International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XIII, No. 1 / 2021

OPTIMIZATION OF PROCESS PARAMETERS FOR MULTI CRITERION DECISION MAKING IN ABRASIVE WATER JET MACHINING OF MAGNESIUM - SILICON BASED ALUMINIUM ALLOYS

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Abstract: Taguchi - Data envelopment analysis based ranking method (DEAR) was implemented to select optimal machining parameters needed for simultaneous multi criteria decision making during abrasive water jet machining process. Results of experimental investigations, showed that the process parameter feed rate had highest influence on material removal rate out of all the four input parameters considered. Also, the abrasive flow rate showed considerable moderate influence on the average surface roughness. The optimum combination of process parameters in the present study are found to be P2-F3-Q1-SD2 i.e 200 MPa water jet pressure, 150 mm/min feed rate, 200 mg/min abrasive slurry flow rate and 4mm standoff distance with a optimal solution of 6.234 milligrams per minute for material removal rate (MRR) and 4.837 microns for average surface roughness (SR) to meet the larger the better condition for material removal rate and smaller the better condition for average surface roughness.The proposed method showed good agreement with a enhanced values of 16.64% and 4% for MRR and SR which is found after confirmation experiment.

Key words: Material removal rate, Surface roughness average, S/N ratio, ANOVA, Taguchi-DEAR based MCDM approach.

1. INTRODUCTION

Among the unconventional machining processes, Abrasive water jet machining (AWJM) can produce precise machined parts and surfaces required for varied engineering applications. Parts manufactured by either metallic or nonmetallic materials found in scientific, domestic, industrial and biomedical fields. The principle involved here is velocity energy in the form of water jet is converted into the abrasive slurry in mixture form which is impact on to the raw material to form a particular shape/geometry based on the principle of mechanical erosion. In general numerous authors consider jet of water pressure (P), feed rate (F), abrasive mass flow rate (Q), standoff distance (SD) as input parameters during AWJM in their research works. The AWJM process is clean and does not involve formation of chips during cutting, chemical reactivity and air pollution, so it is an eco friendly when compared to other cutting processes. Dust or any foreign material thrown away by high pressure jet of water exerted from flow nozzle along with erosion on work part material, therefore this process cannot produce any fumes or gases while cutting. Now a day’s abrasive water jet machining has been concentrate towards thermally sensitive materials which are very difficult to machine with conventional systems. Due to its versatility, ease of operations and extended capabilities, it has become the burning topic among diversified machines in the current manufacturing firms.

AWJM process combined with multiple machining characteristics, so multiple criteria decision making methodology (MCDM) is more important to introduce for optimizing the machining parameters by selecting better combination of input factors and to get optimal responses. In the literature number of multi response optimization techniques found to optimize the process parameters, in that some of the methods like grey based Taguchi methods, design of experiments based surface response methods, feed forward or backward neural networks and multi decision making methods found to be good from the literature.But for every method said above have certain drawbacks i.e. grey theory provides a poor combination of significant parameters which may not guide to different choice of responses like combination of larger the better and smaller the better, assignment of weight method gives lesser flexibility for non-linear cutting processes. The interpretation of results from RSM further needs more awareness towards optimization of combination cutting parameters during any machining and the accuracy prediction in ANN based model depends on training limit. The optimality procedure algorithms engaged in above methods are found to be laborious to researchers. So, in the present paper focused on DEAR based multiple criteria decision making approach to optimize the AWJM process parameters to meet optimum responses in simpler manner.

Deepak Doreswamy et al. (2015) investigated experimentally by Taguchi's L_{27} orthogonal array and found the influence of standoff distance, water jet pressure and feed rate during AWJM process with graphite filled glass fiber reinforced epoxy composite. Kale, A et al. (2020) and Dhaval Sangani & P.S. Puranik (2015) reviewed on abrasive water jet machining and concluded it is one of the latest unconventional machining methods used extensively in precise industrial applications like aero space, aircraft engineering, ship building and automotives because of better-quality especially in mechanical properties even though initial; investment is more. Dhruv Soni and Pritesh R. Patel (2016) focused on experimental investigation of the AWJM process that can be used for a better understanding and mentioned the procedure to select of input parameters. Shyamkumar D. Kalpande (2015) et al. also described the procedure to select input factors for conducting experiments through AWJM process and identified critical factors to raise the performance of machining. The performance of the any machining process was estimated on the basis of maximum material removal rate, the minimum of average surface roughness and depth of cut. Also the authors applied AHP method to prioritize by using pare-wise comparison. Mohammad S. Alsoufi (2017) described in his review paper about basic fundamentals regarding selection of parameters, abrasives suitable for proper materials and provided the information related to type of materials to be preferred. Sreenivasulu R et al. (2013, 2014, 2016) also utilized the concept of Taguchi design of experiments in their work to optimize the machining parameters and concluded that it gives good agreement with other statistical methods. G.Selvakumar et al. (2018) also presented a method for optimization of machining parameters during abrasive water jet machining (AWJM) by developing artificial neural networks (ANN) models to forecast the effect of input factors generally chosen as size of water jet, stand-off positional distance of nozzle w.r.t workpiece and flow rate of abrasive slurry with output responses like material removal rate, average surface roughness with 100000 trial runs. Kumar et al. (2018) also stated material removal rate is highly significant parameter to influence on feed rate and moderately influenced on standoff distance in their experimental study to optimize the abrasive water jet machining parameters by selecting tungsten carbide composite with aluminium reinforcement. Prasad et al. (2019) demonstrated elaborately about latest developments in multi criterion decision making (MCDM) techniques like WASPAS, MAAJM etc. Tripathi et al. (2021) mentioned the importance of AWJM process in investigations on influence of the AWM variables on GFRP composites. Priya U.Shinde et al. (2015) reviewed on AWJ machining on composite materials. Ajit Dhanawade et al. (2017, 2019, 2020) conducted experimental investigations on abrasive waterjet machining by selecting PZT ceramic and carbon epoxy composite. Monika Kulisz et al. (2020) and Duspara M. et al. (2016, 2017) also found AWJM process suitable to cutting of rigid materials. Thamizhvalavan et al. (2019, 2021) and Rajamani et al. (2020) utilized AWJM process in their research, Even though much literature existing on machining of different materials and alloys, it is noticed that only small attention has been given in the background literature towards analyzing the influence of cutting parameters on performance measures such as material removal and average surface roughness during machining of alloys in abrasive water jet machining (AWJM). Taguchi integrated Data Envelopment Analysis based Ranking (DEAR) method involves simple steps where multiple criteria decision making (MCDM) problems are existed to determine the optimal process parameters in any machining process.

