Optimization of Process Parameters of Abrasive Jet Machining on Epoxy Glass Fiber Composite

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ABSTRACT
In abrasive jet machining, abrasive particles are mixed with compressed air in a closed chamber and are directed over the target surface through a nozzle. The stream of particles coming out of the nozzle with very high velocities (175-300 m/s) impinges the target surface and removes the material by erosion. Typically for abrasive jet machining brittle work piece or brittle materials are machined more efficiently. In this project, the highlights are the influence of different process parameters like Pressure, Nozzle Tip Distance, and Nozzle Diameter on the Metal removal (MRR) of Epoxy Glass Fiber Composite by Abrasive jet machining. Tungsten carbide nozzles with diameters 3mm, 4mm, 5mm were considered. For this study, SiC (Silicon Carbide) abrasive with grit size of about 60µm is selected. Other parameters include Pressure (4kg/cm², 6kg/cm², 8kg/cm²), Nozzle Tip Distance (6mm, 8mm, and 10mm) are considered. Experiments were conducted and the results were analyzed and optimized with Response Surface Methodology of optimization and adequacy of the model is evaluated using analysis of variance (ANOVA) technique.

Keywords: Abrasive jet machining, MRR, optimization, Epoxy Glass Fiber Composite, analysis of variance

INTRODUCTION
A composite material is made by combining two or more dissimilar materials. They are combined in such a way that the resulting composite material or composite possesses superior properties which are not obtainable with a single constituent material. So, in technical terms, we can define a composite as ‘a multiphase material from a combination of materials, differing in composition or form, which remain bonded together, but retain their identities and properties, without going into any chemical reactions.’ Composite materials are widely used automobile industries for making aluminium body, marine applications like shafts and hulls, aeronautical applications like components of rockets and missiles, PCB, breadboards and safety equipment like ballistic protection.
Abrasive jet machining (AJM) is a non-conventional machining process where the material is removed by the process of erosion at the contact surface by streamed abrasive particles. The abrasive particles attain velocities up to 300m/s during the process when mixed with compressed carrier gas (air). The high velocity stream of abrasives is generated by converting pressure energy of carrier gas or air to its kinetic energy and hence high velocity jet. Upon impingement, the material is removed by micro-cutting action as well as brittle fracture of material. This is mostly effective on hard, brittle materials like composites, glass and ceramics and whereas on soft materials like plastics which are resilient to the chipping action is less effective.

Epoxy Glass Fiber composite is widely used fiber for its reinforcing nature. The fiber is produced by manufacturing process, direct melting route where in the furnace is charged continuously with raw material (alumino-lime silicate with less than 1% w/w alkali oxides) are melted and refined as that reaches the forehearth above a set of platinum-rhodium bushings from which the fibers are drawn.

Other approaches for optimizing the process parameters have also been attempted which includes design of experiments (DOE), ANOVA (analysis of variance) and Taguchi etc.

**LITERATURE REVIEW**

Nagdeve. L., et al [2] (2012) In this research paper, Taguchi method is applied to find optimum process parameters for Abrasive Water Jet Machining (AWJM). The objective of experimental investigation is to conduct research of machining parameters impact on MRR and SR of work piece of Al 7075. The approach was based on Taguchi’s method, analysis of variance and signal to noise ratio (SN Ratio) to optimize the Abrasive Water Jet Machining process parameters for effective machining and to predict the optimal choice for each AWJM parameter such as Traverse speed, Abrasive flow rate, Standoff distance and Abrasive grit size. This paper also presents analysis of various parameters and on the basis of experimental results, analysis of variance (ANOVA), F-Test and S/N Ratio.

