Optimization of Process Parameters in Abrasive Water Jet Machining by Taguchi Method

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Abstract

Abrasive water jet machining is a non-conventional metal removal process, it removes the material by impact erosion of high pressure, high velocity jet along with high velocity of grit abrasive on work piece. The objective of this paper is to assess the influence of abrasive water jet machining parameters on surface roughness and Kerf characteristics of stainless steel 304 and Aluminum alloy 2024. The input parameters in the present study are stand of distance, jet pressure and abrasive flow rate to achieve minimum surface roughness and Kerf characteristics. Taguchi method is used for the present study and L9 orthogonal array was considered for experimentation for three process parameters and three levels are considered for each parameter. The optimum values of stand of distance, jet pressure and abrasive flow are suggested to get the best possible surface finish and small kerf angel.

Key words: Abrasive flow, Stand of distance, jet pressure, surface roughness, Kerf angel

1. Introduction

Abrasive Water Jet Machine (AWJM) is an unconventional machine, which is an industrial tool capable of cutting a wide variety of materials using a very high pressure jet of water along with an abrasive substance. The term abrasive jet refers specifically to the use of a mixture of water and abrasive to cut hard materials such as metal or granite, while the terms pure water jet and water only cutting refer to water jet cutting without the use of added abrasives, often used for softer materials such as wood or rubber. AWJM cutting is often used during fabrication of machine parts. It is the preferred method when the materials being cut are sensitive to the high temperatures generated by other methods. AWJM cutting is used in various industries, including mining and aerospace, for cutting and shaping, stray heat treatment of work is completely avoided in AWJM.

As water jet cutting moved into traditional manufacturing shops, controlling the cutter reliably and accuracy was essential. Early water jet cutting systems adapted traditional systems such as mechanical pantographs and CNC systems based on John Parsons' 1952 NC milling machine and running using G-code. Challenges inherent to water jet technology revealed the inadequacies of traditional G-Code, as accuracy depends on varying the speed of the nozzle as it approaches corners and details, this led to development of dedicated CNC for AWJM.

Creating motion control systems to incorporate those variables became a major innovation for leading water jet manufacturers in the early 1990s, with Dr John Olsen of OMAX Corporation developing systems to precisely position the water jet nozzle while accurately specifying the speed at every point along the path, and also utilizing common PCs as a controller. The largest water jet manufacturer, Flow International (a spin-off of Flow Industries), recognized the benefits of that system and licensed the OMAX software, with the result that the vast majority of water jet cutting machines spread across worldwide are simple to use, fast, and accurate.

Surface roughness is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough, if they are small, the surface is smooth. Kerf angle is the angel of deviation from top surface of job to the bottom surface of the job. Titanium bodies for military aircraft. engine components Aluminum body parts. Interior cabin panels. Aerospace components are made by using WJM. The major benefits of WJM due to cold cutting no heat affected zones, no hardening, omni-directional cutting, ability to cut in any direction.

WJM Perforates most materials without starting holes, Cuts virtually any material and is ecofriendly. WJM is not suitable for higher depth of lay cutting. Wet cut edges are left the pattern, water needs filtration and de-ionization treatments.

Gursewak Kesharwhani *et al* [1] experimented on using non-spherical sharp edges ceramic abrasives for machining work-pieces in case of applications in aerospace industry. It was concluded that abrasive flow rate and traverse speed has the significant role in controlled depth milling in case of abrasive water jet machining process. They found that by modifying setup, a reduction of 20% time for milling Titanium based alloy can be achieved. The surface waviness can also be reduced. Sidda Reddy [2] investigated optimization of the input parameters of abrasive water jet machining process by means of Taguchi method. The use of signal to noise ratio (S/N) ratio to optimize different parameters for obtaining efficient Material Removal Rate (MRR) and surface roughness. Ahsan Ali Khan et.al [3] studied the effect of thickness of the material, abrasive flow rate and traverse speed during abrasive water jet machining of Aluminium for surface roughness. It was concluded that abrasive flow rate has significant effect on surface roughness at bottom of cut. K.S. Jai Autrin and M.Dev Anand [4] studied work on optimizing of machining parameter in abrasive water jet machining process for Aluminium alloy by means of regression analysis. They investigated the effect of standoff distance, nozzle diameter and water pressure on material removal rate (MRR) and surface roughness.

