the machine table. Electrolyte was passed between the electrode and the grinding wheel.

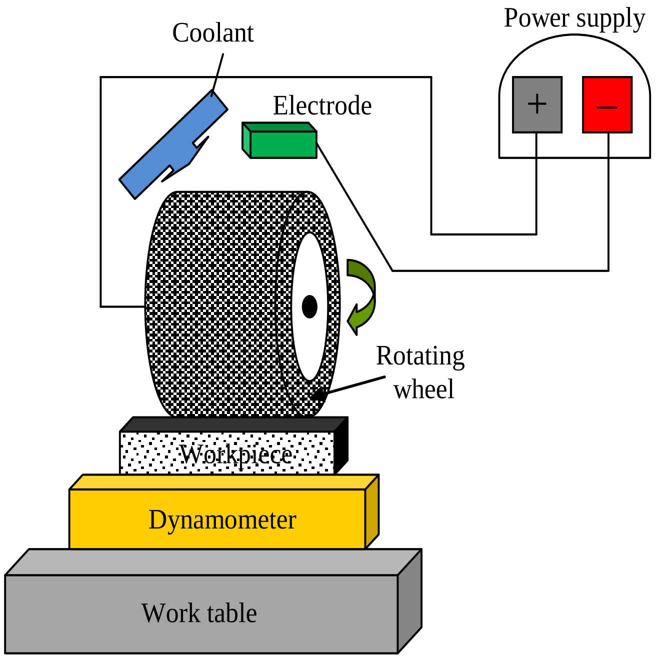

Fig. 2 A schematic of the electrolytic grinding process

The process outputs chosen in this study were: material removal rate, roughness of surfaces generated, hardness of surfaces, normal force and tangential force [8]. The material removal rate was obtained after finding the weight loss during the grinding process. A mitutoyo surftest equipment was used to measure the roughness of machined surfaces. The micro-hardness was measured using a Vickers micro-hardness tester. The tangential and normal forces were obtained using a digital dynamometer.

Table 1 The grinding process outputs (MRR, Ra, Hardness, F_n and F_t [8]

Sl. No	MRR (g/min)	Surface roughness, R_a (µm)	Hardness (HV)	Normal force, F_n (N)	Tangential force, F_t (N)
1	2.78	1.96	120	6.96	0.99
2	2.58	1.42	131	5.78	0.82
3	2.43	1.45	131	5.28	0.74
4	3.62	1.98	120	4.80	0.78
5	2.65	1.46	139	6.28	0.88
6	2.62	1.82	132	7.12	1.12
7	3.98	1.92	135	5.98	0.86
8	2.79	1.78	128	6.37	0.84
9	3.38	1.33	139	8.24	1.08
10	2.81	1.35	125	4.98	0.86
11	2.91	1.92	131	8.86	1.14
12	2.92	1.62	138	9.25	1.21
13	3.06	1.56	119	7.92	0.91
14	2.86	1.36	113	7.29	0.82
15	2.95	1.68	123	10.02	1.25
16	3.23	1.37	131	7.82	0.79
17	3.52	1.42	130	7.51	0.77
18	3.12	1.31	137	10.80	1.34

III. PARAMETRIC ANALYSIS

To understand the influence of processing conditions on the outputs of the process, parametric analysis is performed. Each response variable is chosen separately, and the effects of individual parameters on these variables are estimated independently. This method helps understand the variation in the output with the variation of parameters at different levels. The results of parametric analysis are under the following two heads: i) evaluation of parametric significance using general linear model and ii) evaluation of the trends of grinding process outputs with the input processing conditions.

Parametric analysis of material removal rate: The parametric analysis of material removal rate was conducted based on a general linear model connecting the processing conditions of *N*, *W*, *D*, *C* and *V*. The results are presented in Table 2. It is observed that work speed (mm/min) is the most significant factor at 95% significance level, with an ‘F’ value of 6.9 and a ‘P’ value of 0.018. The factors *D* (depth of cut) and *C* (duty ratio) are significant at 90% confidence level, with the ‘F’ values of 3.1 respectively. The factors *N* (number of passes) and *V* (voltage) are not significant for the present processing conditions. The variations of MRR with these three factors are shown in Figs. 3, 4 and 5 respectively.

