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Original scientific paper

Multi Criteria Optimization Approach for Dressing of Vitrified Grinding Wheel

M. A. K. CHOWDHURY, Ateekh Ur REHMAN, M. S. UDDIN, Mohammed ALKAHTANI, Saqib ANWAR

Abstract: Rotary diamond dressers are widely used for the dressing to improve the efficiency of vitrified grinding wheel. The paper focuses on the process parameters, i.e., feed speed of dresser, depth of cut, grinding wheel velocity, velocity ratio between grinding wheel and rotary dresser, number of pass and dressing method (up-cut or down-cut) in rotary diamond dressing. The objective is to investigate the effect of these process parameters with their interactions for two response parameters, dressing ratio and overlapped dressed area. As far as the response parameters are concerned, the goal is to maximize dressing ratio and minimize overlapped dressed area simultaneously. Thirty-six experiments were designed and performed. Analysis of variance and multi-criteria optimization approach are opted to find out significant process parameters and optimal parameter setting. Finally, the significant process parameters, dressing method and number of pass are identified as well and the optimal parameter setting is also determined.

Keywords: grey relational grade; multi-criteria decision approach; rotary diamond dressing; signal to noise ratio

1 INTRODUCTION

In the manufacturing industry, grinding is the most commonly used material removal process to achieve superior finish and geometric integrity on machined work piece [1]. A grinding wheel is a cutting tool, which has abrasive grains distributed throughout the wheel [2]. The material removal efficiency of a grinding wheel decreases with the underlying grinding operations, e.g., cutting forces due to complex interactions between fixed hard abrasive grits and work piece surface, thus affecting the grinding performance. To restore the removal efficiency of the grinding wheel, dressing is required [3]. The restoration of removal efficiency is performed by sharpening and protruding the abrasive cutting edges on the working surface of the grinding wheel. Mechanical dressing is one of the useful options [4]. The rotary diamond dresser is commonly used as mechanical dresser for dressing grinding wheels, particularly, for vitrified grinding wheel [5]. The grinding wheel surface topography generated from dressing affects the performance of subsequent grinding operation [6, 7]. Therefore, dressing conditions, i.e., parameter setting of dressing has significant effect on the dressing performance and on the grinding performance as well.

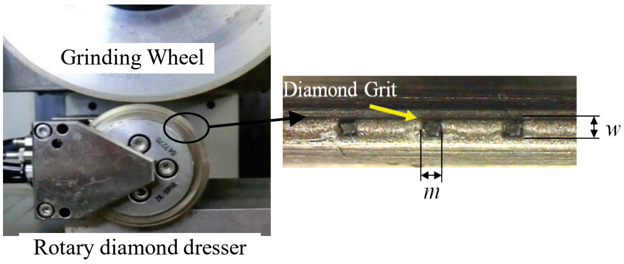


Figure 1 Rotary diamond dressing and geometry of rotary diamond dresser

A rotary diamond dresser has diamond grits embedded on the working surface of the dresser, as shown in Fig. 1. In this study, a rotary diamond dresser is selected, where equally sized diamond grits in a given orientation are embedded onto the working surface. These diamond grits are embedded at regular distance with a constant protrusion height and the cross sectional area of the diamond grits forms a square of side $m = w$ (see Fig. 1). In rotary diamond dressing, both dresser and grinding wheel rotate in the same (up-cut) or opposite direction (down-cut).

While performing dressing, an overlap between the dresser and the grinding wheel is created which is called depth of cut. At the same time, a relative motion, i.e., feed of dresser, is also maintained between the dresser and the grinding wheel. If the whole area of the grinding wheel is not possible to be dressed by a single pass of dresser, multiple passes are applied. The design parameters of rotary diamond dressing are grinding wheel diameter, rotary diamond dresser diameter, number and size of diamond grit on the circumferential surface of rotary diamond dresser, and the process parameters of rotary diamond dressing are feed speed of dresser, depth of cut, velocity ratio between grinding wheel and rotary diamond dresser, number of pass (single or multiple) and dressing method (up-cut and down-cut). There are two important response parameters resulting from the interaction of the above design and process parameters in the dressing operation, which dictate the end performance of the dressing. They are dressing ratio (percent of circumferential area of grinding wheel that has been dressed) [5, 8-11] and overlapped dressed area (percent of circumferential areas of grinding wheel that are dressed more than once) [8] (refer to Fig. 2).

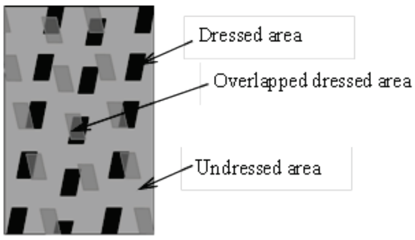


Figure 2 Grinding wheel surface after dressing

The main aim of dressing is to sharpen the abrasive gains of the whole circumferential surface of grinding wheel [12]. To realize the above mentioned objective, the dresser needs to hit all areas of the circumferential surface of the grinding wheel (high dressing ratio) without hitting the same location repeatedly (low overlapped dressed area) [5, 13]. Therefore, in dressing operation, dressing ratio and overlapped dressed area are two critical response parameters for measuring dressing performance directly. It can also be stated that the two response parameters of dressing have conflicting goals. Thus, often it is quite difficult to obtain the optimum performance of the dressing operation and hence, an optimization approach is needed to tackle this problem, identifying the best set of parameters for dressing. In this paper, we did not consider the surface profile of grinding wheel in the depth wise direction and wear of rotary dresser.