Nagdeve. L., et al [3] (2012) In this paper, Taguchi method is applied to find optimum process parameter for Abrasive water jet machining(AWJM). Further experimental investigation were conducted to assess the influence of abrasive water jet machining (AWJM) process parameters on MRR and surface Roughness (Ra) of aluminum. Also, optimize the AWJM process parameter for effective machining and to predict the optimal choice for each AWJM parameter such as pressure, standoff distance. This paper analysis of the Taguchi method reveals that, in general the standoff distance significantly affects the MRR while, Abrasive flow rate affects the surface Roughness. However, experiments are carried out using (L9) orthogonal array by varying pressure, standoff distance, Abrasive flow rate and Traverse rate respectively.

V.C.Venkatesh, et al [4] (1984) was Performed Parametric Studies on Abrasive Jet Machining and explained the effect of feed rate, pressure, abrasive grit size, spray angle, nozzle tip to work distance, and metal removal rate are reported.
Rama Rao, S., et al [5] (2012) In this research paper the influence of the various process parameters, i.e. voltage, feed rate and electrolyte concentration on the predominant machining criteria, i.e. the metal removal rate (MRR) was studied. The orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio, the analysis of variance (ANOVA), and regression analyses are employed to find the optimal process parameter levels and to analyze the effect of these parameters on metal removal rate values. The confirmation test with the optimal levels of machining parameters was carried out in order to illustrate the effectiveness of the Taguchi optimization method.

Balasubramaniam, R., et al [6] (1997) Study of AJM for deburring process. An experiment conducted to identify the effect of various parameters of AJM like jet height and angle of impingement etc. on deburring process. In this experiment stainless steel specimen is used and the excremental design based on taguchi method. A profile protector was used to measure the edge quality and also the visual inspection was conducted to analyze the surface damage of the specimen here the results are also analyze by the ANOVA method. After the experiment some conclusions are obtained. It was found that burr removal was affected by the parameters jet height and angle of impingement.

Balasubramaniam, R., et al [7] (1998) Study the generation of an edge radius an abrasive jet in external deburring. The study was done the affect of various input parameters like abrasive grit size mixing ratio standoff distance and thickness. The variation in the diameters at the entry and exit side of the specimen was also investigated. The edge radius generated was affected by the parameter stand of distance and the variation in the diameter was affected by the nozzle diameter. The results of the edge radius generation was conducted to stainless steel burr specimen.

El-Domiaty. A., et al [8](2009) In this paper Drilling of glass sheets with different thicknesses have been carried out by Abrasive Jet Machining process (AJM) in order to determine its machinability under different controlling parameters of the AJM process. Here both experimental and theoretical analyses were introduced. Also, the effect of nozzle diameter (D) on the material removal rate (MRR), when different sizes of abrasive particles are used. The relationship between the cut-off distance and the required time to drill a glass plate with a 2 mm thickness were also discussed.

Kandpal Chandra, B., et al [9] (2011) In this paper investigated the testing and analyze various process parameters of abrasive jet machining. This paper also includes various results of experiments have been conducted by changing pressure, nozzle tip distance on different thickness of glass plates and ceramic plates. It was observed that as nozzle tip distance increases, material removal rate (MRR) increases as it is in the general observation in the abrasive jet machining process. As the pressure increases material removal rate (MRR) is also increased as we found in AJM process. Similarly as abrasive particle size increases MRR increases.

M. Kantha Babu, O.V. Krishnaiah Chetty., et al [10] (2003) Discussed about the Recycling of Abrasive Particles with different sizes. Recycling leads to further disintegration. The role of fine abrasives in
reduction of cutting is well established. Hence recycling leads to the decreased depth of cut.


P. M. Khodke et al [12] (1996) Discussed about the work samples eroded by AJM shows that, for brittle materials, material removal is due to an intersection and propagation of cracks produced by adjacent impacting particles on the target surface. An analytical model based on the above observations for predicting the material removal in abrasive jet machining process.

Li et al [13] (2008) investigated the process that combined grinding with abrasive jet finishing, the material removal rate (MRR) model in abrasive jet precision finishes with grinding wheel as restraint was investigated. The material removal rate model was found to give a good description of the experimental results.

