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MULTI-OBJECTIVE OPTIMIZATION OF DRILL-BIT ASSISTED ABRASIVE FLOW MACHINING PROCESS THROUGH TAGUCHI BASED GREY RELATIONAL ANALYSIS

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Abstract: The drill-bit assisted abrasive flow machining (AFM) process is usually chosen for finishing operation in manufacturing industries where the fine surface finish of the component is an important criterion and considered as primary response in the present work. A number of experiments have been conducted according to Box-behnken design considering EN 24 as work piece material. Experiments were performed under different machining conditions by varying the parameters such as abrasive particle size, media viscosity, drill bit diameter and number of process cycle. The material removal rate (MRR) has been considered as secondary response of this process. In the present paper, a multi-objective optimization technique using Taguchi based Grey relational analysis has been applied to optimize the process performance of the drill-bit assisted AFM. How could a complicated multiple performance characteristics simplified to a single objective optimization problem has been presented here by this approach. The specific targets are minimum surface roughness and maximum material removal rate. According to importance of quality characteristics there are three criteria for optimization in grey relational analysis, which are 'Larger-the-Better', 'Smaller-the-Better' and 'Nominal-the-Best'. In the present analysis the lower value of surface roughness represents smooth surface i.e. better finishing performance, therefore 'Lower-the-Better' criteria is chosen for surface roughness. On the other hand the higher value of MRR indicates more economical as compared to other finishing processes, therefore 'Higher-the-Better' is chosen for MRR. In the present work smaller surface roughness and larger MRR are desirable. The optimal parametric setting obtained from grey relational analysis has been validated by a confirmation test.

Keywords: Optimization, Taguchi method, AFM, GRA, surface finish.

1. INTRODUCTION

Abrasive flow machining (AFM) is one of the popular advanced finishing processes in which a small quantity of work material is removed by flowing semisolid abrasive-laden putty over the workpiece surface to be finished. AFM is used for finishing and deburring, radiusing and removing recast layers of critical component in aerospace, automotive, electronics and die making industries [1]. Grinding, honing, lapping and super finishing are the traditional methods of finishing, but these processes have some limitations on the production of shapes such as flat, cylindrical etc and finishing of difficult-to-access areas [2]. Later, when high strength materials of complicated shapes are introduced, the need for an accurate and flexible process arises and cost of machining is increased. Thus finishing processes like Abrasive flow Machining, Magnetic Abrasive Finishing, Magnetic Rheological Abrasive Flow Finishing, and Spiral polishing have been developed. Fine surface finish is in high demand in a wide spectrum of industrial applications. Presently, it is required that the parts used in manufacturing semiconductors, atomic energy parts, medical instruments and aerospace components have a very precise surface roughness [3]. Obtaining high quality surfaces with high efficiency is not only an important goal of researchers but also an urgent demand of the manufacturing industry. Finishing operations involved in the manufacturing of precise components are the most labor intensive, time consumable and least controllable ones. Finishing cost in the metal working industries carries at least 15% of the total manufacturing cost [3]. Surface finish has a vital role on important functional properties such as wear resistance and power loss due to friction is influenced by surface roughness of the matching parts.

Jain and Adsul [4,5] performed experiments on AFM and reported that initial surface roughness and hardness of the work piece play an important role in material removal rate (MRR) during the process. Material removal and reduction in surface roughness values are reported higher for the case of softer work piece material as compared to harder materials. In another work, they also reported that MRR is high in the first few cycles due to higher initial coarseness of work piece surface, and thereafter, it gradually decreases at slower rate in every cycle. Jain and Jain [6] also reported that surface roughness (R_a Value) is decreased with increase in extrusion pressure and abrasive concentration, but they also observed that surface roughness (R_a value) is increased with the increase of average grain size.

Gorana et al. [7,8] studied on cutting force analysis during the process and concluded that depth of penetration of abrasive particle depends on extrusion pressure, abrasive medium viscosity, and grain size. Material removal takes place the form of microchip due to the combined effect of radial force and axial force. Mondal et al. [9] studied Taguchi-based gray relational analysis and that applied in finding optimal process parameters combination of laser cladding process. Kumar et al. [10] performed on AFM in which a three start helical drill bit coaxially with a hollow cylinder workpiece is used to improve material removal rate. The developed Helical-Abrasive Flow Machining process (HAFM) employees a standard drill bit which applies forces on the abrasive laden media to follow a helical path within the finishing zone. They concluded that type of workpiece is most dominating parameter followed by number of cycles and extrusion pressure.