In the past, many authors have studied the effect of different dressing parameters on dressing performance and generation of improved grinding wheel surface topography. Xie et al. [14] conducted electro contact discharge dressing experiments to identify the effect of grit protrusion on grinding performance. Klocke and Linke [15] developed a FE (finite element) model for grinding wheel and showed how the wheel wear is affected by different dressing parameters. Bzymek [16] developed a virtual dressing and truing operation model considering vibration of dressing apparatus. In this model, a user is allowed to define the diamond profile of the grit and the virtual model generates the windowed profile of the grinding wheel surface and surface roughness value. Chowdhury et al. [13] developed the analytical model for rotary diamond dressing correlating the parameters of dressing operation, rotary diamond dresser, and grinding wheel. Later on, Chowdhury et al. [5] developed a simulation system to visualize the grinding wheel topography after rotary diamond dressing. Until now, to the best knowledge of the authors, no study focuses on multi-criteria optimization for obtaining optimal parameter setting for dressing.

Optimization of multiple response parameters is a complex scenario as compared to single response parameter [17]. For single response parameter, Taguchi method can provide optimal parameter settings effectively. However, in case of multiple response parameters with contradictory objectives, Taguchi method is not often an effective solution. Grey based Taguchi is getting attention by many researchers as a tool to analyse the processes that have multiple response parameters [18]. Huang and Liao [19] optimized the machining parameters for wire electrical discharge machining using the grey based Taguchi relational analysis. Wang et al. [20] used a hybrid method of design of experiment and grey relational analysis to identify critical criteria and their interactions of multiple criteria decision making problem of different manufacturing processes. Khan et al. [21] investigated the effect of wire electrical discharge machining process parameters on surface roughness of stainless steel specimens using Taguchi based grey relational analysis. Dabade [22] performed multi objective optimization using grey relational analysis to improve the surface integrity of turning process parameters in machining of Al/SiCp composites. Jayaraman and Kumar [23] identified the optimum levels of machining parameters of turning AA6063 T6 aluminium alloy based on values of grey relational grade and then determined the significant contribution of parameters by ANOVA. Uddin [24] studied the effect of process parameters and deployed multi-objective optimization approach to determine the optimum set of turning parameters to achieve the best surface finish and circularity of a metallic hip femoral head. Maiyer et al. [18] illustrated that Taguchi based grey relational analysis is an effective tool for optimization of machining parameters of end milling of Inconel 718 alloy. Patel et al. [25] used grey relation analysis to obtain the single optimal process parameter setting for both responses surface roughness and casting destiny in squeeze casting process. Until now, however, grey based Taguchi approach has not been applied in rotary diamond dressing process for obtaining optimal parameter setting. It can be added that rotary diamond dressing has complex relationships among its process parameters which affect the dressing performance [5, 12]. The grey system theory is found to be useful when complicated inter-relationships among multiple performance response parameters need to be optimized effectively [26, 27]. Grey based Taguchi approach converts the complicated multiple performance response parameters into optimization of a single grey relational grade. As mentioned earlier, optimization of parameters of rotary diamond dressing has multiple response parameters with conflicting objectives (high dressing ratio and low overlapped dressing area). Furthermore, most researchers did not study the combined influence of process parameters on the performance responses. In this research, grey based Taguchi approach is utilized for multiple response optimizations of rotary diamond dressing and to study the effect of the mentioned process parameters along with their interaction with the dressing response parameters.

2 EXPERIMENTAL WORK

For the experimental work, six process parameters (as mentioned earlier) each at either three or two levels have been decided. The process parameters are renamed as factors and the levels of the individual parameters are given in Tab. 1. Usually when an experiment has a mix level of qualitative and quantitative factors (refer Tab. 1), mixed level factorial experimental designs are used [28, 29]. Considering experimental cost required and strenuous measurement method, screening of experiments is done by using mixed level fractional factorial design. Here in the study mixed fractional factorial design of L36 ($2(3-1) \times 3(3-1)$) is used [29, 30]. Using L36 orthogonal array, process parameters are set and respective output response parameters namely dressing ratio and overlapped dressed area are obtained. We used a surface grinding machine for dressing and selected prismatic rotary diamond dresser (SDR50L, Noritake Co. Ltd.) as dressing tool. The design parameters of the selected prismatic rotary diamond dresser are as follows: diameter is 50 mm, number of diamond grits are 120 and the size of each diamond grit is 0.2 mm (i.e., $m = w = 0.2$). In case of vitrified diamond grinding wheel, commonly employed depth of cut is 2 μm to 10 μm during dressing. In this research, depth of cut of 2-6 μm is employed during dressing. Rotary diamond dressing is a type of mechanical cutting process and the transferability of the dressing trajectory determines the topography of the working surface of the grinding wheel [4]. In this study, a vitrified diamond grinding wheel of diameter 150 mm is dressed under oil-mist lubrication. 3D Laser scanning microscope is used for the visualization and measurement of dressed area and overlapped dressed area of grinding wheel surface (refer to Fig. 3(a)-(b)). In this research, we have studied 10 mm^2 of surface area in the middle part of grinding wheel for each experimental run for the measurement of dressed area and overlapped dressed area. It can be added that in each consecutive pass (i.e., 2nd pass, 3rd pass and so on) the depth of cut is increased which enables the measurement of the dressed area in each pass, as the surface height of dressed area of a pass and dressed area in the following consecutive pass are different due to increased depth of cut.

