Impact of Process Parameters on Surface Roughness of Hastelloy using Abrasive Waterjet Machining Technology

Sahith Reddy Madara, Chithirai Pon Selvan, Sampath SS, Swaroop Ramaswamy Pillai

Abstract*: *Abrasive waterjet cutting is one of the unconventional cutting processes capable of cutting extensive range of difficult-to-cut materials. This paper assesses the impact of process parameters on surface roughness which is a significant machining performance measure in abrasive waterjet cutting of hastelloy. The experimental parameters were selected based on Taguch's design of experiments. Experiments were conducted in varying nozzle traverse speed, abrasive mass flow rate and standoff distance for cutting hastelloy using abrasive waterjet cutting process. The effects of these parameters on surface roughness have been discussed.

Index Terms: Hastelloy; mass flow rate; traverse speed; standoff distance; garnet

I. INTRODUCTION

Waterjet Machining or Non-Traditional Machining is one of the well know technology which was founded in the year 1983 and is utilized in the industries as the tool for machining of materials in various industries such as mining, aerospace for cutting of titanium alloy, reaming etc. which are used in the parts such as turbine injectors, space craft's etc. It is mainly used during the manufacturing of the machine parts, because all the machining processes cannot be performed by the traditional machining methods. When we add abrasive particles to the pure water during machining it is said as Abrasive waterjet machining [1]. In this machining, water serves as an accelerating medium and the abrasive particles are utilized for material removal from the surface during cutting. It is able to perform very accurate cutting with precision using needle sharp stream. The kerf means the width of the cut will be as per the setting of the nozzle as well as the abrasive mas flow particles usage during the machining process. The abrasive waterjet cuts will have top kerf and bottom kerf by using the formula we can determine the kerf width of a single cut. The amount of the scrap which is produced in the machining process will be reduced as compared to the traditional machining methods. In waterjet technology by utilizing meat-cutting which will reduce the risk of cross contamination because there is no other contact medium such as a blade.

Revised Manuscript Received on January 25, 2019.

Sahith Reddy Madara, UG Research Scholar, Department of Aerospace Engineering, Amity University Dubai, UAE, E-mail: sahithreddym1@gmail.com

Chithirai Pon Selvan, Head of School, School of Science and Engineering, Curtin University Dubai, UAE, E-mail: pon.selvan@curtindubai.ac.ae

Sampath S S, Assistant Professor, Department of Mechanical Engineering, Manipal Academy of Higher Education, Dubai, UAE, E-mail: sampath@manipaldubai.com

Swaroop Ramaswamy Pillai, Assistant Professor, Department of Electronics and Telecom Engineering, Amity University Dubai, UAE, E-mail: spillai@amityuniversity.ae

Based on the usage of the constant parameters and variable parameters we will be getting the surface roughness and depth of cut in the abrasive waterjet machining technology. By increasing the mass flow rate of the abrasive particles in the waterjet we will receive a smoother surface finishing and by decreasing the abrasive particles the surface starts becoming rougher. Jet pressure assumes a critical part in surface wrap up. As the stream/flow weight expands, surface progresses toward becoming smoother. At the point when water is pressurized to a ultrahigh weight up to around 400MPa or, on the other hand 60,000 psi, and released from a petite hole, the waterjet can cause harm to materials by shearing, splitting, disintegration, cavitation, delamination, and plastic mis-shapening. The cutting force is expanded by including rough abrasive particles into the high speed water stream. Water fills in as a quickening medium and the abrasive particles assume the part of a material evacuation. With increment in stream weight, fragile abrasives separate into littler ones. Because of decreasing of size of the abrasives particles the surface moves toward becoming smoother. Once more, because of increment in stream weight, the dynamic vitality of the particles expands which brings about smoother machined surface [2]. By increasing the traverse speed of the waterjet machine, there will be rougher and inaccurate surface finish in the materials, but when we reduce the traverse speed there will be very accurate cut. By increasing the standoff distance of the waterjet machine there will be inaccurate or rougher surface finish but by decreasing the standoff distance there will be smoother surface finish on the surface of the materials. The nozzles of the waterjet machines are made of composite based tungsten carbide or sintered boride and it has a water pressure in between 210-620 MPa. There are various abrasive particles used in the waterjet machine as per the application of the material, some of the particle like Garnet, silicon carbide, aluminum oxide, olivine etc. There are various advantage of using this technology such as there is no thermal distortion happening during cutting, there will be less stress acting on the cutting material, small cutting force is required and it has high flexibility, it does not used any kind of non-biodegradable chemicals which can harm the environment, the heat effected zones are not created so it can be utilized for the secondary operations. In the present research study, we are investigating on the effect of theprocess parameters on the surface roughness in abrasive waterjet machining of the hastelloy using taguchi approach [3]