In this paper, firstly an experimental study on AFM using Box-behnken design of experiment has been presented and then the experimental data have been used to find out the optimal parametric setting through a Taguchi based grey relational analysis.

2. EXPERIMENTAL DETAILS

2.1 Workpiece Materials

Experiments were carried out with EN 24 steel as work piece material.

2.2 Media Material

Following media materials are used in this work:

i. Silicon Carbide Abrasive powder. (66 % by weight)
ii. Styrene Butadiene Rubber (19-24 % by weight)
iii. Hydraulic Oil (10-15 % by weight)

2.3 Process Variables

The literature survey reveals that the following parameters are predominant role on the responses. As a result, the following parameters are selected as process variables.

i. Abrasive mesh size
ii. Weight percentage of oil concentration in media
iii. Drill bit diameter
iv. Number of cycle

2.4 Design of Experiments

Experiments are performed according to Box-behnken technique. The process parameters (design factors) with their values on different levels are listed in Table1.

2.5 Experimental Procedure

First of all media was rolled up by a two-roll machine to form a slug of length 75 mm and diameter around 60 mm. The lower media cylinder (MC1) was filled completely with this media slug. Then the taper spaces of the two plates were also filled by media. Now the bottom plate (Plate1) was placed on the lower media cylinder (as shown in Fig.1).

Table 1 Control factors and their levels

Control factors	Levels		
	1	2	3
i. Abrasive mesh size	220	800	1200
ii. % age of oil concentration	10	12.5	15
iii. Drill bit diameter (mm)	5	8	11
iv. Number of cycle	100	150	200

Workpieces were fitted inside the fixture barrel by keeping the drill bit and two fixture rings. Then the workpiece fixture was placed between the two plates (plate 1 and 2) and the plates were tightened by nuts and bolts to intricate with the media cylinder. Next, switched on the electric circuit to activate the relay signal. To start hydraulic drive, pressed the MCB switch on the hydraulic power pack. The desired extrusion pressure (say 65 bar) can be controlled by the relief valve. This hydraulic drive can generate pressure up to 160 bar. There were two more pressure relief valves to control the back pressure. The back pressure is necessary in the case when the media was required to be compressed during machining. This will probably help in increasing the depth of cut by making abrasives to penetrate to a greater depth. To activate the control circuit press any limit switch, which sends signal to the relay. This would result the pistons movement simultaneously from lower cylinder to upper cylinder. Now the upper media cylinder MC2 is acting as an extruding cylinder and MC1 as a receiving one for next half of cycle and thus one cycle was completed. In this way reciprocating motion had been imparted to the media. To count the number of cycles, one counter was attached at upper cylinder. At the same time to count machining time one stop watch was used. After completion of desired cycle, first switched off the hydraulic drive from MCB board then switched off the electric circuit. After the finishing is over, the work pieces are taken out from the setup and cleaned with acetone before any measurement is taken.

2.6 Experimental Results

2.6.1 Surface Roughness

The surface roughness values have been measured by a screen touch type SURFO ANALYZER 300 instrument. It can measure R_a value, R_q value, and R_z value and the instrument had a least count 0.01μm. A template was fabricated for marking the same spot on the same workpiece surface (area- 6 mm X13 mm) before and after finishing. Three measurements per workpiece were taken on the marked area by keeping same gap in the longitudinal direction and then average of them is considered. The percentage improvement in surface roughness was calculated as {(Initial R_a value- Final R_a value) / Initial R_a value} x 100 %.

2.6.2 Material Removal

When abrasive laden pliable semi-solid media is forced to flow through the work piece surface, abrasion occurs wherever the medium passes through the highly restrictive passage and in the case of work piece surfaces having single vent for media outflow, the restriction in the passage is higher and the abrasive laden medium moves along the walls thereby resulting in more amount of material removal.