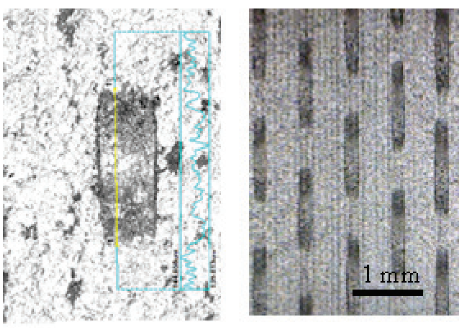
Table 1 Factors and their levels considered in this study

Factors	Type of Parameter	Symbol	DOF	Levels		
				1	2	3
Feed of dresser (mm/min)	PP	A	1	1000	2500	
Dressing method	PP	B	1	up	down	
Grinding wheel velocity (m/sec)	PP	C	1	36.7	51.3	
Depth of cut (µm)	PP	D	2	2	4	6
Velocity ratio	PP	E	2	0.5	0.7	0.9
Number of pass	PP	F	2	1	2	3
Size of diamond grit (mm)	DP	G	0	0.2		
Number of diamond grit	DP	H	0	120		
Grinding wheel dia (mm)	DP	I	0	140		
Rotary diamond dresser dia (mm)	DP	J	0	50		
Note: PP- Process Parameter, DP- Design Parameter, DOF- Degree of Freedom						

Table 2 Levels of process parameters based on L36 standard orthogonal array

Factor (refer above Tab. 1)							Factor (refer above Tab. 1)						
Exp. No.	A	B	C	D	E	F	Exp. No.	A	B	C	D	E	F
1	1	1	1	1	1	1	19	2	1	2	1	2	1
2	1	1	1	2	2	2	20	2	1	2	2	3	2
3	1	1	1	3	3	3	21	2	1	2	3	1	3
4	1	1	1	1	1	3	22	2	1	2	1	2	2
5	1	1	1	2	2	1	23	2	1	2	2	3	3
6	1	1	1	3	3	2	24	2	1	2	3	1	1
7	1	1	2	1	1	2	25	2	1	1	1	3	2
8	1	1	2	2	2	3	26	2	1	1	2	1	3
9	1	1	2	3	3	1	27	2	1	1	3	2	1
10	1	2	1	1	1	3	28	2	2	2	1	3	2
11	1	2	1	2	2	1	29	2	2	2	2	1	3
12	1	2	1	3	3	2	30	2	2	2	3	2	1
13	1	2	2	1	2	3	31	2	2	1	1	3	3
14	1	2	2	2	3	1	32	2	2	1	2	1	1
15	1	2	2	3	1	2	33	2	2	1	3	2	2
16	1	2	2	1	2	3	34	2	2	1	1	3	1
17	1	2	2	2	3	2	35	2	2	1	2	1	2
18	1	2	2	3	1	2	36	2	2	1	3	2	3

The impact of each process parameters at either three or two levels and their interactions are studied. For each trial experiment in the L36 array, the levels of the design and process parameters are indicated in Tab. 2. The design parameters: grinding wheel diameter, rotary diamond dresser diameter, number and size of diamond grits of the rotary diamond dresser are kept constant for the whole set of experiments (refer to Tab. 1).



(a) (b)

Figure 3 Dressed vitrified diamond grinding wheel (a) Microscopic view of a dressing trajectory (b) Dressing trajectories

After each run of experiment, the output parameters as the response parameters (dressing ratio and overlapped dressed area) are obtained. In presented multi-criteria approach, there is a need to obtain the signal to noise ratio for both response parameters for each experiment. The attempt is made to calculate and analyze the signal to noise ratio for all experiments, which is presented in the following section.

3 ANALYSIS OF SIGNAL TO NOISE RATIO

Signal to noise ratios are commonly used within the context of design of experiments in industry to find the best parameter setting for the process input variables; i.e., the level(s) which will optimize the process output variable [30]. From the literature it is evident that the higher the signal to noise ratio (SNR), the more stable the achievable quality will be [30-32]. Here in this research, the response parameter, 'dressing ratio', needs to be maximized, while the response parameter 'overlapped dressed area' needs to be minimized in order to obtain the overall best dressing performance. Eqs. (1) and (2) are used to calculate SNR for dressing ratio and overlap dressed area respectively. In Eqs. (1) and (2), y_i is response parameter value (for i = 1, 2, 3, …, n) and n is number of replications. For dressing ratio (R1):

$$(SNR)_{\text{maximize}} = -10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

For overlapped dressed area (R2):

$$(SNR)_{\text{minimize}} = -10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{2}$$

Thus, experiments are performed and response parameters values of dressing ratio (R1) and overlapped dressed area (R2) for each experiment are converted into respective *SNR* values as per above Eqs. (1) and (2) and are presented in Tab. 3.

