Multi Objective Optimization of parameter of Abrasive Water Jet Machine by Full Factorial Design

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The most important advantages of abrasive water jet are the capability to cut nearly every material, the low cutting temperature and the negligible cutting forces. When end users are interviewed, most of them point out that the most critical problem of abrasive water jet machines is the machining characteristics of the system, together with the difficulty in estimating their cutting qualities. The effect of the three process parameters, i.e., water pressure, abrasive mass flow rate and traverse speed on surface roughness, material removal rate and kerf width will investigated. In this investigation, it will using full factorial method is designed with three levels of AWJM parameters with the help of software Minitab version 16. It is predicted that full factorial method is a good method for optimization of various machining parameters as it reduce number of experiments.

Keywords – AWJM parameter; ANOVA; Full Factorial; Grey relational analysis; MMR; SR; KW

I. INTRODUCTION

Abrasive Jet Machining (AJM) is the removal of material from a workpiece by the application of a high speed stream of abrasive particles carried in gas medium from a nozzle. The AJM process differs from conventional sand blasting in that the abrasive is much finer and the process parameters and cutting action are carefully controlled. The process is used chiefly to cut intricate shapes in hard and brittle materials which are sensitive to heat and have a tendency to chip easily. The process is also used for debarring and cleaning operations. AJM is inherently free from chatter and vibration problems. The cutting action is cool because the carrier gas serves as a coolant.[05]

- Pump System
- Control System
- Abrasive Delivery System
- Nozzle system

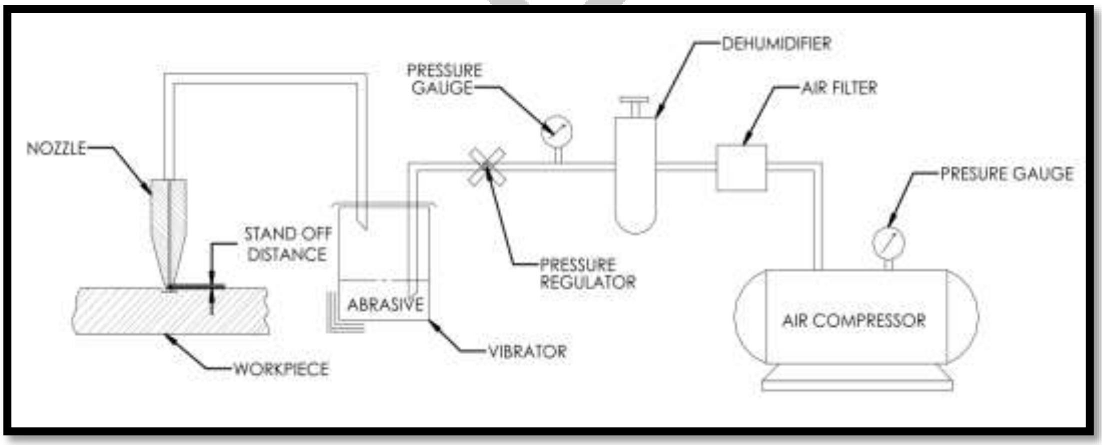

Figure 1: Schematic draw of the abrasive water jet machine components [05]

II. LITERATURE REVIEW

1. Suvradip Mullick and at all carried out experimental used AISI 304 stainless steel sheet of maximum 1.5 mm thickness was cut at 1.4 m/min cutting speed with the present setup at 1800W CW laser power, and the resulting average kerf-width was about 0.75 mm. They found that the heat convection by water jet and the scattering of laser beam by vapour to influence significantly the energy efficiency of the cutting process.[01]

2. A. Alberdi and at all carried out experimental machine-ability index for various composite materials with different thicknesses was found experimentally, which showed very different results for different materials. They carried out the effect of the abrasive water jet process parameters on the quality of cut taper and surface roughness. They revealed that the taper angle may be a function of the absolute traverse feed rate more than a function of its respective percentage to the separation speed.[02]