Table 2 General linear model for material removal rate (g/min)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
N	1	0.0156	0.0156	0.0156	0.2	0.56
W	2	1.100	1.100	0.5500	6.9	0.018
D	2	0.495	0.495	0.2470	3.1	0.100
C	2	0.498	0.498	0.2490	3.1	0.099
V	2	0.015	0.015	0.0077	0.1	0.908
Error	8	0.637	0.637	0.079		
Total	17	2.7618				

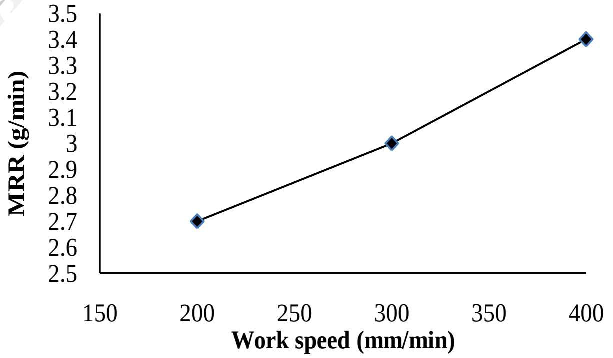

Fig. 3 The relationship between MRR and work speed

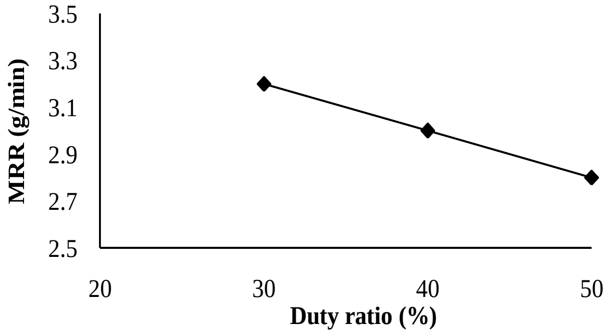

Fig. 4 The relationship between MRR and duty ratio

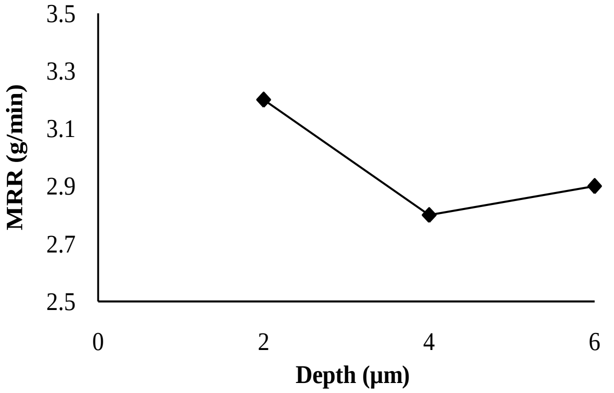

Fig. 5 The relationship between MRR and depth

It is evident from Fig. 3 that the MRR increases linearly with the work speed. As the work speed increases from 200 to 400 mm/min, the MRR increases by 26%. This could be because of the enhancement of material removal in grinding process due to an increase in the work speed. As the duty ratio increases from 30 to 50, a decrease in MRR by 16%, is observed. The relationship is linear decrease at all the processing conditions, please refer Fig. 4. The plot between MRR and depth is shown in Fig. 5. It is observed that the central level of depth (4 µm) yields the lowest MRR. As the depth increases from 2 to 4 µm, the MRR decreases by 19%. However, as the depth increases from 4 to 6 µm, the MRR increases by 8%. Therefore, a variation in the MRR is observed with increase in depth of cut. Further, the normal probability plot presented in Fig. 6 indicates a linear relationship with the probability and the residuals, for the process output MRR.