Ray and Paul [5] studied the effect of the abrasive jet on the surface roughness. Experiments were conducted using silicon carbide as abrasive particles at different air pressure. It was found out that surface roughness has increased due to increase in grain size and nozzle diameter. The SR increases with increase of Standoff distance (SOD). Aliraza Moridi [6] experimented effect of process parameters on the cutting performances in AWJM Process. The excessive abrasive mass flow rate increases inter particle collision increasing of the surface roughness. K.R. Chang et.al.[7] investigated the kerf formation in AWJM for a ceramic plate. During experiment, they found that kerf width increases with increase in pressure and abrasive flow rate. Taper ratio has no effect with increase in abrasive flow rate. Vishal Gupta et.al [8] et.al investigated the surface roughness and kerf taper ratio of composite material by AWJM. They found that by increasing the kinetic energy of jet, better cut quality is produced. Types of abrasive has more significance on kerf taper ratio while SOD and traverse speed are almost equally significance on kerf taper ratio. Jignesh et.al [9] reported the detailed summary of various advances in abrasive water jet machining. Ganesh Singh [10] et.al applied multi response methodology for process analysis. Leeadharan [11] highlighted the usage of Taguchi method for water jet machining. The present study mainly focuses on the influence of stand of distance, abrasive flow rate and jet pressure on surface finish and kerf angel.

II. Experimental set up

Water from Accumulator enters into mixing chamber and abrasive from abrasive chamber enters into mixing chamber. The high-pressure water with required abrasives mixed in chamber enters into nozzle through orifice disc and filter. The nozzle converts the high pressure into high velocity, directs onto the work piece. The work piece is clamped in the catcher tank. The catcher tank contains vertical plates to hold the job, and water to reduce the jet pressure to protect the catcher tank. The nozzle travel is based on the CNC program. It can cut the complex shapes very easily. In AWJM water pressure is most important parameter water pressure developed by the intensifier must not drop. Hence Accumulator is a key component in AWJM. The machine consists of six accumulators a chiller is installed to cool the water to improve the performance of the accumulator. In the AWJM, water is purified 3 times in 6 stages, mixing chamber in the is the place where mixing of the water and abrasive takes place after going through orifice, disc and finally it reaches nozzle. The diameter of these parts is very small. Purity of water increases the strength of the jet to prevent the parts wear and tear. Two materials are considered for experiments the details are shown in table 1 and 2. The two work materials considered for cutting are SS304 and AA 2024, these alloys are used in aero space industry, food processing and marine industries hence investigations on these materials attain significance. Hot cutting leads to stray heat treatment, hence to understand the performance of cold cutting on this alloy experiments are designed and carried out.

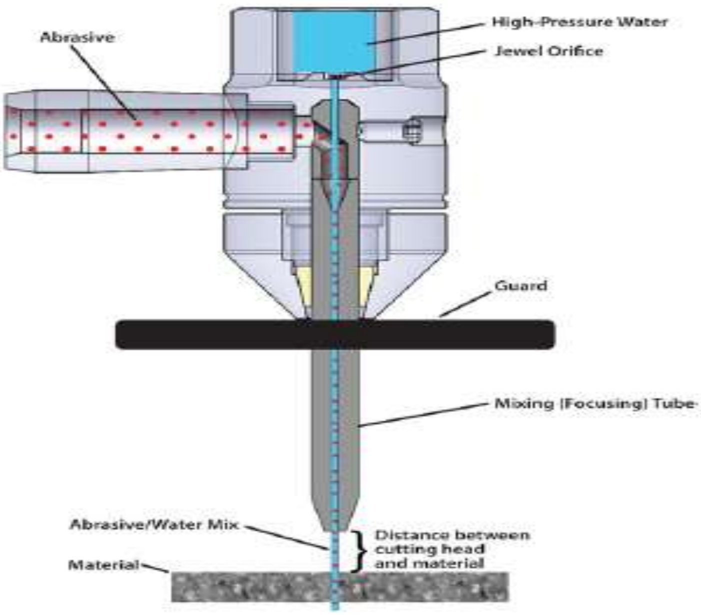

Fig1. Abrasive Water Jet Nozzle

Table-1 Chemical Composition Stainless Steel 304

Element	C	Mn	P	S	Si	Cr	Ni	N	Fe
Values	0.08 max.	2.00 max.	0.045 max.	0.03 max.	0.75 max.	18.-20	8.-10.5	0.10 max.	Balance