3. Divyansh Patel and at all they describes an experimental study of thermally enhanced machining (TEM) by adding an oxy acetylene gas welding setup as an external heat source to the machine setup which heats the work locally and temperature is measured by non-contact laser thermometer. The experimental data of cutting parameters at critical temperatures of hard-to-machine metals Inconel 718, Titanium (Ti6Al4V) and mild Steel (MS-A36) (ductile in nature) with full factorial DOE. They revealed that the increase in material removal rate, reduction in power consumption machining time due to TEM.[03]

4. L. Chen and at all carried out experimental abrasive water jet technology is effective in machining hard materials such as ceramics. The abrasive water jet cutting of ceramics can be improved greatly by using the new technique of cutting head forward oscillation in the plane of the cut. The smooth-zone depth with oscillation can be increased by more than 30% compared with that without oscillation. The head oscillation does not affect the traverse speed, which can be increased considerably without compromising the quality of surface finish. This new technique requires no additional cost and can also be used for AWJ cutting of other materials more effectively.[04]

III. METHODOLOGY

Full Factorial Design

It is used for simultaneous study of several factor effects on the process. By varying levels of factors simultaneously we can find optimal solution response are measured at all combination of the experimental factor levels. The combination of the factor levels represent the conditions at which responses will be measured. Each experiment condition is a run. The response measurement in an observation. The entire set of run is a design of experiment. It is used to find out the variables which are the most influence on the response and their interactions between two or more factors on responses.[06]

Process Parameter and Their Levels

The three primary factors in cutting operation are traverse speed, water pressure and abrasive mass floe rate. Other factors such as environment, type of grade abrasive particle and kind of material have a large influence. So these three are the operator can change by adjusting the control of machine.

Table 1 Range of variable process parameters

Parameter	Unit	Level 1	Level 2	Level 3
Traverse speed	Mm/min	80	120	160
Water pressure	MPa	300	400	500
Abrasive mass flow rate	g/min	80	130	180

Grey Relational Methodology

Through the grey relational analysis, a grey relational grade can be obtained to evaluate the multiple performance characteristic. As a result, optimization of the complicated multiple performance characteristic can be converted into the optimization of a single grey relation grade. For multiple performance characteristic optimizations using GRA, following steps are followed:

1. Conduction of experiments at different settings of parameters based on OA.
2. Normalization of experimental result for all performance characteristics.
3. Performance of grey relational generating and calculation of grey relational coefficient (GRC).
4. Calculation of grey relation grade (GRG) using, weighing factor for performance characteristics.

5. Analysis of experimental results using GRG and statistical analysis of variance (ANOVA).
6. Selection of optimal levels of process parameters.
7. Conducting confirmation experiment to verify optimal process parameter settings.

IV. EXPERIMENTAL RESULTS

Table 2 Experimental Readings

Sr no.	Traverse speed [mm/min]	Water pressure [MPa]	Abrasive mass flow rate [g/min]	Surface roughness[μm]	Kerfs width [mm]	Material removal rate [mm^3/min]
1	80	300	80	2.25	1.156	4.112
2	80	300	130	2.11	1.176	4.255
3	80	300	180	2.17	1.186	4.365
4	80	400	80	2.38	1.136	4.322
5	80	400	130	2.31	1.146	4.362
6	80	400	180	2.22	1.166	4.422
7	80	500	80	3.23	1.126	4.362
8	80	500	130	2.74	1.146	4.422
9	80	500	180	2.32	1.156	4.472
10	120	300	80	3.88	1.116	4.612
11	120	300	130	2.80	1.116	4.674
12	120	300	180	2.51	1.126	4.782
13	120	400	80	4.27	1.076	4.748
14	120	400	130	3.84	1.086	4.918
15	120	400	180	3.63	1.106	5.128
16	120	500	80	4.93	1.066	4.636
17	120	500	130	3.84	1.096	4.701
18	120	500	180	3.60	1.116	4.781
19	160	300	80	4.27	1.022	5.025
20	160	300	130	4.05	1.032	5.155
21	160	300	180	3.73	1.072	5.355
22	160	400	80	4.70	1.002	4.885
23	160	400	130	5.05	1.022	4.915
24	160	400	180	3.15	1.052	5.025
25	160	500	80	5.05	1.002	5.102
26	160	500	130	4.20	1.042	5.187
27	160	500	180	4.00	1.052	5.268