Pandey, et al [14] (1980) and Bhattacharya (1976) studied the effects of abrasive flow rate (AFR) and standoff distance on the material removal rate (MRR). They observed that MRR reaches an optimum value with the increase in AFR and SOD, and then falls with the increase in these parameters.

Ray, P.K., et al [15] (1987) This research paper discusses the study of various input parameters (pressure, mixing ratio, stand of distance etc.) of abrasive jet machining (AJM) on the material removal rate. The experiment carried out with vortex type mixing chamber. The study was restricted to abrasive jet drilling only.

Kumar Karna, Shyam., et al [16] (2012) This paper examined to optimize the process by applying the Taguchi method with orthogonal array robust design. Therefore, Off-line quality control is considered to be an effective approach to improve product quality at a relatively low cost. Also analysis of variance (ANOVA) was used to study the effect of process parameters on the machining process. The approach was based on Taguchi method, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are employed to study the performance characteristics.

**RESPONSE SURFACE METHODOLOGY**

**3.1 Introduction**

Response surface methodology is useful for the modeling and analysis of programs in which a response of interest (output) is influenced by several independent variables (inputs) and the objective is to **optimize** this response. This method permits to find the settings (conditions) of the input variables which produce the most desirable response values. The set of values of the input variables which result in the most desirable values are the set **the set of optimum conditions.**
The first goal for Response Surface Method is to find the optimum response. When there is more than one response, it is important to find the compromise optimum that does not optimize only one response (Oehlert 2000)[17]. When there are constraints on the design data, then the experimental design has to meet requirements of the constraints. The second goal is to understand how the response changes in a given direction by adjusting the design variables.

3.2 Box–Behnken design
Box-Behnken design is an independent quadratic design for response surface methodology. They are very useful in the same setting as the central composite designs. Their primary advantage is in addressing the issue of where the experimental boundaries should be, and in particular to avoid treatment combinations that are extreme. The independent variable is placed at one of three equally spaced values, usually coded as -1, 0, +1. Here in this study we take pressure, nozzle diameter, and standoff distance as process parameters (independent) which will result in three levels each at -1, 0, +1. Now here Box–Behnken design for 3 factors involves three blocks, in each of which 2 factors are varied through the 4 possible combinations of high and low. It is necessary to include centre points as well which would eventually result in a total runs of 15 with extra centre points.

![Fig.1 Experimental Setup of AJM](image)

3.3 Analysis of Variance (ANOVA)
Analysis of Variance (ANOVA) is an analytical tool in finding the mean and variance among the responses. It is used to find out the percentage contribution of each factor and relative significance of each factor by finding out the most significant factor. Based on F-value (Significance factor value) important parameters can be identified. By ANOVA we can find Degree of freedom (DF), Sum of Squares (SS), Mean squares (MS), Significant Factor ratio (F Ratio), Probability (P) and calculated percentage contribution.

EXPERIMENTAL WORK

4.1 Introduction
The experimental setup consists of the following major components:

1. Air compressor.
2. Air filter.
3. Pressure Regulator and Pressure gauge.
4. Dehumidifier.
5. Mixing Chamber
6. Nozzle and Arrangement to hold the work piece

Fig. 2 Dehumidifier with air filter  Fig. 3 Nozzle arrangement  Fig. 4 Different Nozzles

4.2 Process Parameters

For successful utilization of AJM process, it is necessary to analyze the following process criteria

Pressure (Pr)
Nozzle Diameter (ND)
Nozzle tip Standoff Distance (SD)

Experiments are carried out based on the Response surface methodology with Box–Behnken design. This Box–Behnken design is based on 3 continues factors i.e. 3 process parameters with 3 levels of each parameter which would result in a total of 15 runs. The material used for experimentation is Epoxy Glass Fiber Composite rectangular block laminates and the Material Removal Rate (MRR) is the performance measure of the process parameters. The initial weight and the weight after completion of machining are noted in order for calculating the MRR.