Table-2 Chemical Composition of Aluminum Alloy 2024

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Values	0.5	0.5	3.8-4.9	030.-0.9	1.2-1.8	0.1	0.25	0.15	Balance

III. Design of Experiments

In the present study two response parameters are surface roughness and kerf angle, the input parameters are stand of distance, water jet pressure and abrasive flow rate. Extermination is designed based on L9 Orthogonal array for the present study, each experiment is repeated twice and average value is recorded to avoid error and bias. The L9 is selected based on Process parameters and their levels. This is statistical tool proved to minimize the number of experiments and save cost.

The dimensions of the work piece considered for experimentation is 180 x 85 x 2 mm for both the work materials. The work material is placed on the spacing vertical plates in the cather tank. Clamps are used at the catcher tank brim to fix the workpiece on the vertical plates. Fixing the material in the catcher tank and straightening with corresponding to the nozzle position is known as “budding” as per L9 orthogonal array, it is necessary to change the parameters for every experiment. The stand of distance is directly visible on the desktop of the computer. Abrasive flow rate is changed according to the experiment. To study the surface roughness and Kerf properties a slot of 20 mm for SS304 and 20mm for Aluminum are considered with distance between the slots is being maintained at 15mm.

Table3 Process parameters for Stainless Steel 304 and for Aluminum Alloy 2024

Control Parameters	Level		
	1	2	3
	Minimum	Intermediate	Maximum
Stand of distance (mm)	1.5	2	2.5
Jet pressure (KPa)	30	35	40
Abrasive flow rate (kg/min) Stainless Steel 304	0.4	0.5	0.6
for Aluminum Alloy 2024	0.4	0.45	0.5

Table 4: L9 orthogonal array

Expt No	Stand of distance (mm)	Jet pressure (KPa)	Abrasive flow rate (kg/min)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table-5 Experimental results of Stainless Steel 304

S.No	Surface Roughness, Ra (µm)			Kerf Width (mm)		w_t-w_b	Kerf Angle (θ) (degree)	Geometry	
	Ra1	Ra2	Avg	Top w_t (mm)	Bottom w_b (mm)			Top (mm)	Bottom (mm)
1	2.09	1.81	1.95	0.68	0.46	0.22	0.286	10.19	9.90
2	2.05	2.14	2.09	0.801	0.499	0.302	0.393	10.30	9.86
3	1.89	1.94	1.91	0.632	0.424	0.208	0.270	10.18	9.95
4	2.15	2.40	2.27	0.717	0.478	0.239	0.311	10.21	9.84
5	2.43	2.76	2.59	0.729	0.442	0.287	0.373	10.24	9.88
6	2.18	2.06	2.12	0.643	0.437	0.206	0.268	10.18	9.97
7	2.40	2.44	2.42	0.645	0.433	0.212	0.276	10.07	9.91
8	2.26	2.60	2.43	0.655	0.431	0.224	0.291	10.16	9.81
9	2.10	2.37	2.23	0.763	0.499	0.264	0.343	10.20	9.85

Table 6 - Experimental results Material Aluminum Alloy 2024

Surface Roughness, Ra (µm)				Kerf Width (mm)			Kerf Angle(θ) (degree)	Geometry	
S.No	Ra1	Ra2	Avg Value	Top W_t mm	Bottom W_b (mm)	W_t-W_b		Top (mm)	Bottom (mm)
1	3.76	4.50	3.92	0.67	0.51	0.16	0.19	10.43	9.825
2	4.47	4.33	4.14	0.635	0.51	0.125	0.149	10.49	9.89
3	3.66	4.47	4.00	0.705	0.625	0.08	0.095	10.54	9.82
4	4.23	4.61	4.27	0.68	0.645	0.035	0.041	10.56	9.81
5	4.25	4.61	4.3	0.66	0.50	0.16	0.19	10.48	9.87
6	3.62	4.10	4.41	0.63	0.5	0.13	0.155	10.71	10.15
7	4.19	4.45	4.12	0.745	0.655	0.09	0.107	10.57	9.88
8	4.24	4.39	4.48	0.68	0.605	0.07	0.083	10.55	9.83
9	3.74	4.49	4.19	0.60	0.575	0.03	0.035	10.5	10.08

