International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161
Available at http://inpressco.com/category/ijcet

Research Article

Experimental Investigation of Pocket Milling on Inconel 825 using Abrasive Water Jet Machining

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Accepted 05 Feb 2016, Available online 06 Feb 2016, **Vol.6, No.1 (Feb 2016)**

Abstract

Rectangular pocket milling is a new area where abrasive water jet machining is being introduced. The current trend abrasive water jet machining (AWJM) process is getting focused on milling applications. In this investigation experiments were carried out on Inconel 825 to check the possibility of using AWJM process for producing 3D features such as pockets of size 20mm x 10mm. A design of experiment approaching Taguchi method was taken considering the input variables such as step over (SO), traverse speed (TS), pressure (P) and abrasive flow rate (AFR) as process parameters they are varied in three levels fixing the standoff distance(SOD) as 2 mm, orifice diameter as 0.35 mm and AMS size as garnet 85# and the obtained output parameters viz., Depth Of Cut (DOC), Material Removal Rate (MRR) and Surface Roughness (Ra) are recorded in two strategies, namely Hatch strategy and Spiral strategy. Analysis of variance is carried out in order to study process parameters interaction and to calculate the F value. The results have shown that the traverse speed and step over influentially affected the output parameters DOC, MRR and Ra.

Keywords: *Abrasive water jet machining, Inconel825, Taguchi, ANOVA.*

1. Introduction

Abrasive water jet machining (AWJM) is now-a-days one of the best non conventional machining methods used for cutting difficult-to-cut materials at the best to its distinctive benefits. In Abrasive water jet machining water is pumped to a very high pressure (200-500 M Pa) using intensifier technology mixing the required Abrasive particles to water. The water jet is allowed to expel through a sapphire orifice of diameter 0.2 - 0.4 mm to form a water jet with high velocity (300-1000 ms^{-1}). (J.H. Olsen, 1980)

The advantages of AWJM are no thermal distortion on the work piece, high machining versatility to cut virtually any materials, high flexibility to cut in any direction, small cutting forces. (J.H. Olsen, 1980; Want J, 2003)

The preliminary idea of AWJ milling (Non-through cutting) in industrial application was introduced by Hashish. M in 1987. (M. Hashish, 1984). AWJ for Non-through cutting, where the depth of cutting (DOC) is controlled has been less reported. Through AWJ milling we get the opportunity to minimize the machining cost and increase the process flexibility. AWJM is influenced by large number of process parameters. The important parameters that influence the process are Abrasive flow rate (AFR) Abrasive size, pump pressures (P), and traverse speed (TS), standoff distance (SOD). (Chen, F.L., Wang, J. Lemma, E., Siores E, 2003). With the improvement in the hardware technology today a real time control of the process parameters of an Abrasive water jet for selective cavity is practically possible and not many attempts are made in this fashion. Fowler et al (Fowler, G., Shipway, P.H., Pashby, I.R, 2005; Fowler, G., Shipway, P.H., Pashby, I.R 2009; Fowler, G., Shipway, P.H., Pashby, I.R, 2005) worked for controlled depth milling (CDM) tried to characterize the milled surface with the roll of grit size, grit embedment, particle shape and hardness. The present work is carried out varying the input variables water pressure, Abrasive Flow Rate(AFR), Overlap Ratio or Step Over(SO), Traverse rate (TR) keeping the standoff distance (SOD), Abrasive mesh size (AMS) constant and to know the output parameters material removal rate (MRR), Depth of cut (DOC) and Surface roughness (Ra)

1.1 Nomenclature

AFR	Abrasive flow rate (kg/min)
DOC	Depth of cut (mm)
MRR	Material removal rate (mm^3/min)
P	Water pressure (Bar)
SO	Step over (mm)
SOD	Standoff distance (mm)
Ra	Surface roughness (µm)

*Corresponding author **M.Kanthababu** is working as Professor; **U.Goutham** as Assistant Professor; **Basawaraj S.Hasu** as Professor & HOD and **G.Chakraverti** as Professor

TS Traverse speed (mm/min)

2. Cutting Path Strategies

2.1. Hatch Strategy

Also called Direction-parallel, stair case, **Zigzag**, facing, wavering (or) sweep milling. (Hatna A, Grieve, R. J, Broomhead P, 1998) In Zigzag pocketing the cutter removes the machining area in zigzag manner following a sweeping line that is parallel to given direction.

