Multi Objective Optimization for Process Parameters in Abrasive Jet Drilling Process Using Gray Relational Analysis

Mihir Tadvi* Alpesh Kakadiya A.B.Pandey,

[a] Department of Mechanical Engineering Faculty of Technology & Engineering College, Baroda, 390001,

Abstract: Abrasive jet drilling process (AJDP) removes the material by erosion action by simultaneous control of number of process parameters. This paper highlights a logical procedure for selection of optimal process parameters in Abrasive jet drilling process to achieve high quality without cost inflation. In present work authors have tried to investigate effect of various AJDP process parameters such as air pressure, abrasive particle size, stand-of-distance on responses, material removal rate and radial overcut by conducting full factorial experiments. Multi response optimization of the process parameters have been performed and most significant input parameters identified using Gray Relational Analysis (GRA) technique.

Keywords: *AJDP, GRA, Optimization,MRR,ROC*

Introduction:

Precision machining of fragile material with complex geometries is always of concern being labor intensive and difficult to control. Abrasive jet machining is a process in which the material is removed from the work piece due to the impingement of the fine grain abrasives with a high velocity air jet. Material removal occurs through a chipping action, which is especially effective on hard, brittle material such as glass, silicon, tungsten and ceramics. Difference from the other non conventional machining process there is no thermal, mechanical and chemical damage of the work. This technique has been used to micro-fabricate array of components in glass for use in semiconductor, Micro Electro Mechanical Systems (MEMS), optoelectronic industries etc. [1]. For instance AJM is used for cutting a thread in glass rod, cutting titanium foil, and drilling glass wafers [2]. AJM has been successfully employed to manufacture small electronics devices consisting silicon brazed on tungsten of varying thickness in which the silicon wafer must be trimmed and beveled without harming the tungsten disk [3] and also been used for deburring of crossed-drilled holes as secondary erosion [4]. By adding pure water with abrasive in specified quantity it applied to polishing of electrical discharge machined mold steel to a high degree mirror finish [5].

AJM has been subject of research studies because of complex material removal mechanism which depends on various parameters found affecting on output such as stand of distance, mixing ratio, air pressure, grain size, abrasive types etc. in literature [6-7, 8]. Optimal quality of the work piece in AJM can be generated through combine control of various process parameters. Many researchers have studied and investigated the complex relationship between various machining parameters and tried to optimizes the input parameters that give best output for different multivariable manufacturing processes using various modern optimization tools like genetic algorithm, response surface methodology etc. [9-13]. In the present paper, authors have tries to optimize higher-order influences of the various machining parameters of AJDP like stand of distance, air pressure, abrasive particle size on the most dominant machining criteria, i.e. MRR and Radial overcut using grey relational analysis (GRA) approach because of its ability to simplify greatly the complicated multiple performance characteristics noted by various researchers [9-11].

2. Experimentation

Fig. 1 Experimental setup for Abrasive Jet Drilling Process

High pressure air from the compressor passes through dehumidifier and pressure control valve in to the mixing chamber. The abrasive particle and air are thoroughly mixed in mixing chamber and a stream of abrasive mixed air passes through a nozzle on the glass. It causes the indentation and ultimately results in result in the rupture of the particle from the surface and drilling operation is performed. Abrasive jet drilling experimental setup is shown in Figure 1.

Full factorial designs of experiments are conducted with three controllable factor stand of distance, air pressure and abrasive particle size of SiC abrasives. Levels of input parameters are shown in Table 1.

Table 1: Controllable factor with their level in full factorial Design of Experiments

Machining Parameter	Units	Level 1	Level 2	Level 3
Stand of distance	mm	1	2	3
Air pressure	bar	4	5	6
Thickness	mm	1.5	2.2	3

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Based on The randomized experiments condition of each input variables and summary of response parameters are given in Table 2. Total 27 experiments were performed on 1.5 mm, 2.5mm, 3mm thick glass fibre reinforced plastic plate with each experiment producing through hole in which response MRR and radial overcut (ROC) were measured. The material removal rate is obtained in terms of volumetric material removal rate by taking density of glass fiber reinforced plastic as a **2.7 gm/cc**. The top and bottom diameters of each hole were measured using **3 micron** accuracy digital tool maker's microscope at four different positions. Average of this value is taken as the value for top and bottom diameters. Radial overcut was determined by halving the difference between larger of the top and bottom diameters and nozzle diameter was initially **2.5 mm**.