MAIN EFFECTS PLOT FOR SURFACE ROUGHNESS

From the fig.2, it has been conclude that the optimum combination of each process parameter for low Surface Roughness is meeting at Traverse Speed [A1], water pressure [B1] and abrasive mass flow rate [C3].

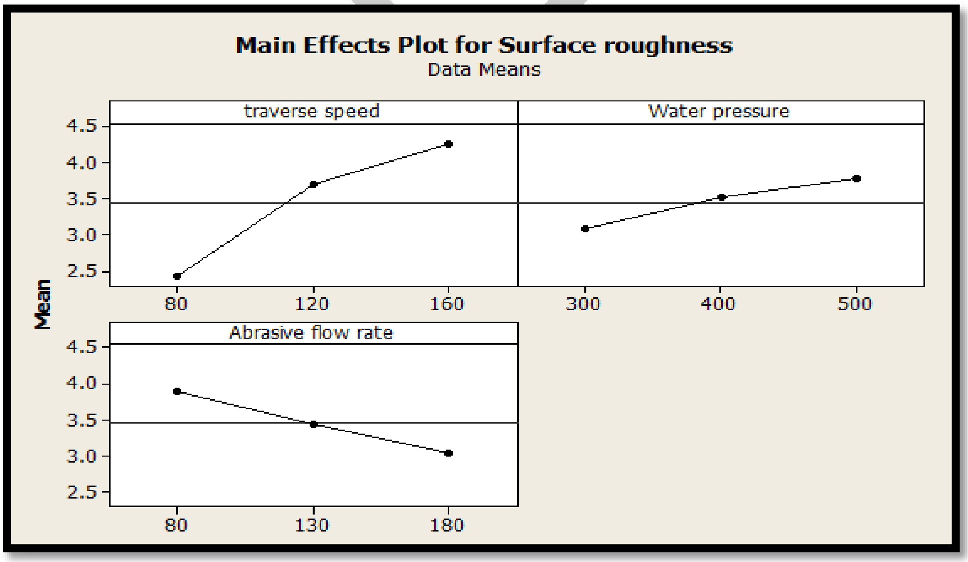

Fig 2- Effect of control factor on Surface Roughness

MAIN EFFECTS PLOT FOR KERFS WIDTH

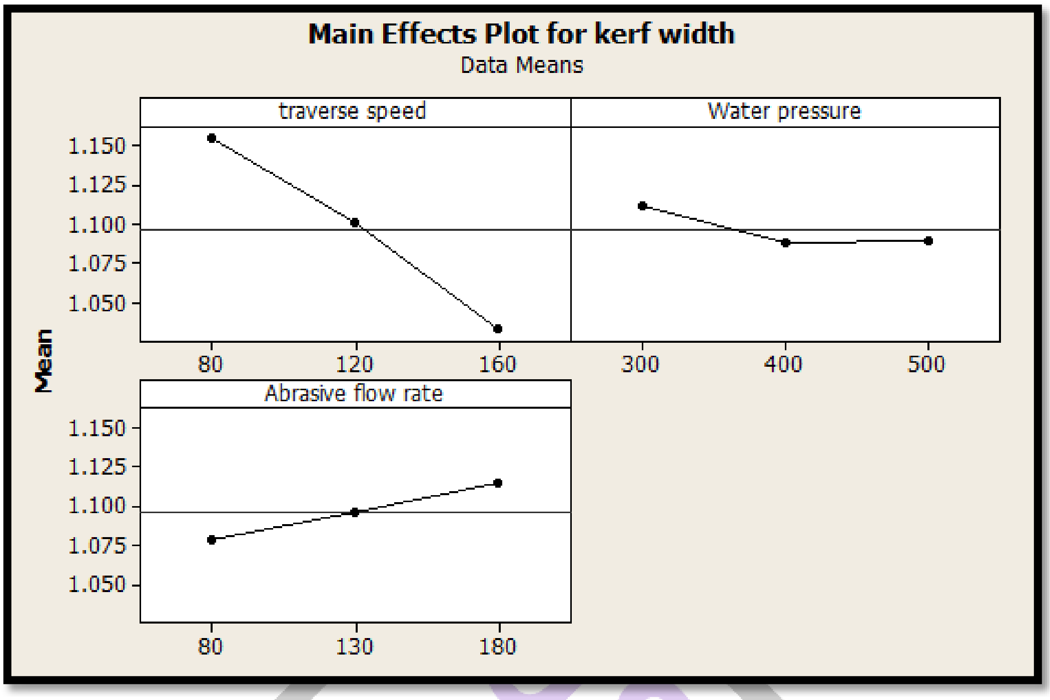

Fig.3 - Effect of control factor on Kerfs Width

