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Machining of FRP Composites by Abrasive Jet Machining Optimization Using Taguchi

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***Abstract*—**Abrasive Jet Machining is an Unconventional machining process in which the metal is removed from brittle and hard material in the form of micro-chips. With increase in need of materials like ceramics, composites, in manufacturing of various Mechanical & Electronic components, AJM has become a useful technique for micro machining. The present study highlights the influence of different parameters like Pressure, SOD, Time, Abrasive grain size, nozzle diameter on the Metal removal of FRP (Fiber Reinforced Polymer) composite by Abrasive jet machining. The results of the Experiments conducted were analyzed and optimized with TAGUCHI method of Optimization and ANOVA for Optimal Value.

***Keywords*—**ANOVA, FRP Composite, AJC.

I. Introduction

THE fiber reinforced composites are composed of axial particulates embedded in a matrix material. The objective of fiber-reinforced composites is to obtain a material with high specific strength and high specific modulus (i.e. High strength and high elastic modulus for its weight.). The strength is obtained by having the applied load transmitted from the matrix to the fibers. Hence, interfacial bonding is important. Fiber reinforced polymer (FRP) composites are increasingly being used in a large number of applications because of the superior advantages they offer compared to other traditional and non-traditional materials. The advantages that FRPs offer compared to other materials are well documented and include high strength to weight ratio, high modulus, high fracture toughness, and corrosion and thermal resistance. In addition to these advantages, the relative ease of manufacture of components using FRPs, thus lower cost of production, makes these materials candidates for more and more applications.

Currently the applications to which FRPs have been put to use include automotive and aircraft components, boat hulls, building panels, household and industrial appliances. The FRP items are often made in a net shape or close to a net shape. Although this reduces machining to a minimum in most cases, the need for machining operations after forming the basic shapes of components to be used for applications that require a high degree of finish remains. In addition, for some applications, it might be more economical to produce components by machining from blank composite panels or rods having the required properties.

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Abrasive jet micro-machining is a process that utilizes small abrasive particles entered into a gas stream (air) to erode material, for creating micro-features such as channels and holes. It is the material removal process where the material is removed or machined by the impact erosion of the high velocity stream of air or gas and abrasive mixture, which is focused on to the work piece. AJM differs from the conventional sand blasting process in the way that the abrasive is much finer and effective control over the process parameters and cutting [2], [4]. This process is mainly used for cutting hard and brittle materials, which are thin and sensitive to heat. Abrasive jet machining (AJM) is commonly used for cutting, cleaning, drilling and etching operations [8].

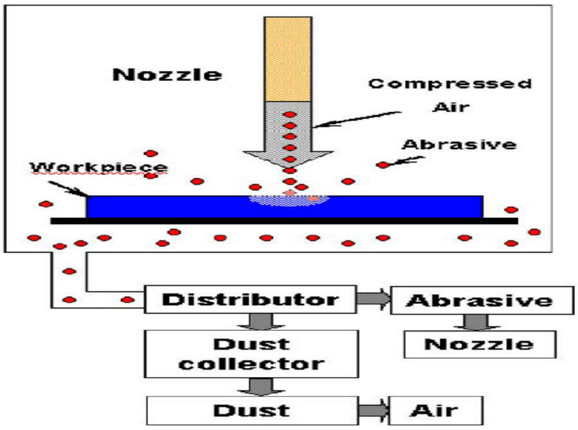

Fig. 1 Abrasive jet processing steps

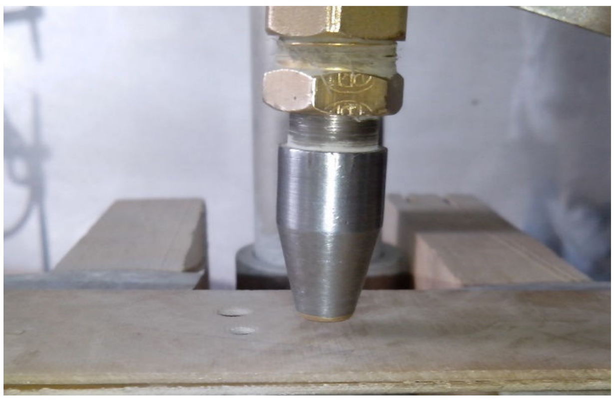

Fig. 2 Impingement of the Nozzle (Setup at SMEC)

AJM is advantageous in two aspects. First, it has a high degree of flexibility. The abrasive media can be carried by a flexible hose to reach internal, difficult-to-reach regions.

