Available online at www.elixirpublishers.com (Elixir International Journal)

Mechanical Engineering

Elixir Mech. Engg. 65 (2013) 19525-19530

ISSN: 2229-712X

Investigation on material removal rate in Abrasive water jet machining

A. S. Patel* and P. D. Patil

Department of Mechanical Engineering, D. N. Patel college of Engineering, Shahada.

ARTICLE INFO

Article history:
Received: 28 October 2013;
Received in revised form:
25 November 2013;
Accepted: 2 December 2013;

Keywords
Abrasive water jet,
Pressure,
Cutting Speed.

ABSTRACT

The AWJM is widely used to process the different materials. The material considered for the experimental study is commercial aluminum, mild steel and EN8. The operating parameters, namely pressure, cutting speed and abrasive flow rate are varied during to find its effect on metal removal rate. Attempt is made to establish relationship between operating parameters and material removal rate by using regression analysis & ANOVA. Experimental study is performed to validate the results. It is observed that pressure & abrasive flow rate are the most significant parameters that affect the material removal rate in AWJM.

Introduction

Abrasive Water jet (AWJ) Machining is a recent non-conventional machining process. In this technology, a very high-pressure beam of water and abrasives is used for machining. This technology is used in industry as it has many advantages.

Studied mechanism and effectiveness of material removal process. Different materials were found to possess different material removal rates in machining [1].

It was found that process variables such as pressure, abrasive mass flow rates, traverse rate influence morphology of cutting surface [2].

Material removal process was studied. In first zone the mode of material removal is by micro cutting and intergranular facture due to impact of abrasive particles at shallow angles. In second zone the mode of material removal is by plastic deformation and intergranular facture[3]. It was also found that there were no heat damage zones, and no mechanical deformation of work piece due to cutting forces and this is an environmentally friendly process [4].

Kerf geometry is ultimately dependent on the variation of standoff distance, abrasive particle velocity distribution and their local impact angle accounted across the jet foot print [5]. Decreasing the SOD and traverse rate may improve the machining performance [6].

Experimentation

Experimentation was carried out with objective to establish relationship between Material removal rate (MRR) and operator controlled parameters. Effort was also made to identify the significant parameters affecting MRR. Experimentation was carried out at **M/s Ainnovative International Co. Ltd. at Ahmadabad**.

The following steps were taken for carrying out the experimentation.

1. Selection of work material.
2. Selection of “parameters to be varied” and “parameters to be kept constant”.
3. A set of experiments was conducted to establish regression equation.
4. A set of validation experiments was conducted to check validity of regression equation developed in step no 3

The material selected for experimentation was Aluminum, Mild steel and EN8, which are commercially used in industries for manufacturing various machine parts.

Machine Used for Experimentation

Figure 1. Abrasive Water Jet Machine

DWJ1525-BB high-pressure system figure 1 is designed and manufactured by M/s Ainnovative international Pvt. Ltd Ahmedabad in collaboration with M/s Dardi, Italy.

Input Parameters Varied

1. Pressure
2. Cutting Speed
3. Abrasive Flow Rate

Above parameters are selected because these parameters are operator controlled.

Input Parameter Kept Constant

1. Standoff Distance
2. Abrasive Material / Size
3. Orifice Diameter
4. Focusing Tube Diameter / Length

Above parameters are machine parameters which are not frequently changed

The main output parameter is material removal rate (MRR) for various combination of factor.

The experimentation was conducted in two sets.

Tele:
E-mail addresses: ashokpatel32000@yahoo.com

The first set of experiment was conducted for 12 runs for calculating the regression equation. In this runs the parameters are set for level of parameter as 3x2x2.

The second set of experiment was conducted for 6 runs for validation test of regression equation.

