PARAMETRIC OPTIMIZATION & ANALYSIS OF PROCESS PARAMETERS OF ABRASIVE WATER JET MACHINE (AWJM)

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ABSTRACT

Abrasive Water Jet Machining (AWJM) is the non-traditional material removal process. It is an effective machining process for processing a variety of Hard and Brittle Material. And has various unique advantages over the other non-traditional cutting process like high machining versatility, minimum stresses on the work piece, high flexibility no thermal distortion, and small cutting forces. Abrasive Water Jet Machining (AWJM) removes material through the action of focused beam of abrasive jet directed at the work piece the resulting erosion can be used for cutting, drilling and debarring etc. For this experimental work type of abrasive particles commonly used is Al Oxide & Garnet. Here the machining parameters will Traverse Speed, Abrasive Flow Rate and Stand of Distance. This work includes that creation and analyzing of response surface. From this paper the overall performance of parameters on Metal Removal Rate (MRR) & Surface Roughness (SR) of work piece with statistically investigate by Taguchi Design.GA is use for Optimize the Values.

Keyword: - *AWJM, MRR, SR, GRA, Abrasive, Taguchi*

1. INTRODUCTION

Abrasive water jet machining (AWJM) is a well-established non-traditional and versatile process which is extensively used in many industrial process & applications. In the early 60's O. Imanaka, University of Tokyo applied pure water for industrial machining. In the late 60's R. Franz of University of Michigan, examine the cutting of wood with high velocity jets. Main applications of pure water jet machining include cutting paper products, wood, cloths, plastics etc. By the end of 1970's composites materials was introduced and its advantages such as high strength, low weight, resistant to heat, hard etc increase its use and applications, but there was no proper method to machine such materials economically. Thus abrasive water jet machine was made available at industries by 1980's to machining hard to machine materials and became commercially available by the end of 1983 and the various types of abrasives are garnet, silicon carbide, aluminum oxide, glass pieces etc. The added abrasives in the water jet increase the range of cutting materials, which can be cut with a Water jet drastically.

In this cutting process, a thin, high velocity water jet accelerates abrasive particles that are directed through an abrasive water jet nozzle at the material to be cut. Advantages of abrasive water jet cutting machine include the ability to cut all types of materials, no thermal distortion, small cutting forces, high flexibility and being environmentally friendly. Because of these capabilities, this cutting process is more cost-effective than traditional and some non-traditional machining processes the cut geometry depends on the type of abrasive grit and cutting parameters. Different types of abrasives are used in AWJM like garnet, olivine, Aluminium oxide (Al_2O_3), silica-sand, glass bead, silicon carbide (SIC), zirconium, etc. But a survey shows that 90% of the AWJM is done using garnet as an abrasive. The hardness of the abrasive particles is an important characteristic which strongly influences the cut geometry and that the depth of jet penetration depends strongly on the ratio of the hardness of the target material to the hardness of the abrasive.

2. WORKING PRINCIPLE OF AWJM

The working principle of AWJM is shown in Fig. 1. The high pressure pump may comprise of an intensifier, prime mover, controller, and an accumulator. Pure water is pressurized to about 200-400MPa (2000-4000bar) and fed to the module called cutting head through high pressure tube. The high pressure water is then passed through a small orifice, to form a very high velocity WJ. This WJ then enters in to the mixing chamber to get mixed with abrasives particles. Though abrasive supplying system and after mixing the abrasives with water, high velocity mixers are strike to the work piece and cut the material. The position and motion of the cutting head is controlled by computerized numerical control (CNC) system.Fig.1 Schematic of an abrasive water jet cutting system.

