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Application of RSM for Optimal response of Process parameters on machining of CFRP composites by using AJM

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Abstract --AJM is a process that can remove material from the brittle and hard work piece efficiently without the help of cutting tool and by applying the mechanical energy. The metal removal takes place due to mechanical erosion in this process. The abrasive and air mixture impinges on the work area with high velocity, ranging between 150m/sec and 300m/sec. The process parameters that influences the metal removal rate are air pressure, nozzle tip distance (NTD), nozzle diameter (ND), and abrasive floe rate (AFR), and machining time. The type of Abrasive particles commonly used are silicon carbide, aluminum oxide etc. CFRP is the type of composite which is of light weight and strong and generally used in aerospace applications. This material is considered as work material in our experimentation. For finding the optimality of process parameters there are many methods like taguchi, RSM etc. In this article the focus is on the RSM optimal response of process parameters on MRR of CFRP composites, and the variation in response with ANOVA.

Keywords-AJM;ND;Air Pressure; NTD; RSM; CFRP

I. INTRODUCTION

Abrasive jet machining is one of the unconventional machining processes which works on mechanical source of energy. Drilling, cutting, surface finishing of Hard and Brittle

Fig. 1 Setup of AJM developed at SMEC

Fig. 2 AJM nozzle erosion

material can be effectively performed by this process. The Metal removal rate (MRR) is influenced by the pressure of carrier gas, Standoff distance between nozzle and the work area, Nozzle diameter etc. Mainly AJM utilizes the pressure of air and abrasive mixture to remove the metal from the work surface [1]. "The inside diameters of the nozzle are about 0.4mm and standoff distance is kept about 0.7 to10mm [2]".The nozzle diameter will be about 0.4mm to 5mm.The nozzle can be made of Tungsten carbide or sapphire, which gives longer life comparing with the normal steel or carbide nozzles. "Till date there has been a through and detailed experiment and theoretical study on the Process [3-4].

CFRP is a Polymer Matrix Composite material reinforced by carbon fibers. CFRP is a composite which is of light in weight with good strength and used in the manufacturing of various products used in automobile applications. Carbon Fiber Reinforced Polymer Composites, or CFRP Composites is a term used to describe a fiber reinforced composite material that uses carbon fiber as the primary structural component. It should be noted that the "P" in CFRP can also stand for "plastic" instead of "polymer "in general, CFRP composites use thermosetting resins such as epoxy, polyester, or vinyl ester. Although thermoplastic resins are used in CFRP Composites, "Carbon Fiber Reinforced Thermoplastic Composites" often go by their own acronym, CFRTP composites.

II. METHODOLOGY

Design of experiments (DOE) is a systematic, rigorous approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions. In addition, all of this is carried out under the constraint of a minimal expenditure of engineering runs, time, and money[5].

The main four area that DOE can be applied are comparative, modelling, Screening, characterizing and optimizing. For the Optimal response the last area of DOE i.e. Optimization is identified. In the optimization the engineer is interested in determining optimal settings of the process factors; that is, to determine the level of each factor that optimizes the process response.

Response Surface Methodology (RSM) of quadratic polynomial was first introduced by Box & Wilson in 1951. Myers & Montgomery emphasized the importance of RSM with DOE. Response Surface Methodology is a collection of mathematical and statistical techniques useful for modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response (Montgomery 2005).

Box–Behnken designs are experimental designs for response surface methodology, devised by George E. P. Box and Donald Behnken in 1960, to achieve the goals like estimation variance, factorial design, block design etc. For the response optimization of process parameters of AJM the Box-Behnken designs are used.

Analysis of variance also called as ANOVA which consists of group of statistical models used in order to analyse the differences between group means and their associated procedures, developed by R. A. Fisher. In the ANOVA setting, the observed variance in a particular variable is partitioned into components attributable to different sources of variation. In its simplest form, ANOVA provides a statistical test of whether or not the means of several groups are equal [6], and therefore generalizes the t-test to more than two groups.

