Effects of process parameters on responses during Machining Ti6Al4V Alloy using Abrasive Water Jet Machining

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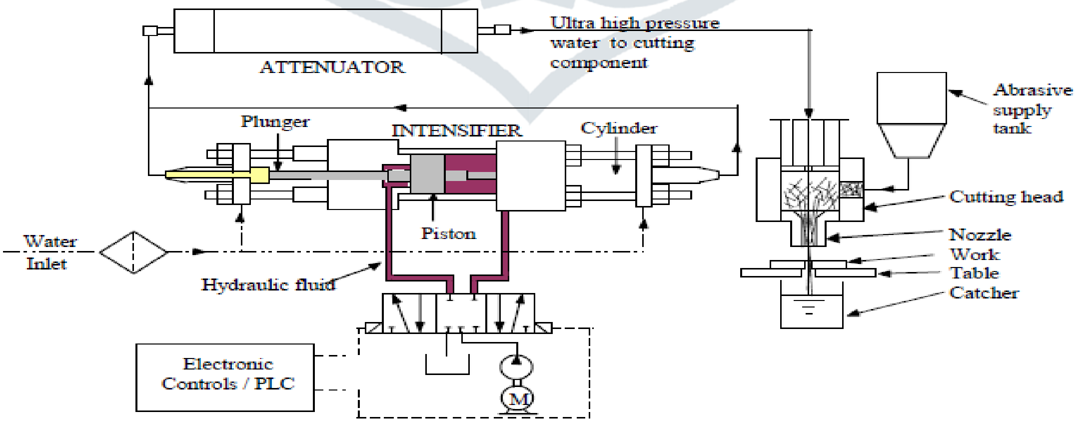
***Abstract*— Abrasive water jet machining (AWJM) is one of the recent non-traditional methods that have been used in industry for machining of different materials in a variety of applications. Material removal in this process is due to the erosion of a small volume with each abrasive particle striking the surface at high velocity. It is highly suitable for ceramics and composite materials. Composite materials are being increasingly used in various applications like space, aircraft, marine, architectural and automobile sector because of their superior physical and mechanical properties even though they are a little bit costly. There are so many process parameter affect quality of machined surface cut by AWJM. Important process parameters which mainly affect the quality of cutting are traverse speed, hydraulic pressure, stand of distance, abrasive flow rate and types of abrasive. Abrasive water jet machining provides some advantages over other machining process for cutting the composite materials like no thermal effect, high machining versatility and small cutting forces. In this paper some of the significant parameters are selected and then are studied by using Taguchi's signal to noise ratio method to find out the optimum working values of those parameters out of the selected values at different levels. For the optimum values of different responses both these graphs and values are compared.**

***Index Terms*—Surface Roughness, Kerf Characteristics, Abrasive Water Jet Machining.**

1. INTRODUCTION

AWJM is a well-established non-traditional machining process. Abrasive water jet machining makes use of the principles of both abrasive jet machining and water jet machining. AWJM is a non-conventional machining process where material is removed by impact erosion of high pressure high velocity of water and entrained high velocity of grit abrasives on a work piece [5]. 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. The first industrial application manufactured by McCartney Manufacturing Company and installed in Alto Boxboard in 1972. The invention of the abrasive water jet in 1980 and in 1983 the first commercial system with abrasive entrainment in the jet became available. The added abrasives increased the range of materials, which can be cut with a Watergate drastically. [2] This technology is most widely used compare to other non-conventional technology because of its distinct advantages. It is used for cutting a wide variety of materials ranging from soft to hard materials. This technique is especially suitable for very soft, brittle and fibrous materials. This technology is less sensitive to material properties as it does not cause chatter. This process is without much heat generation so machined surface is free from heat affected zone and residual stresses.



. Schmatic illustration of an ultra high pressure water preparation and abrasive type waterjet cutting system.

Schematic view of the Abrasive Water Jet Machining process

AWJM has high machining versatility and high flexibility. The major drawback of this process is, it generate loud noise and a messy working environment [5]. AWJM have certain advantageous characteristics, which helped to achieve significant penetration into manufacturing industries. [3]

- Extremely fast set-up and programming
- Very little fixturing for most parts

- Machine virtually any 2D shape on any material
- Very low side forces during the machining
- Almost no heat generated on the part
- Machine thick plates