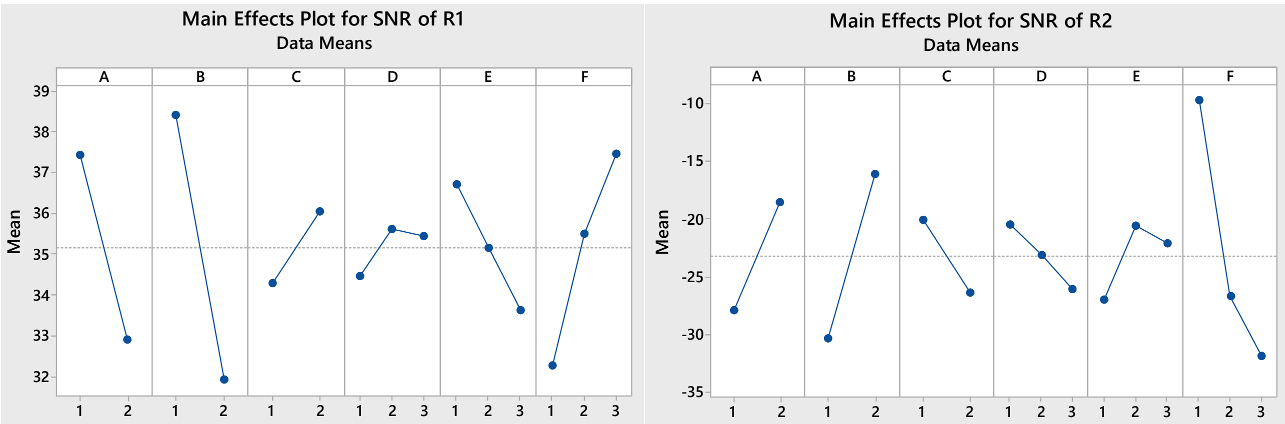
Table 3 Signal to noise ratio of dressing ratio and overlapped dressed area obtained from experiments

Exp. No.	SNR for R1	SNR for R2	Exp. No.	SNR for R1	SNR for R2
1	38.49	−0.14	19	34.24	-0.09
2	39.78	−39.65	20	38.50	−34.82
3	39.88	−39.84	21	39.89	−37.81
4	39.93	−39.87	22	37.65	−29.71
5	39.91	−23.17	23	39.64	−37.93
6	39.92	−39.85	24	35.58	−22.08
7	39.87	−39.83	25	36.43	−27.20
8	39.91	−39.92	26	38.80	−33.68
9	39.92	−36.88	27	33.10	−23.81
10	38.74	−32.11	28	26.73	−6.44
11	31.13	−0.09	29	36.41	−31.48
12	32.51	−14.49	30	27.04	−0.09
13	36.94	−32.17	31	27.29	−6.44
14	29.69	−0.12	32	27.35	−0.09
15	36.86	−35.89	33	29.97	−6.44
16	38.54	−31.71	34	18.51	−0.09
17	34.54	−21.14	35	31.67	−15.12
18	36.81	−36.10	36	33.58	−20.09

Note: SNR for R1 - Signal to noise ratio for dressing ratio and SNR for R2 - Signal to noise ratio for overlapped area

From Tab. 3, it can be found that maximum value of SNR (higher-the-better) is 39.93 for the response parameter 'dressing ratio'. The corresponding experimental 4 and the level of the experimental factors (see Tab. 2) are: 1000 mm/min for feed of dresser, up-cut for dressing method, 36.7 mm/min for grinding wheel velocity, 2 µm for depth of cut, 0.5 for velocity ratio, and number of pass equal to three. On the other hand, as can be seen in Tab. 3, minimum value of SNR (lower-the-better) is found to be -39.92 for the response parameter 'overlapped dressed area'. The corresponding experimental 8 and the level of the experimental factors are: 1000 mm/min for feed of dresser, up-cut for dressing method, 51.3 mm/min for grinding wheel velocity, 4 µm for depth of cut, 0.7 for velocity ratio, and number of pass equal to three. It can further be noted that if the above two response parameters are compared based on experimental factors, some corresponding experimental factor levels are found different.

A comprehensive analysis of SNR values for both responses is performed using MINITAB R16 [28]. For both response parameters i.e. 'dressing ratio' and 'overlapped dressed area', the main effect and the interaction plots for SNR are drawn and presented in Fig. 4 and Fig. 5 respectively.



(a) (b)

Figure 4 Main effect plots (a) SNR for dressing ratio (b) SNR for overlapped dressed area

From Fig. 4 one can note the level of each process parameter that helps in achieving the response parameters objective. While, Fig. 5 helps to sort out the pair of any two process parameters which has interaction in favor of targeted response objective. For example, in case of both response parameters (refer Fig. 5(a)-(b)), depth of cut (D) has interaction with velocity ratio (*E*) and number of pass (*F*). For 'overlapped dressed area', there is an additional interaction between feed of dresser (*A*) and depth of cut (*D*) to achieve the target objective. However, dressing method (B) has no interaction with other factors, for both response parameters. Therefore, it is distinct that effect due to the interactions across various parameters is slightly different for dressing ratio and overlapped dressed area, and this must be taken into consideration when choosing the appropriate dressing parameters as well as optimization approach.

