Abrasive Water Jet Drilling of Titanium and Analysis of Hole Profile

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Abstract: Ti6Al4V is an alpha-beta Titanium alloy with high specific strength and excellent corrosion resistance. These cannot be machined using traditional machining methods because of their poor machinability and low thermal conductivity. This work is focused on the analysis of profile of the holes drilled in Ti6Al4V by abrasive water jet drilling to understand the effect of cutting parameters such as abrasive flow rate, water jet pressure and drilling time. ANOVA was carried out to determine the most influential parameters. It was found that abrasive flow rate, water jet pressure, drilling time are statistically significant and their interaction effects, that is, abrasive flow rate & water jet pressure, abrasive flow rate & drilling time and water jet pressure & drilling time were not statistically significant in variation of entry hole diameter and abrasive flow rate, water jet pressure, drilling time and the interaction effects, that is, abrasive flow rate & water jet pressure, abrasive flow rate & drilling time and water jet pressure & drilling time were found to be statistically significant in variation of hole depth.

Keywords: Abrasive Water Jet Drilling, Titanium Alloy, Cylindricity, ANOVA

1. Introduction:

Titanium alloys have significant applications in aerospace, power generation and biomedical industries. It has excellent strength-to-weight ratio, high fracture resistance characteristics and exceptional corrosion resistance. Ti-6Al4V is the most commonly used titanium alloy and this alpha– beta alloy is regarded as the workhorse of the titanium industry. However, titanium alloys are difficult to machine by traditional mechanical methods because of their poor machinability. Nontraditional machining methods such as abrasive waterjet (AWJ) machining have been applied to overcome these problems [1]. Abrasive waterjet (AWJ) machining is a non-traditional machining process that employs high-pressure water for producing high velocity stream, entrained with abrasive particles for cutting a wide variety of materials ranging from soft to hard materials. It is a versatile process since AWJs can be employed for many manufacturing applications such as cutting, milling, cleaning and surface treatment. AWJ cutting offers certain unique benefits such as negligible heat affected zone, high degree of maneuverability in cutting process and less machining force exertion. However, it is a complex process since the mechanism of material removal depends on the level of various process parameters and is explained by multiple phenomena and waviness observed in the deformation zone is the major drawback. AWJ cutting process parameters can be categorized into hydraulic, abrasive, mixing and cutting parameters [2]. J. John et al. explored the machinability of AWJ of 6063-T6-Aluminium alloy with abrasive flow rate, orifice size, focusing tube size, water jet pressure, traverse rate as input parameters and depth of cut, kerf width & surface roughness as output parameters based on Taguchi method of design of experiments. ANOVA was used to analyze the performance of AWJs in cutting and build empirical models and was conformed experimentally [1]. Weiyi Li et al. studied the AWJ machining of AISI 4340 Steel with the help of FE model and its conformity with the experimental data [3]. Ulas Caydas et al. investigated the machinability of 7075 Aluminium alloy by AWJ with Traverse Speed, Water Jet Pressure, Standoff Distance, Abrasive Grit Size, Abrasive Flow Rate as input parameters and surface roughness as output parameters. The design of experiments was based on Taguchi's method. Analysis of Variance was done to determine the significant factors and SEM investigations were also done [4]. Several other research works was based on AWJ machining of materials such as Macor (Machinable Glass Ceramic) [5], CFRP/Ti6Al4V stacks [6,7]. ANOVA and regression analysis were extensively used by researchers in determining the relationship between the input parameters and the output parameters. From the literature review, it can be observed that work was carried out in the field of abrasive water jet machining of different titanium alloys and other metals with different cutting parameters. But, limited work has been carried in the field of non-traditional drilling of Ti6Al4V. Hole drilling of Ti6Al4V is an important and challenging task for the manufacturing industry. In this work, drilling of holes with abrasive flow rate, water jet pressure, drilling time as the input parameters was carried out. The measured responses are entry hole diameter, hole depth, cylindricity. SEM images of the drilled profile were also studied in this work. Analysis of variance of the output parameters is used to identify the pattern in which process parameters affects the performance of the process and determine the significant parameters.

2. Materials and Methodology:

2.1 Materials used:

The material used in this work is Ti6Al4V which is a Titatnium alloy. The chemical composition of the alloy is given in Table 1.

Table 1 Chemical Composition of Ti6Al4V[2]

Element	V	Al	Sn	Zr	Mo	C	Si	Cr	Ni	Fe	Cu	Nb	Ti
Weight %	4.22	5.48	0.06	0.002	0.005	0.36	0.02	0.009	0.001	0.112	0.02	0.03	90

2.2 Experimental Procedure:

The experimentation was carried out using the OMAX Corporation (MAXIEM 1515) AWJ Machine with 5 axes machining up to 59^0 taper and 8000 mm/min traverse speed. Preliminary experiments were carried out to design the experiments and assess the values and levels of the process parameters. A complete factorial design (3^3) based on Taguchi Method was implemented to study the effects of Abrasive Flow Rate (AFR), Water Jet Pressure (WJP), Drilling Time (DT) on the entry hole diameter, hole depth, cylindricity of the holes drilled with the help of AWJM. The process parameters for AWJ drilling is as shown in Table 2 and the setup of the AWJ of Titanium alloy is as shown in figure 1. The other parameters such as stand-off distance, abrasive mesh size and material, orifice diameter, impact angle were kept constant.