Table 4.1: Parameters with levels for Experimentation

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Units</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Kg/cm²</td>
<td>4</td>
</tr>
<tr>
<td>Standoff Distance</td>
<td>mm</td>
<td>3</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>mm</td>
<td>3</td>
</tr>
</tbody>
</table>

RESULTS

5.1 Box-Behnken Design

Factors:     3  Replicates:  1
Base runs:  15  Total runs:  15
Base blocks:  1  Total blocks:  1
Center points:  3
Table 5.1: Experiments conducted Based on Box-Behnken Design

<table>
<thead>
<tr>
<th>S.No</th>
<th>StdOrder</th>
<th>RunOrder</th>
<th>PtType</th>
<th>Blocks</th>
<th>Pressure</th>
<th>ND</th>
<th>SD</th>
<th>MRR</th>
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<td>1</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>0.156</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>10</td>
<td>0.1141</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>3</td>
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</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>8</td>
<td>0.0675</td>
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<tr>
<td>5</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>8</td>
<td>3</td>
<td>8</td>
<td>0.0361</td>
</tr>
<tr>
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<td>6</td>
<td>6</td>
<td>2</td>
<td>1</td>
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<td>4</td>
<td>6</td>
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<td>1</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>0.1101</td>
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<td>9</td>
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<td>9</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>4</td>
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<td>0.061</td>
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<td>10</td>
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<td>3</td>
<td>10</td>
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<td>8</td>
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<td>14</td>
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<td>1</td>
<td>6</td>
<td>4</td>
<td>8</td>
<td>0.057</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>4</td>
<td>8</td>
<td>0.0584</td>
</tr>
</tbody>
</table>

5.2 Optimal Design: Pressure, ND, SD

Response surface design selected using distance-based optimality

Number of candidate design points: 15
Number of design points in optimal design: 1
Number of factors: 3
Row number of selected design points: 11
Smallest distance between optimal points: 0.000000000
Largest distance between optimal points: 0.000000000

At

<table>
<thead>
<tr>
<th>Pressure</th>
<th>ND</th>
<th>SOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 5 Epoxy Glass Fiber Composite after machining
5.3 Response Surface Regression: MRR versus Pressure, ND, SD

Regression Equation in Uncoded Units:

\[
\text{MRR} = 0.1931 - 0.02220 \text{Pressure} - 0.0937 \text{ND} - 0.00117 \text{SD} + 0.01016 \text{ND} \times \text{ND} + 0.000091 \text{SD} \times \text{SD} + 0.00869 \text{Pressure} \times \text{ND} - 0.000156 \text{Pressure} \times \text{SD}
\]

Regression Coefficients in coded units

Table 5.2: Estimated regression coefficient for MRR

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
<th>SE Coef</th>
<th>T-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.05880</td>
<td>0.00232</td>
<td>25.30</td>
<td>0.000</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.04775</td>
<td>0.02388</td>
<td>0.00142</td>
<td>16.77</td>
</tr>
<tr>
<td>ND</td>
<td>0.08535</td>
<td>0.04268</td>
<td>29.98</td>
<td>0.000</td>
</tr>
<tr>
<td>SD</td>
<td>0.00315</td>
<td>0.00158</td>
<td>1.11</td>
<td>0.319</td>
</tr>
<tr>
<td>Pressure*Pressure</td>
<td>0.00043</td>
<td>0.00021</td>
<td>0.00210</td>
<td>0.000</td>
</tr>
<tr>
<td>ND*ND</td>
<td>0.02032</td>
<td>0.01016</td>
<td>0.00210</td>
<td>0.005</td>
</tr>
<tr>
<td>SD*SD</td>
<td>0.00072</td>
<td>0.00036</td>
<td>0.00210</td>
<td>0.000</td>
</tr>
<tr>
<td>Pressure*ND</td>
<td>0.03475</td>
<td>0.01737</td>
<td>0.00201</td>
<td>0.10</td>
</tr>
<tr>
<td>Pressure*SD</td>
<td>-0.00125</td>
<td>-0.00063</td>
<td>-0.00201</td>
<td>-0.31</td>
</tr>
<tr>
<td>ND*SD</td>
<td>0.00145</td>
<td>0.00073</td>
<td>0.00201</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Model Summary, \( S=0.0040259 \)  \( R^2 = 99.61\% \)  \( R^2 \text{ (adj) } = 98.91\% \)  \( R^2 \text{ (pred) } = 94.32\% \)