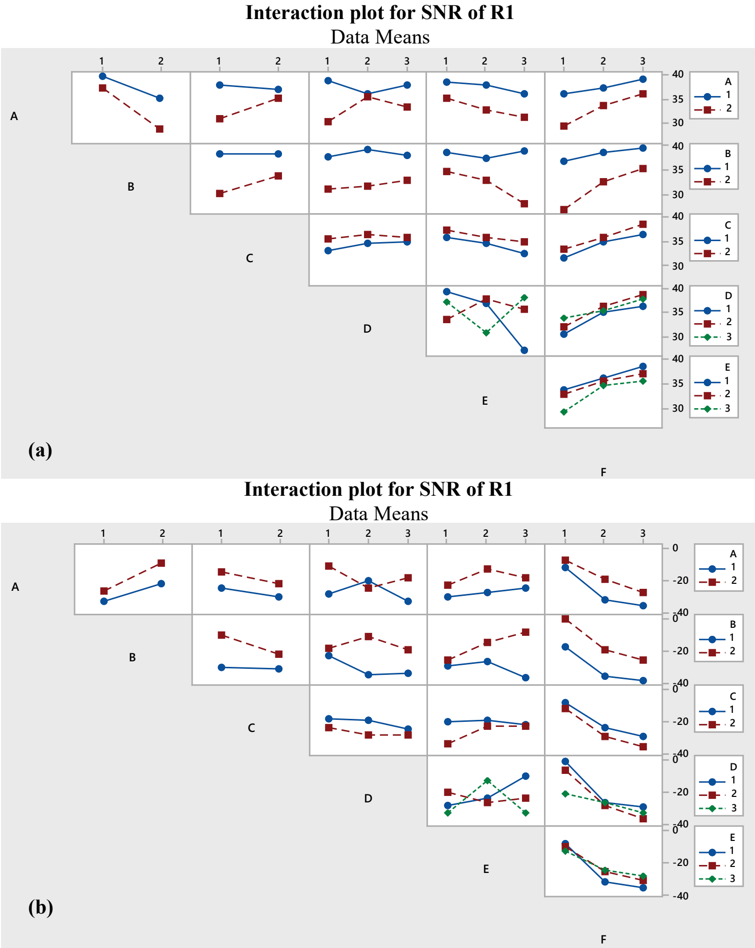


Figure 5 Interaction plots (a) *SNR* for dressing ratio (b) *SNR* for overlapped dressed area

Table 4 ANOVA Table

	Factor	DF#	SS	MS	F	P
For R1	A	1	165.25	165.25	36.37	0.000
	B	1	403.62	403.62	88.83	0.000
	C	1	21.83	21.83	4.80	0.038
	D	2	19.64	9.82	2.16	0.135
	E	2	48.25	24.13	5.31	0.012
	F	2	161.46	80.73	17.77	0.000
	Error	26	118.14	4.54		
	Total	35	937.13			
	R-Sq = 87.39%, R-Sq(adj) = 75.48%					
For R2	Factor	DF#	SS	MS	F	P
	A	1	641.32	641.32	11.85	0.002
	B	1	2066.34	2066.34	38.18	0.000
	C	1	248.42	248.42	4.59	0.042
	D	2	378.58	189.29	3.50	0.045
	E	2	102.56	51.28	0.95	0.401
	F	2	3102.15	1551.08	28.66	0.000
	Error	26	1407.25	54.13		
	Total	35	7941.95			
	R-Sq = 82.28%, R-Sq(adj) = 76.28%					
#DF: Degree of Freedom, SS: Sum of Squares, MS: Mean Squares (Variance), F: F-value and P: p-value						

Analysis of variance (ANOVA) is also used to further assess and determine the relative influence of each experimental factor and the results are presented in Tab. 4. Since 95 % confidence level is used for analysis purpose,

p value less than 0.05 will establish significance of factor. The factors feed of dresser (A), dressing method (B), grinding wheel velocity (C), velocity ratio (E) and number of pass (F) are significant for the response 'dressing ratio', whereas factor depth of cut (D) is found to be the least significant in the maximization of 'dressing ratio'. R-Sq is found to be about 87.39%, meaning that about 87 percent of variability in dressing ratio is due to the process parameters and their interactions. Similarly, factors feed of dresser (A), dressing method (B), grinding wheel velocity (C), depth of cut (D) and number of pass (F) are significant for the response 'overlapped dressed area', whereas factor velocity ratio (E) is found to be the least significant in the minimization of 'overlapped dressed area'. In this case, R-Sq is determined to be 82.28%, indicating about 82 percent of variability in overlapped dressed area.

As mentioned earlier, optimization of parameters of rotary diamond dressing has multiple response parameters with conflicting objectives. SNR and ANOVA results clearly indicate that a single set of same parameters is not able to provide the desired response parameters. Therefore, it is important to study the influence of process parameters on performance response parameters. In this research, grey based Taguchi approach is utilized for multiple response optimizations of rotary diamond dressing and to study the effect of the mentioned process parameters along with their interaction on the dressing response parameters. The details of optimization approach considered in this study are depicted in the following sections.

4 MULTI-CRITERIA OPTIMIZATION BASED ON GREY RELATION

Rotary diamond dressing process is stochastic in nature. Since the process is characterized by random uncertainty, an approach based on integration of signal to noise ratio and grey relational generation is used. The approach was first developed [26] in order to study the uncertainties that exist in the data. It has been applied in the areas such as decision making [33], manufacturing [19, 34], and product development strategies [35-37] etc. The approach consists of the following steps to generate the global comparison among experiments.

Step 1: Normalization of the experimental results (Signal to noise ratio):

Signal to noise ratio values (refer Tab. 3) for dressing ratio and overlapped dressed area are normalized using Eqs. (3) and (4). Eq. (3) is used for dressing ratio where the objective is to maximize its normalized value, while for the overlapped dress area the objective is to minimize its normalized value (refer to Eq. (4)).

$$Z_{ij} = \frac{\max\left(Y_{ij},\ i=1, 2, 3, ..., n\right) - Y_{ij}}{\max\left(Y_{ij},\ i=1, 2, 3, ..., n\right) - \min\left(Y_{ij},\ i=1, 2, 3, ..., n\right)} \quad (3)$$

$$Z_{ij} = \frac{Y_{ij} - \min\left(Y_{ij},\ i=1, 2, 3, ..., n\right)}{\max\left(Y_{ij},\ i=1, 2, 3, ..., n\right) - \min\left(Y_{ij},\ i=1, 2, 3, ..., n\right)} \quad (4)$$

In Eqs. (3) and (4), i = 1, 2, 3, …, n; where n is the number of experiments and j = 1, 2, 3, …, m; where m is the number of performance measures, and Z_{ij} is the normalized value, where $0 \le Z_{ij} \le 1$.