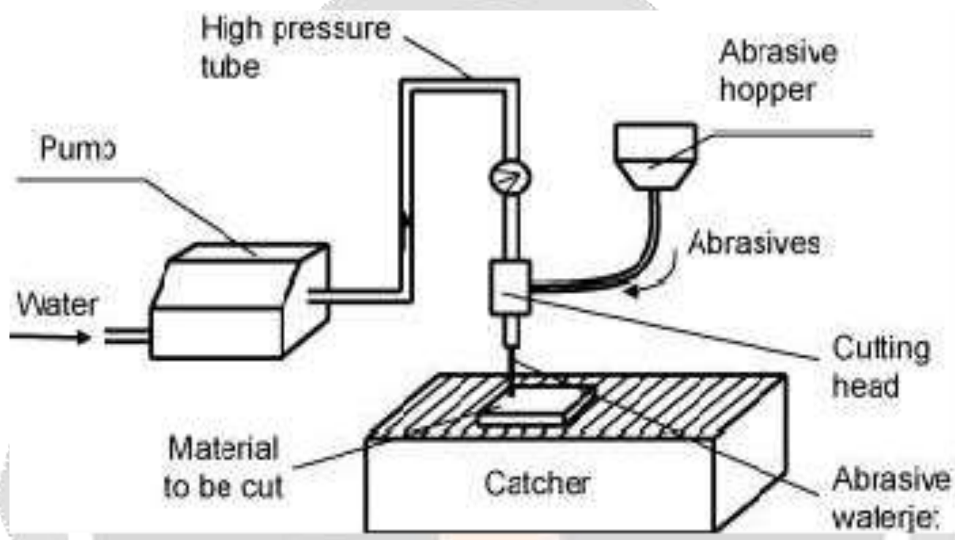


Fig. 2.1 Schematic of an Abrasive Water Jet Cutting System

3. LITERATURE REVIEW

Derzija Begic Hajdarevic et al. [1] carried out study on aluminum material in abrasive water jet cutting machine, the paper presented on the effects of traverse speed, thickness of material and abrasive mass flow rate on surface roughness during abrasive water jet cutting machine.80 mesh size of GMT Garnet was used as an abrasive material. Cutting of aluminum plate have thickness of 15 mm and 30 mm. For cutting of 15 mm plate traverse speed was 77-350 mm/min and abrasive flow rate was 100-320 g/min. And for 30 mm plate traverse speed and abrasive flow rate were 37-130 mm/min and 240-390 g/min respectively. Cutting was occurred at a pressure of 350Mpa. Surface roughness testing was carried out by surf-test Mitutoyo stylus instrument. They found that the first texture was located at the top of the cut having smooth surface. The second texture was located at bottom of the cut having rough surface and also concluded that when the thickness was increased the surface roughness was increased. When the traverse speed increased the surface become rougher, And while the depth of cut increases, the surface roughness also increased. Surface roughness slightly changes by increasing the abrasive mass flow rate. The higher productivity with nominal surface roughness can achieve by minimum traverse speed. By increases in abrasive mass flow rate, smooth surface can be achieved.

Adnan, Akkurt [2] Selected pure aluminum and Al 6061 aluminum alloy as a target material. Adnan Akkurt uses the conventional and various nontraditional machining processes to investigate Microstructures and hardness variations of cut surfaces of the material. Target material had been cut with saw, milling, submerged plasma, plasma, laser, wire electric discharge machining, oxy-fuel and Abrasive water jet. Adnan Akkurt uses GMT Garnet (80mesh) as an abrasive material having hardness 7.5-8 mohs in AWJM. The aluminum alloy plate having thickness of 20 mm. The abrasive mass flow rate 250 g/min was taken. The study shows that the hardness and surface quality of the cut surface is affected from the kind of cutting process. Microstructure of cut surfaces is affected from the kind of cutting process. Adnan Akkurt concluded that Abrasive Water Jet process is a unique process. And there is no adverse affect on microstructure of cut surface. There is cold deformation in mechanical processes and heat affected structure changes with heat based cutting processes but there is no changes in the structure of AWJ cut surfaces.

Adnan, Akkurt et al. [3] focused on the effects of feed rate and thickness of work piece on the surface roughness in AWJ cutting. The study also evaluates the deformation effect of AWJ on different work pieces. And that have the same composition but different thickness 5mm and 20mm. In this present work pure aluminum, Al-6061 aluminum alloy, brass-353, AISI 1030 and AISI 304 steel materials are cut using AWJM, and materials were cut at different feed rates. The most noticeable result is that the surface quality deteriorates when the depth of the cut gets deeper. It was observed that better surface characteristics achieved at upper region where the cutting wear mechanism was active, and surface characteristics deteriorates at the lower region because the cut was carried out by deformation wear mechanism. It was also observed that Better surface quality achieved from top to middle of thickness and surface deteriorates from middle to bottom. It is a known fact that studied brass and steel material have higher strength compare to aluminum. Higher cutting force will be generated between the cutting tool and material for higher strength of materials, as resulted the deformation effect of AWJ is higher for thinner materials and it deteriorates the quality of cut. They concluded that Al-6061 aluminum alloy has better surface smoothness than pure aluminum in AWJ cutting. Alloy element plays important factor in AWJ cutting application. Higher reduction in the feed rate for the same thickness specimen of aluminum-based material results in limited improvement in the surface quality. Results of studied material manifest that "cutting wear" and "deformation wear" mechanisms are effective in brittle and mild material with AWJM. Cutting wear mechanism results in better surface quality than deformation wear mechanism. Surface roughness results higher of 5mm thickness specimens than 20mm thickness specimens for brass and steel-based materials. Feed rate reduction in for 5 mm thickness resulted better surface smoothness and for 20 mm thickness the surface become rougher in AISI 304 stainless steel specimen.

Azmir, A. K. Ahsan [4] has studied on glass/epoxy composite laminate material. Surface roughness (Ra) and kerf taper ratio (TR) characteristics were taken as a response parameters in AWJM. To determine the effect of machining parameters on surface roughness (Ra) and kerf taper ratio (TR), Taguchi's design of experiments and analysis of variance (ANOVA) were used in AWJM. Abrasive types, Hydraulic pressure, Standoff distance, Abrasive flow rate, Traverse rate, Cutting orientation were used as input parameters in their research work and they uses garnet(80mesh) and aluminum oxide as an abrasive materials. Effects of various parameters on surface roughness are given below:

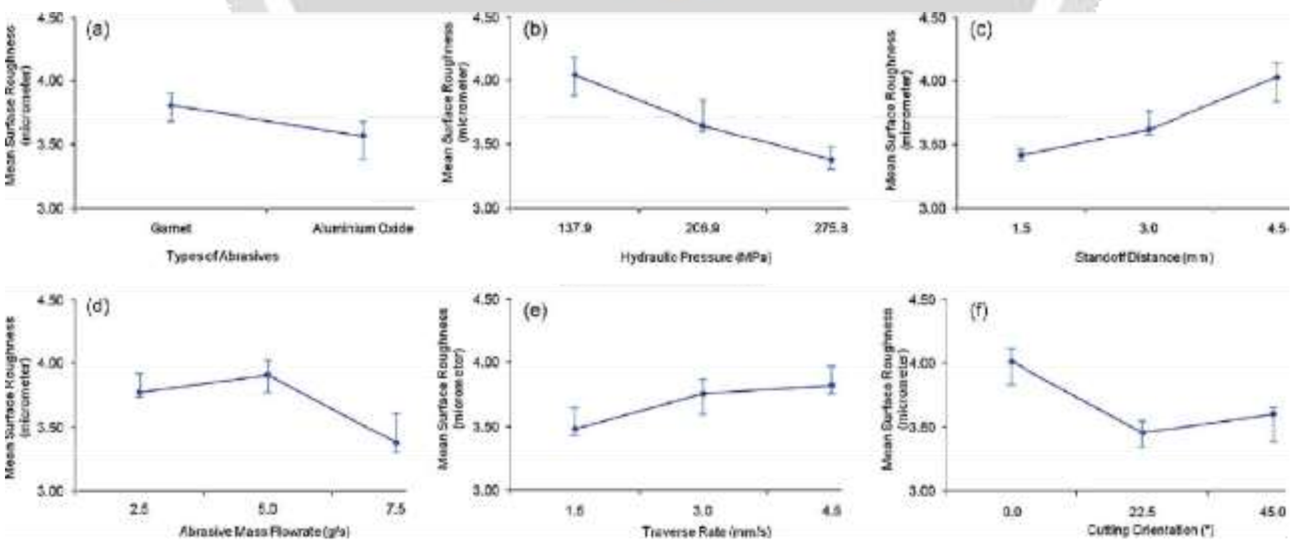


Fig. 3.1 Effect of (a) types of abrasives, (b) hydraulic pressure, (c) standoff distance, (d) abrasive mass flow rate, (e) traverse rate and (f) cutting orientation on surface roughness

The figure shows that increasing in pressure and abrasive flow rate surface become smoother and when the stand-off distance and traverse rate increases, the surface roughness increases. Aluminum oxides reduce the surface roughness compare to garnet due to their high hardness. Effects of various parameters on kerf taper ratio are shown below:

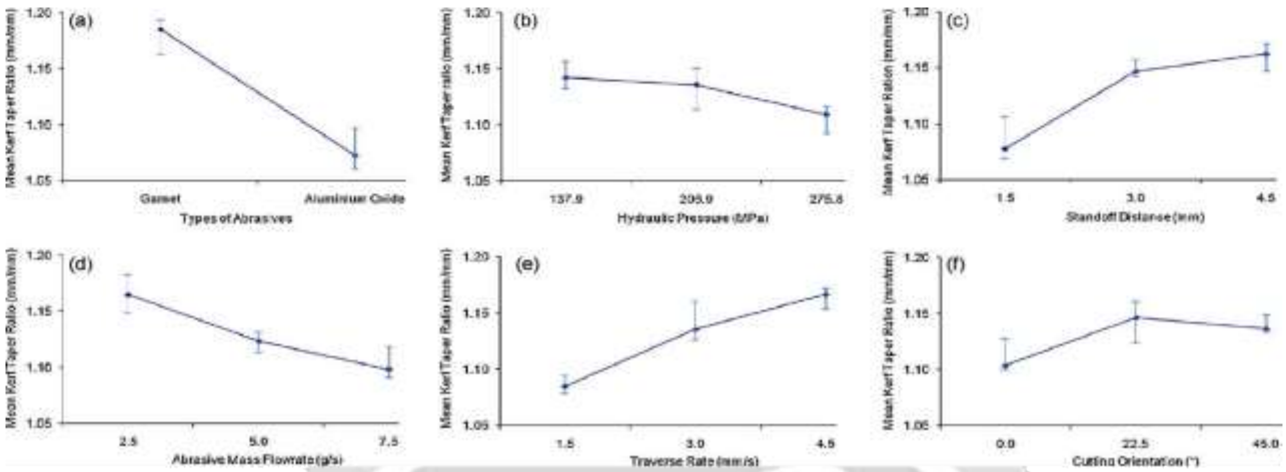


Fig. 3.2 Effect of (a) types of abrasives, (b) hydraulic pressure, (c) standoff distance, (d) abrasive mass flow rate, (e) traverse rate and (f) cutting orientation on kerf taper ratio

The figure shows that the increase the traverse rate and stand-off distance, increases ratio of Kerf taper. And increase in abrasive flow rate and pressure, reduce the kerf taper ratio. And cutting orientation have nominal effect on both cases. M.A. Azmir, A.K. Ahsan concluded that Due to higher hardness of aluminum oxide type of abrasive materials, it performs better than garnet in terms of both machining characteristics. And Hydraulic pressure and abrasive type (i.e. garnet and aluminum oxide) were considered as the most important control factor in influencing Ra and TR and meanwhile, decreasing the standoff distance (SOD) and traverse rate may improve surface roughness and kerf taper ratio. Cutting orientation does not influence the machining performance in both cases. So, it was confirmed that increasing the kinetic energy of abrasive water jet machining (AWJM) process may gives the better surface quality.