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

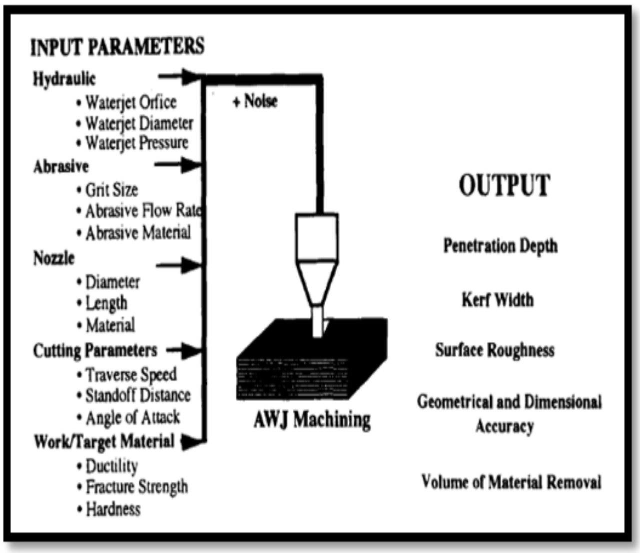

Fig.1 Abrasive Waterjet Machining Process Parameters [3]

II. EXPERIMENTAL WORK

A. Material

The material decided for this test work is Hastelloy C276. Numerous nickel-based steel amalgams display high resistance of corrosion, and Hastelloy is truly outstanding. Extra components, for example, molybdenum and chromium round out the profile of an amalgam that is broadly viewed as one of the world's hardest. Notwithstanding extraordinary resistance from all way of setting and splitting, parts produced using Hastelloy metal mixes tend to discover great use over an extensive variety of synthetic applications that may some way or another oxidize the metal. Hastelloy C-276 composite can be manufactured, hot-vexed and affect expelled. Despite the fact that the compound tends to work-solidify, we can have it effectively spun, profound drawn, press framed or punched [4]. There are various characteristics of Hastelloy C276 such as phenomenal erosion obstruction in diminishing conditions, excellent protection from solid arrangements of oxidizing salts, low carbon content which limits grain-limit carbide precipitation amid welding to keep up protection from consumption in warm influenced zones of welded joints, hastelloy is one of couple of materials to withstand the destructive impacts of wet chlorine gas, hypochlorite and chlorine dioxide.

B. Abrasive waterjet cutting setup

We have used the Classica type abrasive waterjet machine for cutting the sample. It has an Accuracy: + - 0,025 mm, Working Speed: 12 m/min, Rapid feed: 40 000 mm/min, Power: 2 kW, kerf width: 0.9 mm, nozzle height correction: 30 mm, cutting height: 280 mm.