Table 1. Material used for Experiment

Sr. No.	Material	Length mm	Width mm	Thickness mm
1	Aluminum	140	100	30
2	Mild steel	145	110	20
3	EN8	200	130	16

Experiment on Aluminum Plate:

Figure 3. Experiment on Aluminum plate

Parameters for Training data for regression equation in Aluminum plate

Factor 1 Pressure Mpa – Level 1 - 180, Level 2 - 210, Level 3 - 240

Factor 2 Cutting Speed mm/min- Level 1 - 100, Level 2 - 150

Factor 3 Abrasive Flow Rate gm/min – Level 1 - 300, Level 2 – 600

Parameters for validation test in Aluminum plate

Factor 1 Pressure Mpa – Level 1- 180, Level 2 -210, Level 3 - 240

Factor 2 Cutting Speed mm/min - Level 1 -125

Factor 3 Abrasive Flow Rate gm/min – Level 1-300, Level2– 600

Experimental Data and Calculations on Aluminum Plate:

Table 2. Experiment No-1 Summary Data for Regression Equation

Sr. No.	Pressure	Cutting speed	AFR	Average kerf	Average DOC
	Mpa	mm/min	gm/min	mm	mm
1	180	150	600	0.91	9.3397
2	180	150	300	0.8775	7.9989
3	180	100	600	1.0525	11.4345
4	180	100	300	0.8975	10.335
5	210	150	600	0.9025	12.747
6	210	150	300	0.8675	10.6957
7	210	100	600	0.9325	18.2966
8	210	100	300	0.9125	16.2177
9	240	150	600	0.9275	16.4729
10	240	150	300	0.8725	14.7071
11	240	100	600	0.94	23.5082
12	240	100	300	0.925	20.6251

Table 3. Experiment No 2: Summary Data of Depth of Cut for Validation Test

Sr. No.	Pressure	Cutting Speed	AFR	Average KERF	Average DOC
	Mpa	mm/min	gm/min	mm	mm
1	180	125	600	0.925	11.0449
2	180	125	300	0.86	9.6951
3	210	125	600	0.9125	15.1777
4	210	125	300	0.89	12.9894
5	240	125	600	0.9375	18.8129
6	240	125	300	0.87	17.1056

Table 4. Experiment No-1: Calculated Data for Regression Equation

Sr. No.	Pressure	Cutting Speed	AFR	Average Kerf	Average DOC	Exp MRR
	Mpa	mm/min	gm/min	mm	mm	mm^3/min
1	180	150	600	0.91	9.3397	1274.869
2	180	150	300	0.8775	7.9989	1052.855
3	180	100	600	1.0525	11.4345	1203.481
4	180	100	300	0.8975	10.335	927.5663
5	210	150	600	0.9025	12.747	1725.625
6	210	150	300	0.8675	10.6957	1391.778
7	210	100	600	0.9325	18.2966	1706.158
8	210	100	300	0.9125	16.2177	1479.865
9	240	150	600	0.9275	16.4729	2291.792
10	240	150	300	0.8725	14.7071	1924.792
11	240	100	600	0.94	23.5082	2209.771
12	240	100	300	0.925	20.6251	1907.822

Regression Analysis for Aluminum plate

Multiple regression analysis is performed to establish relationship between MRR and pressure, cutting speed and abrasive flow rate. Confidence interval of 95% is used. For calculation MINITAB statistical software is used. An empirical equation is derived to describe the functional relationship between the Material removal rate (MRR) and the pressure, traverse feed, abrasive flow rate parameters.

Regression Analysis: for Aluminum plate

The regression equation is

Exp MRR = - 2326 + 16.1 Pressure + 0.757 Cutting Speed + 0.959 AFR----(1)

Table 5. Estimated Regression Coefficient for MRR

Sr.No	Predictor	Coef	SE Coef	T	P
1	Constant	-2326.0	146.0	-15.93	0.000
2	Pressure	16.1475	0.5723	28.21	0.000
3	Cutting Speed	0.7568	0.5608	1.35	0.214
4	A F R	0.95945	0.09346	10.27	0.000

S = 48.5634 R-Sq = 99.1% R-Sq(adj) = 98.8%

Table 6. Analysis of Variance for MRR

Sr.No	Source	DF	SS	MS	F	P
1	Regression	3	2130191	710064	301.08	0.000
2	Residual Error	8	18867	2358	---	---
3	Total	11	2149058	---	---	---

Comments on % error: The maximum error is 8.5% and average error of prediction is 1.056. The span of error is 11%. This indicates that model is able to predict the outcome with reasonable accuracy.