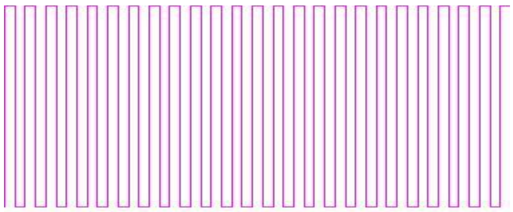


Fig. 1 Hatch strategy

2.2. Spiral Strategy

In this approach, the tool travels along a gradually evolving spiral path. The spiral starts at the pocket boundary and gradually moves towards the centre of the pocket (or) the cutter may start from the centre of the pocket and gradually moves towards the boundary of the pocket (Toh, C.K, 2004).

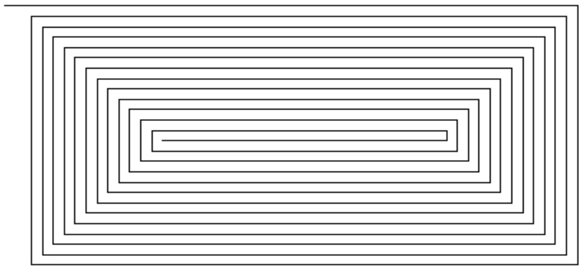


Fig. 2 Spiral Strategies

Table 1 Input & Output Parameter Values for Hatch Strategy

P Bar	SO Mm	TS mm/min	AFR kg/min	DOC Mm	MRR (mm^3/min)	Ra (µ)
1500	0.2	1000	0.22	2.53	311.2	4.3851
1500	0.3	1500	0.32	1.11	250.1	6.3741
1500	0.4	2000	0.42	0.34	117.5	7.4275
1600	0.2	1500	0.42	1.94	303.6	3.8486
1600	0.3	2000	0.22	0.79	200	6.3175
1600	0.4	1000	0.32	1.3	309.5	4.9077
1700	0.2	2000	0.32	2.01	355.7	6.211
1700	0.3	1000	0.42	2.22	397.6	4.5448
1700	0.4	1500	0.22	1.13	118.2	7.931

Table 2 Input & Output Parameter Values for Spiral Strategy

P Bar	SO Mm	TS mm/min	AFR kg/ min	DOC Mm	MRR (mm^3/min	Ra (µ)
1500	0.2	1000	0.22	2	315.3	9.0955
1500	0.3	1500	0.32	0.91	277.2	6.1426
1500	0.4	2000	0.42	0.34	14.5	3.8462
1600	0.2	1500	0.42	1.65	334.8	6.3105
1600	0.3	2000	0.22	0.75	261	6.0236
1600	0.4	1000	0.32	1.17	360	5.7009
1700	0.2	2000	0.32	1.34	312.7	6.859
1700	0.3	1000	0.42	1.9	448.2	8.4401
1700	0.4	1500	0.22	0.76	298	5.8657

Table 3 Machine specifications

High pressure	413 MPa
Table size	1168 x 787 mm.
X-Y cutting travel	737 x 660 mm
Z-axis travel	203 mm.
Accuracy and repeatability	± 0.025 mm.
The mixing tube diameter	0.76 mm
Orifice diameter	0.35 mm

3. Experimental Setup

The experiments were conducted on Inconel 825 super alloy of 6mm plate with AWJM (OMAX 2626) provided at the manufacturing laboratory Anna University, Chennai. This work aims for pocket milling of size 20mm x 10mm. The specimen is fixed to the machine with suitable fixtures and gauges with fixed standoff distance (SOD) as 2mm. The values of the input parameters namely Pressure (P), Step over (SO), Traverse speed (TS) and abrasive flow rate (AFR) in three levels for two strategies. The input variables and the recorded output readings they are namely depth of cut (DOC), Material removal rate (MRR), surface roughness (Ra) are shown in table-1. The input and output parameters of Spiral Strategy are noted in the same manner as in the Hatch Strategy. These details are shown in table-2. The range of process parameters i.e. input variables are varied at three levels with fixing the abrasive mesh size (AMS) at 85#. Based on these process parameters using Taguchi DOE a total number of experiments conducted for each strategy. Those strategies are Hatch strategy and Spiral strategy. All the nine experiments in each strategy were conducted at 90^0 impingement angle and varying the traverse speed in three steps. The orifice and mixing tube with diameters of 0.35mm and 0.76mm respectively were kept same throughout the experiment. The specifications of the machine were shown in table-3.