2. MATERIALS AND METHODS

The experimental setup for abrasive water jet machining consists of the following sub units. Water softenner equipped with two cylindrical tanks, pressure intensifier, hopper, air compressor unit, abrasive water jet cutting head and work holding fixture. The compressed air from the pump forces the abrasive particles into the mixing chamber. The material removed from the work piece gets collected in a catcher tank partially filled with water. The present work was carried out on AQUA TECH 3001.15W abrasive water jet setup of Micro step group. For the present work, work piece made of Al-Mg-Si was chosen with a size and shape of 150 mm X 130mm X 10mm rectangular cross section. The process parameters that are varied during experimentation are: abrasive slurry flow rate (Q), water jet pressure (P), feedrate (F) and standoff distance (SD). From the number of output responses, number of process parameters and levels of each of the input parameters, Taguchi L9 experimental plan is selected. The selected input machining parameters and their levels as per Taguchi's orthogonal array are depicted in Table 1. In AWJM machining, the flow rate of abrasive particles influences the machinability of the work piece considered. The procedure to estimate the material removal rate followed in this experimental work is in accordance with the standard procedures available in the literature. The difference in the weight the raw material and finished component are estimated to calculate MRR. In the present experimental investigations, weight of work piece measured before and after abrasive water jet machining using a high precision digital balance meter (Model: 200D Macro single pan electrically operated analytical balance made by Dhona Instruments (Pvt) Ltd., Kolkata, west Bengal, India) and average values of surface roughness (SR) are measured using portable surface roughness tester Surf test SJ-210 series (0.75mN type, Mitutoyo, Japan) apparatus. Figure 1(a) and Figure 1(b) showed the experimental setup for AWJM process and surface roughness measuring device.

Table 1. Machining parameters and their levels as per Taguchi L_9 orthogonal array

Input parameters	Units	Level 1	Level 2	Level 3
Water-jet pressure (P)	(MPa)	150	200	250
Feed rate (F)	(mm/min)	50	100	150
Abrasive flow rate (Q)	(mg/min)	200	300	400
Stand-off distance (SD)	(mm)	2	4	6

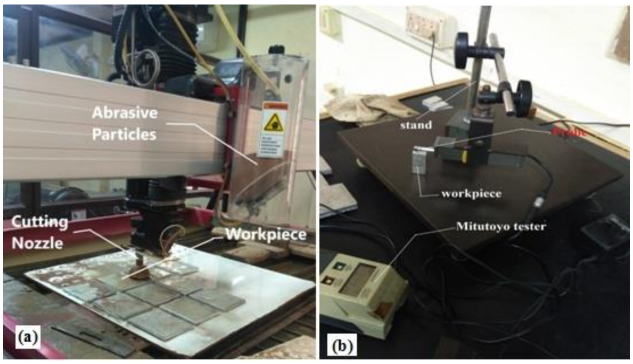

Fig.1. (a) Close view of experimental setup with nine work pieces and (b) Surface roughness apparatus

2.1 Taguchi –DEAR method

Data envelopment analysis based ranking (DEAR) Technique converts the initial output responses into suitable fractions so that, appropriate levels can be considered. From the obtained values of fractions, the magnitude of multi response parameter index is estimated and which inturn gives the optimal combinations of the input parameters.

Algorithm of DEAR approach

1. Carrying out experiments according to the Taguchi L_9 experimental design
2. Weights (w) corresponding to material removal rate and surface roughness for 9 experiments are estimated.
3. Initial response data is converted into weighted data by multiplying the values with suitable weights estimated from step.2.
4. The ratio of larger the better to smaller the better for both the output responses are calculated.
5. The ratio obtained in step 4 is considered as MRPI.

The estimation MRPI and weights of output responses in the present work is carried out by set of equations 1 to 5.

$$MRPI = \frac{LB}{SB} \tag{1}$$

$$LB = MRR \times W_{MRR} \tag{2}$$

$$SB = SR \times W_{SR} \tag{3}$$

$$W_{MRR} = \frac{MRR}{\sum MRR} \tag{4}$$

$$W_{SR} = \frac{1/SR}{\sum 1/SR} \tag{5}$$

3. RESULTS AND DISCUSSIONS

Based on the L_9 orthogonal array as per Taguchi design of experiments, slot cutting was performed on Al-Mg-Si alloy work piece material with abrasive water jet machining and magnitudes of responses recorded with well calibrated instruments and tabulated in Table 2. The MRPI value of corresponding experimental run with different level-wise combinations of input parameters determined as per procedure given under sub section. MRPI values obtained after calculation in the present study shown in Table 3. Merged values of MRPI for four input parameters with level wise depicted in Table 5. The value at maximum level of each process parameters indicates the optimal level of input factors on determining the measure of performance during machining. The optimal combination of input factors in abrasive water jet machining of present investigations obtained 200 MPa of water jet pressure, 400 mg/min of abrasive flow rate, 4 mm of standoff distance and 150 mm/min of feedrate respectively i.e P2-F3-Q3-SD2 is the combination of parameters to decide multi criteria decision making of output responses to optimize the machining parameters.