Graphs for Aluminum Plate

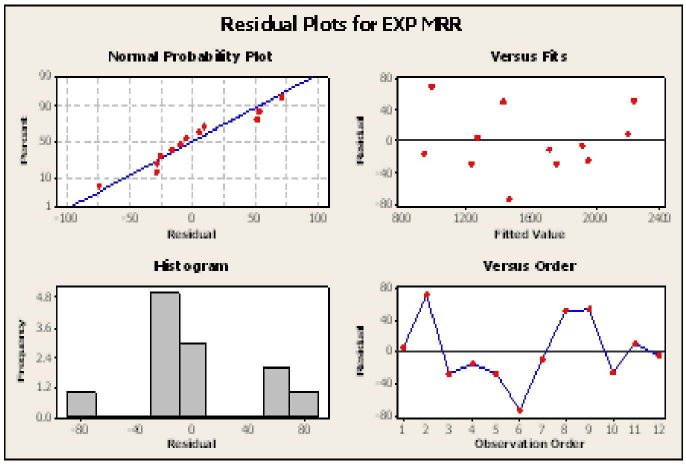

Figure 4. Residual plots

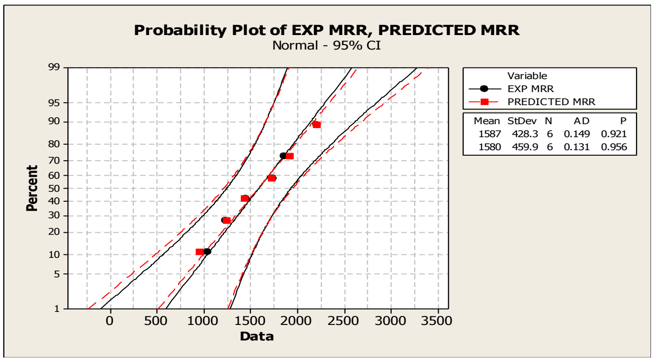

Figure 5. Probability plots

Experiment on Mild Steel Plate:

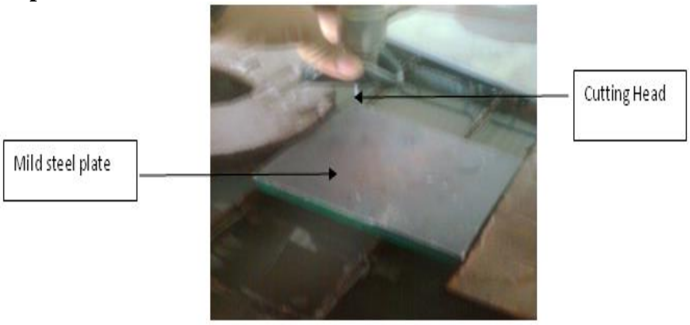

Figure 5. Experiment on Mild steel Plate

Similarly the experiment was conducted by selecting various parameter levels.

Regression Analysis for Mild Steel:

The regression equation is

EXP MRR = - 405 + 2.52 Pressure + 1.23 Cutting Speed + 0.160 AFR---- (2)

Experiment on EN8 Plate

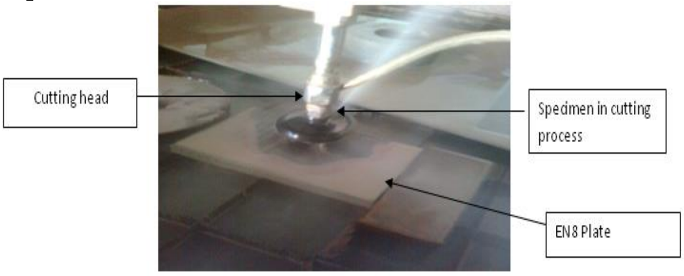

Figure 6 Experiment on EN8 plate

Similarly the experiment was conducted by selecting various parameters levels.

Regression Analysis for EN8 plate

The regression equation is

EXP MRR = - 711 + 4.74 Pressure + 0.415 Cutting speed + 0.395 AFR----(3)

Analysis and discussions

Three Regression equations are given below. eq (1),(2),(3).

Aluminum MRR = -2326+ 16.1 Pressure+ 0.757 Cutting speed +0.959AFR

Mild steel MRR= -405 +2.52 Pressure+1.23 Cutting speed +0.160AFR

EN8 MRR = -711 +4.74 Pressure +0.415 Cutting speed +0.395 AFR

Validation

Validity of this above model was tested by following method.

1. Statistical indicators
2. Experimental validation

1 Statistical Indicators

a) F test - F test of all three materials indicates that model significantly represents the actual process.

b) Coefficient of determination R^2- Examination of R^2 calculated for all three materials indicates that predicators explain 99% of the variance in material removal rate for Aluminum.