Some Basic Terminology used in AWJM Process

Stand-off Distance: -	It is the distance between the work piece and cutting nozzle along the vertical direction.
Traverse Speed: -	The speed at which the water jet nozzle moves along the cutting plane in horizontal direction.
Water Jet pressure: -	It is the pressure of water jet which comes out of the nozzle and it is maintained by a pump at higher values
Surface Roughness: -	It is average value of unevenness in the surface generated during machining (R_a) It is the difference between peak and valley of the uneven surface generated after machining (R_t)
MRR: -	Material Removal Rate is the rate at which material is being removed from the work piece by machining of the same.
Kerf width: -	It is the width of the cut along the cutting plane which exceeds the value of cut by cutting jet.
Kerf Taper: -	It is the curvature generated along the cutting line in vertical direction due to the cutting jet.
Kerf Taper Angle: -	It is the angle of the taper with the vertical plane during the machining. It should be minimized to reduce material wastage as the higher value of it will increase the extra material removal along the taper
Abrasive particle: -	These are small particles with sharp cutting edges used for the cutting purpose when suspended in high speed water jet.
Abrasive Flow Rate: -	The rate at which abrasive flows through the nozzle of the cutting jet during the machining.
Depth of cut: -	The penetration of the water jet in to the work piece is depth of cut for that material.

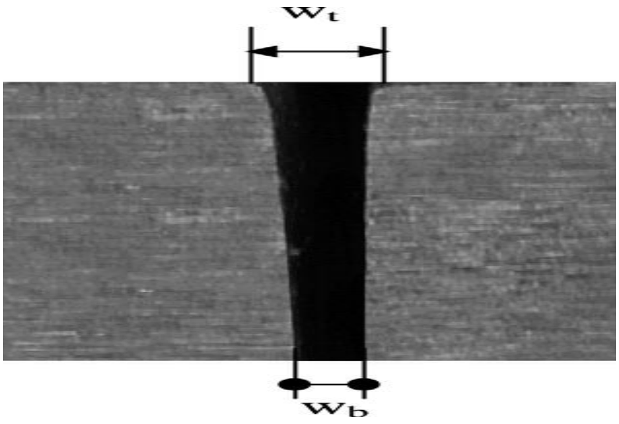
2. LITERATURE SURVEY

H. Hocheng and K.R. Chang [4] has carried out work on the kerf formation of a ceramic plate cut by an abrasive water jet. There is a critical combination of hydraulic pressure, abrasive flow rate and traverse speed for through- out cut below which it cannot be achieved for certain thickness. A sufficient supply of hydraulic energy, fine mesh abrasives at moderate speed gives smooth kerf surface. By experiment they find kerf width increases with pressure increase, traverse speed increase, abrasive flow rate increase and abrasive size increase. Taper ratio increases with traverse speed increases and decreases with pressure increases and abrasive size increases. Taper ratio has no effect with increase in abrasive flow rate.

Vishal Gupta et al. "Minimization of kerf taper angle and kerf width using Taguchi's method in abrasive water jet machining of marble" 3rd International Conference on Material Processing and Charecterisation, 2014 [7]
Design of Experiments (DOE) Experimental design 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. By studying the effects of individual Factors on the results, the best factor combination can be determined.

Optimization based on TAGUCHI approach is used to achieve more efficient cutting parameters. Parameter design is the key step in the Taguchi approach to achieve high quality without increasing cost. To solve this problem Taguchi approach uses a special design of orthogonal arrays where the experimental results are transformed into the S/N ratio as the measure of the quality characteristic deviating from the desired value. Analysis of Variance (ANOVA) is the method used to find out the optimum values of parameters by using signal to noise ratio.

Ahmet Hascalik et al [2] have studied the process for the titanium grade 5 material and their study revealed some important results and discussions which are as below.



They have measured the kerf characteristics of the cut by means of measurement of top width and bottom width of the cut and then relating it with the below equation they have found the kerf characteristics for that material. The results are in form of kerf taper angle.

$$T = \arctan\left(\frac{W_{top} - W_{bottom}}{2 \cdot t}\right)$$

3. EXPERIMENTAL STUDY

The experiments are carried out by using design of experiments planned using Taguchi's L27 orthogonal array with four parameters and with three levels as shown below in the tables.