Fig.2. Abrasive Waterjet Machining Setup

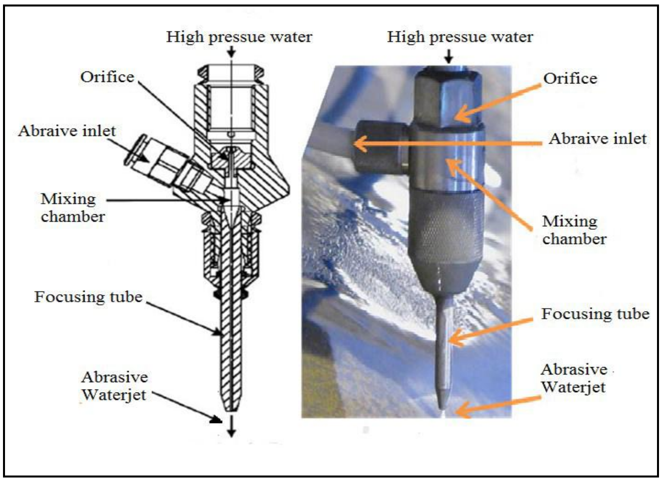

Fig.3. Abrasive Waterjet Cutting Head [3]

We used granite 80 mesh type of abrasive particles along with water it is having dark red color, it can with stand upto temperature of 1300°C, it has a conductivity less than 25/m, it has a specific gravity of 4.1 g/cm3, it has a purity of sample up to 95%, the abrasive grain size is of 0.25-0.6 mm. It has a fixture of mildsteel of about 100mm, which was shaped for mounting as well clamping of the specimen/work piece after that the machining was performed [5]. We have used the sapphire opening for changing the high weight water into a collimated torrent, with a carbide control valve to form an abrasive waterjet. When the experiment was conducted, the nozzle inspection was frequently performed so that when the nozzle was worn out, it will be replaced by a new one. The materials debris & slurry which was formed on the surface was collected into a catch tank.

C. Design of Experiments (DOE)

One of the very powerful tool which is utilized in the various experimental situations is the concept of design of experiments (DOE). The concept of design of experiments which allows the designers to determine instantaneously the discrete and also the collaborative effects of various factors which could affect the output process parameters in a design.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

For achieving a best thorough cut through abrasive waterjet, the process variables combination gives the jet of enough energy to penetrate through the sample specimen. In the current study, as control factors 3 process parameters were selected such as the abrasive mass flow rate, traverse speed, standoff distance, each of them varied at 5 levels. Taguchi's method is used to construct the design of experiments for the process parameters. The three factors varying are: abrasive mass flow rate (g/s) is varying from 0.83 to 4.17 in 5 different levels, traverse speed (mm/s) is varying from 0.67 to 1.33 in 5 different levels, and standoff distance (mm) is varying from 1 to 5 in 5 different levels. In overall the input process parameters and the output process responses were conducted at 25 different compositions by varying the values of the abrasive mass flow rate, traverse speed and the standoff distance, by which the output process responses was found such as surface roughness, metal removal rate, kerf width and kerf angle.

Table 1. Process Parameters and their 5 Levels

Parameters	Unit	Level 1	Level 2	Level 3	Level 4	Level 5
Abrasive Mass Flow Rate (m_a)	g/s	0.83	1.67	2.5	3.33	4.17
Traverse Speed (u)	mm/s	0.67	0.83	1	1.17	1.33
Standoff Distance (s)	mm	1	2	3	4	5

D. Constant Parameters & Data Collection

There are several parameters which we have kept constant during the experiment was conducted which included the nozzle height correction was about 30 mm, high pressure delay was 2 seconds, the orifice diameter was 0.35 mm, nozzle length was 76.2 mm, the abrasive materials which we have used was granite 80 mesh, working speed was about 12 m/min, rapid feed was 40000 mm/min, water consumption is 3.6 lt/min, the diameter of the abrasive particles was about 0.18 mm, energy consumption is about 37 kWh, density of the abrasive particles is 4100 kg/m3. Garnet particles comprises of chemically 33% SiO2, 4% MgO, 3% TiO2, 20% Al2O3, 2% CaO, 2% MnO2 and 36% FeO During the data collection phase, as per the orthogonal array the machining parameters were set to pre-defined stages. Single pass cutting was selected for all the machining procedure for hastelloy material. For each experiment which the machining parameters was set as per the design of experiments (DOE). In the waterjet machine the abrasive particles were carried using the compressed air which was from the hopper to the fraternization chamber and the whole system was controlled using a metric disc. The water pressure of the abrasive waterjet was manually controlled, using a pressure gauge which was present in the machine. Using the controller which was present in the operator control stand the standoff distance of the nozzle was maintained. The transverse speed of the head was measured mechanically by the waterjet system which was programmed by the NC node of the system. At last, some of the additional reading were taken to plot the graphs.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