Second, AJM has localized force and less heat generation than traditional machining processes.

The material removal rate, cut accuracy, surface roughness, and nozzle wear are influenced by the size and distance of the nozzle; composition, strength, size, and shape of abrasives; flow rate; and composition, pressure and velocity of the carrier gas. The material removal rate is mainly dependent on the flow rate and size of abrasives. Larger grain sizes produce greater removal rates. At a particular pressure, the volumetric removal rate increases with the abrasive flow rate up to an optimum value and then decreases with any further increase in flow rate. This is due to the fact that the mass flow rate of the gas decreases with an increase in the abrasive flow rate and hence the mixing ratio increases, causing a decrease in the removal rate because of the decreasing energy available for material removal. The SOD was found to be the most influencing factor in the generation of the edge radius. The diameter of the hole increases with increase in SOD [1].

II. Optimization Methodology

A. Design of Experiments

Experimental design (commonly referred to as DOE) is a useful complement to multivariate data analysis because it generates "structured" data tables, i.e. data tables that contain an important amount of structured variation. This underlying structure will then be used as a basis for multivariate modeling, which will guarantee stable and robust models. The DOE technique helps to study many factors simultaneously and most economically. By studying the effects of individual factors on the results, the best factor combination can be determined.

B. Taguchi & Orthogonal Array

Every experimenter has to plan and conduct experiments to obtain enough and relevant data so that he can infer the science behind the observed phenomenon. He can do so by, Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan, has developed a method based on "ORTHOGONAL ARRAY" experiments which gives much reduced "variance" for the experiment with "optimum settings" of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved with the Taguchi Method [7]. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

C. Analysis of Variance

Analysis of Variance is a statistical test for heterogeneity of means by analyzing the group of variances. ANOVA is implemented as ANOVA [data] in the mathematical package, which was developed by the English statistician R. A. Fisher [9]. This methodology has been applied to a vast array of other fields for data analysis. Despite its widespread use, some practitioners have failed to recognize the need to check the validity of several key assumptions before applying an ANOVA to their data. It is the hope that this article may provide certain useful guidelines for performing basic analysis using such a software package.

III. Experimentation & Analysis

Experiments were conducted to confirm the validity of the proposed model as well as the models found in the literature. The experimental work was carried on a test rig which was designed and manufactured in the workshops of the Mechanical Engineering Department, St Martin's Engineering College, Secunderabad. The abrasive grits (Sic) were mixed with an air stream ahead of the nozzle and the abrasive flow rate was kept constant throughout the machining process. The jet nozzle was made of Tungsten Carbide to carry high wear resistance and increase in Life of the nozzle. Several nozzles were manufactured with different bore diameters of 1mm, 2mm, and 3mm, and conducted different levels of Experiments at three levels of Pressure and SOD.

In the present study L_9orthogonal array was employed to analyze the results of Experiments obtained from 9 levels of experiments by varying the process parameters like pressure, Standoff distance, Nozzle diameter. General Linear model of ANOVA was employed and compared with Taguchi Method [3].

The FRP composites are employed for experimentation with Abrasive Jet Machining set up at various levels designed according to Taguchi. The type of abrasive used for experimentation is Silicon Carbide of different grit sizes. The Abrasive particles mixed with air were impinged on the FRP composites with different pressures to obtain cutting.