Table 1 Table with Levels of parameters

Parameter	Level 1	Level 2	Level 3
Pressure (MPa)	5	10	15
Stand Off Distance (mm)	3	5	8
Traverse Speed (mm/min)	50	100	150
Abrasive Flow Rate (g/min)	100	200	300

Table 2 L27 orthogonal array with levels

Experiment No.	Pressure	Stand-off Distance	Traverse speed	Abrasive flow rate
1	5	3	50	100
2	5	3	50	100
3	5	3	50	100
4	5	5	100	200
5	5	5	100	200
6	5	5	100	200
7	5	8	150	300
8	5	8	150	300
9	5	8	150	300
10	10	3	100	300
11	10	3	100	300
12	10	3	100	300
13	10	5	150	100
14	10	5	150	100
15	10	5	150	100
16	10	8	50	200
17	10	8	50	200
18	10	8	50	200
19	15	3	150	200
20	15	3	150	200
21	15	3	150	200
22	15	5	50	300
23	15	5	50	300
24	15	5	50	300
25	15	8	100	100
26	15	8	100	100
27	15	8	100	100

Now the experiments are conducted on the work material that is titanium grade 5 with its properties and uses as below.

Properties and uses of work material: Titanium Grade 5, also known as Ti6Al4V, Ti-6Al-4V or Ti 6-4, is the most commonly used alloy. It has a chemical composition of 6% aluminium, 4% vanadium, 0.25% (maximum) iron 0.2% (maximum) oxygen and the remainder titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties (excluding thermal conductivity, which is about 60% lower in Grade 5 Ti than in CP Ti). Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, and weldability.

This alpha-beta alloy is the workhorse alloy of the titanium industry. The alloy is fully heat treatable in section sizes up to 15mm and is used up to approximately 400°C (750°F). Since it is the most commonly used alloy – over 70% of all alloy grades melted are a sub-grade of Ti6Al4V.

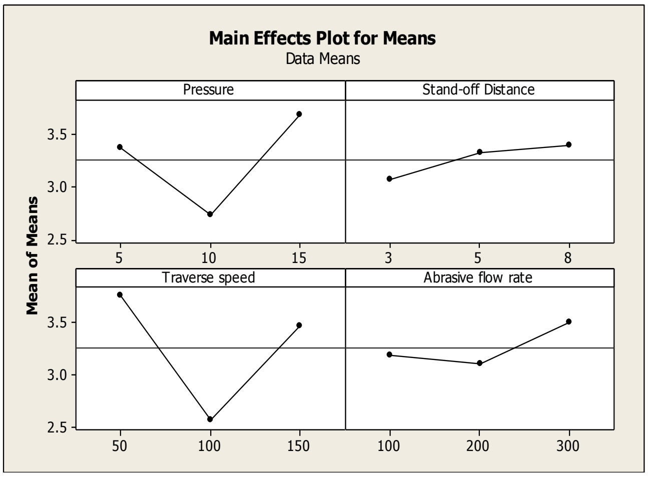
Table 3 table for work material detail

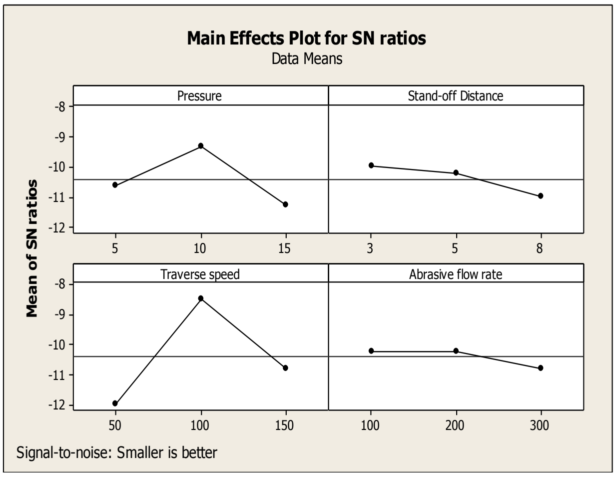
Sr. No.	Work Piece Specification	
1	Material	Ti6Al4V Titanium grade 5
2	Grade	5
3	Hardness Number	379 BHN and 41 Rockwell Hardness number
4	Thickness	3 mm
5	Width and Length	400 mm * 80 mm
6	Chemical Composition	Ti – 89.6 to 90 % , Al – 5.4 to 5.9 % , V – 3.9 to 4.5 % , Fe – 0.1 to 0.2% , Mo – 0.1 to 0.2% , Mn – 0.003% ,