From the fig.3, it has been conclude that the optimum combination of each process parameter for lower Kerfs width is meeting at high Traverse Speed [A3], medium water pressure [B2] and low abrasive mass flow rate [C1].

MAIN EFFECTS PLOT FOR MATERIAL REMOVAL RATE

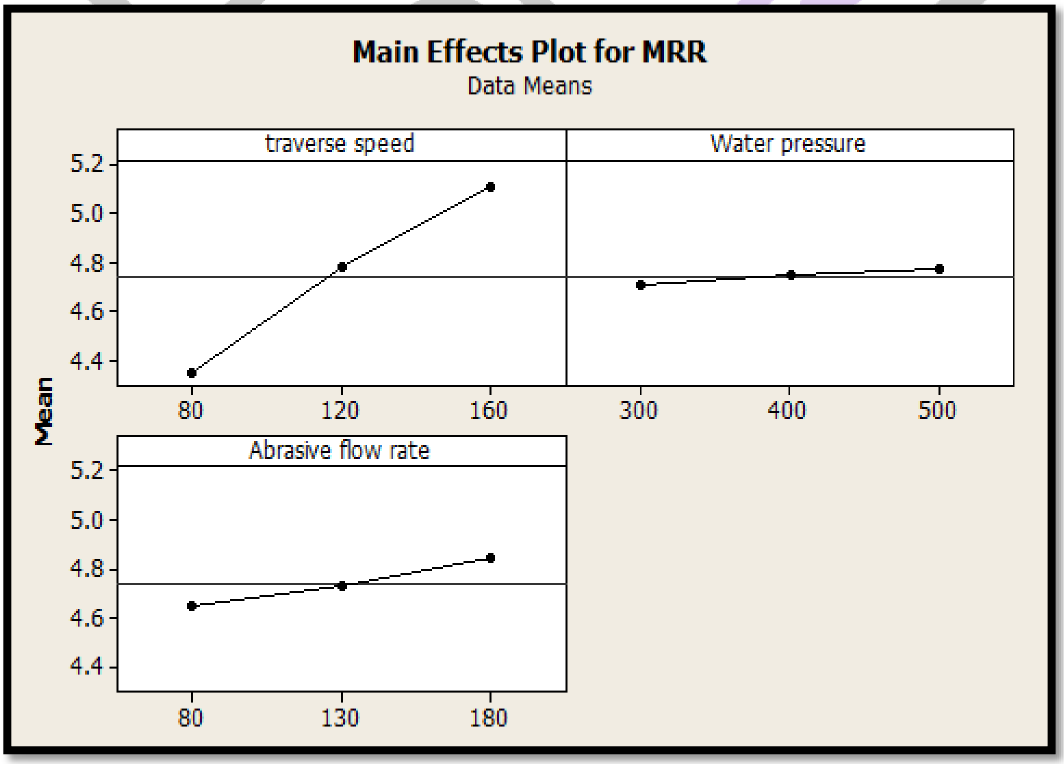

Fig.4 - Effect of control factor on Material Removal Rate

From the fig. 4, it has been conclude that the optimum combination of each process parameter for higher **Material removal rate** is meeting at Traverse Speed[A3], Water Pressure[B3] and Abrasive mass flow rate[C3].