Table 2 Process parameters for Abrasive Water Jet Drilling

Factors	Level 1	Level 2	Level 3
Water Pressure (psi)	15000	22500	30000
Abrasive Flow Rate (g/min)	200	300	400
Drilling Time (s)	80	140	200
Standoff Distance (mm)	3		
Abrasive Mesh size	80		
Orifice Diameter (mm)	0.25		
Focusing nozzle diameter (mm)	1.07 and material is Tungsten Carbide		
Abrasive Material	Garnet		
Impact Angle	90^{O}		

Figure 1 Setup of Abrasive Water Jet Drilling of Ti6Al4V

3. Results and Discussion:

The quality of the holes drilled using Abrasive Water Jet Drilling Process were evaluated with the help of Profile Projector, Coordinate Measuring Machine, Vernier Height Gauge and Scanning Electron Microscope.

3.1 Measurement of Entry Hole Diameter

To measure the entry hole diameter a Nikon V24B profile projector which has a magnification accuracy of 0.05% for contour illuminations and 0.075% for surface illuminations, effective screen diameter of 600 mm was used. The entry hole diameter was measured using the profile projector and was tabulated and is as shown in Table 3. ANOVA was performed to determine the significant factors among AFR, WJP, DT and a regression equation was modelled to predict the effect of process parameters on entry hole diameter. ANOVA was done with the help of Minitab software. The ANOVA table for entry hole diameter is as shown in Table 4. The observations from the ANOVA table are as follows:

The F-ratios presented in table 4 for Abrasive Flow Rate, Water Jet Pressure and Drilling Time are more than F-ratios given in the statistical tables. Further, the P-values obtained from the ANOVA analysis for these parameters are less than 0.05. Therefore, it can be concluded that these parameters are most statistically significant parameters influencing the entry hole diameter. Further, the interaction effects are not significant as their P-values are greater than 0.05. The contribution of abrasive flow rate, water jet pressure and drilling time on entry hole diameter was found to be 21.35 %, 12.55 %, 58.63 % respectively. The total contribution of abrasive flow rate, waterjet pressure and drilling time amounts to around 92.5 % on entry hole diameter. Percentage contribution of interactions, that is, abrasive flow rate and waterjet pressure, abrasive flow rate and drilling time, waterjet pressure and drilling time adds up to around 3.6%, but the interaction effects are not significant and hence can be neglected.

The percentage error column around 3.8 % indicates the contribution of other parameters such as dimensions of orifice and focusing nozzle, variation in size of abrasives used in the waterjet and etc. on the entry hole diameter. The interaction of abrasive flow rate, waterjet pressure and drilling time is not considered in ANOVA. The main effect plots for entry hole diameter is as shown in figure 2. The following inferences can be made from the graph:

The entry hole diameter was found to increase with increase in abrasive flow rate. As the abrasive flow rate increases there is an increase in scattering of abrasive particles that leads to increase in entry hole diameter. It was observed that entry hole diameter increases with increase in water jet pressure and drilling time. When there is a rise in in water jet pressure and drilling time, the divergence of the abrasive water jet increases and as a result there is an increase in entry hole diameter.

Table 3 Values of Entry Hole Diameter, Hole Depth, Cylindricity Deviation

Sl. No.	Abrasive Flow Rate (g/min)	Water Pressure (psi)	Drilling Time (s)	Entry Hole Diameter (mm)	Hole Depth (mm)	Cylindricity Deviation (mm)
1	200	15000	80	1.909	14.16	0.0181
2	200	15000	140	2.024	21.20	0.0428
3	200	15000	200	2.136	23.16	0.0198
4	200	22500	80	1.957	16.58	0.0050
5	200	22500	140	2.078	23.06	0.0453
6	200	22500	200	2.184	30.08	0.0319
7	200	30000	80	2.044	19.32	0.0303
8	200	30000	140	2.124	26.76	0.0153
9	200	30000	200	2.282	34.04	0.0587
10	300	15000	80	1.942	15.02	0.0180
11	300	15000	140	2.125	22.16	0.0425
12	300	15000	200	2.191	26.84	0.0166
13	300	22500	80	2.035	18.74	0.0208
14	300	22500	140	2.110	25.90	0.0368
15	300	22500	200	2.251	33.74	0.0462
16	300	30000	80	2.090	21.36	0.0216
17	300	30000	140	2.194	31.00	0.0343
18	300	30000	200	2.393	38.50	0.0359
19	400	15000	80	2.108	16.58	0.0283
20	400	15000	140	2.191	23.38	0.0470
21	400	15000	200	2.253	27.56	0.0107
22	400	22500	80	2.068	20.18	0.0200
23	400	22500	140	2.263	29.12	0.0270
24	400	22500	200	2.404	36.38	0.0201
25	400	30000	80	2.115	23.80	0.0454
26	400	30000	140	2.313	33.38	0.0246
27	400	30000	200	2.315	43.26	0.0380