Ahmet Hascalik et al. [5] have studied on Ti-6Al-4V alloy material, which is known as difficult-to-cut material using traditional machining process. Kerf geometries, the profiles of cut surfaces, and micro structural features of the machined surfaces in terms of traverse speed in AWJM. The machining process carried out under different traverse speed of 60, 80, 120,150, 200, 250 mm/min and fixed pressure of 150 Mpa with abrasive water jet machine. The target material has thickness of 4.87 mm. 80 mesh size Garnet was used, abrasive flow rate was 0.005 kg/s, and stand-off distance was 3 mm. The machined surfaces were examined using surface profilometry and scanning electron microscopy (SEM).they concluded that micro structural evaluation of the cutting surfaces of samples an initial damage region (IDR), which is occurred at shallow angles of attack, a smooth cutting region (SCR), which is carried out at large angles of attack, and a rough cutting region (RCR), which is jet upward deflection zone. It was generated from instantaneous penetration of Abrasive water jet. As the traverse speed increases, the number of particles impinging on target area decreases hence reduced the IDR width slightly. With increase in traverse speed, SCR also decreased. In past study cutting mechanism in IDR and SCR consider as a cutting wear and deformation wear.

D. K. Shanmugam et al. [6] perform their investigation on two types of composites: epoxy pre-impregnated graphite woven fabric and glass epoxy. Taguchi experimental design used to construct Design of Experiments (DOE) for various process parameters like the traverse speed, abrasive flow rate, standoff distance and water pressure. Laminate composites have a thickness of 6 mm used. They adopting the energy conservation approach Using the dimensional technique. Garnet (80mesh) used as abrasive in this process. Kerf taper angle is the response variable of this research work. Effects of various parameters on kerf taper angle are as follows:

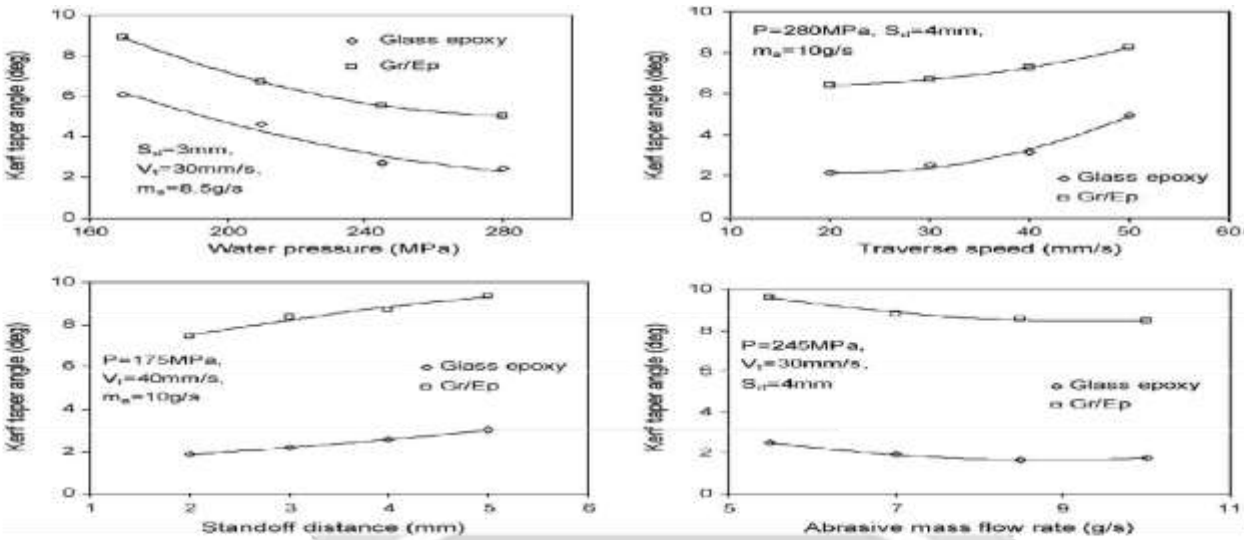


Fig. 3.3 Comparison of predicted and experimental kerf taper angles (symbols represent the experimental data and solid lines represent the predicted values)

As shown in figures the water pressure increases, the kerf taper angle reduces. Kerf taper angle increases, with increase in stand-off distance and traverse rate increased. And abrasive flow rate increased, then kerf taper minimize. The figure resulted that there is no waste difference between predicted values and experimental data. Based on the test conditions they resulted that the combination of high water pressure, low traverse speed, and low standoff distance were used to minimize the kerf taper angle. Such a model has been built based on an energy conservation approach with the hypothesis that the velocity of the particles is the same as that of the jet with only the particle energy is the important factor for the removal of the material. Though the traverse speed influences the kerf angle, it could only be minimized and it cannot be completely eliminated.