One of the most important criteria in abrasive waterjet machining technology is the measuring the surface roughness of the work piece, by which it is possible to find out how rough is the surface of the material is present. For a low strength materials the roughness of the surface will be more, but when the strength of the material increases the surface roughness of the material during machining will be very smoother. After analyzing the experimental data, it is found that the optimum selection of the three parameters i.e., abrasive mass flow rate, traverse speed, standoff distance are very important during the finding of the process outputs such as the surface roughness of the material. The effects of each parameter were studied by keeping other parameters measured in the study as constants. The experimental results are shown in table 2.

Table 2. Input Process Parameters & Output Process Responses

Input Process Parameters			Output Process Responses			
Abrasive Mass Flow Rate (g/s)	Traverse Speed (mm/s)	Standoff Distance (mm)	Surface Roughness (µm)	Metal Removal Rate (mm^3/min)	Kerf Width (mm)	Kerf Angle (°)
0.83	0.67	1	0.0141	1.18	1.923	0.117
0.83	0.83	2	0.015	1.21	1.828	0.056
0.83	1	3	0.016	1.24	1.367	0.034
0.83	1.17	4	0.0178	1.31	1.852	0.031
0.83	1.33	5	0.0179	1.27	4.651	0.191
1.67	0.67	2	0.0135	1.16	3.011	0.07
1.67	0.83	3	0.0152	1.12	3.61	0.193
1.67	1	4	0.0159	1.15	4.601	0.168
1.67	1.17	5	0.0176	1.21	4.902	0.008
1.67	1.33	1	0.0172	1.12	4.551	0.039
2.5	0.67	3	0.0156	0.99	3.541	0.268
2.5	0.83	4	0.0152	1.09	5.012	0.049
2.5	1	5	0.0158	1.14	6.201	0.022
2.5	1.17	1	0.0136	1.11	4.741	0.072
2.5	1.33	2	0.0148	1.13	4.882	0.025
3.33	0.67	4	0.0137	1.12	5.732	0.108
3.33	0.83	5	0.017	1.14	6.651	0.012
3.33	1	1	0.014	1.08	7.051	0.007
3.33	1.17	2	0.0145	1.19	6.782	0.048
3.33	1.33	3	0.0148	1.2	6.593	0.011
4.17	0.67	5	0.015	1.08	5.564	0.159
4.17	0.83	1	0.013	1.06	5.701	0.002
4.17	1	2	0.015	1.13	7.592	0.013
4.17	1.17	3	0.015	1.14	7.042	0.014
4.17	1.33	4	0.0148	1.17	8.101	0.031

The regression equation is generated by Minitab-18 software for Surface Roughness (µm) vs Abrasive Mass Flow Rate (g/s),

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Traverse Speed(mm/s) and Standoff Distance (mm):-

Surface Roughness (μm) = 0.01656 - 0.000513 Abrasive Mass Flow Rate (g/s)

Surface Roughness (μm) = 0.01308 + 0.002202 Traverse Speed (mm/s)

Surface Roughness (μm) = 0.01364 + 0.000548 Standoff Distance (mm)