The evaluating criteria of the surface produced were wide of cut, taper of the cut slot and work surface roughness. It was found that in order to minimize the width of cut; the nozzle should be placed close to the work surface. Increase in jet pressure results in widening of the cut slot both at the top and at the exit of the jet from the work. However, the width of cut at the bottom (exit) was always found to be larger than that at the top. It was found that the taper of cut gradually reduces with increase in standoff distance and was close to zero at the standoff distance of 8mm. The jet pressure does not show significant influence on the taper angle within the range of work feed and the standoff distance considered. Both standoff distance and the work feed rate show strong influence on the roughness of the machined surface. Increase in jet pressure shows positive effect in terms of smoothness of the machined surface. With increase in jet pressure, the surface roughness decrease. This is due to fragmentation of the abrasive particles into smaller sizes at a higher pressure and due to the fact that smaller particles produce a smoother surface. So within the jet pressure considered, the work surface is smoother, near the top surface and gradually it becomes rougher at higher depths.

The top surface diameter (upper Kerf) and the bottom surface diameter (lower Kerf) should be identically equal but practically both differ. The average of both top and bottom surface diameters are taken into consideration. The metal removal rate of the FRP Composite was calculated by measuring the initial weight before the drilling and shape of the hole drilled by Abrasive jet machine and by finding the difference in weights the MRR will be calculated.

TABLE I
PROCESS PARAMETERS AND LEVELS

Machining Parameters	Level 1	Level2	Level3
Pressure	3	5	7
Stand Off Distance	7	8	9
Nozzle Diameter	1	2	3

A. Signal & Noise Ratio

The term "signal" represents the desirable value and the “noise" represents the undesirable value. The formulae for signal-to-noise are designed such that the experimental list canal ways select the larger factor level settings to optimize the quality characteristics of an experiment. Therefore, the method of calculating the signal-to-noise ratio depends on whether the quality characteristic has smaller-the-best, larger-the-better or nominal-the-better formulation is chosen [9].

Taguchi method stresses the necessity of studying the response of variance using the signal–to–noise(S/N) ratio, resulting in the minimization of quality characteristic variation due to uncontrollable parameter. The metal removal rate was considered as the quality characteristic with the concept of the larger–the-better. The S/N ratio used for this type response is given by [10].

Taguchi’s SN-Ratio for smaller**-the-better** (Quality characteristics are usually an undesired output, say *Defects)*

$$\text{S/N Ratio} \quad \eta = -\ 10\ \text{Log10}\left(\frac{1}{n}\Sigma\ \text{Yi2}\right) \tag{1}$$

Taguchi’s SN-Ratio for **Larger-The-Better** (Quality characteristics is usually a desired output, say *Current)*

$$\text{S/N Ratio} \quad \eta = -\ 10\ \text{Log10}\left(\frac{1}{n}\frac{\Sigma 1}{\text{Yi2}}\right) \tag{2}$$

Taguchi’s SN-Ratio for Nominal**-The-Best** (Quality characteristics is usually a nominal output, say *Diameter)*

$$\text{S/N Ratio} \ \eta = \ 10\ \text{Log10}\left(\frac{\mu 2}{\sigma 2}\right) \tag{3}$$

where n = no of measurements in a Trail $Y_i = I^{th}$ value in a run/row

TABLE II
EXPERIMENTAL DESIGN MATRIX AND RESULTS

Exp No	Parameters Of Ajm			Mrr	Psnra1	Kerf	Psnra2
	Pr	Sod	Nd				
1	3	7	1	0.00865	-40.3575	3.51	-10.2274
2	3	8	2	0.02350	-32.6670	4.25	-12.7315
3	3	9	3	0.03290	-30.4699	4.75	-14.0489
4	5	7	2	0.05460	-26.0700	2.75	-9.3017
5	5	8	3	0.07540	-21.5504	3.25	-9.5589
6	5	9	1	0.07320	-22.7981	1.93	-5.8749
7	7	7	3	0.05210	-25.7516	5.25	-14.5669
8	7	8	1	0.06410	-24.6767	2.92	-9.8227
9	7	9	2	0.09760	-19.3088	5.05	-13.3871