Naser Haghbin et al. [7] Have studied compares the performance of submerged (inside water) and un submerged (outside of water) abrasive water jet micro-milling of channels in stainless steel 316L and 6061-T6 aluminum at different nozzle angles and stand-off distance. Target sample having 3mm thickness and Garnet (320mesh) was used as an abrasive material. The performance was carried out at constant pressure of 138 Mpa. The submerged depth was taken 20 mm. The effect of submergence on the diameter and effective footprint of AWJ erosion footprints was measured and compared. It was resulted that the centerline erosion rate decreased with channel depth because the spreading of the jet as the effective standoff distance increased. The erosive jet spread over a larger effective footprint in air compared to water. Moreover, the instantaneous centerline erosion rate and volumetric erosion rates reduced with channel depth. The decrease in erosion rate due to the stagnation zone was shown to be only a function of channel geometry, and was independent of the standoff distance, jet angle, jet direction (forward or backward machining) and whether the jet was submerged or in air. Width of the channel machined in water was thin compared to the air. It is shown that submerged AWJM results in narrower features than those produced while machining in air, without a decrease in centerline etch rate Submerged AWJ micro machining also has the great benefits that it releasing less abrasive debris to the air and noise can be reduced.

M. Gent et al. [8] tests with six mineral and one high density glass abrasives to identify the abrasive properties required for the optimum machining of ductile materials by abrasive water jet cutting. Rate of erosion, the abrasive mass flow rate, abrasive particle size, and abrasive particle density these are parameters were presented. They selected 12mm thick stainless steel 316 as a work material. And six different mineral used as an abrasives. Tests were perform with pressure 304 Mpa and stand-off distance 1.5 mm. The six different minerals are HDG, GMA 80, Zircon, TC-C1, TC-K1, TC- TU. They resulted that the impact or contact number of abrasive particles is not as significant as the mass (size and density) of the particles. It was observed that cutting of steel with silica and garnet resulted breakage of abrasive particles.

A. A. Khan, M. M. Haque [9] have studied on AWJM of glass with various abrasive materials and taken stand-off distance, work feed rate and jet pressure as an input parameters and width of cut and taper of cut as an response parameters. They have taken three types of abrasives on their work garnet, aluminum oxide, and silicon carbide. Three types of abrasives used in the present study were garnet, Al2O3 and Sic Their hardness of the abrasives was 1350, 2100 and 2500 knoops, respectively. The width of cut was measured in optical microscope after the cutting process done. Effects the various parameters on taper of cut are discuss below:

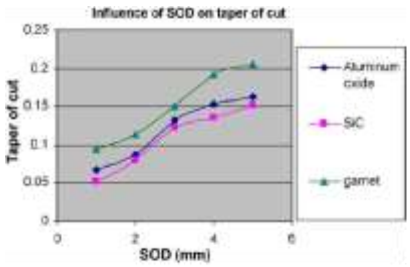


Fig. 3.4 Influence of SOD

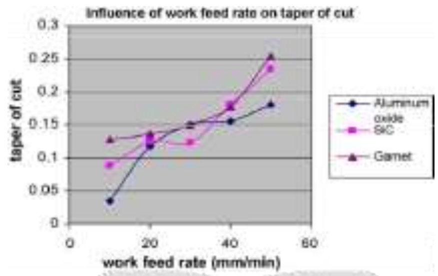


Fig. 3.5 Influence of feed rate on taper of cut

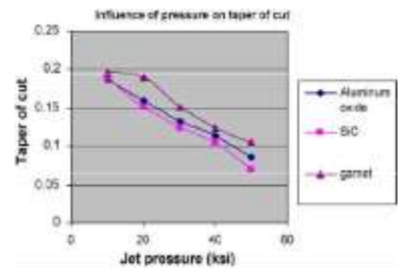


Fig.3.6 Effect of pressure on taper of cut

The study showed that taper of cut increases as the stand-off distance is increased which is due to divergence shape of the abrasive water jet. Taper of cut also increases with increase in work feed rate. But taper of cut reduces with increase in pressure. Increase in feed rate reduces the average width of cut. A higher jet pressure increases the kinetic energy of the abrasive particles and enhances their cutting ability. Effects of same parameters on width of cut are shown below:

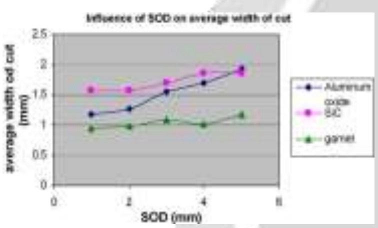


Fig.3.7 Effect of SOD on width of cut

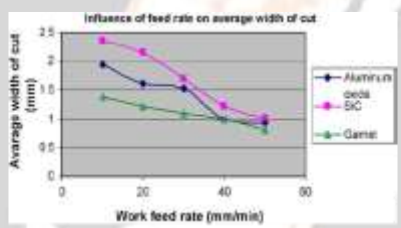


Fig. 3.8 Effect of feed on width of cut

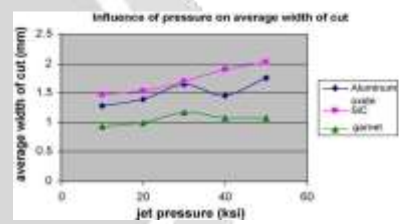


Fig. 3.9 Effect of pressure on width of cut

The figures shows that stand off distance and pressure increases width of cut increased, feed rate increased width of cut decreased. Garnet abrasives produce a larger taper of cut followed by Al2O3 and SiC. This is due to higher hardness of SiC compared to Al2O3 and garnet. SiC is harder than Al2O3 and garnet hence the average width of cut produced by SiC is higher than those produced by Al2O3 and garnet.