A. Effect of mass flow rate on surface roughness

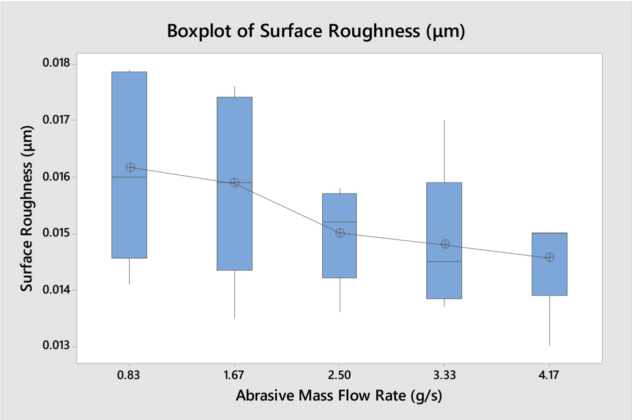

Fig. 4. Boxplot of surface roughness vs abrasive mass flow rate

It needs countless number of unit area under a specific strain to conquer the holding quality of any material. With the expansion in grating mass stream/flow rate, surface roughness diminishes. This is a direct result of more number of effects and front lines accessible per unit region with a higher rough stream rate. Abrasive stream/flow rate decides the quantity of affecting rough abrasive particles and also add up to dynamic vitality accessible. In this manner, higher rough stream/flow rate, higher ought to be the cutting capacity of the jet.

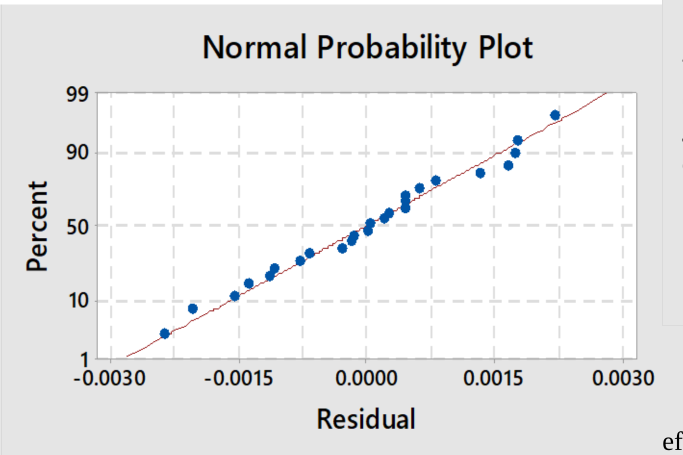

Fig. 5. Normal Probability Plot for Surface roughness vs abrasive mass flow rate

Table 3. Calculation of Means, Standard Deviation & Confidence Interval for abrasive mass flow rate

Abrasive Mass Flow Rate (g/s)	N	Mean	Standard Deviation	95% Confidence Interval
0.83	5	0.016160	0.001683	(0.014925, 0.017395)
1.67	5	0.015880	0.001645	(0.014645, 0.017115)
2.50	5	0.015000	0.000872	(0.013765, 0.016235)
3.33	5	0.014800	0.001302	(0.013565, 0.016035)
4.17	5	0.014560	0.000876	(0.013325, 0.015795)

However, for higher rough stream rate, abrasives crash among themselves and free their dynamic vitality. It is clear that the surface is smoother close to the stream entrance and step by step the surface roughness increments towards the jet exit. By analyzing the normal probability plot we can see the experimental values indicated by dots and theoretical values by line, the values are nearly equal, by this we can tell that the values which we got by experimental results are correct. By the mean value we see by increasing the values of the abrasive mass flow rate (g/s) from 0.83 to 4.17 for N=5, the mean values is changing between 0.016160 and 0.014560, the mean value decreased from top to bottom when the mass flow rate increases. The stand deviation also decreased from 0.001683 to 0.000876 by increasing the mass flow rate. For all the values of the abrasive mass flow rate the 95% confidence level values are present in the table.