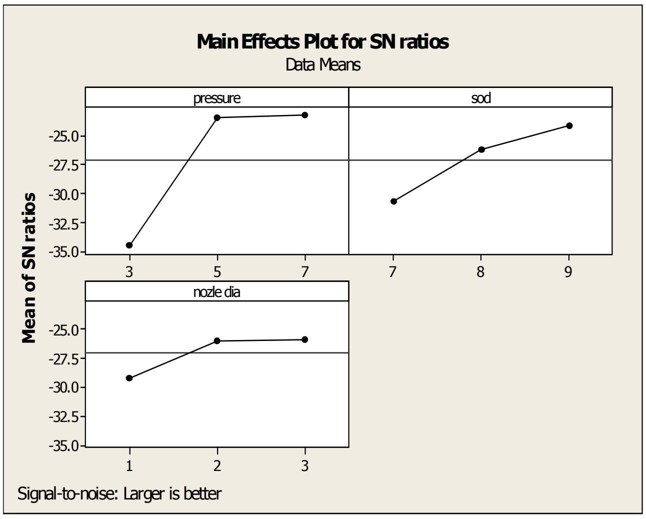

Fig. 3 Graphs indicate the Effect of Pressure, Sod, ND on MRR

TABLE III
RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS FOR MRR (LARGER IS BETTER)

Level	Pressure	SOD	ND
1	-34.50	-30.73	-29.28
2	-23.47	-26.30	-26.02
3	-23.25	-24.19	-25.92
Delta	11.25	6.53	3.35
Rank	1	2	3

TABLE IV
RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS FOR KERF (SMALLER IS BETTER)

Level	Pressure	SOD	ND
1	-12.336	-11.365	-8.642
2	-8.245	-10.704	-11.807
3	-12.592	-11.104	-12.725
Delta	4.374	0.661	4.083
Rank	1	3	2

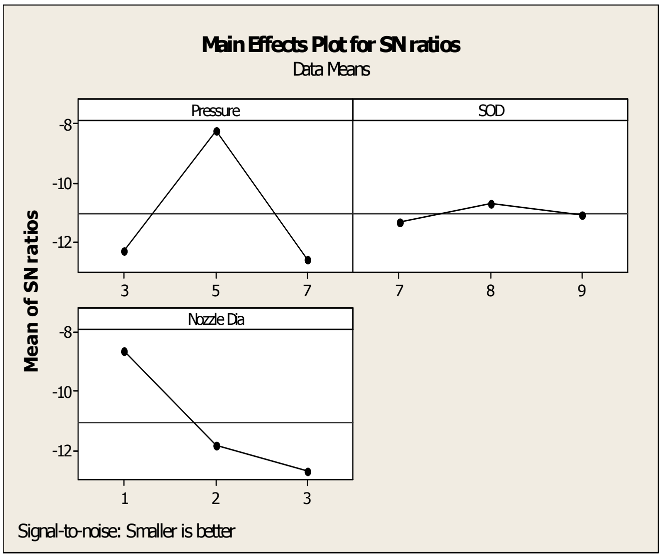

Fig. 4 Graphs indicate the Effect of Pressure, Sod, Nd on Kerf

The effect of individual parameter on entire process is not effectively rated by using Taguchi Method. By using ANONA the contribution of Individual Parameter can be well determined. The general linear model of ANOVA model was employed to investigate the effect of Parameters on MRR and Kerf. The software used for executing the validation is Minitab.

B. Validation for Optimization Using ANOVA

Analysis of variance is a collection of statistical models used to analyze the differences between group means and their associated procedures [6]. The optimized values produced in Taguchi are validated by using ANOVA

TABLE V
General Linear Model: MRR versus Pressure, SOD, Nozzle DIA

Factors	Type	Levels	Values
Pressure	Fixed	3	3,5,7
SOD	Fixed	3	7,8,9
ND	Fixed	3	1,2,3

TABLE VI
Analysis of Variance for MRR, Using ADJ SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pressure	2	0.0045916	0.0045916	0.0022958	20.77	0.046
SOD	2	0.0013036	0.0013036	0.0006518	5.90	0.145
ND	2	0.0001476	0.0001476	0.0000738	0.67	0.600
Error	2	0.0002211	0.0002211	0.0001106		
Total	8	0.0062639				

S = 0.0105144 **R-Sq = 96.47%** R-Sq(adj) = 85.88%

Table VI shows Analysis of Variance for MRR. F Value (20.77) of the parameter indicates the Air Pressure is significantly contributing more towards cutting performance. F value (0.67) of parameter indicates the Contribution of Nozzle diameter is less. The review highlights that the effect of Nozzle diameter on MRR.As increase in diameter of the Nozzle will increase the MRR meanwhile the variation in depth of cut may be increased.