4. OBJECTIVES

1. Optimization of the cutting condition and abrasive particles having different hardness based on SR and MRR.
2. Develop the functional relationship by statistical method (ANOVA, Regression analysis, RSM etc.) that would be helpful for design consideration of abrasive water jet process (AWJM).
3. Validate the result with the predictions.

5. EXPERIMENTAL SETUP, DOE & OPTIMIZATION

KMT abrasive water jet machine will use in the experiments. The jet-line JL-50 ultra high pressure pump is used in industries And having pressure of machine is 3500 bar. The machine equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, pneumatic control valve and work piece table with dimension of 3000 x 3000 mm. orifice used to transform the high pressure water into collimated jet, with the help of carbide nozzle to from an abrasive water jet. Throughout the experiments the nozzle was checked and replaced significantly if the nozzle worn out. The abrasive passes to mixing chamber using compressed air. Debris of material and abrasives were collected into the catcher tank. Many hard materials can be easily cut by abrasive water jet machine and here Stainless Steel 304 will use as a test material. Many abrasive materials are used in abrasive water jet cutting machine such as silica, garnet, aluminum oxides, silicon carbide etc. We will use Garnet and aluminum oxide materials as an abrasive. And the materials will cut by both abrasives and the result will be investigated. Standard 80mesh grit size will be select for experiment.

Fig. 5.1 Abrasive Water Jet Machine

Material will use as work piece: AISI 302 as a work piece material. Stainless steel 302 is oxidation resistant, corrosion resistant and high strength material.

Table1. Chemical Composition of AISI302 Stainless Steel

Alloying Element	Carbon	Silicon	Manganese	Phosphorus	Sulphur	Chromium	Nickel
% by mass	0.065%	0.462%	1.325%	0.018%	0.025%	18.631%	8.118%

The L9 Orthogonal Array methodology has been used to plan the experiments. Three factors are chosen the design becomes a 5 level 3 factorial Taguchi design. The version 16 of the MINITAB 16 software was used to develop the experimental condition for L9 Orthogonal Array (OA).

Table2. Factors and Levels

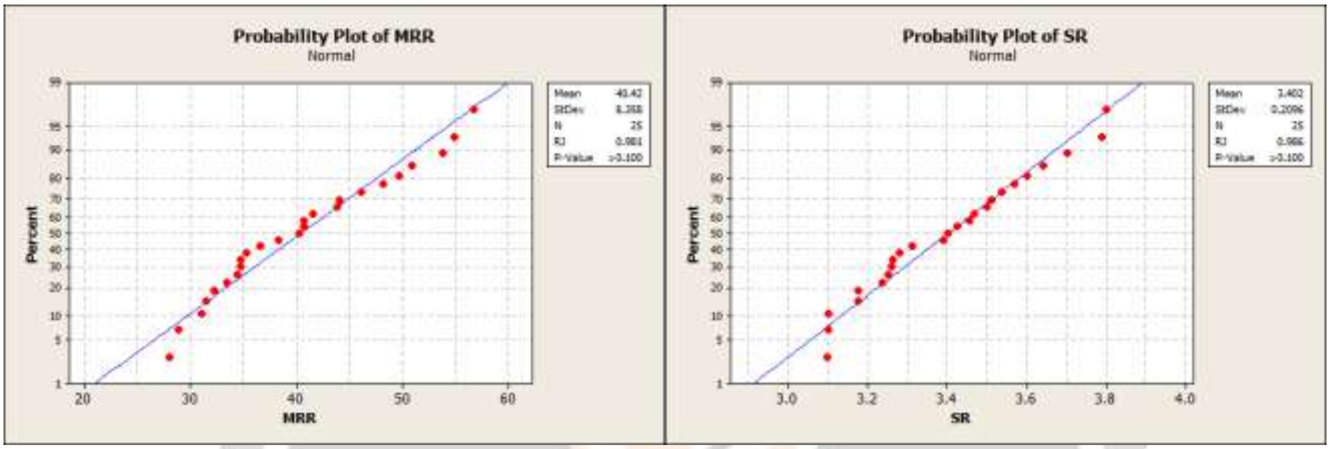
Symbol	Input Parameters	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
A	Traverse Speed (mm)	**100**	**110**	**120**	**130**	**140**
B	Abrasive Flow Rate (g/min)	**200**	**230**	**250**	**280**	**300**
C	Stand-off Distance (mm)	**2**	**2.5**	**3**	**3.5**	**4**