Step 2: Setting reference sequence:

Reference sequence Y_{oj} is obtained using Eq. (5).

$$Y_{oj} = \begin{cases} \min\forall_j \left\{Y_{ij}\right\} \text{ for smaller the best} = 0 \\ \max\forall_j \left\{Y_{ij}\right\} \text{ for larger the best} = 0 \end{cases} \quad (5)$$

Subsequently, each experiment results are compared with Y_{oj} and the grey relational coefficient is calculated.

Step 3: Calculate Grey relation co-efficient:

For each experimental run, grey relational co-efficient (GRC_{ij}) is calculated for each response parameters using Eq. (6).

$$GRC_{ij} = \frac{\min\,(\Delta_{ij}) + \xi \max\,(\Delta_{ij})}{\Delta_{ij} + \xi \max\,(\Delta_{ij})} \quad (6)$$

ξ is user-selected resolution coefficient which is defined in the range between zero and one. If experiment parameters are equally weighted, then $\xi = 0.5$ as explained by Deng [18] and Wen [19]. Δ_{ij} is calculated using the Eq. (7).

$$\Delta_{ij} = \text{Abs}\,(Y_{oj} - Y_{ij}) \quad (7)$$

Here, Y_{oj} is reference sequence for the response j and Y_{ij} is response parameter value corresponding to experiment i and the response measure j.

Step 4: Calculate Grey relational grade:

For both response parameters, a grey relational grade value (GRG_i) for each experiment is calculated by using the Eq. (8).

$$GRG_i = \frac{1}{m} \sum_{j=1}^{m} GRC_{ij} \quad (8)$$

In Eq. (8), GRG_i is the grey relational grade value for the experiment i. GRC_{ij} is the grey relational coefficient corresponding to the experiment i for the response parameter j. And m is the number of response parameters. This equation is used, if there is equal weightage to all response parameters. In the case of unequal weights for each response parameters, the above Eq. (8) is extended to Eq. (9), where W_k denotes the normalized weight for each response parameters.

$$GRG_i = \sum_{j=1}^{m} W_k GRC_{ij} \quad (9)$$

Thus, the above approach converts multiple response parameter values into a single grey relational grade, for each experiment. The experiment with maximum grey relational grade value is ideal and optimized solution. Thus, for a given experimental factor setting, its grey relational grade value reveals the closeness of the experimental performance with respect to the performance of the optimized experimental factor setting. This approach can be used to rank the experimental runs.

5 MULTI RESPONSE OPTIMIZATION RESULTS

*SNR*s of each response parameter (refer Tab. 3) are taken as input for multi response optimization. As described in Section 4, sequentially SNRs are normalized, grey relational coefficients are obtained for each response parameters, and grey relational grades are obtained for each experiment. The entire results of grey relational grade calculations are summarized in Tab. 5. It can be seen that the process parameter setting of experiment 5 (first ranked) realizes the best possible optimized response parameters. From main effect plot of grey relational grade (refer to Fig. 6), the optimum levels are found to be 1000 mm/min for feed of dresser, up cut for dressing method, 36.7 mm/min for grinding wheel velocity, 4 μm for depth of cut, 0.7 for velocity ratio, number of pass equal to one.

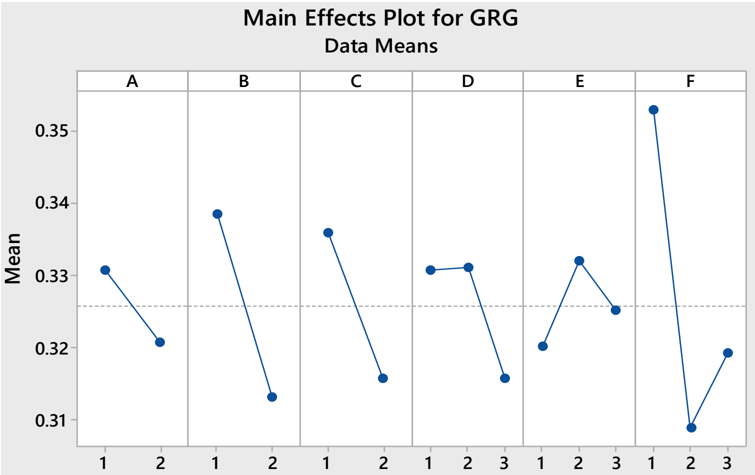


Figure 6 Main effect plot of Grey relational grade (GRG)