TABLE VII
General Linear Model: KERF versus Pressure, SOD, ND

Factors	Type	Levels	Values
Pressure	Fixed	3	3,5,7
SOD	Fixed	3	7,8,9
ND	Fixed	3	1,2,3

TABLE VIII
Analysis of Variance for KERF, Using ADJ SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pressure	2	5.4961	5.4961	2.7480	15.97	0.059
SOD	2	0.3281	0.3281	0.1640	0.95	0.145
ND	2	4.3298	4.3298	2.1649	12.58	0.600
Error	2	0.3441	0.3441	0.1720		
Total	8	10.4980				

S = 0.414769 **R-Sq = 96.72%** R-Sq(adj) = 86.89%

Table VIII shows Analysis of Variance for KERF. F Value (15.97) of the parameter indicates the Air Pressure is significantly contributing towards Kerf width. F value (0.95) of parameter indicates the Contribution of SOD is less. It is desirable to have lower SOD which may produce Smoother surface due to kinetic energy [5]. SOD is the most influencing factor in Kerf width.

The difference in Top surface diameter (Upper Kerf) and bottom surface diameter (Lower Kerf) can be reduced by maintaining lower SOD and medium nozzle diameter. The top surface diameter and bottom surface diameter of hole obtained were measured and plotted. These were compared with previous experimental results and with it was observed that as nozzle tip distance increases, the top surface diameter and bottom surface diameter of the hole increases as it is in the general observation in the abrasive jet machining process. The Drilled and machined FRP Composite specimens by using Abrasive Jet Machining are depicted in the photographs. It is clearly observed that the Efficiency in Cutting process is less because of the drop in Pressure.

Performance found at smaller is Better Kerf was identified as air pressure (7 kg/cm^2) SOD (7 mm) nozzle diameter (3 mm). Further different methods of modeling can be adopted for the optimal results of machining.

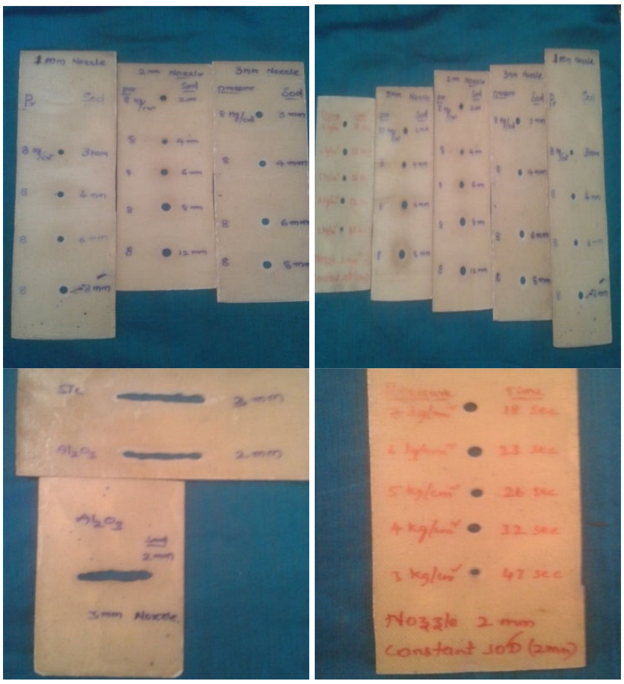

Fig. 5 Results obtained on FRP composites at various pressures, SOD's, and Nozzle diameters

IV. Conclusions

Taguchi experimentation was performed with different factors on metal removal rate and Kerf width and analyzed and compared these results with ANOVA. The Optimal levels of Performance Found at Large is Better MRR was identified as air pressure (7 kg/cm^2) SOD (9 mm) nozzle diameter (2 mm).The optimal level of performance found at smaller is

Better Kerf was identified as air pressure (7 kg/cm^2) SOD (7 mm) Nozzle diameter (3 mm). Further different methods of modelling and Analysis can be adopted for the optimal results of machining.

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