Fig. 5 Surface Plot of MRR vs Pressure, ND  Fig. 6 Surface Plot of MRR vs Pressure, SD  Fig. 7 Surface Plot of MRR vs ND, SD

5.4 Analysis of Variance for MRR

Validation of the response surface methodology (RSM) values are carried out by analysis of variance (ANOVA), where it calculates the variance about the Mean results for each other and relatively too. The significance of the necessary parameters are attained based on the Significan factor value called F – Value. ANOVA validation is carried out in Minitab 17 software and values are obtained.

Validation is carried out on General Linear Model with MRR as response and pressure, nozzle Diameter (ND) and standoff distance (SD) as factors.
Table 5.3 Analysis of Variance for MRR

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>2</td>
<td>0.004560</td>
<td>0.002280</td>
<td>64.12</td>
<td>0.002</td>
</tr>
<tr>
<td>ND</td>
<td>2</td>
<td>0.014951</td>
<td>0.007475</td>
<td>26.28</td>
<td>0.000</td>
</tr>
<tr>
<td>SD</td>
<td>2</td>
<td>0.000020</td>
<td>0.000010</td>
<td>5.06</td>
<td>0.939</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.001292</td>
<td>0.000162</td>
<td>4.54</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>0.020825</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Summary, \( S = 0.0127096 \) \( R\text{-sq} = 93.79\% \) \( R\text{-sq (adj)} = 89.14\% \) \( R\text{-sq (pred)} = 75.25\% \)

ANOVA Table contain Degree of freedom (DF), Sum of Squares (SS), Mean squares (MS), Significance Factor ratio (F Ratio), Probability (P) and calculated percentage contribution. Pressure has most significant contribution of 64.12 \% on MRR, while Nozzle diameter has contribution of 26.28\% and 5.06\% contribution levels towards Standoff distance.

5.5 Response Optimization: MRR

Response optimization is carried out with response optimizer in Minitab 17 with goal as maximizing the MRR with no upper value and target value of 0.156 g/s MRR and lower value of 0.0171g/s MRR.

Multiple Response Prediction

<table>
<thead>
<tr>
<th>Variable</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>8</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>5</td>
</tr>
<tr>
<td>Standoff Distance</td>
<td>10</td>
</tr>
</tbody>
</table>

MRR = 0.15514

Composite Desirability = 0.993790 = 99.37\%

![Fig. 8 Optimization Plot for MRR](image)

CONCLUSIONS

The optimization with the help of response surface methodology of the process parameters and the regression analysis by ANOVA has been successfully studied and reported in this paper. The effective values for attaining the optimum response are found at 8kgf/cm² pressure with 4mm Nozzle Diameter with a Standoff Distance of 10mm. The results can be further improved by the response optimization. With the help of RSM, the optimization of the various process parameters was solved in an elucidated manner. Into further future scope an Artificial Neural Network can be developed for the design and help in understanding
the data fitting, pattern recognition, clustering, time-series prediction, and dynamic system modeling and control of the system.

ACKNOWLEDGEMENT

With deep regards and heartfelt respect, I use this opportunity to express my deep sense of gratitude and indebtedness to Associate Prof. Vijayasree and Associate Prof. D V Srikanth for introducing the present research topic and for their inspiring guidance, constructive criticism and valuable suggestion throughout this research work. It would have not been possible for me to bring out this report without their help and constant encouragement.

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