Fig. 3 Photograph of AWJ machining centre at Anna University

Table 4 Mechanical properties of Inconel 825

Density	=8.14 gr/cm³
Hardness	=83-85 HRB
Modulus of rigidity(G)	=75.9 N/mm²
Melting point	=1400 C
Coefficient of expansion	=14.0 m/m/C
Modulus of elasticity	=196 KN/mm²

Table 5 Chemical composition of Inconel 825

Ni = 38-46%	Fe = 22%	Cr = 19.5-22.5%
Mo = 2.5-3.5 %	Cu = 1.5-3%	Ti = 0-1.2%
Mn = 1%	Si = 0.5%	Al = 0.2%
C = 0.05%	S = 0.03%	

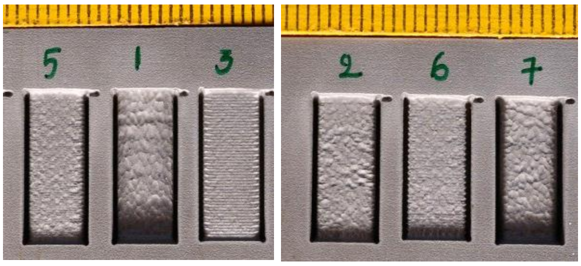


Fig. 4 Milled Part of Hatch Strategy

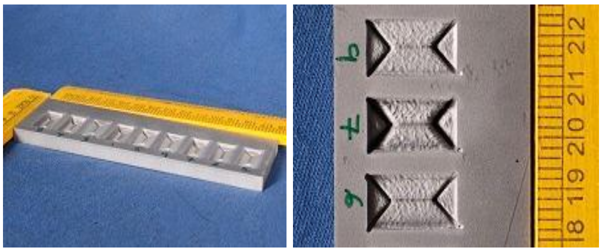


Fig. 5 Milled part of Spiral Strategy

4. Results and Discussions

Investigation is carried out subjecting Inconel 825 super alloy as specimen work piece to produce pockets by milling in two strategies, those are Hatch strategy and spiral strategy. It is investigated that how the process parameters determines the output parameters. After conducting the experiments with different setting of input parameters like step over (SO), Transverse speed (TS) Pressure (P) and Abrasive Flow Rate (AFR). The output parameters Depth of Cut (DOC) , Material Removal Rate (MRR) and surface Roughness (R_a) are recorded and according to the produced values the graphs are plotted. The analysis of results obtained has been performed according to the standard procedure recommended by Taguchi. The analysis of the response data is done by the software MINITAB 17.

4.1. Hatch Strategy

4.1.1. Effect of input parameters on D.O.C

Table 6 Response Table for Signal to Noise Ratios Larger is better

Level	P Bar	SO mm	TS mm/min	AFR kg/ min
1	-0.1339	6.6275	5.7561	2.3588
2	1.9958	1.9287	2.5747	3.0831
3	4.6842	-2.0100	-1.7847	1.1042
Delta	4.8180	8.6375	7.5408	1.9789
Rank	3	1	2	4

Table 7 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	1.3267	2.16	2.0167	1.4833
2	1.3433	1.3733	1.3933	1.4733
3	1.7867	0.9233	1.0467	1.5
Delta	0.46	1.2367	0.97	0.0267
Rank	3	1	2	4