ANALYSIS OF VARIANCE FOR SURFACE ROUGHNESS

From ANOVA result it is observed that the Traverse Speed and abrasive mass flow rate of influencing parameter for **Surface Roughness** as they are all less than 0.05 p. but P value for water pressure has 0.350 so it is not effective for surface roughness.

Table 3 - ANOVA Table of Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Traverse speed	2	15.8939	15.8939	7.9470	55.60	0.000	65.89 %
Water pressure	2	2.1318	2.1318	1.0659	7.46	0.004	8.83 %
Abrasive flow Rate	2	3.2374	3.2374	1.6187	11.32	0.001	13.42 %
Error	20	2.8587	2.8587	0.1429			
Total	26	24.1218					
R-Sq = 88.15%				R-Sq(adj) = 84.59%			

ANALYSIS OF VARIANCE FOR KERFS WIDTH

According to the analysis done by the MINITAB software, if the values of probability are less than 0.05, it indicated that the factors are significant to the response parameters. Comparing the p-value to a commonly used α- level = 0.05, it is found that if the p-value is less than or equal to α, it can be concluded that the effect is significant.

Table 4 – ANOVA Table for Kerfs width

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Traverse speed	2	0.066983	0.066983	0.033492	411.03	0.000	86.11 %
Water pressure	2	0.003119	0.003119	0.001559	19.14	0.000	4.01 %
Abrasive flow Rate	2	0.006052	0.006052	0.003026	37.14	0.000	7.78 %
Error	20	0.001630	0.001630	0.000081			
Total	26	0.077783					
R-Sq = 97.90%				R-Sq(adj) = 97.28%			

ANALYSIS OF VARIANCE FOR MATERIAL REMOVAL RATE

From ANOVA result it is observed that the Traverse Speed, water pressure and abrasive mass flow rate of cutting influencing parameter for **material removal rate** as they are all less than 0.05 p. The confidence level (CL) is taken 95% for this investigation.

Table 5 - ANOVA Table for Material Removal Rate(MRR)

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution
Traverse speed	2	2.60297	2.60297	1.30149	88.32	0.000	84.02 %
Water pressure	2	0.02036	0.02036	0.01018	0.69	0.513	0.65 %
Abrasive flow Rate	2	0.17973	0.17973	0.08987	6.10	0.009	5.80 %
Error	20	0.29473	0.29473	0.01474			
Total	26	3.09779					
R-Sq = 90.49%				R-Sq(adj) = 87.63%			

V. MULTI-RESPONSE OPTIMIZATION OF PROCESS PARAMETER

Table 6 Normalization, Grey relational coefficient and grey relational grade of experimental data