Similarly 88.5% for Mild Steel plate.

Similarly 96.1% for EN8 plate.

c) P-value- P value in Analysis of variance table shows 0.000. Value indicates that equation estimated by regression process is significant at α =0.05

2) Experimental Validation

a) Experimental validation was carried out using validation test run and % of error between predicted material removal rate and experimental material removal rate as shown in table- 7,11,15. This test run also indicates model significantly explain the relationship between material removal rate and independent variables.

Comparison of Three Materials

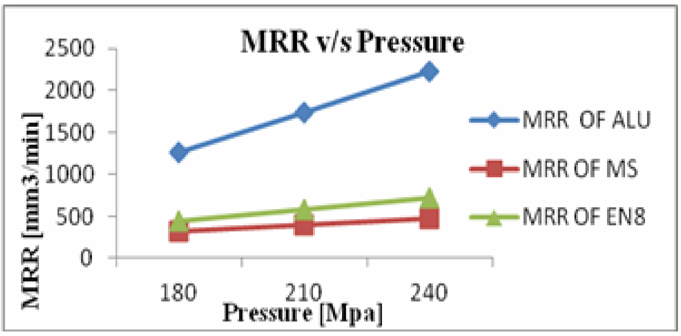

Figure 7. MRR versus Pressure at Maximum Cutting Speed

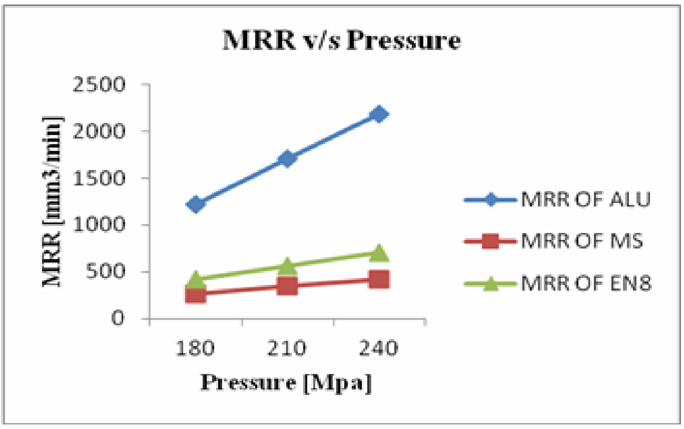

Figure 8. MRR versus Pressure at Minimum Cutting Speed

Comments on Effect of Pressure on MRR

The graphical interpretation in figure 7 and 8 shows that as the pressure increases the MRR increases. This is due to fact that as the pressure increases; velocity of jet stream of water also increases. The potential energy of the jet stream is converted in to kinetic energy and increase in the velocity of the stream of water consequently increases the metal removal rate.

It is observed that rate of increased of MRR is higher in aluminum as compared to EN8 and Mild Steel. The reason behind this is the hardness of material. Hardness is resistance to abrasion or resistance to cutting. Hardness of aluminum, Mild steel and EN8 are 95, 120, 152 BHN resp. Therefore rate of increase of MRR is higher in Aluminum. Inspite of higher hardness of EN8 compared to M.S; higher MRR for EN8 is seen. This is due to fact presence of manganese and sulfur in EN8, which increases the machinability, which enhances the material removal rate.

Table 7. Comparison of Experimental MRR V/S Predicted MRR

Sr. No	Pressure Mpa	Cutting Speed mm/min	AFR gm/min	Avg Kerf Mm	Avg. DOC mm	Exp MRR mm3/ min	Predicted MRR mm3/ min	% Error
1	180	125	600	0.925	11.0449	1277.067	1241.15	2.812427
2	180	125	300	0.86	9.6951	1042.233	953.45	8.517681
3	210	125	600	0.9125	15.1777	1731.206	1724.15	0.407601
4	210	125	300	0.89	12.9894	1445.071	1436.45	0.596562
5	240	125	600	0.9375	18.8129	2204.637	2207.15	-0.114
6	240	125	300	0.87	17.1056	1860.234	1919.45	-3.18326
							Avg Error	1.506168