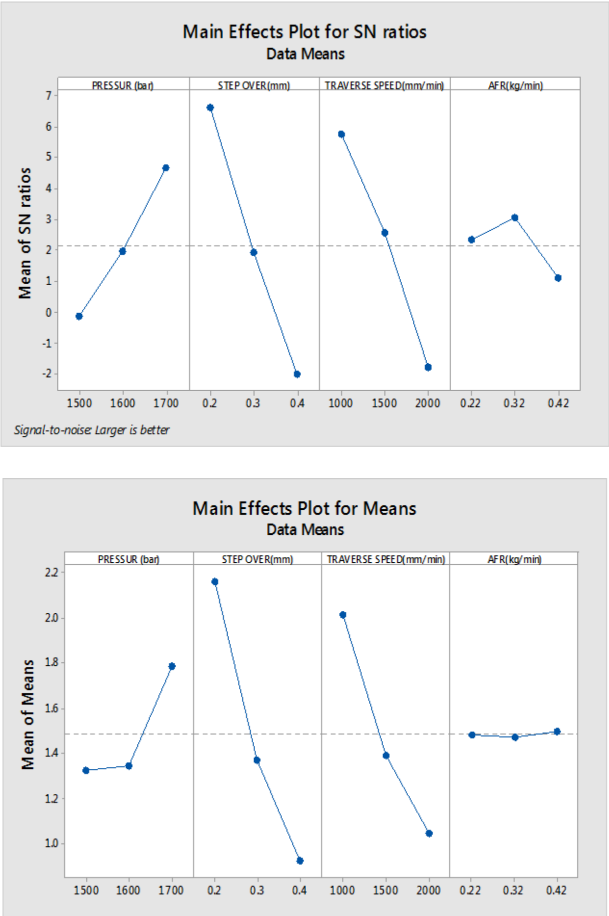


Fig. 6 Response Graphs for D.O.C

From the response table no6&7 and response graph fig no 6 the step over is highly influenced the depth of cut, secondly the traverse speed influenced the depth of cut, pressure affected DOC placed in third place and AFR at last place it's influence is almost nil and hence it may be neglected.

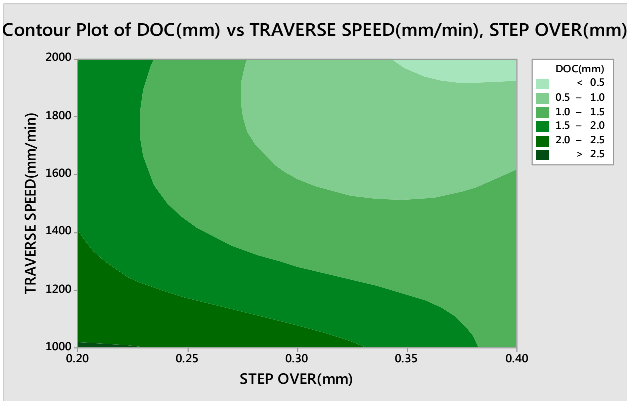


Fig. 7 Doc Vs Traverse Speed (mm/min), Step over (mm)

By the graph fig 7 it can be depicted that at the dark green zone the DOC is at maximum i.e., more than 2.5mm and the light green zone it is minimum i.e., less than 0.5mm.

4.1.2. Effect of input Parameters on M.R.R

Table 8 Response Table for Signal to Noise Ratios Larger is better

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	46.41	50.18	50.55	45.78
2	48.49	48.66	46.35	49.6
3	48.15	44.22	46.15	47.68
Delta	2.09	5.95	4.41	3.82
Rank	4	1	2	3

Table 9 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	226.3	323.5	339.4	209.8
2	271	282.6	224	305.1
3	290.5	181.7	224.4	272.9
Delta	64.2	141.8	115.5	95.3
Rank	4	1	2	3

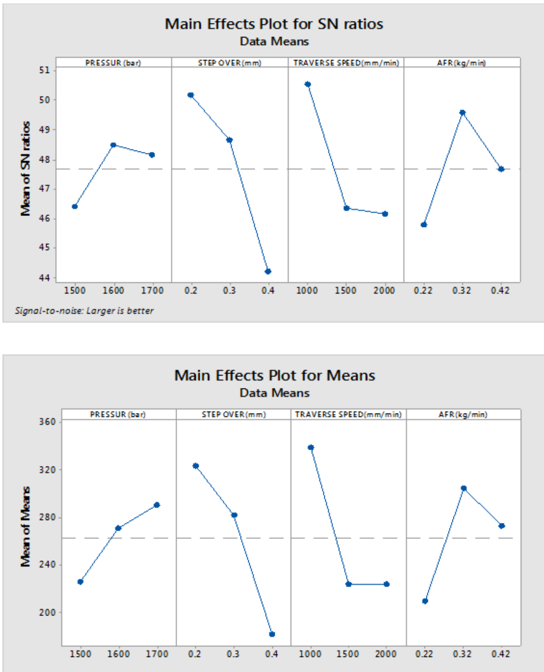


Fig. 8 Response Graphs for MRR

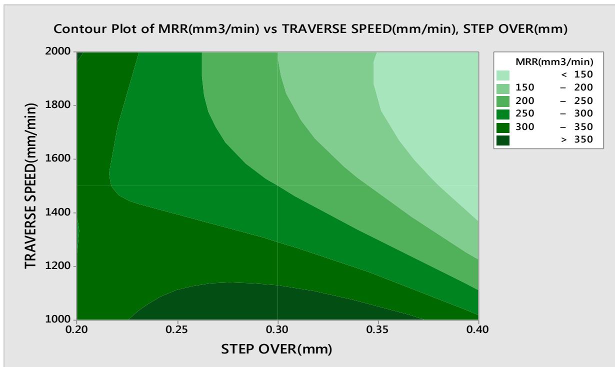


Fig. 9 MRR Vs Traverse Speed (mm/min), Step over (mm)