Table 5 Grey relational grade values for each experiment

Exp.	Run	Grey relational Generation		Grey relation coefficient		Grey relation grade	
No.	Level	R1	R2	R1	R2		Rank
1	21	0.7148	1.0000	0.3574	0.5000	0.4287	2
2	35	0.9252	0.3402	0.4626	0.1701	0.3164	27
3	32	0.9771	0.3354	0.4885	0.1677	0.3281	16
4	24	0.9948	0.3347	0.4974	0.1673	0.3324	13
5	6	0.9974	0.7748	0.4987	0.3874	0.4431	1
6	9	1.0000	0.3351	0.5000	0.1676	0.3338	9
7	2	0.9948	0.3356	0.4974	0.1678	0.3326	12
8	26	0.9974	0.3333	0.4987	0.1667	0.3327	11
9	31	1.0000	0.4152	0.5000	0.2076	0.3538	4
10	4	0.7468	0.5515	0.3734	0.2757	0.3246	18
11	36	0.3784	1.0000	0.1892	0.5000	0.3446	6
12	1	0.4005	0.9034	0.2003	0.4517	0.3260	17
13	34	0.5677	0.5496	0.2839	0.2748	0.2793	33
14	14	0.3589	1.0000	0.1795	0.5000	0.3397	7
15	29	0.5661	0.4430	0.2830	0.2215	0.2523	35
16	7	0.7188	0.5627	0.3594	0.2814	0.3204	24
17	16	0.4536	0.8130	0.2268	0.4065	0.3166	26
18	28	0.5594	0.4371	0.2797	0.2186	0.2491	36
19	27	0.4467	1.0000	0.2234	0.5000	0.3617	3
20	17	0.7188	0.4735	0.3594	0.2367	0.2981	31
21	22	1.0000	0.3894	0.5000	0.1947	0.3473	5
22	10	0.6271	0.6182	0.3136	0.3091	0.3113	29
23	33	0.9342	0.3861	0.4671	0.1930	0.3301	15
24	13	0.4990	0.7960	0.2495	0.3980	0.3238	21
25	12	0.5382	0.6839	0.2691	0.3420	0.3055	30
26	18	0.7693	0.5064	0.3847	0.2532	0.3189	25
27	15	0.4166	0.7617	0.2083	0.3809	0.2946	32
28	19	0.3333	0.9593	0.1667	0.4797	0.3232	22
29	8	0.5405	0.5692	0.2703	0.2846	0.2774	34
30	3	0.3342	1.0000	0.1671	0.5000	0.3336	10
31	5	0.3363	0.9593	0.1681	0.4797	0.3239	20
32	30	0.3360	1.0000	0.1680	0.5000	0.3340	8
33	11	0.3626	0.9593	0.1813	0.4797	0.3305	14
34	25	0.2974	1.0000	0.1487	0.5000	0.3244	19
35	20	0.3872	0.8968	0.1936	0.4484	0.3210	23
36	23	0.4297	0.8307	0.2148	0.4153	0.3151	28

For 95 % confidence level, the two factors namely, dressing method (B) and number of pass (*F*), have significant impact on the maximization of dressing ratio and minimization of overlapped dressed area simultaneously (refer to Tab. 6).

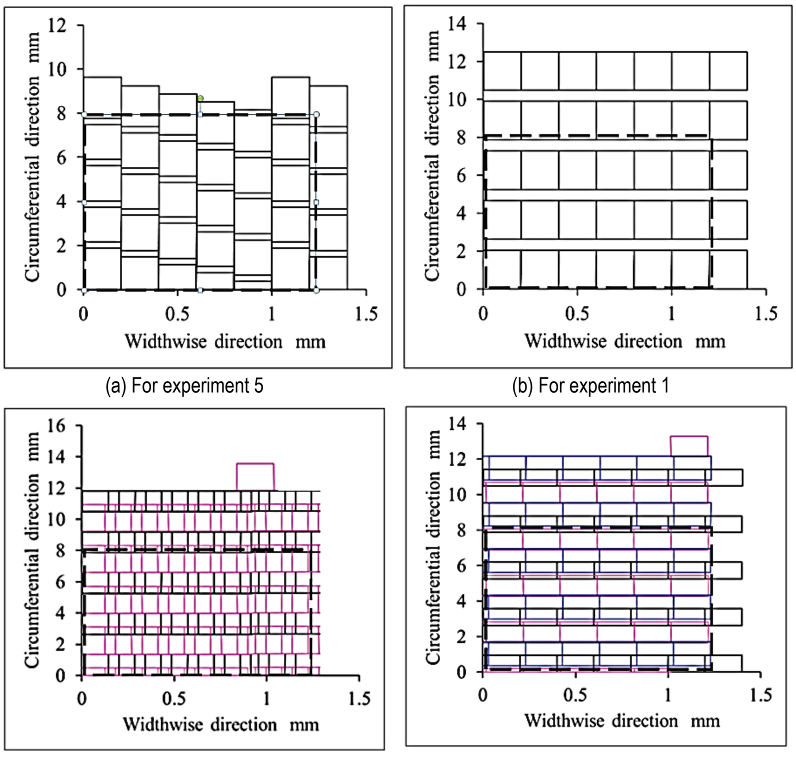
The next step is to perform validation experiments for confirming the optimum parameters settings that are obtained for rotary diamond dressing. In the confirmation experiments, the grinding wheel surface topography after rotary diamond dressing is generated using simulation system and compared with the obtained results that are found using the developed method. The details of experiments are illustrated in the following section.