Sr. No.	Normalized Data			GRC			GRG
	Surface roughness[μm]	Kerf width [mm]	Material removal rate [mm^3/min]	Surface roughness[μm]	Kerf width [mm]	Material removal rate [mm^3/min]	
1	0.952381	0.163043	0	0.344262	0.754098	1	0.699454
2	1	0.054348	0.115044	0.333333	0.901961	0.81295	0.682748
3	0.979592	0	0.20354	0.337931	1	0.710692	0.682874
4	0.908163	0.271739	0.168946	0.355072	0.647887	0.747444	0.583468
5	0.931973	0.217391	0.201126	0.349169	0.69697	0.713138	0.586426
6	0.962585	0.108696	0.249397	0.34186	0.821429	0.667203	0.610164
7	0.619048	0.326087	0.201126	0.446809	0.605263	0.713138	0.588403
8	0.785714	0.217391	0.249397	0.388889	0.69697	0.667203	0.584354
9	0.928571	0.163043	0.289622	0.35	0.754098	0.633214	0.579104
10	0.397959	0.380435	0.402253	0.556818	0.567901	0.554169	0.559629
11	0.765306	0.380435	0.452132	0.395161	0.567901	0.525137	0.496067
12	0.863946	0.326087	0.539019	0.366584	0.605263	0.481223	0.484357
13	0.265306	0.597826	0.511665	0.653333	0.455446	0.494235	0.534338
14	0.411565	0.543478	0.648431	0.548507	0.479167	0.435377	0.487684
15	0.482993	0.434783	0.817377	0.508651	0.534884	0.379542	0.474359
16	0.040816	0.652174	0.421561	0.924528	0.433962	0.542558	0.633683
17	0.411565	0.48913	0.473854	0.548507	0.505495	0.513424	0.522475
18	0.493197	0.380435	0.538214	0.503425	0.567901	0.481596	0.517641
19	0.265306	0.891304	0.734513	0.653333	0.359375	0.405018	0.472575
20	0.340136	0.836957	0.839099	0.595142	0.373984	0.373385	0.447504
21	0.44898	0.619565	1	0.526882	0.446602	0.333333	0.435606
22	0.119048	1	0.621883	0.807692	0.333333	0.445679	0.528902
23	0	0.891304	0.646018	1	0.359375	0.436293	0.598556
24	0.646259	0.728261	0.734513	0.436202	0.40708	0.405018	0.4161
25	0	1	0.79646	1	0.333333	0.385666	0.573
26	0.289116	0.782609	0.864843	0.633621	0.389831	0.366342	0.463265
27	0.357143	0.728261	0.930008	0.583333	0.40708	0.349648	0.446687

MAIN EFFECT OF FACTORS ON GREY RELATIONAL GRADE (GRG)

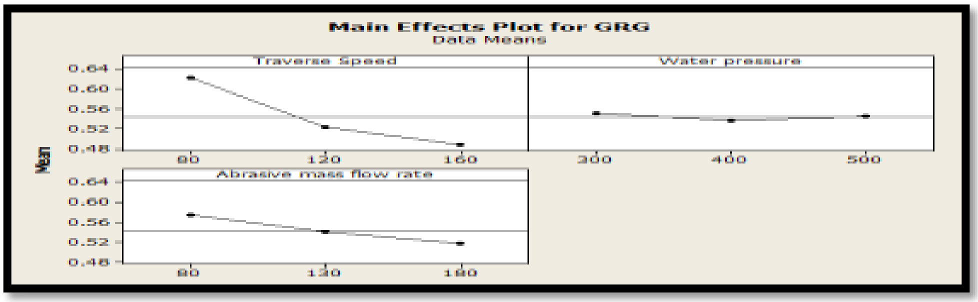

Figure 5 Effect of control factors plot of GRG

For the combined response maximization or minimization, fig. 5 gives optimum value of each control factor. It interprets that level A1, B1 and C1 gives optimum result. The mean of grey relational grade for each level of the other machining parameters can be computed in similar manner. The mean of grey relational grade for each level of the machining parameters is summarized and shown in following table.

Table 7 Main effect of factors on Grey Relational Grade

Symbol	Control Factor	Level-1	Level-2	Level-3
A	Traverse speed	**0.699454**	0.559629	0.472575
B	Water pressure	**0.551201**	0.535555	0.545401
C	Abrasive mass flow rate	**0.574828**	0.541009	0.516321

As we know that higher grey relational grade value will give optimum value of kerf width, surface roughness and material removal rate. So from above table 7, it is concluded that level-1 is higher for cutting speed and level-1 is higher than for abrasive flow rate and as well as level 1 higher for water pressure. Thus it is revealed that response will be optimum at traverse speed 80 mm/min, abrasive mass flow rate 80 gm/min and 300 MPa water pressure.