Table 2 Experimental Schema and Results

Run Order	Thickness	Air Pressure	Stand of Distance	MRR (mg/sec)	ROC (mm)	Taper (Rad)
1	1.5	4	1	0.0042	0.7933	1.5867
2	1.5	4	2	0.0052	0.8570	1.7140
3	1.5	4	3	0.0022	0.9748	1.9496
4	1.5	5	1	0.0060	0.7726	1.5452
5	1.5	5	2	0.0030	0.7592	1.5185
6	1.5	5	3	0.0015	0.9429	1.8858
7	1.5	6	1	0.0028	0.7044	1.4089
8	1.5	6	2	0.0050	0.8867	1.7733
9	1.5	6	3	0.0059	0.9073	1.8147
10	2.2	4	1	0.0004	0.3949	0.7899
11	2.2	4	2	0.0005	0.4555	0.9111
12	2.2	4	3	0.0017	0.6965	1.3929
13	2.2	5	1	0.0027	0.5000	1.0000
14	2.2	5	2	0.0008	0.4645	0.9291
15	2.2	5	3	0.0006	0.3247	0.6495
16	2.2	6	1	0.0007	0.4939	0.9879
17	2.2	6	2	0.0030	0.4914	0.9827
18	2.2	6	3	0.0022	0.4676	0.9352
19	3	4	1	0.0002	0.4067	0.8133
20	3	4	2	0.0005	0.4284	0.8569
21	3	4	3	0.0009	0.5392	1.0784
22	3	5	1	0.0008	0.4300	0.8600
23	3	5	2	0.0004	0.4551	0.9102
24	3	5	3	0.0006	0.4659	0.9318
25	3	6	1	0.0010	0.4504	0.9007
26	3	6	2	0.0022	0.4956	0.9911
27	3	6	3	0.0020	0.2478	0.4956

3. OPTIMIZATION USING GRAY RELATIONAL ANALYSIS

A multi attribute decision making approach for optimization of AJDP process parameters are carried out using Gray relational analysis based on experimental data. Their steps are discussed in this section.

3.1 Data pre-processing

If the number of experiments is "m" and the number of response (i.e. performance characteristics) is "n then the i^{th} experiment can be expressed as $Y_i = (y_{i1}, y_{i2}, \ldots, y_{ij}, \ldots, y_{in})$ in decision matrix form, where y_{ij} is the performance value (or measure of performance) of response j (j = 1, 2, ….., n) for experiment i (i = 1, 2, ….., m). The decision matrix for single response is shown in Table 2. The term Y_i can be translated into the comparability sequence $X_i = (x_{i1}, x_{i2}, \ldots, x_{ij}, \ldots, x_{in})$ where x_{ij} is the normalized value of y_{ij}.

$$x_{ij} = \frac{Max\{y_{ij}, i = 1,2,\dots.m\} - y_{ij}}{Max\{y_{ij}, i = 1,2\dots.m\} - Min\{y_{ij}, i = 1,2,\dots.m\}} \quad for\ i = 1,2,\dots.m;\ j = 1,2,\dots.n \qquad (1)$$

$$x_{ij} = \frac{yij - Min\{yij, i = 1,2,\dots.m;\}}{Max\{yij, i = 1,2\dots.m\} - Min\{yij, i = 1,2,\dots.m\}} \quad for\ i = 1,2,\dots.m;\ j = 1,2,\dots.n \qquad (2)$$

The response results (Y_i) shown in Table 3 are normalized in x_{ij} values for the response smaller-the-better i.e. radial overcut, using equation (1) and larger-the-better i.e. MRR, using equation (2).

3.2 Reference sequence

In comparability sequence all performance values are scaled to (0, 1) for a response j of experiment i, if the value x_{ij} which has been processed by data pre-processing procedure is equal to 1 or nearer to 1 then the performance of experiment i is considered as best for the response j. X_0 is defined as, (x_{01}, x_{02}, ….., x_{0j}, ….., x_{0n}) = (1, 1, ….., 1, …..,, 1), where x0j is the reference value for j^{th} response and it aims to find the experiment whose comparability sequence is closest to the reference sequence. Table 4 shows the sequences (X_{ij}) after the grey relational generating sequence.

3.3 Gray relational coefficient

Gray relational coefficient is used for determining closeness of xij is to x0j. The larger the gray relational coefficient, the closer x_{ij} and x_{0j} are the gray relational coefficient can be calculated by using Equation (3).

$$\gamma(x_{oj}, x_{ij}) = \frac{\Delta_{min} + \xi\Delta_{max}}{\Delta_{ij} + \xi\Delta_{max}}, \quad for\ i = 1,2,\dots.m;\ j = 1,2,\dots.n\ and\ \Delta_{ij} = |x_{oj} - x_{ij}| \qquad (3)$$

Where, γ = the gray relational coefficient between x_{ij} and x_{oj}, ξ = distinguishing coefficient and its value is in range between zero to one, because of all parameter have equal weight age, ξ is set to be 0.5 [14-15]. The smaller distinguishing coefficient, higher is its distinguishing ability. The purpose of distinguishing coefficient is to expand or compressed the range of the gray relational coefficient. Different distinguishing coefficient may lead to different solution results. Decision makers should try several different distinguishing coefficients and analyze the impact on GRA results.