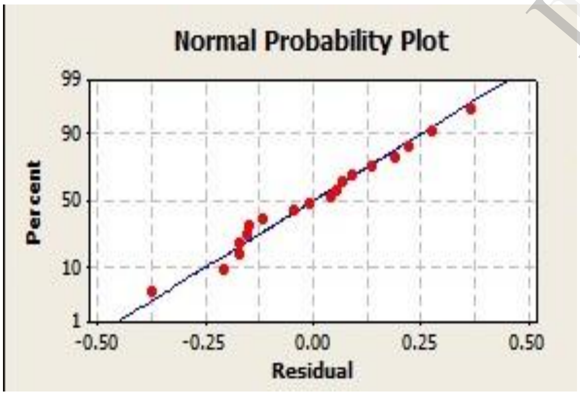

Fig. 6 Normal probability plot for MRR

Parametric analysis of surface roughness: Similar to the earlier model for material removal rate, analysis was done based on a general linear model for surface roughness (R_a) with the processing conditions of *N*, *W*, *D*, *C* and *V*. The result is presented in Table 3. Among the five input parameters, the voltage, *V* was significant at 90% confidence level and number of pass, *N* at 85% confidence level. This is confirmed by the significance of parameters from Table 3. The highest ‘F’ value is observed for voltage (3.1) and is followed by number of passes (3.0). Accordingly, the lower ‘P’ values are observed for voltage (0.10) and number of passes (0.12). The other factors, viz. work speed, duty ratio and depth of cut are relatively less influential for surface roughness.

Table 3 General linear model for surface roughness (µm)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
N	1	0.13	0.13	0.130	3.0	0.12
W	2	0.05	0.05	0.025	0.5	0.50
D	2	0.08	0.08	0.040	0.9	0.42
C	2	0.13	0.13	0.060	1.5	0.27
V	2	0.26	0.26	0.130	3.1	0.10
Error	8	0.34	0.34	0.04		
Total	17	1.00				

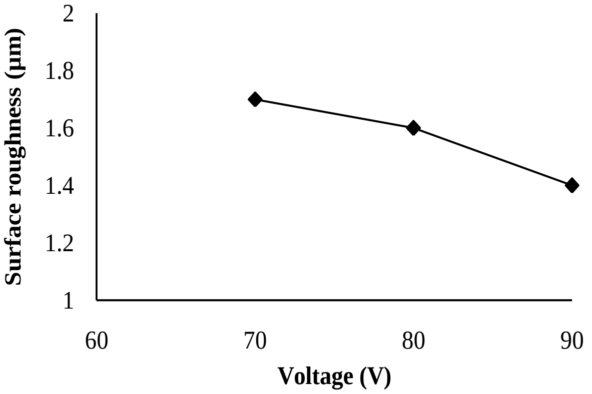

Fig. 7 The relationship between surface roughness and voltage

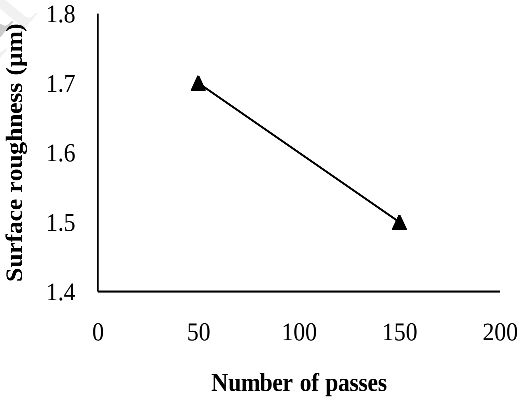

Fig. 8 The relationship between surface roughness and number of passes

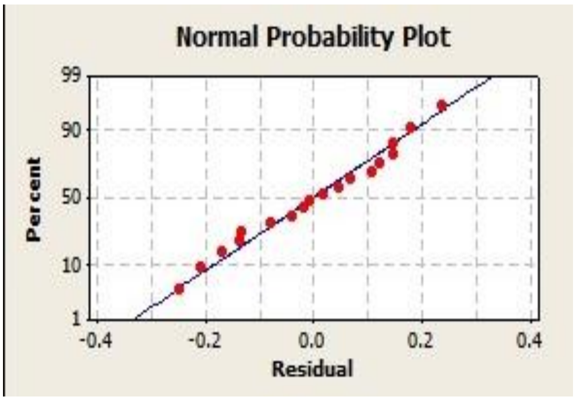

Fig. 9 Normal probability plot for surface roughness

The trends of the surface roughness are shown in Figs. 7 and 8. The normal probability plot is presented in Fig. 9. As the voltage increases from 70 to 90 V, a slight decrease in surface roughness is observed. Similarly, as the number of passes increases from 50 to 150, a drastic reduction in surface roughness is achieved.

Parametric analysis of surface hardness: The parametric analysis for hardness is presented in table 3. The general linear model was used for this analysis. From table 3, it is evident that work speed (*W*) and depth (*D*) control the hardness of the ground surfaces.