Table 4 Experimental Data table

Top Kerf Width (mm)	Lower Kerf Angle (degree)	Upper Kerf Angle (degree)	Surface Roughness (R_a)(micron)	Surface Roughness (R_z)(micron)
0.96	0.76	1.81	2.80	18.90
0.93	1.15	1.24	5.24	31.61
0.92	0.95	1.62	2.73	17.65
0.90	1.24	1.91	2.19	15.56
1.05	0.86	3.05	2.47	19.62
1.00	1.05	2.67	3.06	18.59
0.99	1.91	2.86	3.24	20.73
1.05	0.95	3.53	4.33	28.95
1.09	0.86	4.19	4.24	31.41
0.90	1.24	2.00	2.93	16.81
0.92	1.24	2.10	2.68	16.91
0.96	1.15	2.29	0.62	6.48
1.13	0.95	1.34	2.77	17.33
1.11	1.34	1.43	3.25	17.13
1.14	0.95	1.62	2.72	19.07
1.11	0.95	2.00	3.24	18.40
1.18	1.24	2.48	5.36	32.20
1.14	1.05	2.00	0.99	6.28
1.14	1.24	1.15	4.22	24.08
1.11	1.05	1.34	3.43	26.40
1.07	1.34	0.76	2.93	20.03
1.14	1.05	1.91	4.97	35.30
1.15	1.24	1.53	4.26	24.57
1.12	1.24	1.62	4.23	27.19
1.21	0.86	0.76	2.84	14.75
1.34	1.05	1.24	3.53	24.57
1.31	0.95	1.15	2.76	15.16

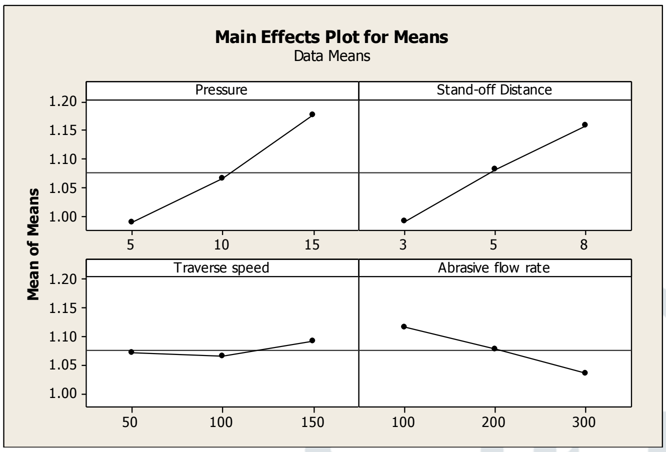
Now the above outcomes are one by one optimized using Taguchi's SN ratio method with mean of means and signal to noise ratio. The graphs are as below.

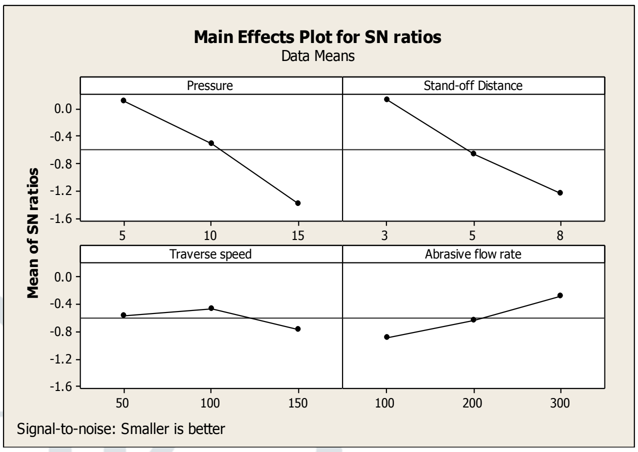




Above graphs are for the effect of parameters on the Surface Roughness and it is required that the value of surface roughness should be minimum which is as below.

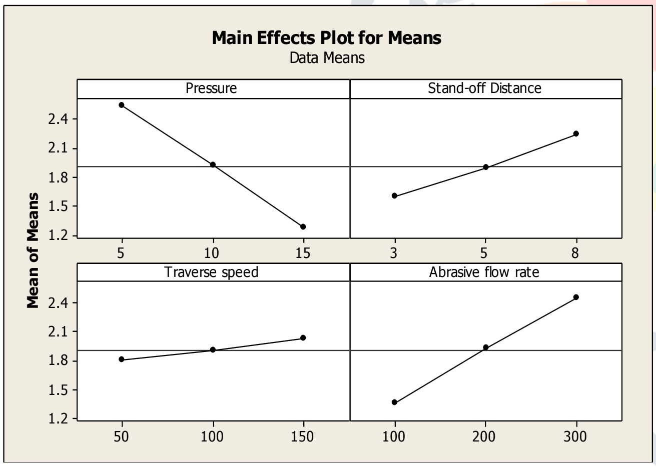
From Signal to Noise graph it is		from means of mean graph it is	
Pressure (MPa)	15	Pressure (MPa)	10
Stand-off distance (mm)	8	Stand-off distance (mm)	3
Traverse Speed (mm/min)	50	Traverse Speed (mm/min)	100
Abrasive Flow Rate (g/min)	300	Abrasive Flow Rate (g/min)	200