Single Response Optimization for Aluminum alloy 20241

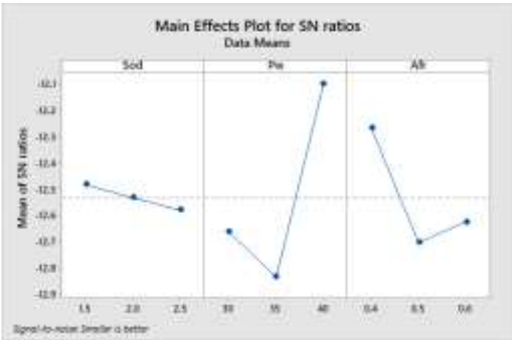

Fig2: Surface Roughness: Smaller is better

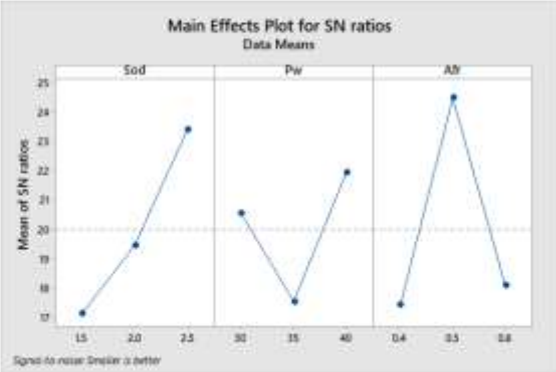

Fig 3: Kerf angel: smaller is the better

Single response optimization for Stainless Steel 304:

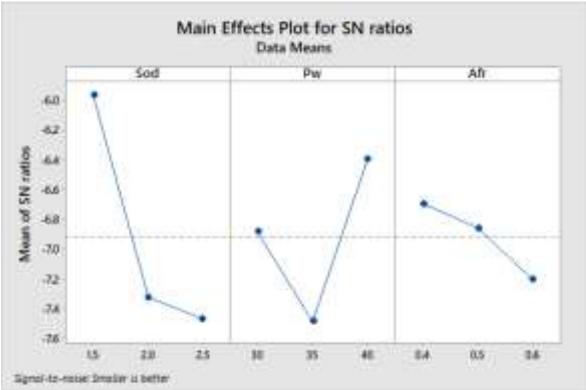

Fig 4. Surface Roughness: Smaller is better

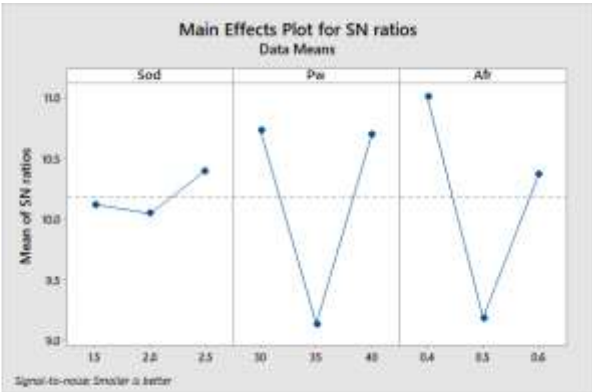

Fig 5. Kerf Angle **:** Smaller the better

3.1 Multi-response Optimization:

In Taguchi methods mainly deal with only single response optimization problems. Depen dent variable (response) is considered and the optimal levels for the parameters are determined b ased on the mean response /maximum of mean S/N ratio. However, in practice one may have mo re than one dependent variable. Taguchi method cannot be used directly to optimize the multi-re sponse problems. However, by observing the data for each response used in Taguchi design can be used for analysis by different methods developed by various researchers. In multi response pr oblems try to determine the optimal levels for the factors based on one response at a time by get ting a set of optimal levels for each response. And it will be difficult to select the best set. Usual ly, the general approach in these problems is to combine the multi responses into a single statisti c (response) and then obtain the optimal levels.