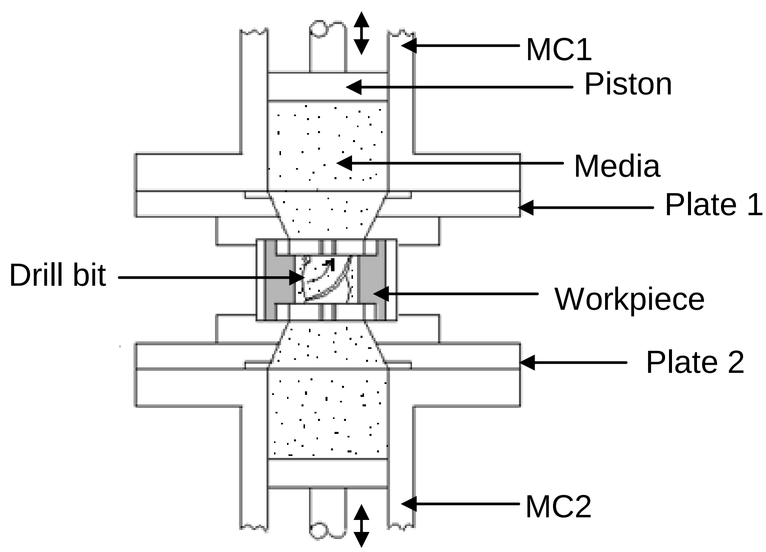

Fig.1: Sectional View of Modified AFM setup
(The central arrow is showing the media flow path)

Table 2 Experimental results

Sl. No.	Abrasive mesh size	% age of oil concentration	Drill bit diameter (mm)	Number of cycle	Surface Roughness- R_a (micron)	Material removal (mg)
1	220	10	11	150	0.187	1.1
2	800	15	11	200	0.2	1.1
3	800	12.5	9	100	0.163	0.2
4	800	12.5	11	150	0.22	0.7
5	800	11.5	11	100	0.193	0.6
6	800	12.5	13	100	0.22	0.5
7	800	10	9	150	0.177	0.6
8	1200	12.5	11	150	0.24	0.7
9	800	12.5	13	200	0.247	1.2
10	220	12.5	13	150	0.213	0.8
11	800	10	13	150	0.24	0.9
12	220	12.5	11	200	0.187	1.5
13	800	10	11	100	0.203	0.6
14	1200	12.5	11	100	0.217	0.3
15	1200	10	11	150	0.204	0.5
16	800	15	9	150	0.157	0.3
17	220	10	11	150	0.16	0.4
18	800	10	11	150	0.25	0.7
19	220	12.5	11	100	0.16	0.5
20	800	12.5	11	200	0.22	0.7
21	1200	12.5	13	150	0.246	0.5
22	800	12.5	11	100	0.17	0.7
23	800	12.5	9	200	0.20	0.8
24	800	10	11	200	0.27	1.5
25	1200	12.5	11	125	0.223	0.4
26	800	15	11	100	0.15	0.2
27	1200	15	11	150	0.21	0.1
28	1200	12.5	11	200	0.24	1.1
29	220	12.5	9	150	0.21	0.9
30	800	15	13	150	0.20	0.8
31	1200	12.5	9	150	0.247	0.6

The material removal of the samples has been measured with the help of electronic weight balance “AFCOSET FX 400”. It has digital scale and having least count 0.1 mg. First of all the tare button was pressed to set initially zero display on the screen. Now place the specimen on the platform of the weight balance and waited for a few seconds until the reading becomes stable. This gives the weight of the sample and it is noted down. Again picked up the sample from the platform and set it zero display on the screen; then placed the sample on the platform. This would give the 2nd reading of workpiece weight. In this way 3 measurements per sample have been taken. Then, the average weight of the workpiece was calculated. Finally, the material removals were evaluated by computing the difference of weight of samples before and after finishing.

The experimental results for surface roughness and material removal have been shown in Table 2.

3. GREY RELATIONAL ANALYSIS AND DISCUSSION ON EXPERIMENTAL RESULTS

The grey relational analysis is a quantitative analysis (GRA) to explore the similarity and dissimilarity among factors. It uses the grey relational grade to find the correlation degree of factors. In the GRA the first step is to perform the normalization of experimental data to make the range within 0 to1. This step is called grey relational generating [11-12]. The GRG also expresses the deviation between the experimental value and the ideal value. According to importance of quality characteristics there are three criteria for optimization in grey relational analysis, which are 'Larger-the-Better', 'Smaller-the-Better' and 'Nominal-the-Best'. In the present analysis the higher value of MRR indicates better machining performance, therefore 'Higher-the-Better' criteria are chosen for MRR. On the other hand the lower value of surface roughness represents better finishing performance, therefore 'Lower-the-Better' is chosen for this. Therefore, normalized values of the MRR are computed according to Eq. 1 and the normalized values of surface roughness are calculated by Eq. 2. If the expectancy is larger-the-better, then the normalized value of grey relation can be expressed as:

$$X_{ij} = \frac{Y_{ij} - \min Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \quad \textbf{(1)}$$