Table 3 General linear model for surface hardness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
N	1	43.56	43.56	43.56	1.15	0.315
W	2	244	244	122	3.22	0.094
D	2	209.33	209.33	104.67	2.76	0.122
C	2	157	157	78.5	2.07	0.188
V	2	21	21	10.5	0.28	0.765
Error	8	303.11	303.11	37.89		
Total	17	978.0				

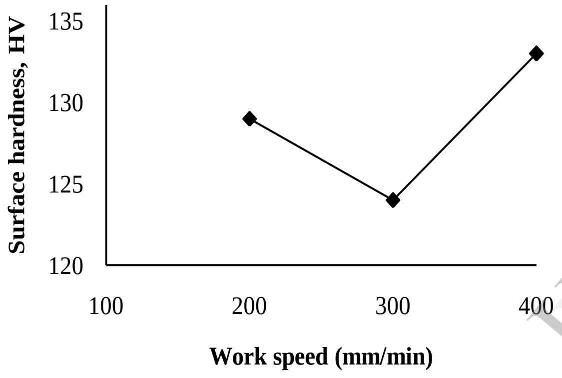

Fig. 10 The relationship between surface hardness and the work speed in grinding

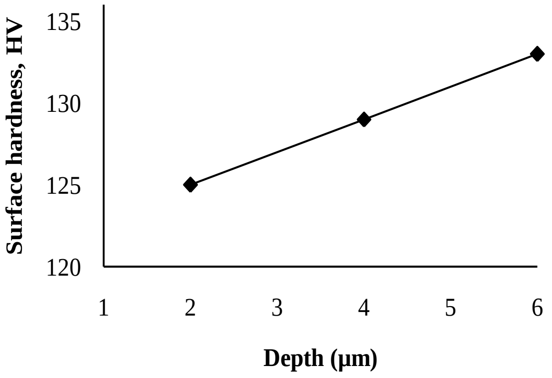

Fig. 11 The relationship between surface hardness and the depth in grinding

It is observed that the central level of work speed of 300 mm/min gives the lowest surface hardness of 124 HV (see Fig. 10). As the work speed increases from 200 to 300 mm/min, the hardness decreases by 5 HV. Further, as the work speed increases from 300 to 400 mm/min, the hardness increases by 9 HV. With an increase in depth from 2 to 6 µm, the surface hardness increases linearly. The normal probability plot presented in Fig. 12 also indicates a linear relationship.

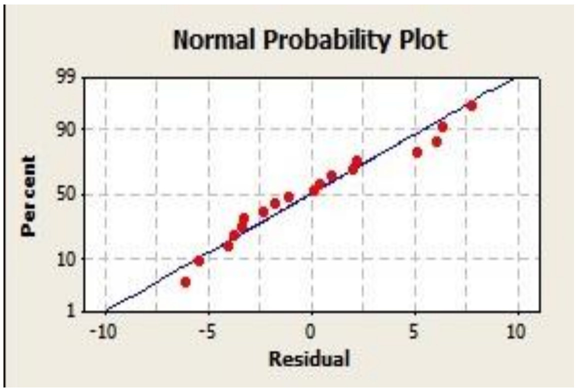

Fig. 12 Normal probability plot for surface hardness

Parametric analysis of normal force: Table 4 shows the analysis of normal force data based on a general linear model. As evident from the table, the factors number of passes (*N*), depth (*D*), duty ratio (*C*) and voltage (*V*) influence the normal force (F_n).

Table 4 General linear model for normal force

Source	DF	Seq SS	Adj SS	Adj MS	F	P
N	1	17.2872	17.2872	17.2872	22.02	0.002
W	2	2.6488	2.6488	1.3244	1.69	0.245
D	2	13.1969	13.1969	6.5984	8.41	0.011
C	2	5.9982	5.9982	2.9991	3.82	0.068
V	2	3.8739	3.8739	1.9369	2.47	0.146
Error	8	6.2799	6.2799	0.7850		
Total	17	49.2849				