Table 8. Experimental MRR in Mild Steel Plate

Sr No	Pressure Mpa	Cutting Speed mm/min	AFR gm/min	Average Kerf mm	Average DOC mm	Exp. MRR mm^3/min
1	180	170	600	0.6525	2.8842	319.929
2	180	170	300	0.635	2.7765	298.543
3	180	110	600	0.6525	4.5377	325.693
4	180	110	300	0.6325	3.7558	262.342
5	210	170	600	0.6575	3.7916	423.806
6	210	170	300	0.64	3.3407	362.048
7	210	110	600	0.6575	4.4744	323.610
8	210	110	300	0.6375	4.2943	302.318
9	240	170	600	0.645	5.01	549.3465
10	240	170	300	0.6375	4.45	482.268
11	240	110	600	0.6575	5.7688	415.642
12	240	110	300	0.6375	5.1813	363.338

Table 9. Estimated Regression coefficient for MRR

Sr.No	Predictor	Coef	SE Coef	T	P
1	Constant	-404.53	99.14	-4.08	0.004
2	Pressure	2.5198	0.3945	6.39	0.000
3	Cutting Speed	1.2324	0.3221	2.48	0.038
4	A F R	0.15991	0.06441	3.83	0.005

S = 33.4705 R-Sq = 88.5% R-Sq(adj) = 84.2%

Table 10. Analysis of Variance for MRR

Sr.No	Source	DF	SS	MS	F	P
1	Regression	3	69024	23008	20.54	0.000
2	Residual Error	8	8962	1120	---	---
3	Total	11	77987	---	---	---

Table 11. Comparison of Experimental MRR v/s Predicted MRR in Mild Steel

Sr No	Pressure Mpa	Cutting speed mm/min	AFR gm/min	Avg Kerf Mm	Avg Doc mm	Exp MRR mm3/ min	Predicted MRR mm3/ min	%Error
1	180	140	600	0.6575	4.0577	373.5113	316.8	-4.36
2	180	140	300	0.6425	2.87444	258.5523	268.8	-3.96
3	210	140	600	0.6575	4.61631	424.9313	392.4	7.65
4	210	140	300	0.6375	3.7631	335.8567	344.4	-2.54
5	240	140	600	0.6575	5.8148	535.2523	468	9.72
6	240	140	300	0.6475	4.3845	394.3858	420	-6.49
							Average Error	0.0027

Table 12. Experiment No -1 Calculated Data for Regression Equation

Sr. No.	Pressure Mpa	Cutting Speed mm/min	AFR gm/min	Average kerf mm	Average doc mm	Exp MRR mm^3/min
1	180	110	600	0.7475	5.2323	430.2259
2	180	110	300	0.7125	4.1089	322.035
3	180	60	600	0.7525	8.36	377.454
4	180	60	300	0.72	7.4177	320.4446
5	210	110	600	0.75	6.9236	571.197
6	210	110	300	0.7175	5.1436	405.9586
7	210	60	600	0.7525	11.4629	517.5499
8	210	60	300	0.7225	9.9737	432.3599
9	240	110	600	0.755	9.1072	756.353
10	240	110	300	0.725	7.0074	558.8402
11	240	60	600	0.755	15.13	685.389
12	240	60	300	0.725	13.49	586.815

Table 13. Estimated Regression coefficient for MRR

Sr.No	Predictor	Coef	SE Coef	T	P
1	Constant	-711.26	91.23	-7.80	0.000
2	Pressure	4.7385	0.3820	12.40	0.000
3	Cutting Speed	0.4153	0.3743	1.11	0.299
4	A F R	0.39540	0.06238	6.34	0.000

Table 14. Analysis of Variance (ANOVA) for MRR

Sr.No.	Source	DF	SS	MS	F	P
1	Regression	3	205169	68390	65.09	0.000
2	Residual Error	8	8405	1051	---	---
3	Total	11	213574	---	---	---

Table 15. Experiment No-2 Calculated Data for Validation Test:

Sr No	Pressure	Cutting Speed	AFR	Avg. Kerf	Average DOC	Exp. MRR	Predicted MRR	% Error
	Mpa	mm/ min	gm/ min	mm	mm	mm^3/ min	mm^3/ min	
1	180	85	600	0.7525	6.0215	385.1502	414.475	-7.61386
2	180	85	300	0.715	5.204	316.2731	295.975	6.417903
3	210	85	600	0.7525	8.7953	562.5694	556.675	1.04776
4	210	85	300	0.715	6.9013	419.4265	438.175	-4.47003
	240	85	600	0.755	11.2417	721.4361	698.875	3.127248
6	240	85	300	0.725	9.3213	574.4251	580.375	-1.0358
							Average Error	0.42113