Table 6 ANOVA for grey relational grade values

		Grey relational grade values			
Factor	DF	SS	MS	F	P
A	1	0.001351	0.001351	1.55	0.225
B	1	0.004781	0.004781	5.47	0.027
C	1	0.002854	0.002854	3.26	0.082
D	2	0.002034	0.001017	1.16	0.328
E	2	0.000282	0.000141	0.16	0.852
F	2	0.010591	0.005296	6.06	0.007
Error	26	0.022732	0.000874		
Total	35	0.046363			
		R-Sq = 50.97%, R-Sq(adj) = 7.10%			
DF: Degree of Freedom, SS: Sum of Squares, MS: Mean Squares (Variance), F: F-value and P: p-value					

6 CONFIRMATION EXPERIMENT

The grey relational grade generation analysis provides the ranking of the parameters setting. As shown in Tab. 5 and Fig. 6, the parameter setting of experiment 5 (first ranked) realizes the best optimized performance response parameters possible. The evaluation of response parameters (i.e. dressing ratio and overlapped dressed area) of the generated grinding wheel surface after rotary diamond dressing is an important issue. Generation of grinding wheel surface topography after dressing by rotary diamond dresser is a complex phenomenon [8, 12, 15]. Subsequently, the grinding wheel surface topography is generated using our developed simulation system [5] for optimum parameters setting of rotary diamond dressing and compared with the experimental results. The process parameters setting of experiment numbers (refer to Tab. 2) 5, 1, 18 and 10 are used in simulation model to generate the grinding wheel topography after rotary diamond dressing. The generated topographies are as presented in Fig. 7(a-d). It is mentioned earlier that we studied the 10 mm^2 of the surface area in the middle part of grinding wheel for each experimental run for the experimental measurement of dressed area and overlapped dressed area.



(a) For experiment 5 (b) For experiment 1

(c) For experiment 18 (d) For experiment 10

Figure 7 Generation of the grinding wheel topography after rotary diamond dressing by simulation (black marks are for 1st pass, red marks are for 2nd pass and blue marks are for 3rd pass). Here black dotted box represents 10 mm^2area.

From simulation result as presented in Fig. 7(a), the generated topography for the first ranked (experiment 5) parameters setting it is found that the dressing ratio is 89% and the overlapped dressed area is 1.8 mm^2 (out of 10 mm^2). In real measurement of experiment 5, it is found that dressing ratio is 91% and 1.5 mm^2 of surface area (out of 10 mm^2) is overlapped dressed area. From the generated topography of the second ranked (experiment 1) parameters setting (refer Fig. 7(b)) we observe that the dressing ratio is 76%, but there is zero overlapped dressed area. Whereas, in real measurement of experiment 1, the dressing ratio is found to be 79% and the overlapped dressed area is 0.7 mm^2. Similarly, the parameters setting of experiment 18 (the 36th ranked) is also used to simulate the grinding surface topography after dressing (Fig. 7(c)) and it is found that the dressing ratio is 71% and the overlapped dressed area is 2.6 mm^2. While from the real experiment 18, the dressing ratio is 67% and 3.1 mm^2 is overlapped dressed area. For the simulation of experiment 10 (18th ranked), the generated grinding wheel surface topography (Fig. 7(d)) realizes 94% dressing ratio and 4.1 mm^2 of overlapped dressed area. Whereas, in real measurement of experiment 10, it is found that dressing ratio is 91% and 4.5 mm^2 is overlapped dressed area. After comparison of simulation and experimental results for the parameter settings of the experiment 5, 1, 18 and 10, it can be stated that the corresponding results from simulation and experiments are in close agreement. The above stated results clearly demonstrate the conformity among the outcome of the multi-criteria optimization, simulation results and real experimental results.

In experiment 18, the number of pass is two and depth of cut is 4 μm (which are larger compared to the one used in experiment 5 where number of pass is 1 and depth of cut is 2 μm), which confirms that higher number of pass and larger depth of cut increases the possibility of overlapped dressed area [8].

7 CONCLUSION

In this paper, optimization of rotary diamond dressing has been studied. Experiments are conducted to examine the effect of process parameters on the response parameters i.e., dressing ratio and overlapped dressed area. Grey relational optimization approach is used. Based on the results, the following conclusions can be made:

- Using the signal to noise ratio analysis, dressing ratio and overlapped dressed area are optimized individually. Two different sets of optimal parameter settings are found for dressing ratio and overlapped dressed area. Here, by using analysis of variance, parameters namely feed of dresser, dressing method, grinding wheel velocity, velocity ratio and number of pass are found to be significant factors for the response parameter 'dressing ratio'. For 'overlapped dressed area', feed of dresser, dressing method, grinding wheel velocity, depth of cut and number of pass are significant factors.
- Multi criteria grey relational generation is adopted to determine the optimum parameter setting to optimize both response parameters together. This approach converts multiple response parameter values into single grey relational grade, for each experiment. From analysis of variance of grey relational grade, it is evident that dressing method and number of pass are significant factors while both the response parameters are optimized simultaneously.
- Grey relational generation provides the optimum parameter setting for the rotary diamond dressing and the setting of different process parameters are as follows: 1000 mm/min for feed of dresser, up cut for dressing method, 36.7 mm/min for grinding wheel velocity, 4 μm for depth of cut, 0.7 as velocity ratio and number of pass equal to one.

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Contact information:

M. A. K. CHOWDHURY, Assistant Professor
Corresponding author
Industrial Engineering Department, King Saud University
P.O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia
Email: mchowdhury@ksu.edu.sa

Ateekh Ur REHMAN, Associate Professor
Industrial Engineering Department, King Saud University
P.O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia
Email: arehman@ksu.edu.sa

M. S. UDDIN, Lecturer
School of Engineering, University of South Australia,
Adelaide, Australia.
Email: Mohammad.Uddin@unisa.edu.au

Mohammed ALKAHTANI, Assistant Professor
Industrial Engineering Department, King Saud University
P.O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia
Email: moalkahtani@ksu.edu.sa

Saqib ANWAR, Assistant Professor
Industrial Engineering Department, King Saud University
P.O. Box 800, Riyadh 11421, Kingdom of Saudi Arabia
Email: sanwar@ksu.edu.sa