Table 4 ANOVA Table for entry hole diameter

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Abrasive Flow Rate	2	0.092945	21.35%	0.092945	0.046472	22.01	0.001
Water Jet Pressure	2	0.054605	12.55%	0.054605	0.027302	12.93	0.003
Drilling Time	2	0.255177	58.63%	0.255177	0.127588	60.43	0.000
Abrasive Flow Rate * Water Jet Pressure	4	0.008131	1.87%	0.008131	0.002033	0.96	0.478
Abrasive Flow Rate * Drilling Time	4	0.004619	1.06%	0.004619	0.001155	0.55	0.707
Water Jet Pressure * Drilling Time	4	0.002885	0.66%	0.002885	0.000721	0.34	0.843
Error	8	0.016891	3.88%	0.016891	0.002111		
Total	26	0.043525	100.00%				

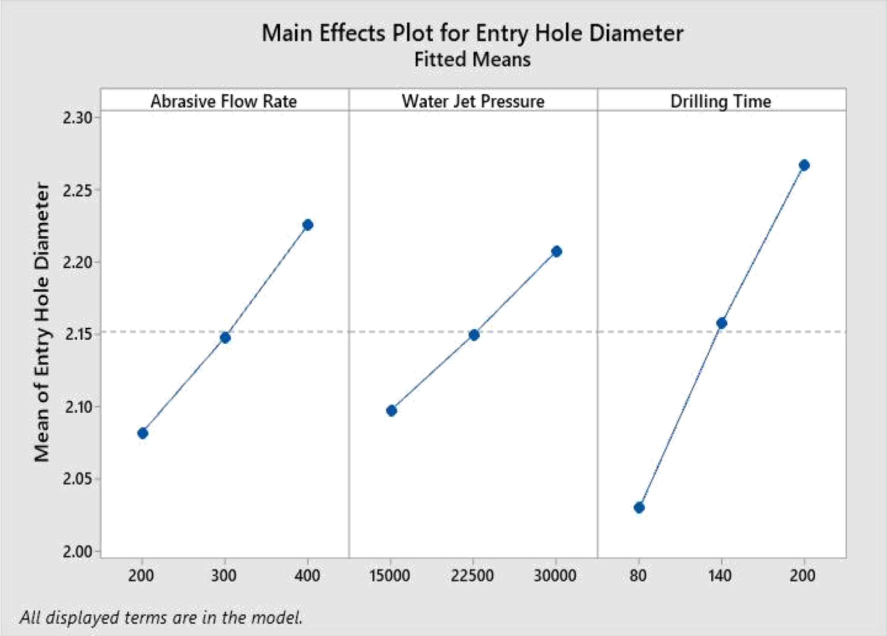


Figure 2 Main Effects Plot for Entry Hole Diameter

The regression equation is an algebraic equation which determines the relationship between the input parameters and the output parameters. For entry hole diameter, it was found that mass flow rate, water jet pressure and drilling time was found to be statistically significant and was to be included in the regression equation. Whereas, the interaction between the input parameters were not significant and hence they were excluded. The regression equation along with the coefficients was obtained with the help of Minitab software. The regression equation for entry hole diameter is as follows:

Entry Hole Diameter = $a + b(\dot{m}) + c(P) + d(t) + \varepsilon$ (1) where,

Constant, $a = 1.52$
Regression Coefficients, $b = 0.000718$
$c = 0.000007$
$d = 0.001982$

ε = Error
$\dot{m}$ is Abrasive Flow Rate, P is Water Jet Pressure, t is Drilling Time

The values of entry hole diameter which was measured with the help of profile projector was compared with the values calculated with the help of the regression equation. The comparison between the two values and the error is calculated and is as shown in the table 5. As the analysis was done at 95 % confidence level and there were other factors affecting the entry hole diameter such as dimensions of orifice and focusing nozzle, variation in size of abrasives used in the waterjet, the errors obtained is in the acceptable limit. Hence, the obtained regression equation is deemed as fit and can be used to predict the values of entry hole diameter for different values of Abrasive Flow Rate, Water Jet Pressure, Drilling Time other than the experimental values.

Table 5 Error Analysis of regression equation for Entry Hole Diameter

Hole No.	Experimental Value	Calculated Value	Percentage Error
1	1.909	1.927	0.94
2	2.024	2.046	1.08
3	2.136	2.165	1.34
4	1.957	1.980	1.14
5	2.078	2.099	0.98
6	2.184	2.218	1.51
7	2.044	2.032	0.58
8	2.124	2.151	1.26
9	2.282	2.270	0.53
10	1.942	1.999	2.85
11	2.125	2.118	0.34
12	2.191	2.237	2.05
13	2.035	2.051	0.80
14	2.110	2.170	2.78
15	2.251	2.289	1.67
16	2.090	2.104	0.66
17	2.194	2.223	1.30
18	2.393	2.342	2.19
19	2.108	2.071	1.80
20	2.191	2.190	0.06
21	2.253	2.309	2.41
22	2.068	2.123	2.60
23	2.263	2.242	0.93
24	2.404	2.361	1.82
25	2.115	2.176	2.79
26	2.313	2.295	0.80
27	2.315	2.414	4.09

3.2 Measurement of Cylindricity

The cylindricity is a method of measurement which determines the closeness of a drilled hole to a true cylinder. It was measured using a Coordinate Measuring Machine Contura G2 supplied by ZEISS 3D CNC. The cylindricity was measured with the positive tolerance kept constant at 0.1 mm. The deviation was measured using CMM and was tabulated as shown in Table 3. The graphical representation of cylindricity deviation is as shown in Figure 3.