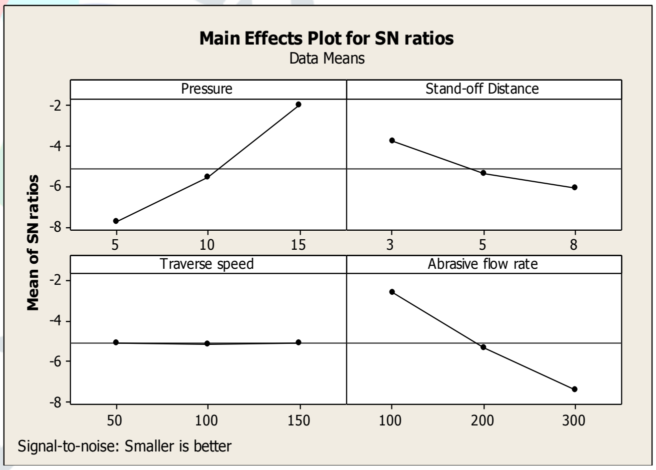




Above graphs are for the effect of parameters on the Kerf Width and it is required that the value of surface roughness should be minimum which is as below.

From Signal to Noise graph it is		from means of mean graph it is	
Pressure (MPa)	15	Pressure (MPa)	5
Stand-off distance (mm)	8	Stand-off distance (mm)	3
Traverse Speed (mm/min)	150	Traverse Speed (mm/min)	100
Abrasive Flow Rate (g/min)	100	Abrasive Flow Rate (g/min)	300





Above graphs are for the effect of parameters on the Kerf Angle and it is required that the value of surface roughness should be minimum which is as below.

From Signal to Noise graph it is		from means of mean graph it is	
Pressure (MPa)	5	Pressure (MPa)	15
Stand-off distance (mm)	8	Stand-off distance (mm)	3
Traverse Speed (mm/min)	100	Traverse Speed (mm/min)	50
Abrasive Flow Rate (g/min)	300	Abrasive Flow Rate (g/min)	100

4. RESULTS AND DISCUSSION

From above experimental work and data obtained from the SN ratio and mean of means that the dependency of the output on the input parameters follows the order which is as shown below.

Response table for means for Kerf Angle				
Level	P	SoD	TS	A F R
1	2.542	1.590	1.801	1.357
2	1.918	1.898	1.908	1.929
3	1.273	2.246	2.024	2.448
Delta	1.269	0.656	0.223	1.091
Rank	1	3	4	2

Response table for Signal to Noise ratio for Kerf Angle				
Level	P	SoD	TS	AFR
1	-7.75	-3.81	-5.087	-2.623
2	-5.551	-5.39	-5.143	-5.3
3	-2.026	-6.126	-5.096	-7.404
Delta	5.724	2.315	0.056	4.781
Rank	1	3	4	2

Similarly for Kerf Width rank order for the dependency of parameters is as below.

For Signal to Noise ratio						For means of mean			
Parameter	P	SoD	TS	AFR		P	SoD	TS	AFR
Rank	1	2	4	3		1	2	4	3

Similarly for Surface Roughness rank order for the dependency of parameters is as below.

For Signal to Noise ratio						For means of mean			
Parameter	P	SoD	TS	AFR		P	SoD	TS	AFR
Rank	2	3	1	4		2	4	1	3

From above tables it is clear that the parameter dependency changes for the different outputs and also the rank order changes for SN ratio as well as the mean of means study.

5. CONCLUSION

The quality of the cut that is with low kerf characteristics and low surface roughness majorly dependent on the pressure and the other parameters affects in random manner with order. Hence the conclusion drawn from this research study is that the major parameter is pressure and then the other major parameter being Stand-off distance.

The other outcome of the study is that as the pressure increases above certain value it will give more surface roughness and stand-off distance also plays vital role in surface roughness. Kerf characteristics also affected mostly by pressure, Stand-off Distance and Abrasive flow rate. Traverse speed also affects the output but not in the way other parameters.

6. FUTURE SCOPE

The future scope of the work for this process has scope in nozzle parameters such as forming a revolving nozzle as per the computer controller program which will reduce the kerf generated during the machining using this process. One more point is in the optimization of parameters by using multi objective approach in which more than one objective function is used as the responses are more than one like Surface Roughness, Kerf characteristics,

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