From the response table no 8&9 and response graph Fig 8 Step over and Transverse speed significantly influenced the material Removal rate respectively, AFR takes third place and pressure is in last place and is negligible to influence the MRR and can be neglected.

As shown in the graph fig 9 the dark green zone indicates the maximum MRR i.e., more than 350 mm^3/min and light green zone indicates the minimum MRR i.e., less than 150 mm^3/min.

4.1.3. Effect of input Parameters on R_a

Table 10 Response Table for Signal to Noise Ratios Smaller is better

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	-15.45	-13.47	-13.27	-15.61
2	-13.84	-15.08	-15.26	-15.26
3	-15.67	-16.41	-16.43	-14.09
Delta	1.82	2.94	3.16	1.52
Rank	3	2	1	4

Table 11 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	6.062	4.815	4.613	6.211
2	5.025	5.745	6.051	5.831
3	6.229	6.755	6.652	5.274
Delta	1.204	1.941	2.039	0.938
Rank	3	2	1	4

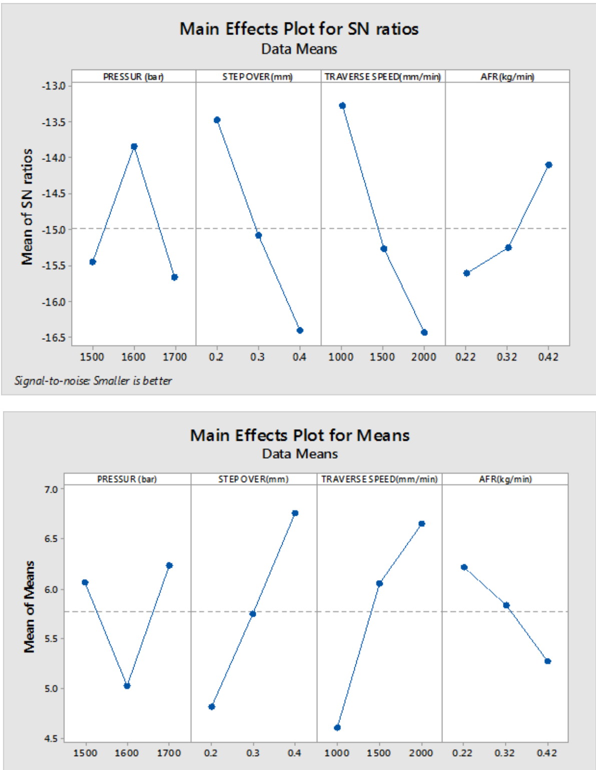


Fig. 10 Response Graphs for Ra

From the response table10&11 and response graph fig 10 Transverse speed in first place and step over in second place influenced significantly the R_a , and pressure took third place and found the influence of AFR is less and can be neglected.

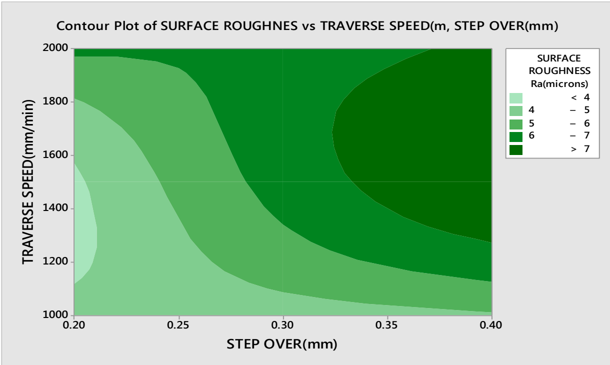


Fig. 11 Surface Roughness Ra Vs Traverse Speed (mm/min), Step over (mm)

From the graph fig 11 the light green area resembles the minimum R_a value i.e., less than 4 microns and dark green area has the maximum R_a value i.e., more than 7 microns.