Table 2. Parameter combinations as per Taguchi L_9 orthogonal array

Exp. No.	Input process Parameters				Output responses	
	P (MPa)	F (mm/min)	Q (mg/min)	SD (mm)	MRR (mg/min)	SR (µm)
1	150	50	200	2	2.7352	4.085
2	150	100	300	4	6.2565	4.380
3	150	150	400	6	7.4626	3.875
4	200	50	300	6	5.1969	4.205
5	200	100	400	2	8.8633	3.740
6	200	150	200	4	8.9552	5.045
7	250	50	400	4	3.8293	3.800
8	250	100	200	6	5.2137	6.145
9	250	150	300	2	11.1940	4.970

In multi criterion machining process, the elevated value of significant parameter is decided by the max – min condition and obtained values are depicted in the Table 4. The main effects plot of MRPI with respect to input parameters water jet pressure (P), feedrate (F), abrasive flow rate (Q) and standoff distance (SD) is drawn and shown in Figure 2. From graph, it is found that the abrasive flow rate has the most significant influence on MRR, surface roughness. Material removal during the machining process is on account of continuous impingement of high pressure water jet coupled with a flow of abrasive slurry from the nozzle. The impact force of the abrasive water jet forms depressions on machined surface of the work piece. The location and size of the machined surface depressions are found and this givea a measure of the average surface roughness on specimens after slotting. The rate at which, the material is removed from the work piece and the surface finish of the work piece obtained after slotting operation are measured.

Table 3. MRPI magnitudes of all experiments

Exp. No.	Weights		MRPI
	MRR	SR	
1	0.12527	0.11873	1.05508
2	0.65555	0.11073	5.92025
3	0.93267	0.12517	7.45122
4	0.45234	0.11535	3.67039
5	1.31566	0.12969	10.1446
6	1.34310	0.09614	13.9702
7	0.24559	0.12764	1.9241
8	0.45536	0.07893	5.76789
9	2.09865	0.09759	2.15034

Table 4. Level wise average of MRPI values

Parameters	Level 1	Level 2	Level 3
P	14.42655	**27.785**	9.8421
F	6.6495	21.831	**23.572**
Q	20.793	11.741	**31.566**
SD	13.350	**21.814**	16.889

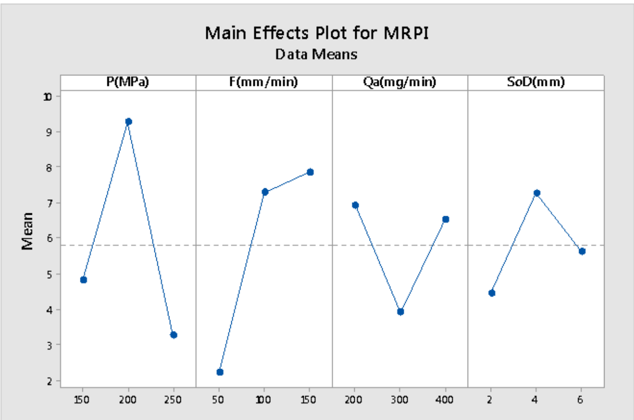

Fig. 2. Significance of process parameters on MRPI

In design of experiments by Taguchi method, the output or desired response is indicated by the term 'signal' and the undesirable error or deviation from the desired response is represented by the term 'noise'. The S/N ratio is used to measure the deviation of response characteristic from the desired value. The S/N ratio (η) is mathematically expressed as $\eta = -10 \log (M.S.D)$, Where M.S.D is the mean square deviation for the output response. The responses of S/N ratios for both material removal rate (MRR) as well as surface roughness average (SR) indicated in the Table 5 and Table 6 respectively. Figures 3 and 4 shows the main effects plot for material removal rate and surface roughness. From the main effects plots, the optimal combination of process parameters for measured output responses are as given in the following order. Feedrate, water jet pressure, abrasive slurry flow rate and standoff distance respectively for MRR. From Table 5 for MRR (larger the better) the optimal sequence is (i.e P2-F1-Q3-SD4). For surface roughness (smaller the better) the optimal sequence is abrasive flow rate, water jet pressure, feedrate and standoff distance (i.e P2-F3-Q1-SD4) respectively as obtained through Taguchi method.

Table 5. Response Table for S/N Ratio (MRR)

Level	MRR (Larger is better)			
	P	F	Q	SD
1	14.04	11.57	14.04	16.22
2	17.44	16.41	17.07	15.54
3	15.66	19.16	16.02	15.37
Delta	3.39	7.59	3.03	0.85
Rank	2	1	3	4

Table 6. Response Table for S/N Ratio (SR)

Level	SR (Smaller is better)			
	P	F	Q	SD
1	-12.27	-12.10	-14.02	-12.54
2	-12.66	-13.35	-13.08	-12.83
3	-13.76	-13.25	-11.61	-13.34
Delta	1.49	1.25	2.41	0.80
Rank	2	3	1	4