Table3. Experimental Table

Exp. No.	Process parameters			Output Parameters	
	Traverse speed (mm/min)	Abrasive flow rate (g/min)	Stand off distance (mm)	MRR mm^3/sec)	SR (µm)
1	100	200	2	28.1	3.281
2	100	230	2.5	28.9	3.251
3	100	250	3	31.1	3.178
4	100	280	3.5	34.4	3.102
5	100	300	4	32.3	3.103
6	110	200	2.5	31.5	3.426
7	110	230	3	33.4	3.390
8	110	250	3.5	34.8	3.312
9	110	280	4	35.3	3.262
10	110	300	2	38.3	3.102
11	120	200	3	34.7	3.538
12	120	230	3.5	36.6	3.512
13	120	250	4	40.7	3.468
14	120	280	2	40.3	3.237
15	120	300	2.5	41.6	3.178
16	130	200	3.5	40.7	3.602
17	130	230	4	44.0	3.569
18	130	250	2	43.8	3.458
19	130	280	2.5	46.1	3.402
20	130	300	3	48.1	3.259
21	140	200	4	49.7	3.799
22	140	230	2	50.8	3.788

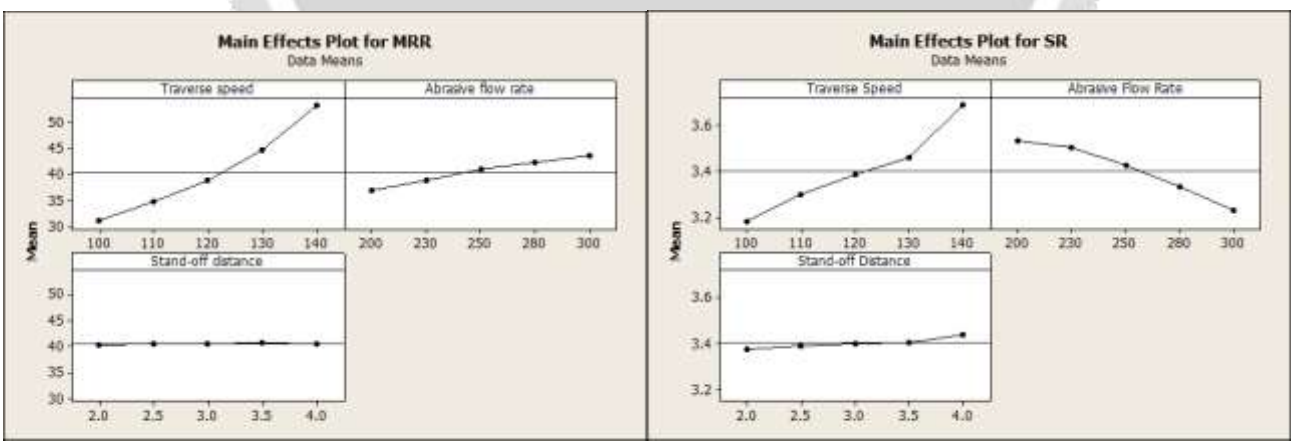
23	140	250	2.5	53.8	3.701
24	140	280	3	54.9	3.642
25	140	300	3.5	56.1	3.500

5.1 Normality Testing Of Output Results



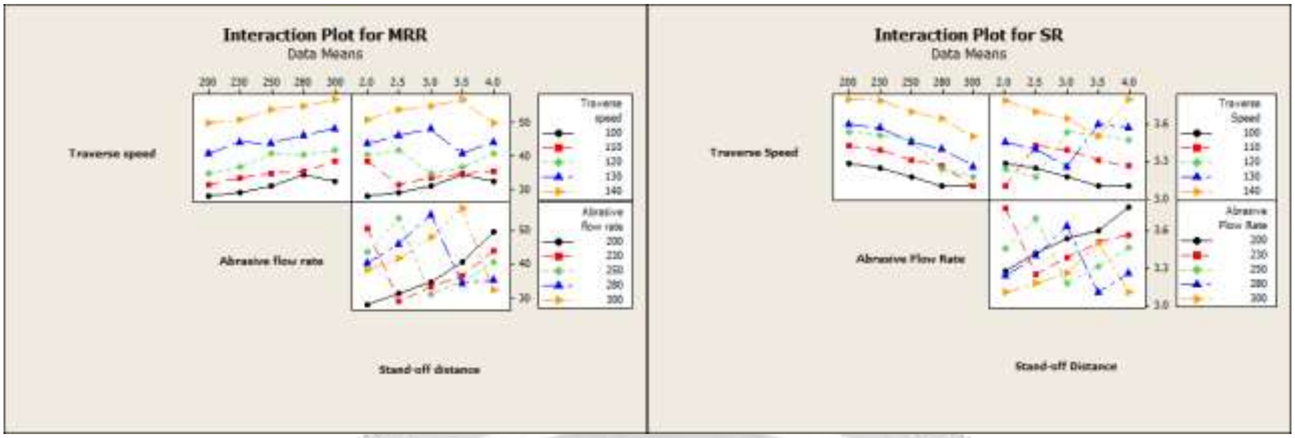
Here, in above two Normality Testing Graphs, the P value is > 0.05. So, the output results are Normal.

5.2 Main Effect Plots



Here, in above two graphs, we can see the main effect plot. Main effect plots shows the effect of input parameters on the output parameters.