B. Effect of traverse speed on surface roughness

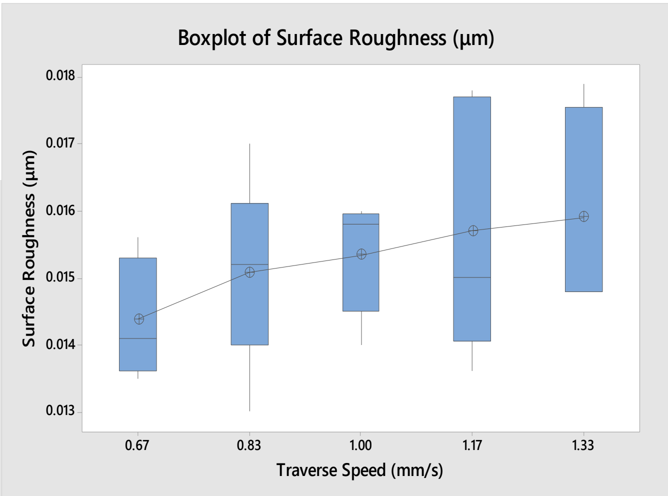

Fig. 6. Boxplot of surface roughness vs traverse speed

Transverse speed didn't demonstrate an unmistakable effect on surface roughness. For diminishing of the machining costs each client/user attempt to pick the nourish rate of the cutting head as high as could reasonably be expected, however expanding the cross speed dependably causes expanding of error and surface harshness. In any case, with increment in work sustain rate the surface harshness expanded. This is because of the way that as the work moves quicker, less number of particles are accessible that go through a unit zone.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

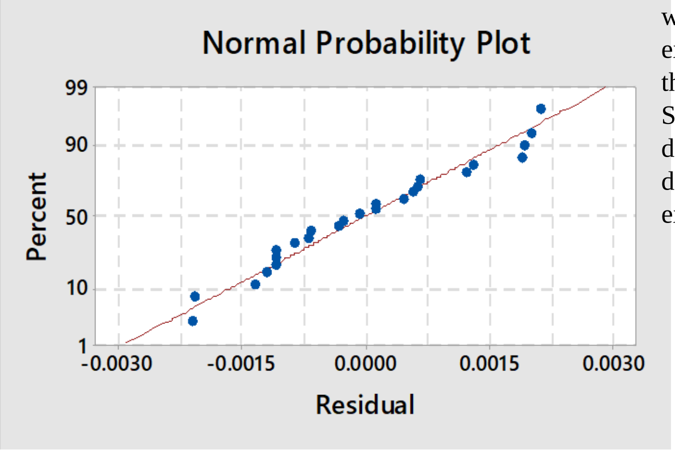

Fig. 7. Normal probability plot for Surface roughness vs traverse speed

Accordingly, less number of effects and front lines are accessible per unit zone, which comes about a rougher surface. By analyzing the normal probability plot we can see the experimental values indicated by dots and theoretical values by line, the values are nearly equal, by this we can tell that the values which we got by experimental results are correct.

By the mean value we see by increasing the values of the traverse speed (mm/s) from 0.67 to 1.33 for N=5, the mean values is changing between 0.014380 and 0.015900, the mean value increased from top to bottom when the traverse speed increases. The stand deviation increases from 0.000893 to 0.001526 by increasing the mass flow rate. For all the values of the traverse speed the 95% confidence level values are present in the table.

Table 4. Calculation of Means, Standard Deviation & Confidence Interval for traverse speed

Traverse Speed (mm/s)	N	Mean	Standard Deviation	95% Confidence Interval
0.67	5	0.014380	0.000893	(0.013098, 0.015662)
0.83	5	0.015080	0.001418	(0.013798, 0.016362)
1.00	5	0.015340	0.000847	(0.014058, 0.016622)
1.17	5	0.015700	0.001895	(0.014418, 0.016982)
1.33	5	0.015900	0.001526	(0.014618, 0.017182)

C. Effect of standoff distance on surface roughness

Surface roughness increment with increment in standoff distance. For the most part, higher standoff distance enables the jet to grow before impingement which may build powerlessness to outer drag from the encompassing condition. The impacts of standoff distance are most transcendent close to the jet passage inside the underlying damage zone. Standoff distance impacts the surface roughness in this locale region because of its impact on the coherency of the rough abrasive jet preceding impingement on the work piece. Higher standoff distance enables the jet to extend before impingement, which builds defenselessness to outside drag from the encompassing condition. Densities of rough abrasive particles in the external border of the extending jet plane are low because of this extension. In this way, increment in the standoff distance outcomes an expanded stream/flow measurement as cutting is started and thusly, decreases the active vitality of the jet at impingement. So surface roughness increases with increment in standoff distance. It is alluring to have a lower standoff separate distance which may create a smoother surface because of expanded active vitality.