3.4 Gray relational grade

The measurement formula for quantification in gray relational space is called gray relational grade. A gray relational grade (gray relational degree) is a weighted sum of gray relational coefficients and it can be calculated using Equation (4).

$$\Gamma(x_o, x_i) = \sum_{j=1}^{n} w_j \gamma(x_{oj}, x_{ij}) \quad for\ i = 1,2,\dots.m\ \ and\ j = 1,2,\dots..n \qquad (4)$$

In above equation $\Gamma(X_0, X_i)$ is the gray relational grade between comparability sequence X_i and reference sequence X_0. It represents correlation between the reference sequence and the comparability sequence. w_j is the weight of response surface j and depends on decision maker's judgment. The primary interests in optical industries are the Radial overcut and MRR as well as burrs which may be formed at the jet exit. In such cases for AJDP process application MRR and Radial overcut have equal weight and is equal to 50%.
Hence from above discussion, for multi-objective optimization for the input parameters are selected weights

are assigned and gray relational coefficient of the individual quality characteristics are determined. Using assigned weights to MRR and Radial overcut average grade $\Gamma(X_0, X_i)$ is calculated using Equation (4). Ranks of the experiments are determined based on calculated average grades and they are shown in Table 3.

Table 3 Gray relational coefficients of the individual quality characteristics based on weights

Exp. No.	Equal Weight		Roughing		Finishing	
	Grade	Rank	Grade	Rank	Grade	Rank
1	0.5293	6	0.6530	3	**0.9619**	**1**
2	0.5142	8	0.6159	4	1.2725	3
3	0.4368	18	0.4756	17	3.0265	13
4	0.5660	3	0.6748	2	0.9813	2
5	0.4945	10	0.5436	10	0.8356	8
6	0.4507	16	0.4401	20	2.1042	24
7	0.5302	5	0.5392	11	0.7152	11
8	0.5461	4	0.5265	12	1.4700	15
9	**0.8266**	**1**	**0.7110**	**1**	1.7095	12
10	0.4800	14	0.5725	7	**0.3954**	**4**
11	0.4829	11	0.5704	8	0.4292	6
12	0.4182	21	0.4348	21	0.6861	19
13	0.5040	9	0.5772	6	0.4837	7
14	0.4352	19	0.4455	19	0.4373	18
15	0.4820	13	0.4646	18	0.3654	22
16	0.4822	12	0.4941	14	0.4562	14
17	0.5232	7	0.5054	13	0.4821	17
18	**0.6591**	**2**	**0.5900**	**5**	0.4541	16
19	**0.4727**	**15**	**0.5655**	**9**	**0.3992**	**5**
20	0.4382	17	0.4929	15	0.4134	9
21	0.3876	26	0.4106	23	0.4915	20
22	0.4333	20	0.4866	16	0.4169	10
23	0.3919	24	0.4075	24	0.4285	23
24	0.3734	27	0.3780	26	0.4366	26
25	0.4063	22	0.4215	22	0.4310	21
26	0.4037	23	0.4018	25	0.4737	25
27	0.3900	25	0.3738	27	0.3520	27

3.5 Analyze the results of grey relational grade

From the value of grey relational grade, the relational degree between main factor and other factors is computed concerning of all performance characteristic. The average value of the grey relational grade for each level of the operating parameters is shown in the response Table 4.

Table 4 Response Table for Gray Relational Grade

Parameter	**Max-Min**
MRR	0.0059-0.0002(0.0057)
ROC	0.7933-0.2478(0.5455)
Taper	1.5452-0.4956(1.0496)

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4. RESULT AND DISCUSSION.

The gray relational grade indicates the degree of similarity between the reference sequence and the comparability sequence. Similar to roughing case, grey relational grades are found for semi-finishing and finishing cases and given ranks in descending order of the grade. These results are listed in Table 3.

From the listing of grey relational grades in Table 3 for abrasive jet drilling of GFRP, it is observed that for both these machining operations and for roughing as well semi-finishing the best rank is attributed to DOE serial 9 which relates to lowest thickness and maximum pressure and maximum SoD. This is matching with the experimental findings and subsequent analysis showing that MRR is higher for lower thickness values and higher pressure and SoD values. In case of semi-finishing the effective contribution of MRR to the grade is greater as compared to the combined effect of ROC and taper which leads to the same combination being selected as the best for semi-finishing. In case of finishing cut, however, due to the significant importance given to reduction in ROC and taper, the lowest combination of all variables as in DOE serial 1 is found to be optimum. These combinations are indicated in bold in Table 3.

5. CONCLUSION

Multi-objective optimization gives multiple combinations with close values of combined objectives This study applies the grey relational analysis to optimize the AJDP process for the multi-objective optimization such as minimizing the radial overcut and Taper and maximization of MRR based on selected weights .The response tables for each level of the machining parameters are obtained from the grey relational grade, and select the optimal levels of machining parameters. It is obviously shown that the above performance characteristics in the AJDP process are greatly improved together. Significant levels of input parameters for optimal responses are identified using GRA. With different weight combinations corresponding to roughing, semi-finishing and finishing conditions of drilling, different parameter combinations which are best for these conditions could be determined using GRA. The lowest thickness and highest SoD and pressure are found to be most suitable for high material removal rates desired in case of roughing cuts. While the lowest thickness and lowest SoD and pressure are found desirable for semi-finishing and finishing where reduction in taper and overcut are the chief goals.

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