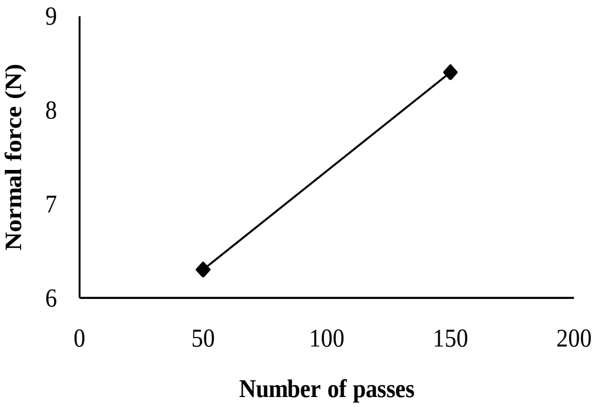

Fig. 13 The relationship between normal force and the number of passes

Figs. 13, 14, 15 and 16 show the relationships between normal force and different factors: *N*, *D*, *C* and *V*. From these plots, it is evident that the normal foce increases linearly with number of passes. As the depth increases from 2 to 6 µm, the normal force increases by 31%. The normal force decreases with an increase in duty ratio. As the voltage increases from 70 to 80 V, the normal force decreases by 5%. Furthermore, with an increase in voltage from 80 to 90 V, a decrease in normal force by 8% is observed. The normal probability plot presented in Fig. 17 gives a linear relationship, as anticipated.

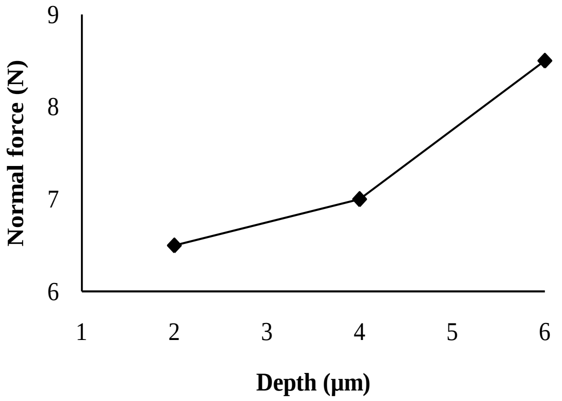

Fig. 14 The relationship between normal force and the depth

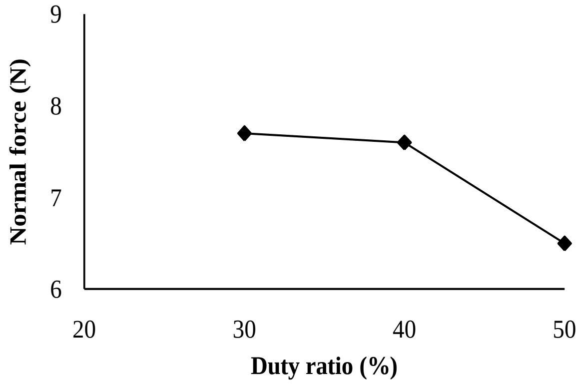

Fig. 15 The relationship between normal force and the duty ratio

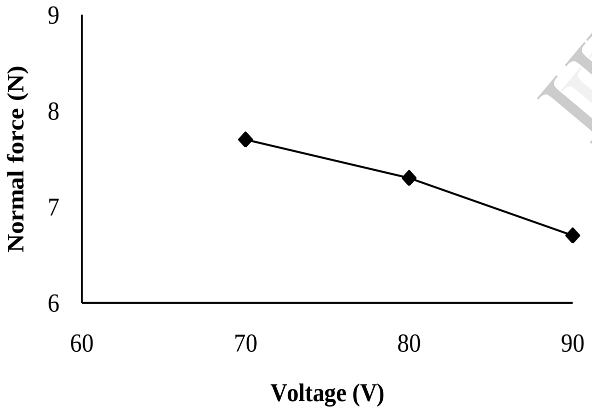

Fig. 16 The relationship between normal force and the voltage

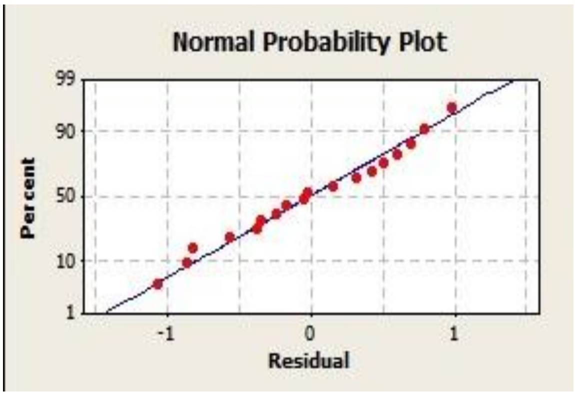

Fig. 17 The normal probability plot for normal force (F_n)

Parametric analysis of tangential force: The analysis of tangential force for the grinding process, based on the general linear model is shown in Table 5. As evident from table 5, number of passes (*N*) and depth (*D*) are significant at 90% confidence level. The duty factor and voltage are significant at 85% confidence level.