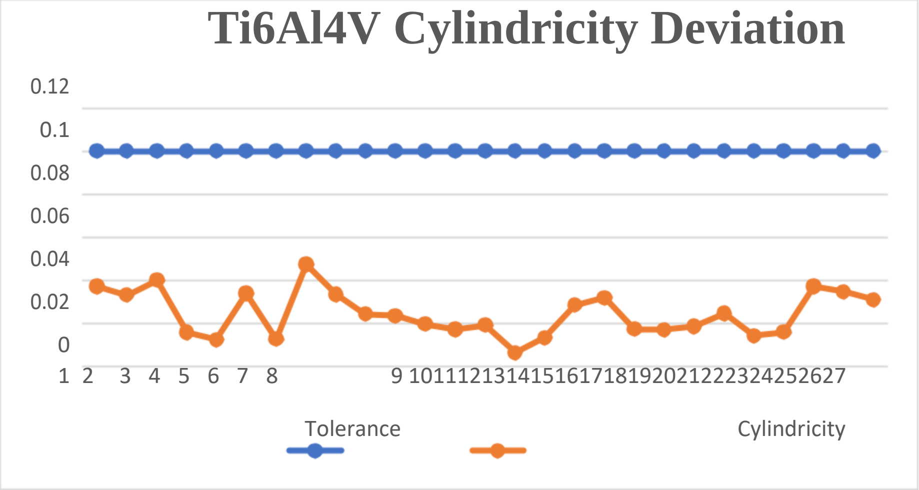


Figure 3 Cylindricity Deviation for Ti6Al4V

It was found that deviations measured for each hole was within the tolerance limit of 0.1 mm and with the help the graph it can be seen that the drilled holes behave as true cylinders.

3.3 Measurement of Hole Depth

To measure the hole depth, a vernier height gauge with a least count of 0.02 mm was used. The hole depth was tabulated and is as shown in Table 3. The front view of the workpiece after drilling 27 holes is as shown in figure 4. The workpiece was cut across center of each row of holes so as to view the hole profile of the drilled holes. The cross-sectional view of the workpiece is as shown in figure 4. The hole depth was measured using these cross-sectional cuts.

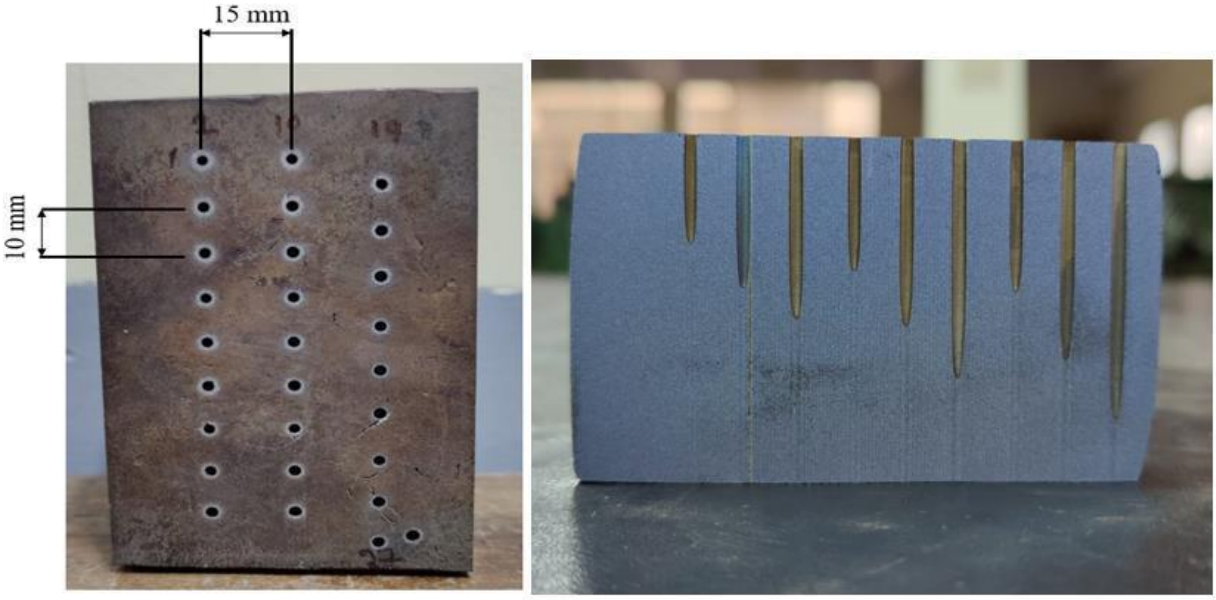


Figure 4 Front View and Cross Sectional View of the workpiece

In AWJ drilling, the hole produced is substantially wider than the jet stream, due mostly to the additional wall erosion resulting from the forceful upward ejection of the jet out of the blind cavity. The annular backflow region surrounding the incoming jet presents a highly turbulent and chaotic flow situation. The ejected stream is a churning mixture of water and air, laden with both shattered and intact abrasive particles as well as fragments of removed material. It interacts with both the incoming flow and the irregular, continuously evolving cavity surface. The abrasive water jet is stopped after the drilling time reaches the desired value in each trial which leads to formation of a blind hole. Hence as the per the explanation given, the end of the blind hole takes the shape of a cone. ANOVA was performed to determine the significant factors among AFR, WJP, DT and a regression equation was modelled to predict the effect of process parameters on hole depth. The ANOVA table for hole depth is as shown in Table 6.