If the expectancy is smaller-the-better, then it can be expressed as:

$$X_{ij} = \frac{\max Y_{ij} - Y_{ij}}{\max Y_{ij} - \min Y_{ij}} \quad \textbf{(2)}$$

If the expectancy is nominal-the-better, then it can be expressed as:

$$X_{ij} = 1 - \frac{|Y_{ij} - OB|}{\max\{\max Y_{ij} - OB, OB - \min Y_{ij}\}} \quad \textbf{(3)}$$

Where, X_{ij} represents the normalized value of jth response at ith number of experiment and Y_{ij} represents the actual value of jth response at ith number of experiment.

3.1 Grey Relational Coefficient

The grey relational coefficient (ζ_{ij}) is determined to express the relationship between reference and actual experimental normalized data. The grey relational coefficient can be calculated as:

$$\zeta_{ij} = \frac{\Delta_{\min} + \xi\Delta_{\max}}{\Delta_{ij} + \xi\Delta_{\max}} \quad \textbf{(4)}$$

Where, $\Delta_{ij} = |X_{oj} - X_{ij}|$

X_{oj} = Reference data or best data

$\Delta_{\max}$ = maximum value of Δ_{ij} and

$\Delta_{\min}$ = minimum value of Δ_{ij} and

ξ = the distinguishing or identification coefficient, and its value lies between 0 and 1. Usually, the distinguishing coefficient is assumed at 0.5 to fit the practical requirements.

3.2 Grey Relational Grade

After calculating the grey relational coefficient from Eq. 5 of three quality characteristics for cladding of EN24 steel are directly integrated to determine single grey relational grade by utilizing a weighting method [13].

The grey relational grade (γ_i) for the i-th experiment can be calculated as

$$\gamma_i = \frac{1}{2}\sum W_j \zeta_{ij} \qquad \textbf{(5)}$$

Where, W_j = weighting factor for j-th response. The higher value of grey relational grade is considered as the stronger relational degree between the ideal sequence X_{0j} and the given sequence X_{ij}. Since the ideal sequence X_{0j} is the best process response in the experimental layout, therefore higher relational grade implies that the corresponding process parameter combination is closer to the optimal. In order to study the influence of process parameters viz. Abrasive mesh size, Weight percentage of oil concentration in media, Drill bit diameter and Number of cycle on the two responses (i.e. surface roughness and material removal rate) together, the response diagram is drawn by calculating multi signal to noise ratio based on grey relational grade [8] and shown in Fig. 2. It is seen that process performance improves with the increase of media oil percentage and decreases with the increase of drill bit diameter. But for abrasive mesh size the performance improves up to mid level and then deteriorates, similarly for number of cycle it decreases first and later increases. The normalized data, grey relational coefficient and grey relational grade have been shown in Table 3, calculated on the basis of Table 2.