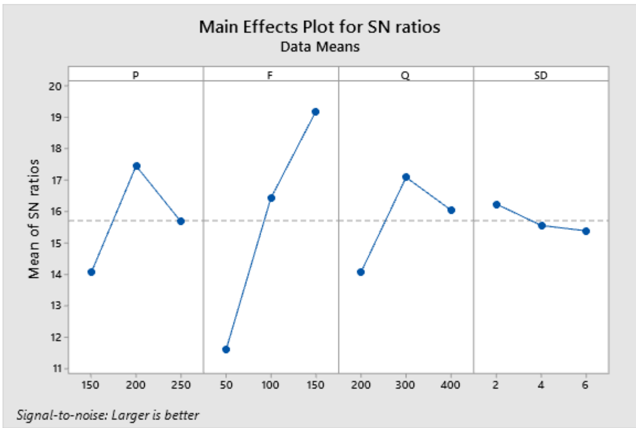

Fig. 3. Main effects plot for MRR

Main effects plot of material removal rate (MRR) shown in Figure 3 reveals that P2-F3-Q2- SD1 are the most influenced input parameters based on larger the better performance. Similarly, from main effects plot of average surface roughness (SR) illustrated in the Figure 4 observed as P1-F1-Q3- SD1are influenced input factors based on smaller the better performance. From these individual observations found that it is difficult to establish the experimental plan to meet above performance. So that Taguchi combined with Data envelopment analysis based ranking (DEAR) Technique merge the above two different (larger the better and smaller the better criterias) decision criterias in to single criteria (i.e MCDM) by converting MRPI. Significance of process parameters on MRPI shown in Figure 2 describes the MCDM such that P2-F3-Q1-SD2 provides best combination of machining parameters to satisfy both MRR and SR requirements.

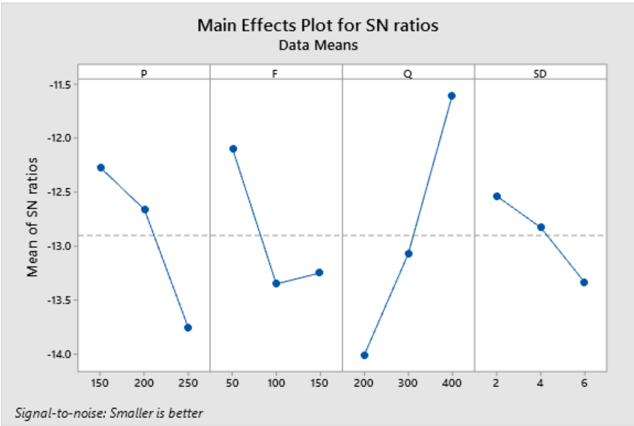

Fig. 4. Main effects plot for SR

To know the influence of more than one parameter at a time, interaction plots are one of the facity in the statistical software like Minitab 17. So, interaction plots drawn by taking one of the parameter remains constant and observed the variation of responses with alter the other parameters (four in one) in single diagram.

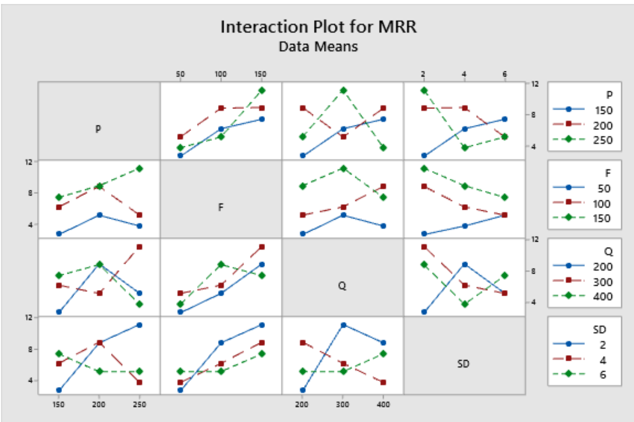

Fig. 5. Interaction plot for MRR

To draw interaction plot for MRR, along the y-axis estimated MRR values considered and along the x-axis values of input parameters selected by keeping P=constant observed the combined influence over MRR by varying the remaining three (F, Q, SD) parameters. Similarly F = constant and P, Q, SD varying; Q = constant and P, F, SD varying; SD= constant and P, F, Q varying observed the combined influence over MRR. Interaction plot for SR is drawn by taking average surface roughness values along ordinate and along the abscissa inparameter values selected by keeping one of the parameter maintain constant every time and found the combined effect of these parameters over SR.

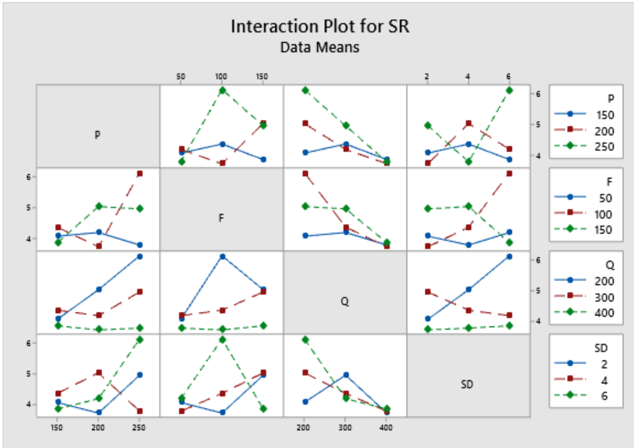

Fig. 6. Interaction plot for SR

3.1 Analysis of Variance (ANOVA)

The effect of input machining parameters were analyzed by ANOVA to determine the influence of process parameters at 95% confidence level using statistical method shown in Tables 7 and 8.

Table 7. ANOVA for Material removal rate (MRR)

Source	DF	Adj SS	Adj MS	F-value	p-value
P	2	7.231	3.615	1.5	0.045
F	2	41.97	20.98	8.71*	0.005
Q	2	5.530	2.765	1.14	0.027
SD	pooled				
Error	2	4.825	2.412	--	--
Total	8	59.55	--	--	--

*indicates most significant

It is observed that feedrate and abrasive slurry flow rate is greater than remaining parameters. Based on this significance of machining parameters can be ranked. Further, it is observed from the interaction plot shown in Figure 5 and Figure 6 and ANOVA values that there is no significant interaction effect between jet pressure and standoff distance.