Minitab is a statistics package developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. It provides a simple and effective way to input statistical data, manipulate that data, identify trends and patterns, and then extrapolate answers to the problem at hand. That's a rather simplistic way of describing this vital and extremely effective tool.

III. EXPERIMENTATION & ANALYSIS

Experiments are conducted according to Design of Experiments i.e. RSM, by selecting the Box-Behnken method .27 experiments are conducted based on the parameters (Factors) such as Pressure, AFR, ND, SOD and the response found is Metal removal rate. 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 mathematical formula used for finding the metal removal rate is developed by A. El-Domiaty et al [7] and the formula is

$$\dot{m}_t = \frac{K_3\, \eta_a\, P^{1.25}\, D^2\, \rho^{0.5}}{\sigma_{fw}^{0.75}}; g_{material}/s \quad (1)$$

Where k=constant, η =efficiency, P=air pressure, D= nozzle diameter, ρ=density of abrasive σ =strength of work material

The table of process parameters starts from low level to high level based on Box-Behnken method of RSM

Table No. 1. Factor selection for Optimal Response

Machining Parameters	LOW	MIDDLE	HIGH
PRESSURE	4	6	8
AFR	3.5	4.5	5.5
ND	3	4	5
SOD	6	8	10

The Process parameters of Abrasive jet machining are considered as the Factors of Analysis. The outputs i.e. MRR was considered as Response. The CFRP material is employed for experimentation with Abrasive Jet Machining set up according to Box-Behnken design of RSM. The type of abrasives used for experimentation is Silicon Carbide of different grit sizes. The Abrasive particles mixed with air are impinged on the CFRP with different Pressures to obtain drilling.

Table No. 2. RSM table indicates run orders of factors and the objective value (MRR).

S.No	StdOrder	RunOrder	PtType	Blocks	pressure	AFR	ND	SOD	MRR(g/sec)
1	9	1	2	1	4	4.5	4	6	0.03
2	27	2	0	1	6	4.5	4	8	0.0498
3	3	3	2	1	4	5.5	4	8	0.03
4	6	4	2	1	6	4.5	5	6	0.0973
5	25	5	0	1	6	4.5	4	8	0.0498
6	16	6	2	1	6	5.5	5	8	0.0983
7	19	7	2	1	4	4.5	5	8	0.0586
8	20	8	2	1	8	4.5	5	8	0.1394
9	22	9	2	1	6	5.5	4	6	0.0498
10	26	10	0	1	6	4.5	4	8	0.0498
11	14	11	2	1	6	5.5	3	8	0.021
12	21	12	2	1	6	3.5	4	6	0.0498
13	15	13	2	1	6	3.5	5	8	0.0973
14	10	14	2	1	8	4.5	4	6	0.0713
15	17	15	2	1	4	4.5	3	8	0.0126
16	24	16	2	1	6	5.5	4	10	0.0498
17	2	17	2	1	8	3.5	4	8	0.0713

18	23	18	2	1	6	3.5	4	10	0.0508
19	18	19	2	1	8	4.5	3	8	0.0301
20	13	20	2	1	6	3.5	3	8	0.021
21	7	21	2	1	6	4.5	3	10	0.031
22	5	22	2	1	6	4.5	3	6	0.021
23	11	23	2	1	4	4.5	4	10	0.03
24	8	24	2	1	6	4.5	5	10	0.0973
25	12	25	2	1	8	4.5	4	10	0.0713
26	1	26	2	1	4	3.5	4	8	0.03
27	4	27	2	1	8	5.5	4	8	0.0713

2.1. Box-Behnken Design

Factors: 4 Replicates: 1
Base runs: 27 Total runs: 27
Base blocks: 1 Total blocks: 1
Center points: 3

2.2.Optimal Design: pressure, AFR, ND, SOD

Response surface design selected according to D-optimality
Number of candidate design points: 27
Number of design points in optimal design: 28

2.3.Response Surface Regression: MRR(g/sec) versus pressure, AFR, ND, SOD

The analysis was done using coded units.