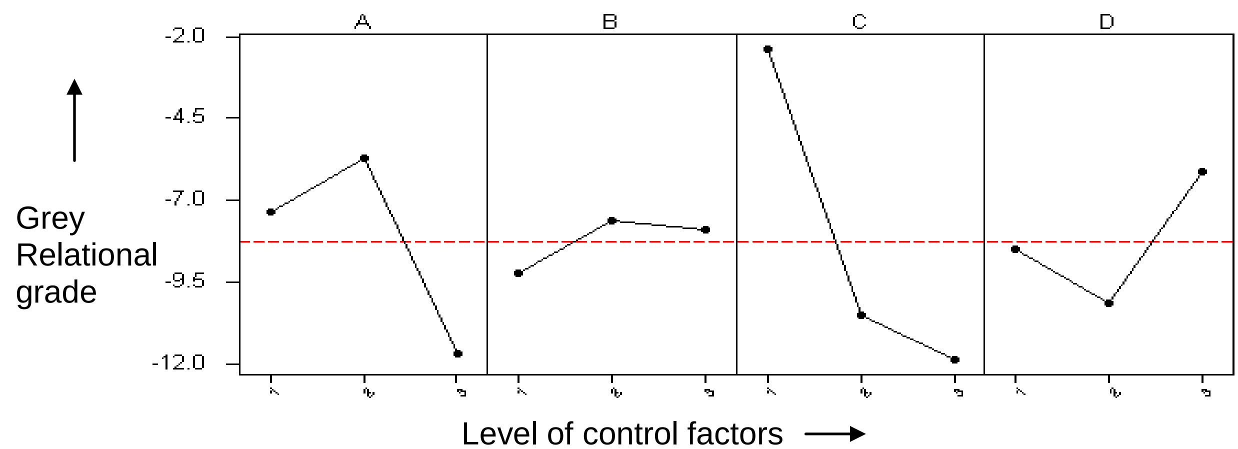

Fig. 2: Graph of grey relational grade

Table 3 Grey relational coefficients and grades

Sl. No.	Normalized data		Grey relational coefficient		Grey relational grade	
	SR	MRR	SR	MRR	Value	Order
1	0.691666667	0.975610183	0.442477876	0.953488	0.305556	10
2	0.583333333	0.707317369	0.5	0.630769	0.271577	19
3	0.891666667	0.195121998	0.364963503	0.383178	0.185487	29
4	0.416666667	0.58536609	0.625	0.546667	0.299575	13
5	0.641666667	0.780488137	0.467289719	0.694915	0.271203	20
6	0.416666667	0.634146602	0.625	0.577465	0.304657	11
7	0.775	0.487805067	0.406504065	0.493976	0.217685	26
8	0.25	0.58536609	0.833333334	0.546667	0.369367	8
9	0.191666667	0.780488137	0.943396228	0.694915	0.430699	1
10	0.475	0.682927114	0.574712643	0.61194	0.293499	15
11	0.25	0.780488137	0.833333334	0.694915	0.393828	5
12	0.691666667	1.000000439	0.442477876	1	0.31323	9
13	0.558333333	0.780488137	0.515463917	0.694915	0.287341	17
14	0.441666667	0.341463532	0.602409638	0.431579	0.273018	18
15	0.55	0.390244044	0.520833333	0.450549	0.24882	23
16	0.941666667	0.195121998	0.349650349	0.383178	0.180357	30
17	0.916666667	0.292683021	0.357142857	0.414141	0.187976	27
18	0.166666667	0.58536609	1	0.546667	0.4252	2
19	0.916666667	0.634146602	0.357142857	0.577465	0.214925	27
20	0.416666667	0.58536609	0.625	0.546667	0.299575	14
21	0.2	0.390244044	0.925925927	0.450549	0.384526	6
22	0.833333333	0.58536609	0.384615384	0.546667	0.219046	25
23	0.583333333	0.487805067	0.5	0.493976	0.249006	22
24		1.000000439	0.714285714	1	0.404286	3
25	0.391666667	0.370731839	0.649350649	0.442765	0.290589	16
26	1	0.195121998	0.333333333	0.383178	0.174891	31
27	0.5	-4.87807E-08	0.555555555	0.333333	0.241111	24
28	0.25	0.707317369	0.833333334	0.630769	0.383244	7
29	0.5	0.780488137	0.555555555	0.694915	0.300772	12
30	0.583333333	0.682927114	0.5	0.61194	0.26847	21
31	0.191666667	0.487805067	0.943396228	0.493976	0.397544	4

4. CONCLUSION

In this paper, an experimental study on Drill bit Assisted Abrasive Flow Machining Process and the application of Taguchi-method based grey relational analysis to optimize the abrasive flow machining process with the multiple performance characteristics have been reported. An expression of grey relational analysis that directly integrates the multiple performance characteristics (i.e. Abrasive mesh size, Weight percentage of oil concentration in media, Drill bit diameter and Number of cycle) into a single performance characteristic called grey relational grade. Therefore, optimization of the complicated multiple performance characteristics can be greatly simplified to a single objective optimization problem through this approach. It is found that the performance characteristics of the AFM process such as surface finish and material removal rate are improved together using this methodology. In the present study the predicted optimal setting is $A_2B_2C_1D_3$.

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