Table 8. ANOVA for Surface roughness average (SR)

Source	DF	Adj SS	Adj MS	F-Value	p-value
P	2	1.195	0.598	1.986	0.049
F	2	0.901	0.451	1.498	0.038
Q	2	2.593	1.297	4.31*	0.002
SD	pooled				
Error	2	0.602	0.301	--	--
Total	8	5.291	--	--	--

*indicates most significant

The three dimensional response surface plots were drawn by using Minitab17 software for both the ouput parameters considering the input machining parameters during experimentation. These plots are illustrated the influence of water jet pressure (P), feedrate (F), abrasive flow rate (Q) and standoff distance (SD) on the material removal rate (MRR) as shown in the Figure 7 to Figure 12 clearly.

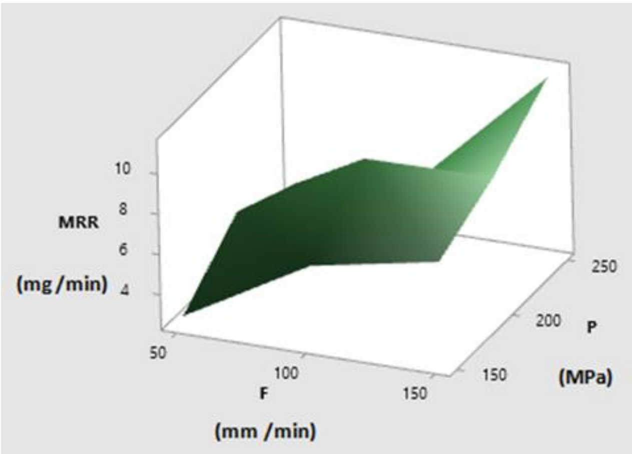

Fig. 7 Three dimensional surface plot of MRR vs P, F

From Figure 7, it is revealed that material removal rate (MRR) is increased moderately by increasing the feedrate (F) up to 100mm/min then suddenly falls beyond that but water jet pressure (P) influenced proportionally.

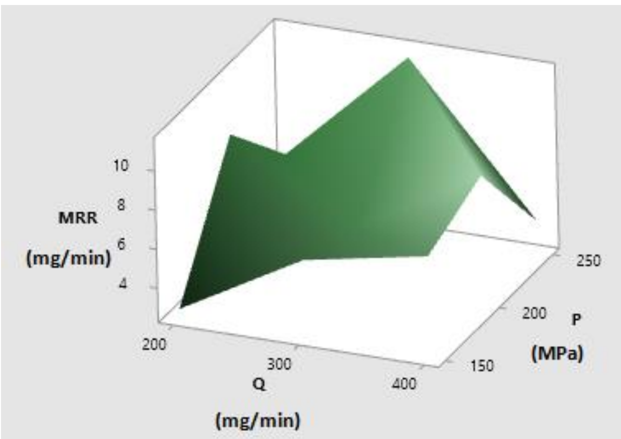

Fig. 8. Three dimensional surface plot of MRR vs P, Q

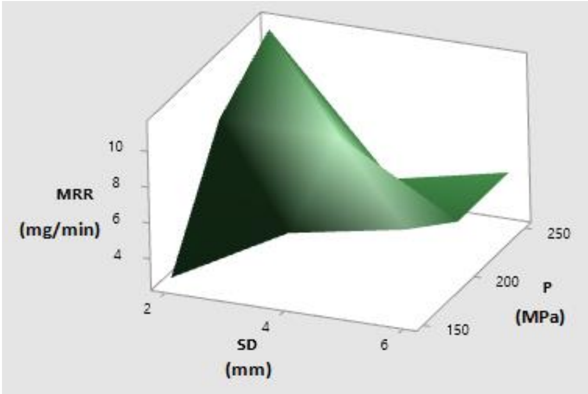

Fig. 9. Three dimensional surface plot of MRR vs P, SD

Figure 8 showed that material removal rate (MRR) is increased drastically by increasing the abrasive flow rate (Q) but there is a lower influence at lower values of water jet pressure (P). From Figure 9, it is observed that material removal rate (MRR) is raised proportionally while increased values of water jet pressure (P) and lower values of standoff distance. Also it is found that MRR suddenly falls ones the values of P & SD increased.

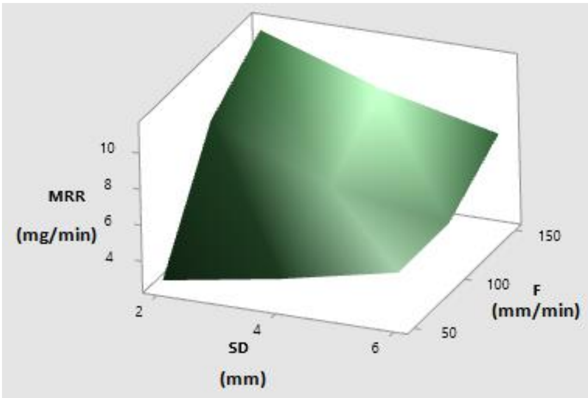

Fig. 10. Three dimensional surface plot of MRR vs F, SD

It is observed from Figure 10, material removal rate (MRR) is peak at moderate values of feedrate (F) and standoff distance (SD).

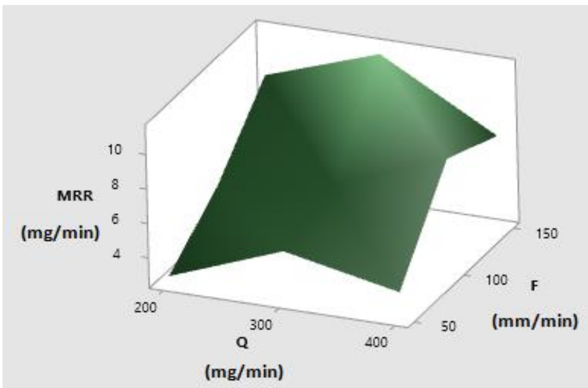

Fig. 11. Three dimensional surface plot of MRR vs Q, F

With moderate values of abrasive flow rate (Q) and feedrate (F), it is found from Figure 11 material removal rate (MRR) is enhanced highly.