Table 16. MRR Calculated for Three Materials Parameters using Regression Equation

Sr.No.	Pressure	Cutting Speed	AFR	MRR of ALU	MRR of MS	MRR of EN8
	Mpa	mm/min	gm/min	mm^3/min	mm^3/min	mm^3/min
1	180	150	600	1260.95	329.1	441.45
2	180	150	300	973.25	281.1	322.95
3	180	125	600	1242.025	298.35	431.075
4	180	125	300	954.325	250.35	312.575
5	180	100	600	1223.1	267.6	420.7
6	180	100	300	935.4	219.6	302.2
7	210	150	600	1743.95	404.7	583.65
8	210	150	300	1456.25	356.7	465.15
9	210	125	600	1725.025	373.95	573.275
10	210	125	300	1437.325	325.95	454.775
11	210	100	600	1706.1	343.2	562.9
12	210	100	300	1418.4	295.2	444.4
13	240	150	600	2226.95	480.3	725.85
14	240	150	300	1939.25	432.3	607.35
15	240	125	600	2208.025	449.55	715.475
16	240	125	300	1920.325	401.55	596.975
17	240	100	600	2189.1	418.8	705.1
18	240	100	300	1901.4	370.8	586.6

Table 17. Effect of Pressure on MRR (At Maximum Cutting Speed)

Sr. No.	Pressure	Cutting Speed	AFR	MRR of ALU	MRR of MS	MRR of EN8
	Mpa	mm/min	gm/min	mm^3/min	mm^3/min	mm^3/min
1	180	150	600	1260.95	329.1	441.45
2	210	150	600	1743.95	404.7	583.65
3	240	150	600	2226.95	480.3	725.85

Table 18. Effect of Pressure on MRR (At Minimum Cutting Speed)

Sr. No.	Pressure	Cutting Speed	AFR	MRR of ALU	MRR of MS	MRR of EN8
	Mpa	mm/min	gm/min	mm^3/min	mm^3/min	mm^3/min
1	180	100	600	1223.1	267.6	420.7
2	210	100	600	1706.1	343.2	562.9
3	240	100	600	2189.1	418.8	705.1

Table 19. Effect of Cutting Speed on MRR (At Maximum Pressure)

Sr. No.	Pressure	Cutting Speed	AFR	MRR of ALU	MRR of MS	MRR of EN8
	Mpa	mm/min	gm/min	mm^3/min	mm^3/min	mm^3/min
1	240	100	600	2189.1	418.8	705.1
2	240	125	600	2208.025	449.55	715.475
3	240	150	600	2226.95	480.3	725.85

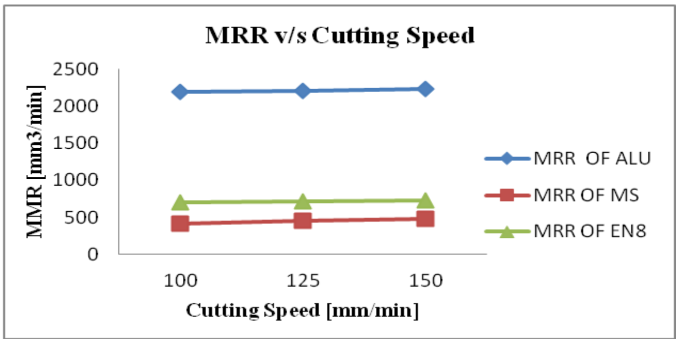

Figure 9 MRR versus Cutting Speed at Maximum Pressure

Comments on Effect of Cutting Speed on MRR

The trend in the cutting speed figure 9 shows that the MRR in all three materials marginally increases as the cutting speed increases. This shows that there is no impact of cutting speed on material removal rate (MRR).

This happens due to following reason; MRR is product of DOC, width of kerf, and cutting speed. When cutting speed increases time for penetration reduces, as a result depth of cut decreases, the product of DOC, cutting speed remains constant hence MRR remains unaffected. It indicates that cutting speed is not a significant parameter to MRR. This is also reflected in p-value in regression analysis tables.