Table No. 3. Estimated RegressionCoefficients for MRR(gm/sec)

Term	Coef	SE Coef	T	P
Constant	0.049800	0.001553	32.075	0.000
pressure	0.021958	0.000776	28.286	0.000
AFR	-0.000000	0.000776	-0.000	1.000
ND	0.037625	0.000776	48.467	0.000
SOD	0.000917	0.000776	1.181	0.261
pressure*pressure	0.000408	0.001164	0.351	0.732
AFR*AFR	-0.000279	0.001164	-0.240	0.815
ND*ND	0.010283	0.001164	8.831	0.000
SOD*SOD	0.000846	0.001164	0.726	0.482
pressure*AFR	0.000000	0.001345	0.000	1.000
pressure*ND	0.015825	0.001345	11.769	0.000
pressure*SOD	-0.000000	0.001345	-0.000	1.000
AFR*ND	0.000250	0.001345	0.186	0.856
AFR*SOD	-0.000250	0.001345	-0.186	0.856
ND*SOD	-0.002500	0.001345	-1.859	0.088

S = 0.00268916 PRESS = 0.000499848
R-Sq = 99.65% R-Sq(pred) = 97.97% R-Sq(adj) = 99.24%
The R-Square value obtained by this method is 99.65%

2.4. General Linear Model: MRR (g/sec) versus pressure, AFR, ND, SOD

Factor Type Levels Values
Pressure fixed 3 4, 6, 8

AFR	fixed	3	3.5, 4.5, 5.5
ND	fixed	3	3, 4, 5
SOD	fixed	3	6, 8, 10

Analysis of Variance for MRR(g/sec), using Adjusted SS for Tests

Table No. 4. Analysis of varience of factors for F-test and P-Test (MRR)g/sec.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
pressure	2	0.0058067	0.0057869	0.0028935	46.75	0.000
AFR	2	0.0000600	0.0000004	0.0000002	3.90	0.997
ND	2	0.0175879	0.0175517	0.0087758	141.80	0.000
SOD	2	0.0000139	0.0000139	0.0000069	6.11	0.894
Error	18	0.0011140	0.0011140	0.0000619		
Total	26	0.0245824				

S = 0.00786696 **R-Sq = 95.47%** R-Sq(adj) = 93.45%

After conducting the F-Test the R-Sq value that is attained is 95.47%

The R-Square values of both RSM and ANOVA are more than 90%.The Optimality in the Process is analyzed by F-Test.

Analysis of Variance for MRR. F Value (141.80) of the parameter indicates the Nozzle diameter is significantly contributing more towards cutting performance. F value (3.90) of parameter indicates the Contribution of AFR is less comparing with Pressure, ND and SOD. The results highlight that the effect of Nozzle diameter on MRR. The increase in diameter of nozzle increases MRR, and is directly proportional to the depth of cut.

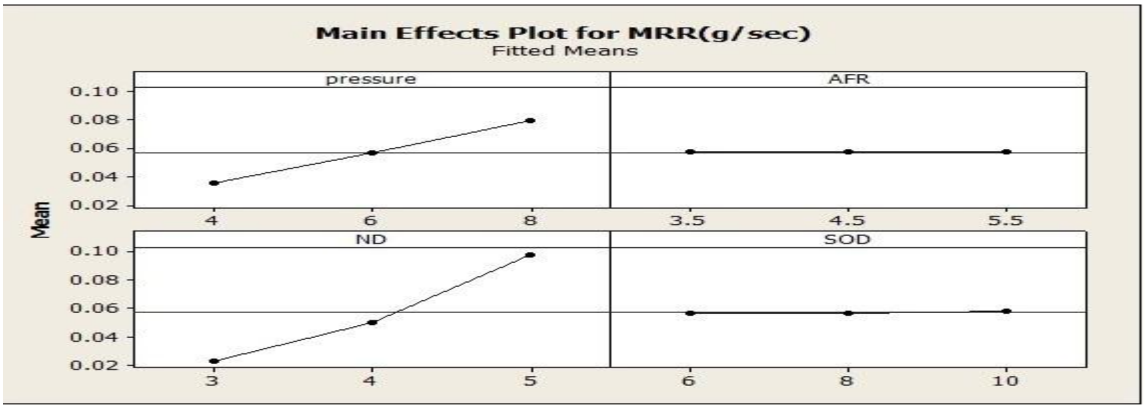

Fig. 3 Main effect plot of MRR with all process parameters

The surface and contour plots of various process parameters on Metal removal rate are given below