VI. EXPERIMENTAL VALIDATION

For experimental validation, there is another specific combination of input parameter used and nine combinations generate as per based on new range of process parameters. In this method, combination traverse speed, abrasive mass flow rate and water pressure are smaller and higher than to combination of which are used in full factorial design approach. For this concern traverse speed are range of 100, 150 and 200 mm/min, abrasive mass flow rate are range of 120, 160 and 240 gm/min and water pressure 350, 450 and 500 mpa are used. Thus these ranges are smaller, intermediate and higher than full factorial combination. Taguchi combination described in following table no. 8 and 9 with actual kef width, surface roughness and material removal rate which are experimental result and predicted response.

Table 8 Actual experimental data

Traverse speed	Abrasive mass flow rate	Water pressure	SR	KW	MRR
100	120	350	2.72	1.145	4.625
100	160	450	2.87	1.149	4.714
100	240	500	2.77	1.158	4.889
150	120	350	3.97	1.111	4.481
150	160	450	3.92	1.119	4.987
150	240	500	3.59	1.118	5.125
200	120	350	4.76	1.012	5.356
200	160	450	4.87	1.019	5.521
200	240	500	4.27	1.000	5.712

Table 9 Predicted data

Traverse speed	Abrasive mass flow rate	Water pressure	SR	KW	MRR
100	120	350	2.9119	1.13319	4.51265
100	160	450	2.9137	1.13677	4.62535
100	240	500	2.4058	1.16058	4.80110
150	120	350	4.0569	1.05719	4.98665
150	160	450	4.0587	1.06077	5.09935
150	240	500	3.5508	1.08458	5.27510
200	120	350	5.2019	0.98119	5.46065
200	160	450	5.2037	0.98477	5.57335
200	240	500	4.6958	1.00858	5.74910

VII. CONCLUSION

The AISI4140 has been cut by abrasive water jet cutting machine. The conclusions relevant to this investigation are outlined below:

1. The surface roughness increase with increase traverse speed and water pressure from 80 to 160 mm/min and 300 to 500 MPa respectively, when the other two parameter are kept constant as well as surface roughness decrease with increase abrasive mass flow rate 80 to 180 gm/min.
2. While studying the effect of the cutting parameters on the kerfs width, it was observed that both the traverse speed and abrasive mass flow rate play equally important roles in the effect on the both kerfs width. The role of the water pressure given is not crucial to the same extent. The optimum condition for machining to reduce kerfs width would be A3 B2 C1. The traverse speed kept at 160 mm/min, the water pressure kept at 400 Mpa and the abrasive mass flow rate kept at 80 gm/min. From This study, it has been seen that the kerfs width play very important role in qualities of water jet cutting object.
3. The optimum condition for machining to reduce surface roughness would be A1 B1 C3. The cutting[traverse] speed kept at 80 mm/min, water pressure 300 MPa and the abrasive mass flow rate kept at 180 gm/min
4. While studying the effect of the cutting parameters on the surface roughness, it was observed that both the traverse speed and abrasive mass flow rate play equally important roles in the effect on the surface roughness. The role of the water pressure given is less crucial to the same extent.
5. For material removal rate, all input parameter has been very crucial for increasing material removal rate. And for maximum material removal rate, traverse speed should kept at 160 mm/min, water pressure 500 MPa and abrasive mass flow rate 180 gm/min.
6. Through use of regression equation, engineer can manipulate range of cutting traverse speed, abrasive mass flow rate and water pressure for this particular work- material. Also it has been find out and predicted kerfs width, material removal rate and surface roughness at any combination of process parameter.
7. The optimal parameter values are optimum at traverse speed 80 mm/min, abrasive mass flow rate 80 gm/min and 300 MPa water pressure. At these parameters the values of kerfs width, surface roughness and MRR are 1.156 mm, 2.25 µm and 4.112 mm^3/min respectively.
8. It is shown that the performance characteristics of the AWJM process, namely water jet pressure, abrasive flow rate and water pressure are improved together by using Grey Relational Analysis.

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