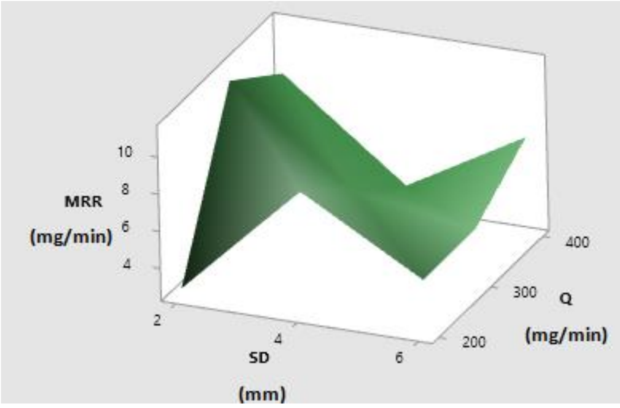

Fig. 12. Three dimensional surface plot of MRR vs Q, SD

From Figure 12, it is identified that material removal rate (MRR) is raised slowly by decreasing the values of abrasive flow rate (Q) and standoff distance (SD) and also observed that down trend of MRR obtaind by raising a standoff distance(SD) and abrasive flow rate (Q). Similarly, the influence of water jet pressure (P), feedrate (F), abrasive flow rate (Q) and standoff distance (SD) on surface roughness average (SR) depicted in the Figure 13 to Figure 18.

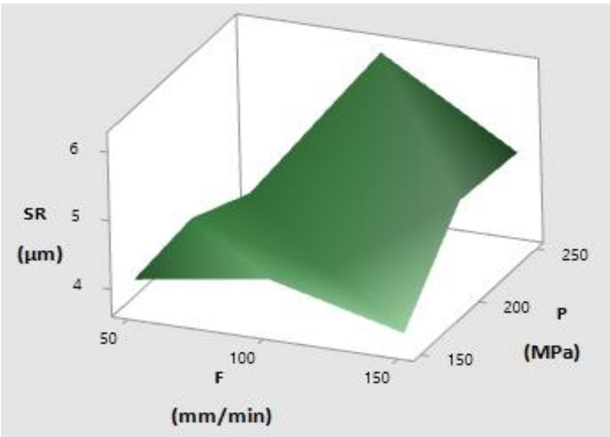

Fig. 13. Three dimensional surface plot of SR vs P, F

From Figure 13 it is revealed that surface roughness average (SR) undergoes by lower influenced at the beginning of feedrate (F) and waterjet pressure (P) then it is raised by increasing P & F simultaneously.

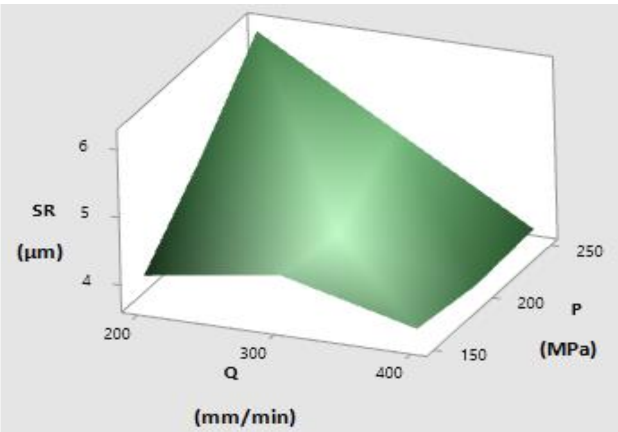

Fig. 14. Three dimensional surface plot of SR vs P, Q

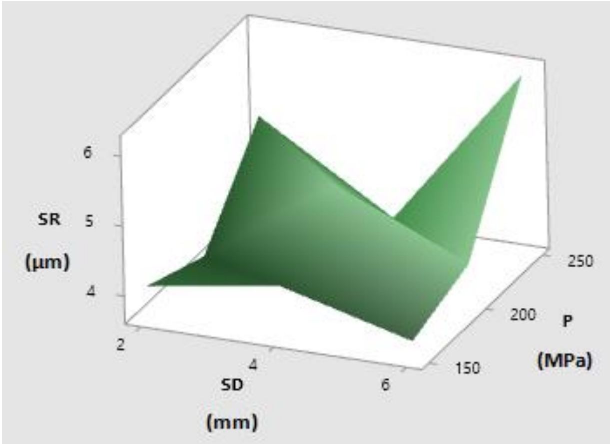

Fig. 15. Three dimensional surface plot of SR vs P, SD

Figure 14 showed that surface roughness average (SR) enhanced highly with moderate values of both water jet pressures (P) and abrasive flow rate (Q) respectively. From Figure 15, it is found that surface roughness average (SR) influenced highly at the extremities of standoff distance and waterjet pressure but less influence identified with medium values of standoff distance and waterjet pressure. From Figure 16, it is observed that surface roughness average (SR) influenced highly with medium values of feedrate (F) and standoff distance (SD).