4.2. Spiral Strategy

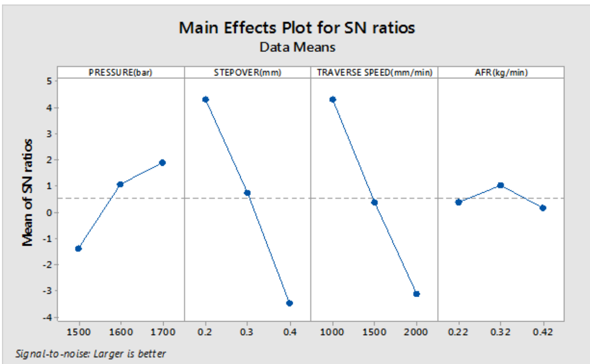
4.2.1. Effect of Input Parameters on D.O.C

Table 12 Response Table for Signal to Noise Ratios Larger Is Better

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	-1.3897	4.3041	4.3198	0.3794
2	1.0715	0.7524	0.3823	1.0289
3	1.9111	-3.4635	-3.109	0.1848
Delta	3.3008	7.7676	7.4288	0.8441
Rank	3	1	2	4

Table 13 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	1.0833	1.6633	1.69	1.17
2	1.19	1.1867	1.1067	1.14
3	1.3333	0.7567	0.81	1.2967
Delta	0.25	0.9067	0.88	0.1567
Rank	3	1	2	4



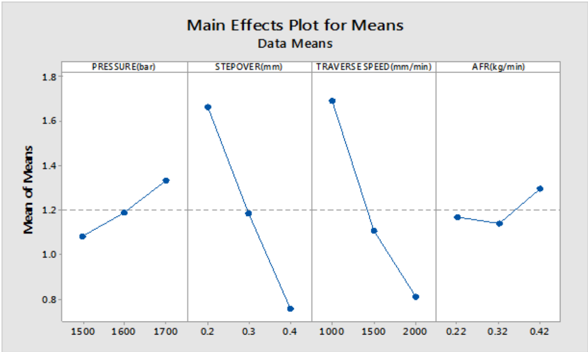


Fig. 12 Response Graphs for DOC

As shown in the tables 12&13 and graph Fig 12 the influence of step over and Transverse speed can be placed in first and second places, the pressure (P) can be laid in the third place and AFR influenced very less on DOC and can be neglected.

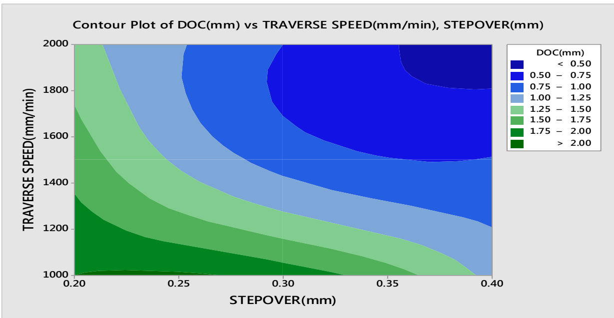


Fig. 13 Doc Vs Traverse Speed (mm/min), Step over (mm)

By graph fig 13 it can be depicted that the DOC is maximum i.e., more than 2 mm at the dark green zone, and minimum i.e., less than 0.5mm at the dark blue zone.

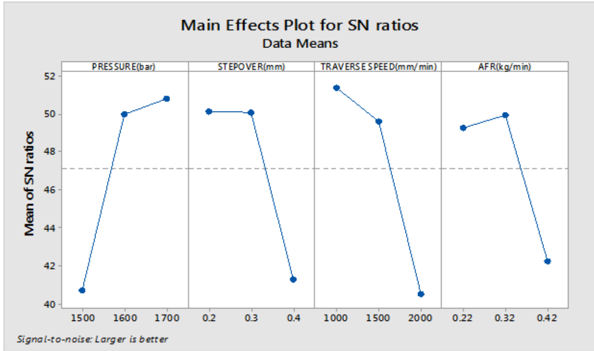
4.2.2. Effect of input Parameters on MRR

Table 14 Response Table for Signal to Noise Ratios Larger is better

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	40.69	50.12	51.38	49.26
2	49.98	50.07	49.61	49.96
3	50.81	41.28	40.49	42.25
Delta	10.12	8.85	10.89	7.71
Rank	2	3	1	4

Table 15 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	202.3	320.9	374.5	291.4
2	318.6	328.8	303.3	316.6
3	353	224.2	196.1	265.8
Delta	150.6	104.6	178.4	50.8
Rank	2	3	1	4