From the ANOVA table it can be observed that:

The F-ratios presented in the table 6 for Abrasive Flow Rate, Water Jet Pressure and Drilling Time are more than F-ratios given in the statistical tables. Further, the P-values obtained from the ANOVA analysis for these parameters are less than 0.05. Therefore, it can be concluded that these parameters are most statistically significant parameters influencing the hole depth. Further, the interaction effects are not significant as their P-values are greater than 0.05.

Table 6 ANOVA Table for Hole Depth

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Abrasive Flow Rate	2	114.28	7.87%	114.28	57.141	129.33	0.000
Water Jet Pressure	2	368.43	25.38%	368.43	184.216	416.93	0.000
Drilling Time	2	910.61	62.74%	910.61	455.307	1030.49	0.000
Abrasive Flow Rate * Water Jet Pressure	4	10.89	0.75%	10.89	2.722	6.16	0.015
Abrasive Flow Rate * Drilling Time	4	7.87	0.54%	7.87	1.968	4.45	0.035
Water Jet Pressure * Drilling Time	4	35.87	2.47%	35.87	8.967	20.29	0.000
Error	8	3.53	0.24%	3.53	0.442		
Total	26	1451.49	100.00%				

The contribution of abrasive flow rate (A), water jet pressure (B) and drilling time (C) on hole depth was found to be 7.87 %, 25.38 %, 62.74 % respectively. The total contribution of abrasive flow rate, waterjet pressure and drilling time amounts to around 96% on hole depth. Percentage contribution of interactions, that is, abrasive flow rate and waterjet pressure, abrasive flow rate and drilling time, waterjet pressure and drilling time adds up to around 3.7%, and the interaction effects are significant and is to be included in the regression equation. The percentage error around 0.24 % indicates the contribution of other parameters such as dimensions of orifice and focusing nozzle, variation in size of abrasives used in the waterjet and etc. on the hole depth. The interaction of abrasive flow rate, waterjet pressure and drilling time (ABC) is not considered in ANOVA. The main effect plots for hole depth is as shown in figure 5. The following inferences can be made from the graph: The hole depth was found to increase with increase in abrasive flow rate. This is due to the fact that a greater number of abrasive particles participate in eroding the target material as the abrasive flow rate increases. The hole depth was found to increase with increase in water jet pressure. With increase in water jet pressure, the energy possessed by the jet is higher since the velocity of abrasive particles is very high. The hole depth was found to increase with increase in drilling time. This is due to the fact that abrasive particles participating in erosion are in contact with the target material for longer duration as the drilling time increases.

The regression equation is an algebraic equation which determines the relationship between the input parameters and the output parameters. For hole depth, it was found that mass flow rate, water jet pressure and drilling time was found to be statistically significant and was to be included in the regression equation. The interactions between the input parameters, that is, mass flow rate & water jet pressure (A&B), mass flow rate & drilling time (A&C), water jet pressure & drilling time (B&C) were also found to be significant and hence they were also included. Since the interactions were found to be significant, they were included in the regression equation. As the individual terms and the interactions were to be included in the regression equation, a quadratic equation involving both the individual and the interaction terms was formulated. The regression equation along with the regression coefficients was obtained with the help of Minitab software. The regression equation for hole depth is as follows:

Hole Depth $= a + b(\dot{m}) + c(P) + d(t) + e(\dot{m}^2) + f(P^2) + g(t^2) + h(\dot{m}P) + i(\dot{m}t) + j(Pt)$ (2)

where,

a	**b**	**c**	**d**	**e**	**F**	**g**	**h**	**i**	**j**
5.19	0.0064	0.000011	0.0523	0.000025	0.000001	0.000195	0.000001	0.000131	0.000004