$$(MRPI)_1 = W_1R_1 + W_2R_2 + \ldots + W_9R_9$$

$MRPI_i$ = MRPI of the i^{th} trial/experiment, W_j = Weight of the j^{th} response/dependant variable R_{ij} = Observed data of i^{th} trial/experiment under j^{th} response. Using Weighted Mean Analysis for Multi-Objective optimization

for Aluminum specimen AA2024

Table -7 MRPI table for Surface Roughness for AA2024

S.no.	Surface roughness (μm)	1/Avg	Weights	$MRPI_{sr}$
1	4.13	0.2421	0.1135	0.0274
2	4.4	0.2272	0.1065	0.0242
3	4.065	0.2460	0.1153	0.0283
4	4.42	0.2262	0.1060	0.0239
5	4.43	0.2257	0.1058	0.0238
6	3.86	0.2590	0.1214	0.0314
7	4.32	0.2341	0.1085	0.0253
8	4.315	0.2317	0.1086	0.0251
9	4.115	0.2430	0.1139	0.0276

Table-8 MRPI table for Kerf Angle for AA2024

S.no.	Kerf angle	1/Kerf angle	weights	$MRPI_{kerf}$
1	0.19	5.263	0.0483	0.2542
2	0.149	6.711	0.0617	0.4140
3	0.095	10.526	0.0967	1.017
4	0.041	24.39	0.2242	5.468
5	0.19	5.263	0.0483	0.2542
6	0.15	6.66	0.0612	0.4075
7	0.107	9.345	0.0859	0.8027
8	0.083	12.04	0.1106	1.3316
9	0.035	28.57	0.2626	7.502

Table-9 summation of $MRPI_{sr}$ and $MRPI_{kerf}$ for AA2024

$MRPI_{sr}$	**$MRPI_{kerf}$**	$MRPI_0$
0.0274	0.2542	0.2816
0.0242	0.4140	0.4382
0.0283	1.017	1.045
0.0239	5.468	5.491
0.0238	0.2542	0.278
0.0314	0.4075	0.4389
0.0253	0.8027	0.828
0.0251	1.3316	1.3567
0.0276	7.502	7.529

The graph is obtained in the Minitab for MRPI sum values, which provides the optimum values for multi-response optimization.

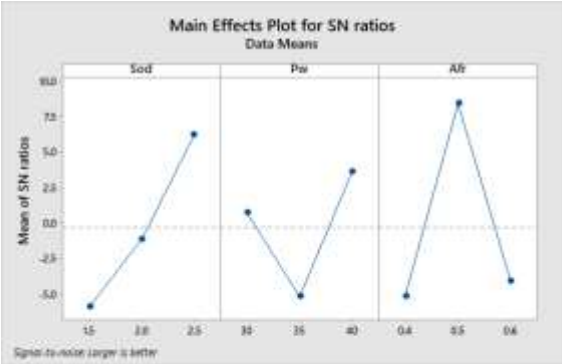

Fig 6. S/N Ratios of both Surface Roughness and Kerf angle for AA2024

The optimum values for Aluminum alloy 2024 is observed in the above graph .i.e., Stand of distance 2.5 mm, water pressure 40 KPa, Abrasive flow rate =0.5 kg/min

For the Stainless steel 304

Table-10 MRPI table for Surface Roughness for SS304

Sl.No	Surface roughness (μm)	1/ μm	weights	MRPI $_{sr}$
1	1.95	0.5128	0.1255	0.0643
2	2.09	0.4784	0.1170	0.0559
3	1.91	0.5235	0.1281	0.067
4	2.27	0.4405	0.1078	0.0474
5	2.59	0.3861	0.0944	0.0364
6	2.12	0.4716	0.1154	0.0544
7	2.42	0.4132	0.1011	0.0417
8	2.43	0.4115	0.1007	0.0415
9	2.23	0.4484	0.1097	0.0491
		Σ 1/ avg = 4.086		