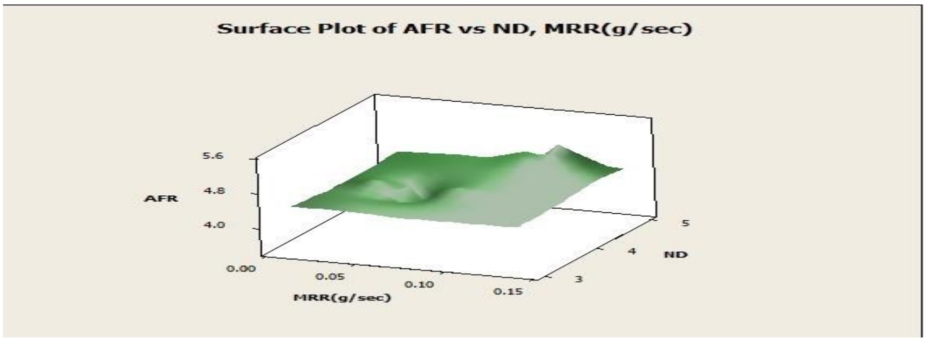

Fig. 4 Surface plot of AFR vs ND,MRR

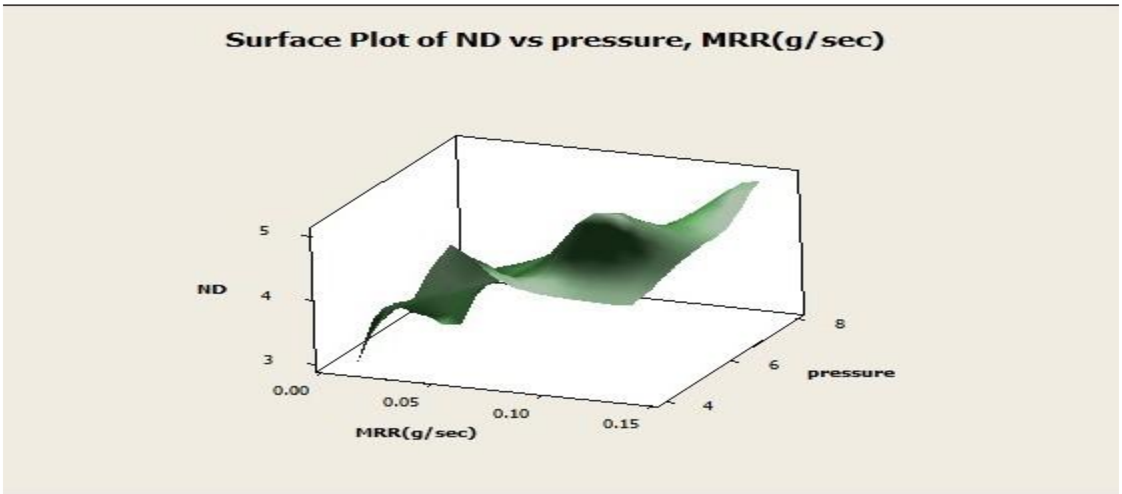

Fig. 5 Surface plot of ND vs pressure, MRR

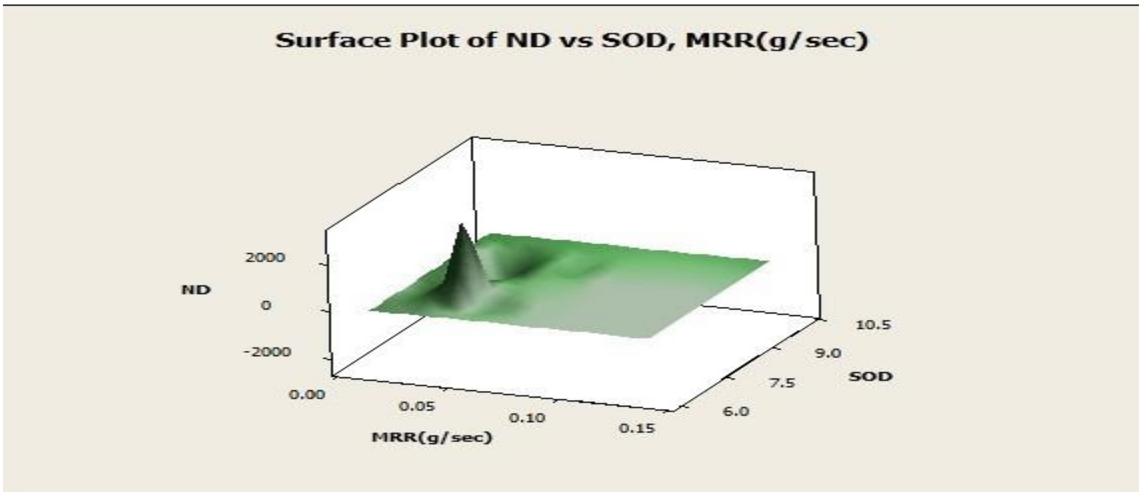

Fig. 6 Surface plot of ND vs SOD,MRR

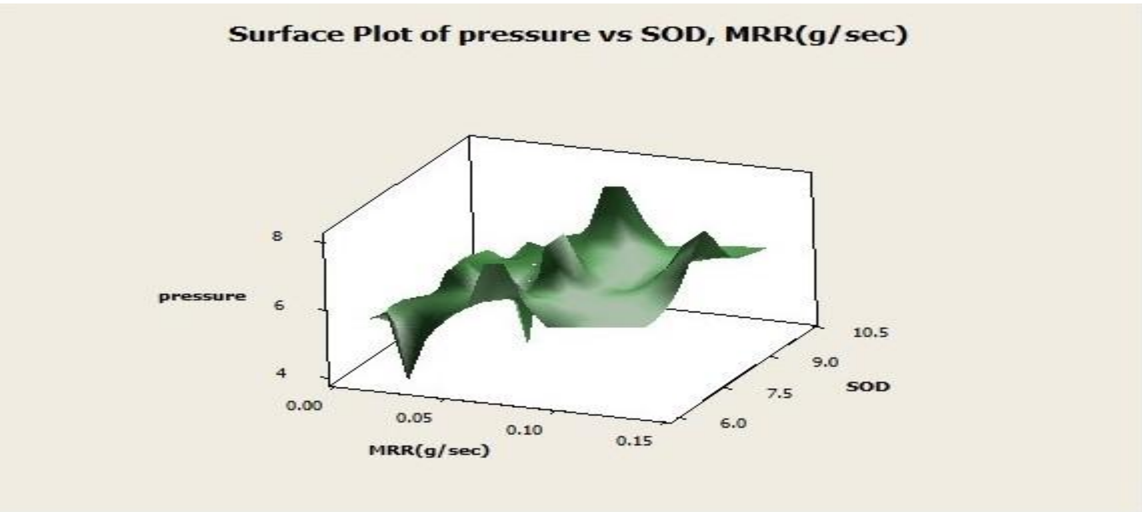

Fig. 7 Surface plot of Pressure vs SOD,MRR