$\dot{m}$ is Abrasive Flow Rate, P is Water Jet Pressure, t is Drilling Time

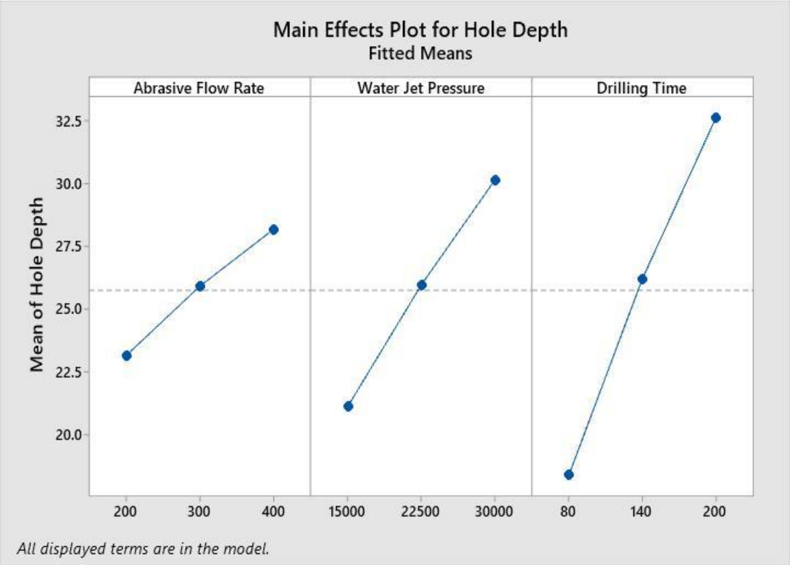


Figure 5 Main Effects Plot for Hole Depth

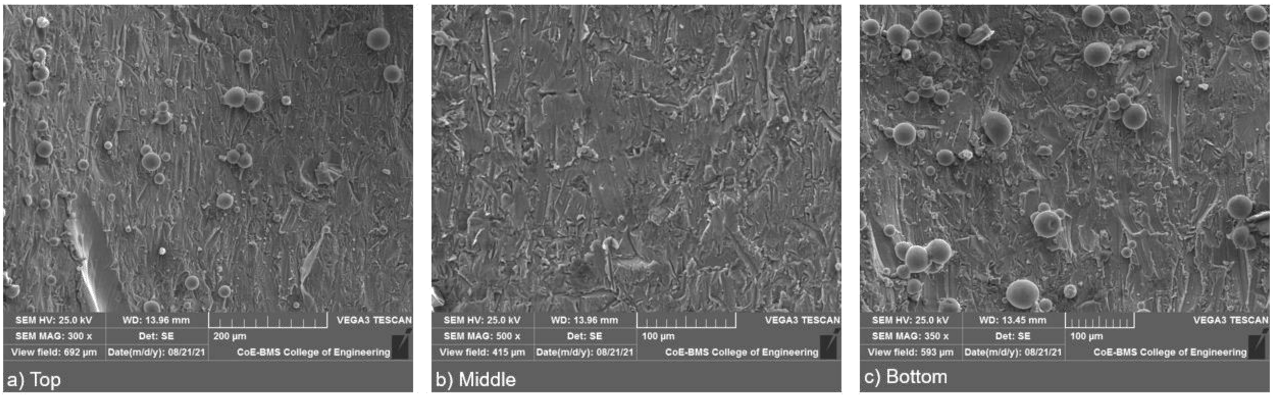
The values of hole depth which was measured with the help of vernier height gauge was compared with the values calculated with the help of the regression equation. The comparison between the two values and the error is calculated and is as shown in the table 7. As the analysis was done at 95 % confidence level and there were other factors affecting the hole depth such as dimensions of orifice and focusing nozzle, variation in size of abrasives used in the waterjet, the errors obtained is in the acceptable limit. Hence, the obtained regression equation is deemed as fit and can be used to predict the values of hole depth for different values of Abrasive Flow Rate, Water Jet Pressure, Drilling Time other than the experimental values.

Table 7 Error Analysis of regression equation for Hole Depth

Hole No.	Experimental Value	Calculated Value	Percentage Error
1	14.16	14.26	0.70
2	21.20	20.94	1.24
3	23.16	22.54	2.75
4	16.58	16.60	0.12
5	23.06	22.46	2.67
6	30.08	29.88	0.67
7	19.32	19.42	0.51
8	26.76	26.84	0.30
9	34.04	33.92	0.35
10	15.02	15.08	0.40
11	22.16	22.42	1.16
12	26.84	27.01	0.63
13	18.74	17.96	4.34
14	25.90	26.22	1.22
15	33.74	32.64	3.37
16	21.36	22.08	3.26
17	31.00	30.96	0.13
18	38.50	38.30	0.52
19	16.58	16.22	2.22
20	23.38	23.12	1.12
21	27.56	27.24	1.17
22	20.18	21.02	4.00
23	29.12	28.96	0.55
24	36.38	35.91	1.31
25	23.80	23.64	0.68
26	33.38	32.88	1.52
27	43.26	44.04	1.77

3.4 Scanning Electron Microscope

The Scanning Electron Microscope (SEM) images reveal the erosion behavior of holes drilled in Ti6Al4V. The SEM images of holes with minimum, mean, maximum depth is as shown in figures 6, 8, 9.



a) Top b) Middle c) Bottom

Figure 6 SEM images of hole drilled with Abrasive flow rate at 200 g/min, Water jet pressure at 15000 psi, drilling time at 80 seconds (Minimum Hole Depth)

In order to determine the chemical composition of the sample with minimum hole depth, Energy Dispersive X-Ray Analysis (EDS or EDX) was used which gives the distribution as shown in figure 7 and concentration of the elements in the sample as shown in table 8.