Table-11 MRPI table for Kerf angle for SS304

Sl. No	Kerf angle	1/kerf angle	weights	MRPI $_{kerf}$
1	0.286	3.496	0.1193	0.4170
2	0.393	2.544	0.0868	0.2208
3	0.272	3.676	0.1254	0.4609
4	0.311	3.215	0.1097	0.3526
5	0.375	2.66	0.0908	0.2415
6	0.268	3.731	0.1273	0.4749
7	0.276	3.623	0.1236	0.4478
8	0.291	3.436	0.1172	0.4026
9	0.343	2.914	0.0994	0.2896
		Σ1/kerf angle = 29.295		

Table-12 Summation of MRPI $_{sr}$ and MRPI $_{kerf}$ for SS304

MRPI $_{sr}$	MRPI $_{kerf}$	MRPI $_{0}$
0.0643	0.4170	0.4813
0.0559	0.2208	0.2767
0.067	0.4609	0.5279
0.0474	0.3526	0.4000
0.0364	0.2415	0.2779
0.0544	0.4749	0.5293
0.0417	0.4478	0.4895
0.0415	0.4026	0.4441
0.0491	0.2896	0.3387

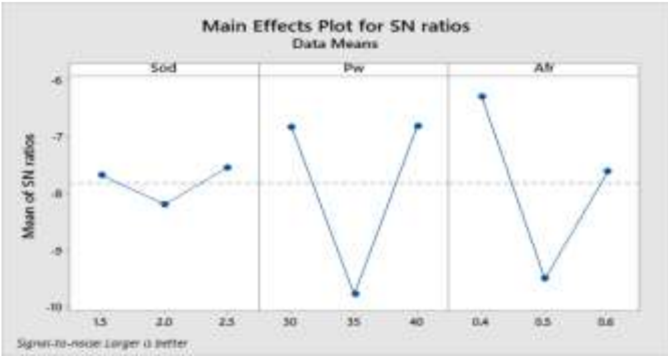

Fig7. S/N Ratios of both Surface roughness and Kerf angle for SS 304: smaller is better

3.2 Results

Optimum input parameter for single response of surface roughness for Aluminum alloy 2024 are Stand of distance 1.5 mm water pressure 40 KPa, Abrasive flow rate 0.4 kg/min. Optimum input parameter for single response of kerf angle for AA 2024 Stand of distance 2.5 mm, water pressure 40 KPa, Abrasive flow rate 0.5 kg/min. Optimum parameters for surface roughness for Stainless steel 304 from graph are Stand of distance 1.5 mm , Water Pressure 40 KPa, Abrasive flow rate 0.4 kg/min. Optimum input parameters for single response kerf angle to get optimum value for SS304 Stand of distance 2.5 mm, Water pressure 30 KPa, Abrasive flow rate 0.4 kg/min. The optimum process parameters in multi-response optimization: The optimum values for aluminum alloy 2024 material are Stand of distance 2.5 mm, Water pressure 40 KPa, Abrasive flow rate 0.5 kg/min. Similarly, optimum values for stainless steel 304 material for both Surface Roughness and kerf Angle are Stand of distance 2.5 mm, water pressure 30 KPa and abrasive flow rate 0.4 kg/min.

IV. Conclusion

In the present study three input parameters stand of distance, water pressure and abrasive flow rate are used to analyze surface roughness and Kerf angles for SS304 and AA2024 materials. The input parameters are optimized through Taguchi method of optimization by considering single response and multi-responses. Following conclusions are drawn from this work

1. For stainless steel 304 surface roughness decreases as stand of distance and Abrasive flow rate increases and Kerf angle decreases with decrease in water pressure and Abrasive flow rate.

2. For **A**luminum alloy 2024, Surface Roughness decreases with decrease in Stand of distance and kerf angle decrease with increase in Abrasive flow rate.
3. Optimum parameters from Multi-response for a) Stainless steel304 material is stand of distance= 2.5 mm, water pressure 30 KPa and flow rate 0.4 kg/min for Aluminum alloy2024 material is stand of distance = 2.5 mm, water pressure 40 KPa and flow rate 0.5 kg/min.

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