5.3 Interaction Plots



5.4 Regression Model

Regression Model analysis for MRR :

The Regression equation is

MRR = - 41.5 + 0.543 Traverse Speed + 0.0653 Abrasive Flow Rate + 0.108 Stand-off Distance

Source	P
Regression	0.001
R-Sq = 96.0%	R-Sq(adj) = 95.4%

Regression Model analysis for SR :

The Regression equation is

SR = 2.69 + 0.0117 Traverse Speed - 0.00306 Abrasive Flow Rate + 0.0296 Stand-off Distance

Source	P
Regression	0.002
R-Sq = 93.6%	R-Sq(adj) = 92.7%

5.5 Problem Formulation Using Regression Model

function MRR = DOE_MRR(x)

MRR = - (- 41.5 + 0.543 * x(1) + 0.0653 * x(2) + 0.108 * x(3));

function MRR = DOE_SR(x)

SR = 2.69 + 0.0117 * x(1) - 0.00306 * x(2) + 0.0296 * x(3));

Constraints for all the three functions are as follows:

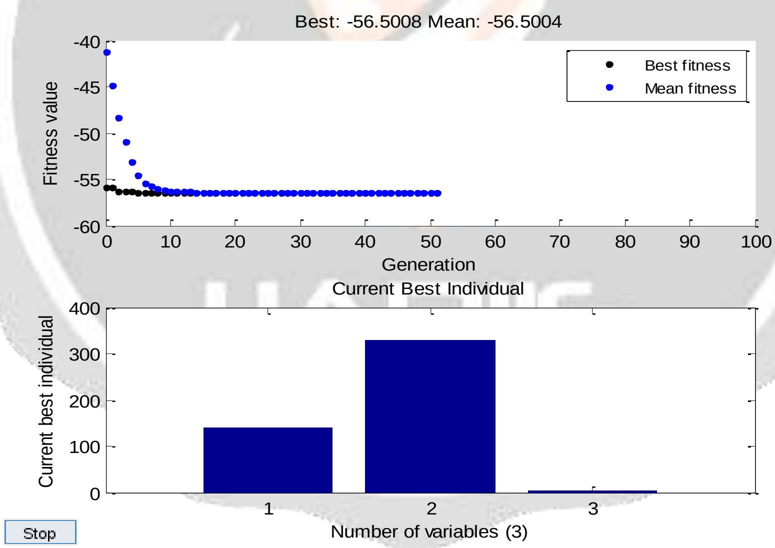
TS x(1) : $TS_{min} \leq x(1) \leq TS_{max}$, i.e. 100 mm $\leq$ TS $\leq$ 140 mm

AFR x(2) : $AFR_{min} \leq x(2) \leq AFR_{max}$, i.e. 200 g/min $\leq$ AFR $\leq$ 300 g/min

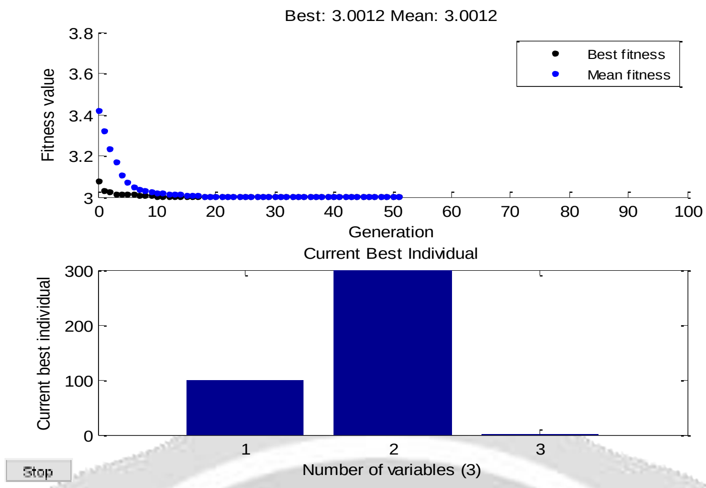
SOD x(3) : $SOD_{min} \leq x(3) \leq SOD_{max}$, i.e. 2 mm $\leq$ SOD $\leq$ 4 mm

5.6 Optimization Using GA

Ext No.	Process Variables			Response
	TS	AFR	SOD	MRR
Population size : 200				
1	**140**	**300**	**4**	**56.50**



Ext No.	Process Variables			Response
	TS	AFR	SOD	SR
Population size : 200				
1	100	300	2	3.00



5.7 Validation through Regression Model:-

Input parameters	Value*	Optimized value of MRR	Experimental value of MRR	% Error
TS	140	56.50	57.90	2.41%
AFR	300			
SOD	4			

Input parameters	Value*	Optimized value of SR	Experimental value of SR	% Error
TS	100	3.00	3.08	2.59%
AFR	300			
SOD	2			

6. CONCLUSIONS

1. By Increasing All Three Input Parameters MRR is Increasing.
2. By Increasing Transverse Speed & Stand off Distance Input Parameters SR is Increasing & Increasing Abrasive Flow rate SR is decreasing.
3. If the pressure is increased, surface become smoother and width of cut increased. And increase in traverse speed surface roughness increased.
4. If the abrasive flow rate increased, surface roughness decreased.
5. Aluminum oxide have a better surface characteristics compare to Garnet abrasives due to its higher hardness.
6. If the stand-off distance increase, width of cut and surface roughness increased.
7. If the traverse speed increased, depth of cut and surface roughness increased.

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