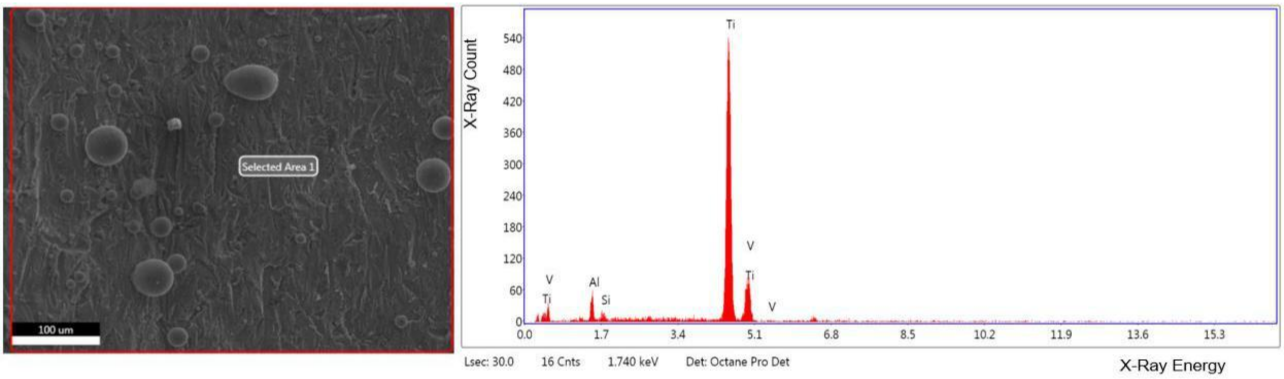


Figure 7 EDX spectrum of hole with maximum hole depth

Table 8 EDX analysis results of hole with maximum hole depth

Element	Shell	Weight %
Al	K	5.52
Si	K	1.42
Ti	K	88.16
V	K	4.90

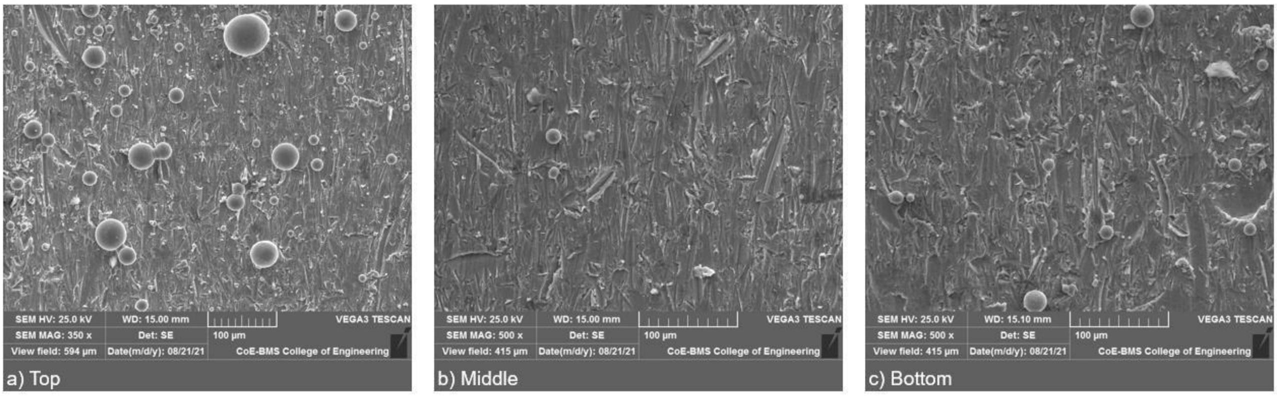


Figure 8 SEM images of hole drilled with Abrasive flow rate at 300 g/min, Water jet pressure at 15000 psi, drilling time at 200 seconds (Intermediate Hole Depth)

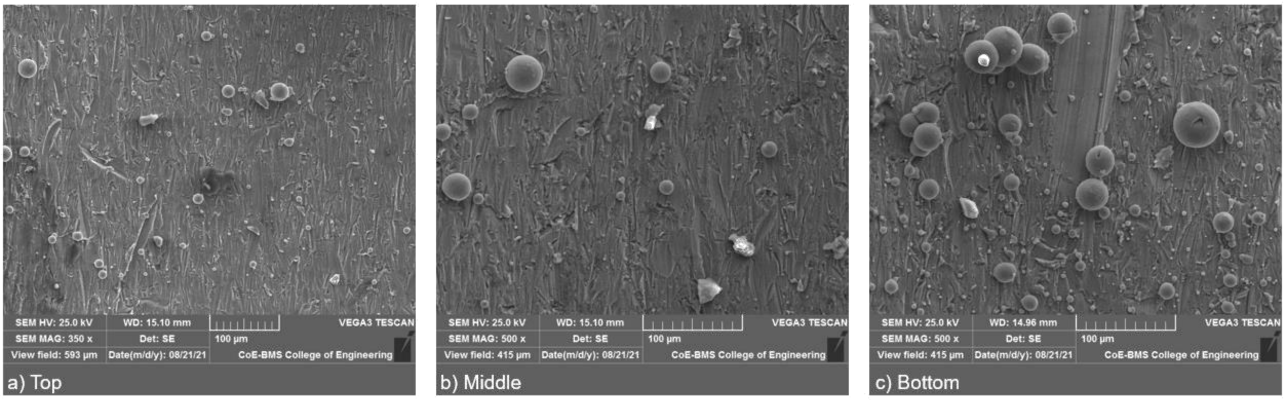


Figure 9 SEM images of hole drilled with Abrasive flow rate at 400 g/min, Water jet pressure at 30000 psi, drilling time at 200 seconds (Maximum Hole Depth)

In order to determine the chemical composition of the sample with maximum hole depth, Energy Dispersive X-Ray Analysis (EDS or EDX) was used which gives the distribution as shown in figure 10 and concentration of the elements in the sample as shown in table 9.