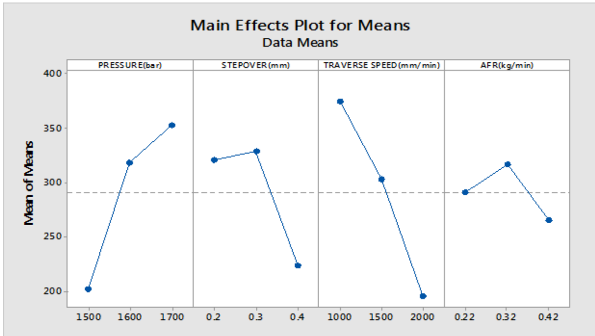


Fig. 14 Response Graphs for MRR

As shown in the table13&14 and graph fig 14 the transverse speed highly influenced the MRR, the pressure took second place to influence, step over in third place and AFR took last place and less influenced so, can be neglected

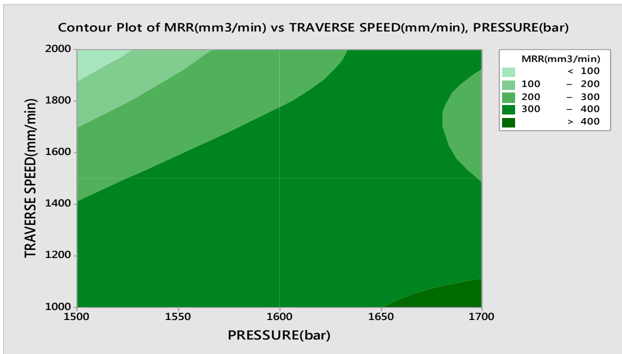


Fig. 15 MRR VS Traverse Speed (mm/min), Pressure (Bar)

By the graph fig 15 it is found that the MRR is maximum i.e., more than 400 mm^3/min At dark green zone and minimum i.e., less than 100 mm^3/min at light green zone.

4.2.3. Effect of Input parameters on R_a

Table 16 Response Table for Signal to Noise Ratios Smaller is better

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	-15.55	-17.3	-17.61	-16.71
2	-15.57	-16.63	-15.71	-15.87
3	-16.87	-14.06	-14.67	-15.41
Delta	1.32	3.24	2.93	1.3
Rank	3	1	2	4

Table 17 Response Table for Means

Level	P Bar	SO mm	TS mm/min	AFR kg/min
1	6.36	7.422	7.745	6.995
2	6.012	6.869	6.106	6.234
3	7.055	5.138	5.576	6.199
Delta	1.043	2.284	2.169	0.796
Rank	3	1	2	4

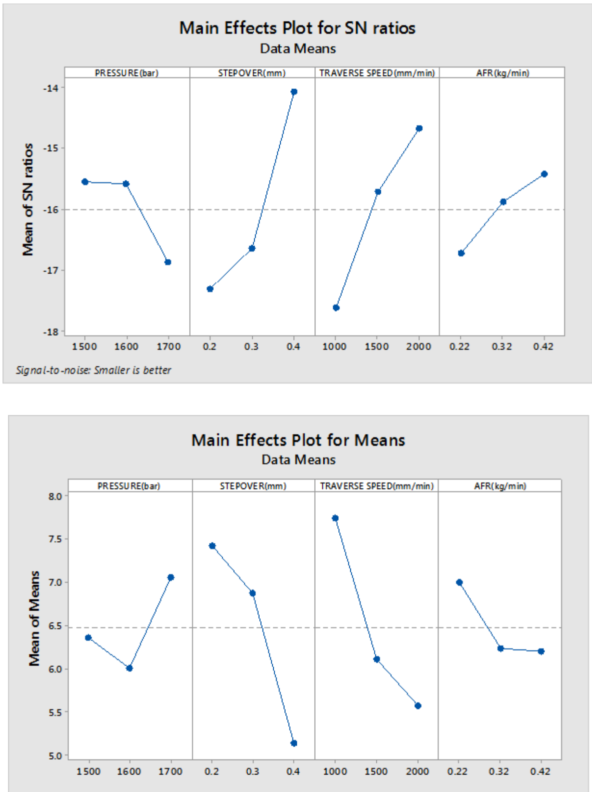


Fig. 16 Response Graphs for Ra

As shown in the table 15&16 and from graph fig 16 step over and Transverse speed influenced significantly on R_a the pressure and AFR less influenced, AFR is neglected.