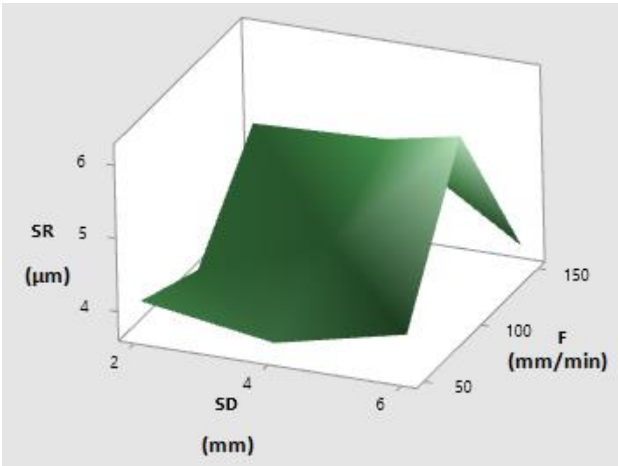

Fig. 16. Three dimensional surface plot of SR vs F,SD

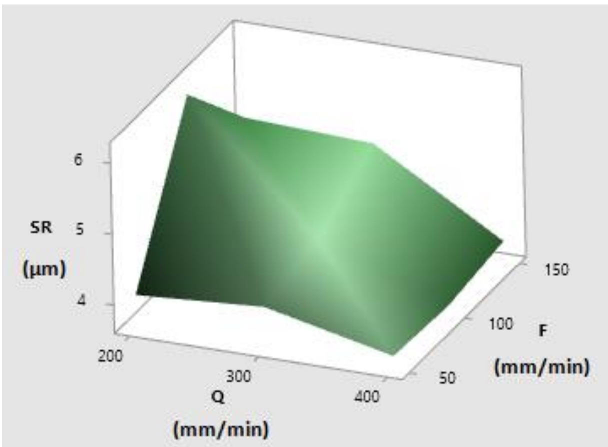

Fig. 17. Three dimensional surface plot of SR vs F,Q

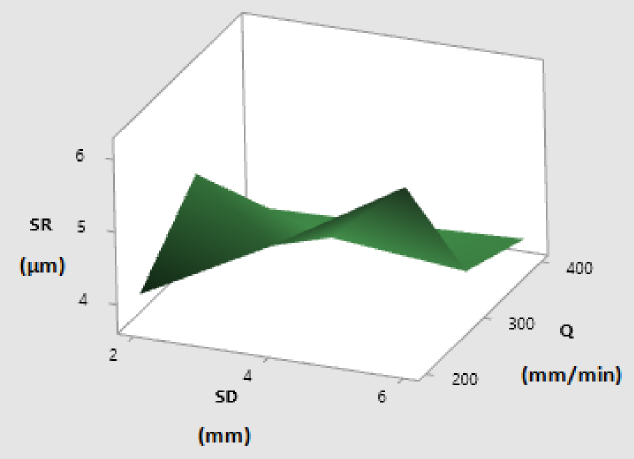

Fig. 18. Three dimensional surface plot of SR vs Q,SD

It is observed from Figure 17, the lower values of input parameters feedrate (F) and abrasive flow rate (Q) helped to increase the output response surface roughness average (SR). From Figure 18, it is identified that surface roughness average (SR) is raised with the lower range of standoff distance (SD) and medium range of abrasive flow rate (Q).

4. CONFIRMATION EXPERIMENT

Confirmation test are carried out to validate and verify improvement in output responses based on the optimal values of process parameters obtained and depicted in Table 9. The equation shown in below is used to estimate the response value based on the optimum level of the machining parameter,

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q}(\bar{\gamma}_j - \gamma_m) \qquad (6)$$

Where is γ_m the total mean of the response value, γ_j is the mean of the response value at the optimum level, i = 1, 2…6 and 'q' is the number of machining parameters that significantly effects the multiple performance characteristics.

Table 9. Optimal values of individual responses

Machining Characteristics	Optimal combination of parameters	Significant parameters (95% confidence level)	Predicted optimum value	Experimental value
MRR	P2F1Q3 SD4	Feedrate	6.234	5.196
SR	P2F3Q1 SD4	Abrasive flow rate	4.837	5.045

The main advantage associated with the implementation of DEAR method is the elimination of ambiguity in conduct of conformity test, which is the case in Taguchi method.That is, with the use of DEAR method coupled with Taguchi technique, simultaneous optimization of both the responses under one single condition is possible.

5. CONCLUSIONS

In this work, (DEAR) method coupled with taguchi based design of experiments was implemented to estimate optimum process parameters and desired responses in abrasive water jet machining. The following conclusions are drawn from the work carried out.

1. From the results of optimization, it is found that water jet pressure at a moderate level of 200 MPa, abrasive flow rate at a high level 400 mg/min, standoff distance at a peak value of 4 mm and feedrate at moderate level 150 mm/min are desirable.
2. Among all the input process parameters, abrasive flow rate showed highest followed by water jet pressure on output responses in abrasive water jet machining.
3. For the present problem, which is a max-min case [Higher material rate and lower surface roughness], Taguchi method independently could not provide the results of simultaneous optimization of both the responses.
4. Multi criterion decision making through a combination of Taguchi-DEAR method showed good efficacy in simultaneous optimization of min-max [Minimum surface roughness- Maximum material removal rate] type objective functions.