Table 5 General linear model for tangential force

Source	DF	Seq SS	Adj SS	Adj MS	F	P
N	1	0.05336	0.05336	0.05336	3.68	0.091
W	2	0.00071	0.00071	0.00036	0.02	0.976
D	2	0.25388	0.25388	0.12694	8.75	0.010
C	2	0.07934	0.07934	0.03967	2.73	0.124
V	2	0.08888	0.08888	0.04444	3.06	0.103
Error	8	0.11608	0.11608	0.01451		
Total	17	0.59224				

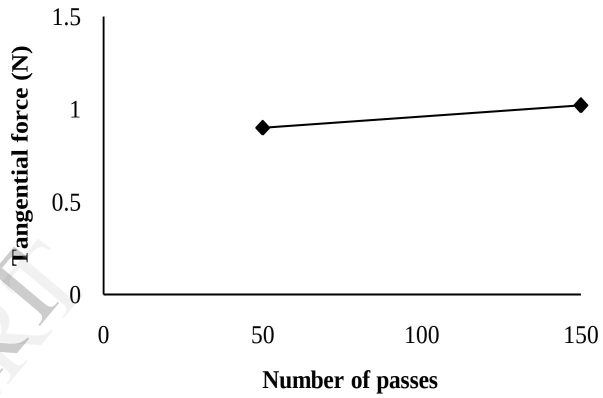

Fig. 18 The relationship between tangential force and the number of passes

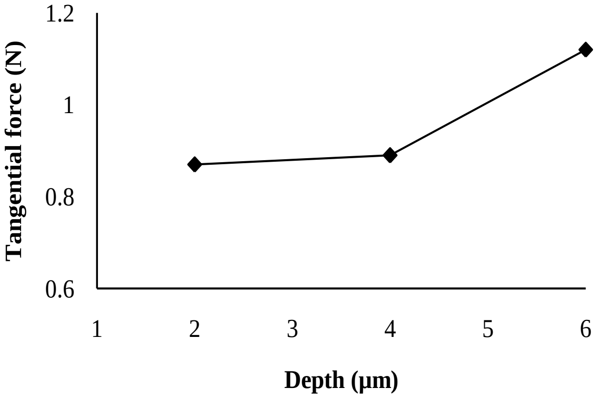

Fig. 19 The relationship between tangential force and the depth

As the number of passes increases from 50 to 150, a linear increase in the tangential force is observed, see Fig. 18. The increase in the tangential force is by 13%. Further, with an increase in the depth, an increase in the tangential force is obtained (Fig. 19).

V. CONCLUSIONS

The investigation on the influence of processing conditions on grinding process is performed. A detailed parametric analysis considering number of pass, work speed, depth of cut, duty ratio and voltage as the input conditions is performed. The following conclusions can be drawn:

- The design of experiment was based on the L_{18} orthogonal array. Considering the process outputs, the average MRR was observed to be close to 3 g/min. The work speed, duty ratio and depth of cut significantly control the process MRR.
- The trends of process outputs were captured using the plots of the outputs with the processing conditions. The variation of MRR with work speed was linear increase, whereas those with duty ratio and depth were of linear decrease, as obtained. The result is because of an increase in debris with removal with an increase in speed.
- A finer surface finish and better ground surface quality could be achieved by increasing the voltage upto 90 V and the number of passes upto a maximum level of 150.
- A linear variation of probability with residuals in normal probability plots of MRR, surface roughness, surface hardness, normal force and tangential force indicate the reliability of data chosen for the investigation of the effect of processing conditions.
- The normal grinding force increase linearly with number of passes and depth of cut. It is therefore, evident that the number of passes beyond 150 and a depth of cut beyond 6 µm could cause significant increase in the normal grinding force.
- It is observed that an increase in the depth of cut from 4 to 6 µm, causes a considerable linear increase in the tangential grinding forces. The sudden increase was observed to be 30%.

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