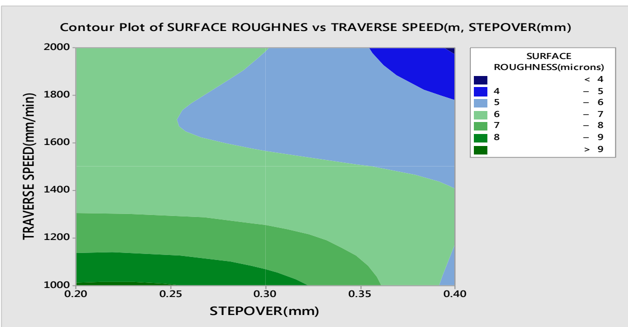


Fig. 17 Surface Roughness Ra Vs Traverse Speed (mm/min), Step over (mm)

The graph fig 17 depicts that the R_a value is low i.e., less than 4 microns at the dark blue region and high i.e., more than 9 microns at the dark green region.

4.3. Statistical analysis of the significance of process parameters

As the process parameters significantly influencing the output parameters should be identified the analysis of variance (ANOVA) is carried in the software MINITAB 17 and the correspondent tables are shown below for the two strategies.

4.3.1. Hatch Strategy

4.3.1.1. ANOVA for depth of cut (DOC)

Table 18 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
P(bar)	2	0.40842	0.20421	375.08	0.003
SO(mm)	2	2.35069	1.17534	2158.8	0
TS(mm/min)	2	1.44962	0.72481	1331.29	0.001
Error	2	0.00109	0.00054		
Total	8	4.20982			

Table 19 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0233333	99.97%	99.90%	99.48%

4.3.1.2. ANOVA for Material Removal Rate (MRR)

Table 20 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
SO(mm)	2	31941	15970	4.91	0.169
TS(mm/min)	2	26565	13283	4.08	0.197
AFR(kg/min)	2	14101	7050	2.17	0.316
Error	2	6509	3254		
Total	8	79116			

Table 21 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
57.0479	91.77%	67.09%	0.00%

4.3.1.3. ANOVA for Surface Roughness (Ra)

Table 22 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
SO(mm)	2	5.651	2.8257	4.24	0.191
TS(mm/min)	2	6.590	3.2951	4.94	0.168
P (bar)	2	2.555	1.2774	1.91	0.343
Error	2	1.334	0.6671		
Total	8	16.131			

Table 23 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.816767	91.73%	66.91%	0.00%

4.3.2. Spiral Strategy

4.3.2.1. ANOVA for depth of cut (DOC)

Table 24 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P- Value
P(bar)	2	0.09442	0.04721	2.28	0.305
SO(mm)	2	1.23416	0.61708	29.75	0.033
TS(mm/min)	2	1.20269	0.60134	28.99	0.033
Error	2	0.04149	0.02074		
Total	8	2.57276			

Table 25 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.144029	98.39%	93.55%	67.34%

4.3.2.2. ANOVA for Material Removal Rate (MRR)

Table 26 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
P(bar)	2	37389	18695	9.66	0.094
SO(mm)	2	20374	10187	5.26	0.160
TS(mm/ min)	2	48409	24205	12.51	0.074
Error	2	3871	1936		
Total	8	110044			

Table 27 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
43.9945	96.48%	85.93%	28.77%

4.3.2.3. ANOVA for Surface Roughness (Ra)

Table 28 Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
P(bar)	2	1.692	0.8458	1.39	0.418
SO(mm)	2	8.52	4.2598	7.02	0.125
TS(mm/min)	2	7.674	3.8368	6.32	0.137
Error	2	1.214	0.6068		
Total	8	19.098			

Table 29 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.778981	93.65%	74.58%	0.00%

Conclusions

- As per the results obtained it can be concluded that the step over and traverse speed are the most influential parameters on the output parameters
- The results obtained in spiral strategy are better than the results obtained in Hatch strategy
- It was shown that water jets are versatile, non-traditional machining now-a-days used in many industrial operations. AWJM found its way into a variety of applications such as rock, wood, composites, glass etc.
- Most of the research on optimisation work has been carried out on process parameters for improvement of a single quality characteristic such as DOC, R_a and MRR. There is no any research paper found based on the optimisation for the power consumption, dimension accuracy and multi objective optimisation of AWJM process.

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