6. REFERENCES

1. Doreswamy, D., Shivamurthy, B., Anjaiah, D., & Sharma, N. Y. (2015). *An investigation of abrasive water jet machining on graphite/glass/epoxy composite*, International Journal of Manufacturing Engineering, 627218, 11 pages, https://doi.org/ 10.1155/2015/627218.
2. Kale, A., Singh, S. K., Sateesh, N., & Subbiah, R. (2020). *A review on abrasive water jet machining process and its process parameters*. Materials Today: Proceedings, **26**, pp. 1032-1036.
3. Dhruv Soni, Pritesh R. Patel, (2016). *An experimental investigation and parametric study of abrasive water jet cutting process*, International Journal of Emerging Technologies and Innovative Research, **3**(6), pp.155-162, http://www.jetir.org /papers/JETIR1606026.pdf.
4. Kalpande, Shyamkumar, D., and Badgujar, P. (2015). *Investigation of abrasive water jet cutting quality process parameter by AHP method*. International Journal of Management and Enterprise Development, **14**(3), pp. 242-249, https://doi.org/10.1504 /IJMED.2015.073443.
5. Alsoufi, M. S. (2017). *State-of-the-art in abrasive water jet cutting technology and the promise for micro-and nano-machining*, International Journal of Mechanical Engineering and Applications, **5**(1), pp. 1.
6. Sreenivasulu, R. and Rao, C. S. (2013). *Modeling and optimization of thrust force and torque during*

drilling of aluminum 6061 alloy using Taguchi–grey analysis approach, International Journal of Advanced Materials and Manufacturing Characterization, **l**(3), pp 413-418.

7. Sreenivasulu, R. (2014). *Multi response characteristics of process parameters during end milling of GFRP using Grey-based Taguchi method*, Independent Journal of Management & Production, **5**(2), pp 299-313.

8. Sreenivasulu, R. and Rao, C. S. (2016). *Effect of drilling parameters on thrust force and torque during drilling of aluminium 6061 alloy-based on Taguchi design of experiments*, Journal of Mechanical Engineering, **46**(1), pp 41-48.

9. Selvakumar, G., Prakash, S. S. R. and Lenin, N. (2018). *Experimental study on abrasive water jet machining of AA5083 in a range of thicknesses*, International Journal of Abrasive Technology, **8**(3), pp. 218-231.

10. Kumar, K. R., Sreebalaji, V. S., & Pridhar, T. (2018). *Characterization and optimization of abrasive water jet machining parameters of aluminium/tungsten carbide composites*, Measurement, **117**, pp. 57-66. https://doi.org/10.1016/j.measurement.2017.11.059.

11. Prasad, S. R., Ravindranath, K., and Devakumar, M. L. S. (2019). *Experimental Study and Optimization in Modified Air Abrasive Jet Machining on Nickel-233 Alloy Using MCDM Techniques*, Manufacturing Technology, **19**(6), pp. 1010-1019.

12. Tripathi, D. R., Vachhani, K. H., Bandhu, D., Kumari, S., Kumar, V. R., and Abhishek, K. (2021). *Experimental investigation and optimization of abrasive water jet machining parameters for GFRP composites using metaphor-less algorithms*, Materials and Manufacturing Processes, pp. 1-11. https://doi.org/10.1080/10426914.2020.1866193.

13. Priya U.Shinde and T.Z.Quazi, (2015). *Composite Materials - Abrasive Water Jet Machining*, International Journal of Scientific & Engineering Research, **6**(12), pp 299-303.

14. Ajit Dhanawade, Ravi Upadhyai, Arunkumar Rouniyar and Shailendra Kumar, (2017). *Experimental Study on Abrasive Water Jet Machining of PZT Ceramic*, Journal of Physics: Conference Series, **870**, pp 012019, 2nd International Conference on Measurement Instrumentation and Electronics 9–11 June, Prague, Czech Republic.

15. Monika Kulisz, Ireneusz Zagórski and Jarosław Korpysa, (2020). *The effect of abrasive water jet machining parameters on the condition of Al-Si Alloy*, Materials, **13**(3), pp 1-22.

16. Ajit Dhanawade, Puneet Kumar & Shailendra Kumar, (2020). *Experimental study on abrasive water jet machining of carbon epoxy composite*, Advances in Materials and Processing Technologies, **6**(1), pp. 40-53, doi: 10.1080/2374068X.2019.1703338.

17. Duspara, M., Starčević, V., Samardžić, I., & Horvat, M. (2017). *Optimization of abrasive waterjet machining process parameters*, Tehnički glasnik, **11**(4), pp 143-149.

18. Duspara, M., Palatinuš, T., Samardžić, I., Marić, D., Starčević, V., and Stoić, A. (2016). *Influence of abrasive feeding and cutting direction on the surface roughness*. Procedia Engineering, **149**, pp.48-55.

19. Thamizhvalavan, P., Yuvaraj, N. and Arivazhagan, S., (2021). *Abrasive Water Jet Machining of Al6063/B4C/ZrSiO4 Hybrid Composites: a Study of Machinability and Surface Characterization Analysis*, Silicon. https://doi.org/10.1007/s12633-020-00888-2.

20. Dhanawade, AjitKumar, Shailendra, (2019). *Abrasive water jet machining of carbon epoxy composite: Cutting performance, predictive models and optimization*, IJEMS, **26**(3&4). http://nopr.niscair.res.in/handle/123456789/51672.

21. Thangaraj, M., Loganathan, G., Atif, A., and Palanisamy, S., (2019). *Multi Response Optimization on Machining Titanium Alloy Using Taguchi-DEAR Analysis in Abrasive Water Jet Cutting*, SAE Technical Paper 2019-28-0070, https://doi.org/10.4271/2019-28-0070.

22. Rajamani, D., E. Balasubramanian, G. Dilli Babu, and K. Ananthakumar, (2020). *Experimental investigations on high precision abrasive waterjet cutting of natural fibre reinforced nano clay filled green composites.* Journal of Industrial Textiles: 1528083720942962, https://doi.org/10.1177%2F1528083720942962.

23. Sangani D. and Puranik P.S. (2015). *A Review on Abrasive Water Jet Machining Process and its process parameters*, International Journal of Emerging Technologies and Innovative Research (www.jetir.org), **2**(3), pp. 485-489, http://www.jetir.org/papers/JETIR1503015.pdf.

Received: March 23, 2021 / Accepted: June 15, 2021 / Paper available online: June 20, 2021 © International Journal of Modern Manufacturing Technologies