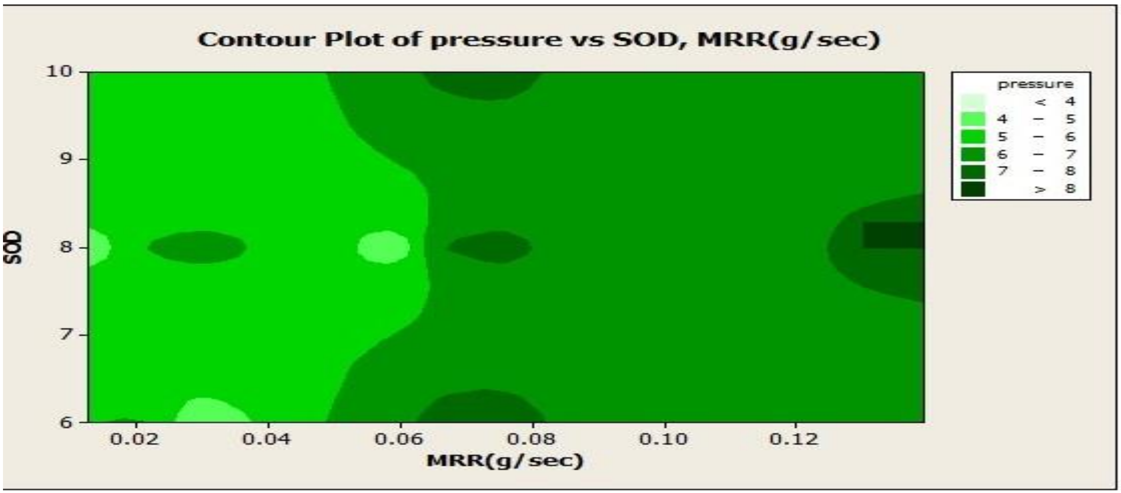

Fig. 8 Contour plot of Pr vs SOD,MRR

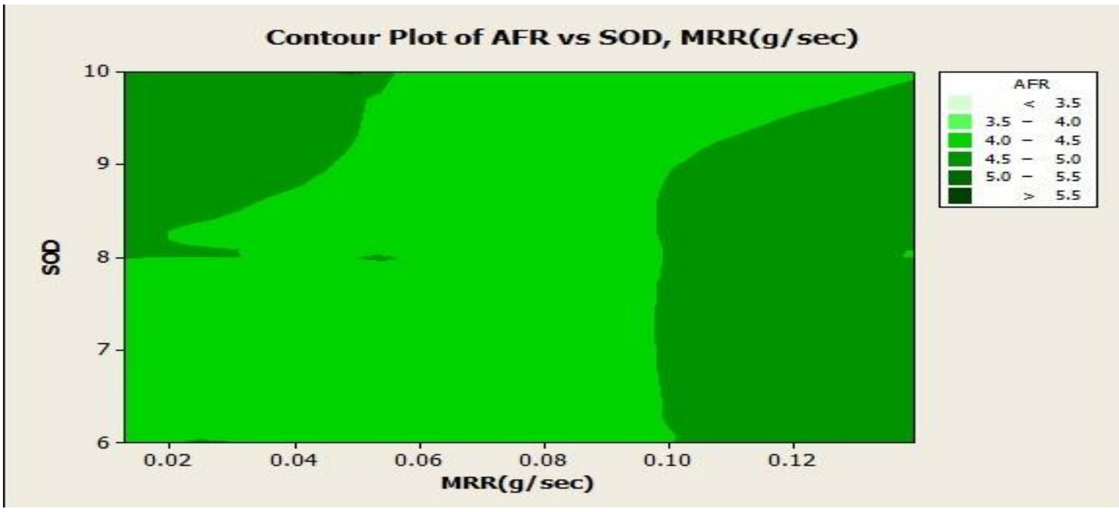

Fig. 9 Contour plot of AFR vs SOD,MRR

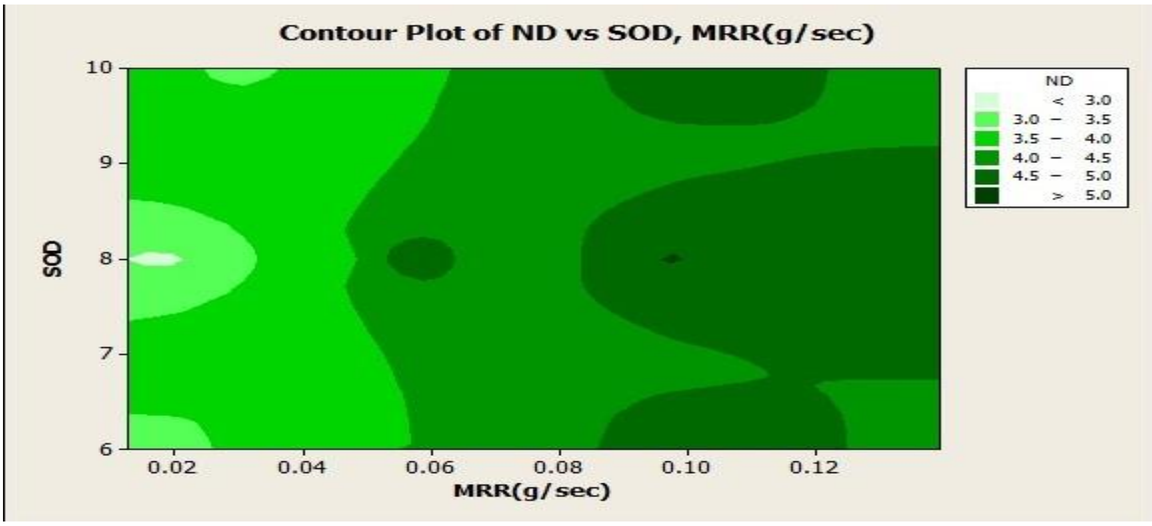

Fig. 10 Contour plot of ND vs SOD,MRR

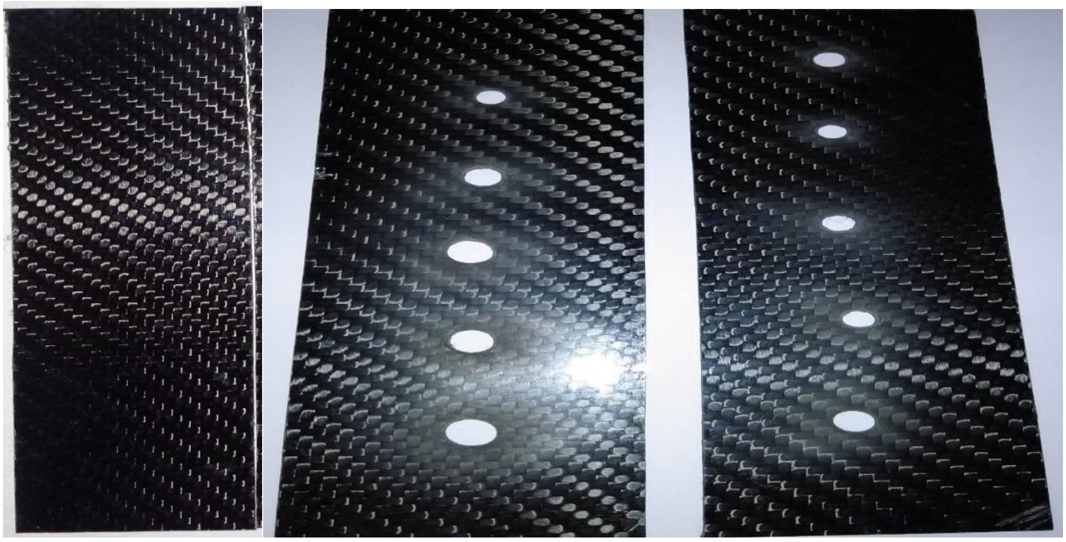

Fig. 11 CFRP sheets before and after drilling by Abrasive jet machining

CONCLUSIONS

Response surface methods are implemented on the factors and the objective selected is metal removal rate (MRR g/sec).According to design of experiments 27 experiments are conducted and the response optimality is found and these optimal values are validated with ANOVA.As per the main effect plot the influence of Nozzle diameter is more on MRR, the second factor considered is Pressure, ND and AFR follows. The influence of AFR is very less on the metal removal rate of CFRP composites. Further different methods of modelling and Analysis can be investigated for the optimal results of AJM machining process.

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