Discussions:

- There are number of phenomenon associated with AWJ cutting such as particles interference and fragmentation.
- The water pressure and abrasive flow rate is associated with an increase in the depth of cut. Abrasive particle available in jet which make effective impact on the work material automatically enhance the MRR.

Conclusions

- The parameters effective to MRR were identified using ANOVA technique. Assumptions of ANOVA were tested using residual analysis. After careful testing results show that pressure and abrasive flow rate parameters are most significant factor.
- While cutting speed are non-significant factor to MRR in AWJM. Machining of all the material with AWJM is accomplished by solid erosion.

This means that increasing the pressure the abrasive grains or particles will have high speed and high energy which result good material removal rate

- The maximum prediction error for Aluminum plate in 8.5% and average error of prediction in 1.506, Mild Steel plate maximum error of prediction 9.72% and average error of prediction is .0027 and EN8 Plate maximum error of prediction is 7.61% and average error of prediction is 0.42.

Future Scope

- Present study shows effect of three main operating parameters on material removal rate. This can be further extended to include remaining machine parameters such as standoff distance, abrasive size and focusing tube diameter/length to get deeper understanding of process.

Acknowledgement

We are Thankful to the M/s Ainnovative International Ltd Ahmedabad.

References

1. H. Hocheng and K. R. Chang "Material Removal Analysis in Abrasive Water Jet Cutting of Ceramic" Journal of Material Processing Technology,40 (1994)287-304
2. Stanislav Fabian and Sergej Hloch "The effect of abrasive water jet process parameter to Micro geometrical quality of stainless steel AISI 304" International Multidisciplinary Conference.
3. S. Paul, A. M. Hoogstrate, C. A. Van Luttervelt "Analytical Modeling of The Total Depth of Cut in the Abrasive Water Jet Machining of Polycrystalline Brittle Material" Journal of Material Processing Technology in 1986.
4. Janet Flokes "Water jet – An innovative tool for manufacturing" Journal of Material Processing Technology 209(2009) 6181-6189
5. D. S. Srinivasu, D. A. Axinte, J Flokes "Influence of Kinematic Operating Parameter on kerf Geometry in Abrasive Water Jet Machining of Silicon Carbide Ceramics" International Journal of Machine Tool and Manufacture 49(2009) 1077-1088
6. B.N. Parmar, Dhaval M. Patel "Parameter Evaluation of Abrasive Water Jet Machining – Glass" International Conference on Advance in Mechanical Engg. in 2010.
7. Mahabalesh Palleda"A Study of Taper Angles and Material Removal Rate of Drilled Holes in the Abrasive Water Jet Machining Process" Journal of Material Processing Technology 189(2007)292-295
8. www.waterjet.org - Website of- M/s Super Jet AWJM.
9. "Water jetand Abrasive Waterjet Machining" Lesson No-37 version M.EIIT Kharagpur
10. www.wardjet.com - Website of - Water jet university Boeing M/s K M T machine.
11. Pratik J. Parikh, Sarah S. Lam "Parameter Estimation for Abrasive Water Jet Machining Process using Neural Networks" International Journal Advance Manufacturing Technology 40(2009)497-502.
12. Ranjeet Chitale "Statistical and Quantitative Method"10th edition 2009, Chapter No-5 Nirali Prakashan..
13. Vishal Parashar, A. Rehman, J. L. Bhagoria, Y. M. Puri "Statistical and Regression Analysis of Material Removal Rate for Wire Cut Electro Discharge Machining of SS 304L using Design of Experiments". International Journal of Engg. Science and Technology 2(5).(2010). 1021-1028
14. C. B. Gupta and Vijay Gupta "An introduction to Statistical Methods" 23rd revised Edition Page no 443 to 500, Vikas Publishing House Pvt. Ltd.
15. Madhusarathi Nanduri, David G. Taggart, Thomas J. Kim "The effect of system and Geometric Parameter on Abrasive Water Jet Nozzle Wear" International Journal of Machine Tool and Mfg.42(2002) 615-623
16. Phillip J. Ross "Loss function, orthogonal Experiment parameter and Tolerance design" McGraw Hill International Edition 1996.
17. R.S. Bharawaj "Business statistics" Chapter "Correlation"
18. Error! Hyperlink reference not valid. Website of- M/s Mach AWJM.