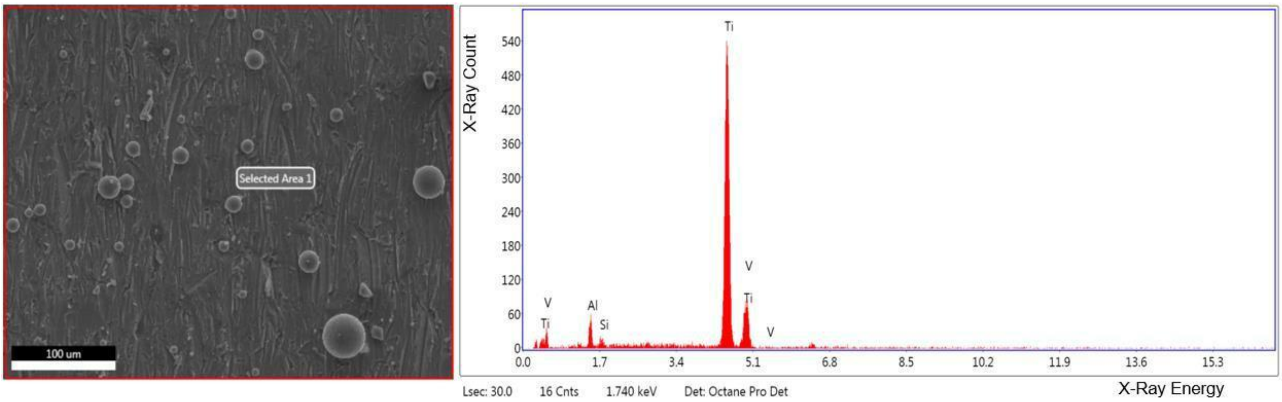


Figure 10 EDX spectrum of hole with maximum hole depth

Table 9 EDX analysis results of hole with maximum hole depth

Element	Shell	Weight %
Al	K	5.38
Si	K	1.06
Ti	K	88.15
V	K	5.41

3.4.1 Observations from SEM and EDX analysis

The SEM images of three different drilled holes are as shown in the figure 6, 8 and 9. The observations from the SEM and EDX analysis are as follows:

- From figure 6 (a), 6 (b), 6 (c) it was seen that the eroded surface was very rough and the eroded particles are not in uniform in their shape and size.
- The metal substrate was analysed using Energy Dispersive X-Ray Analysis to determine the weight percentage of each element and was found that Titanium, Aluminium and Vanadium had higher weight percentages as seen in table 8. This is due to the fact that when material is removed by abrasive water jet, due to raise in localized temperatures in some areas, the eroded particles are adhered to the substrate.
- The Silica element found in the EDX analysis is found to have the weight percentage of around 1.06%. This is because 98.5% of the abrasive particles entrained in the water jet participate in the material removal and that energy is harnessed to cut the material. About 1.5% do not participate in the erosion mechanism and are lodged on the surface as their kinetic energy is less to cut the material. This residue is reflected in the EDX analysis.
- The SEM images and EDX analysis of the intermediate hole depth and maximum hole depth are as shown in figure 8 (a), 8 (b), 8 (c) & 9 (a), 9 (b), 9 (c) and figure 10 respectively. The same trend was seen in the SEM images of intermediate hole depth and maximum hole depth.

4. Conclusions

Abrasive Water Jet Drilling, a non-traditional machining technique was used to drill Ti6Al4V and was performed based on the experiments designed according to Taguchi method. The conclusions that can be drawn from analysis of the hole profile are as follows:

Entry Hole Diameter was found to increase with increase in input parameters, that is, abrasive flow rate, water jet pressure, drilling time based on ANOVA results. It was not significantly affected by the interactions between the input parameters and hence was neglected in the formulation of regression equation. Cylindricity was measured for all the 27 holes and it was found that all the holes were within the tolerance limit of 0.1 mm. If the tolerance limit is within 0.025 mm, the deviations obtained in this study does not adhere to it. Hence, for accurately drilling of hole with tolerance limit less than 0.025 mm, abrasive water jet drilling cannot be used for this material. Hole depth was found to increase with increase in input parameters, that is, abrasive flow rate, water jet pressure, drilling time based on ANOVA results. It was significantly affected by the interactions between the input parameters and hence was included in the formulation of regression equation. The SEM images of three different drilled holes are as shown in the images above and the eroded surface is found to be very rough and the eroded particles are not in uniform in their shape and size and when analysed using Energy Dispersive X-Ray Analysis it was found that Titanium, Aluminium and Vanadium had higher weight percentages. This is due to the fact that when material is removed by abrasive water jet, due to raise in localized temperatures in some areas, the eroded particles are adhered to the substrate. The silica elements found during EDX analysis is due to the residue of abrasive particles.

This research work can be used as a data bank in machining industries for applications such as marine industries where drilling of Ti6Al4V is necessary. There is scope for further study where these experimental results can be validated using Finite Element Analysis. It can also be referred for a study where an empirical and analytical model can be developed to obtain the relationship between input parameters and output parameters such as entry hole diameter and hole depth.

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