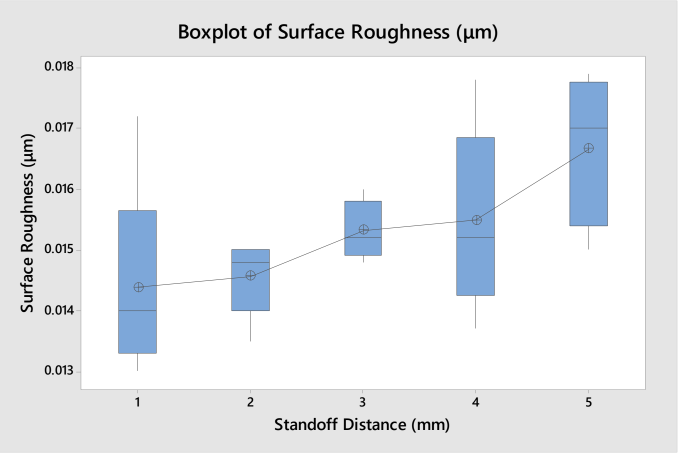

Fig. 8. Boxplot of surface roughness vs standoff distance

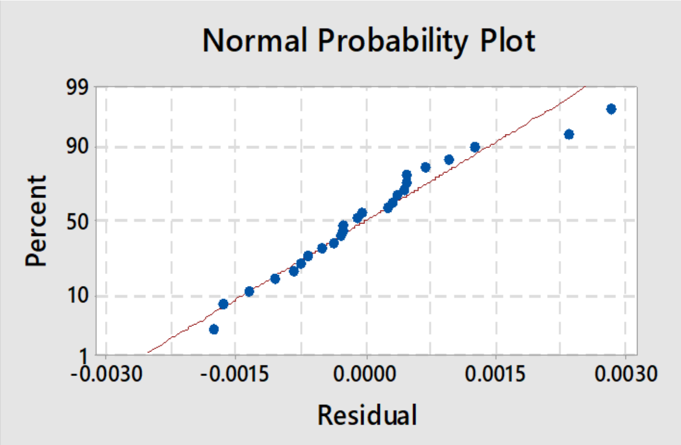

Fig. 9. Normal Probability plot for Surface roughness vs standoff distance

The machined surface is smoother close to the highest point of the surface and ends up noticeably rougher at more prominent profundities/depth from the top surface. By analyzing the normal probability plot, the experimental values are shown by dots and theoretical values by line, the values are nearly equal, and thereby it was found that the values of experimental results are correct. By the mean value we see by increasing the values of the standoff distance from 1 to 5 for N=5, the mean values is changing between 0.014380 and 0.016660, the mean value increased from top to bottom when the mass flow rate increases. The stand deviation increases from 0.001635 to 0.001228 by increasing the standoff distance. For all the values of the standoff distance the 95% confidence level values are present in the table.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Table 5. Calculation of Means, Standard Deviation & Confidence Interval of standoff distance

Stand off Distance (mm)	N	Mean	Standard Deviation	95% Confidence Interval
1	5	0.014380	0.001635	(0.013267, 0.015493)
2	5	0.014560	0.000627	(0.013447, 0.015673)
3	5	0.015320	0.000482	(0.014207, 0.016433)
4	5	0.015480	0.001522	(0.014367, 0.016593)
5	5	0.016660	0.001228	(0.015547, 0.017773)

D. Taguchi Analysis: Surface Roughness (µm) vs Abrasive Mass Flow Rate (g/s), Standoff Distance (mm), Transverse Rate (mm/s)

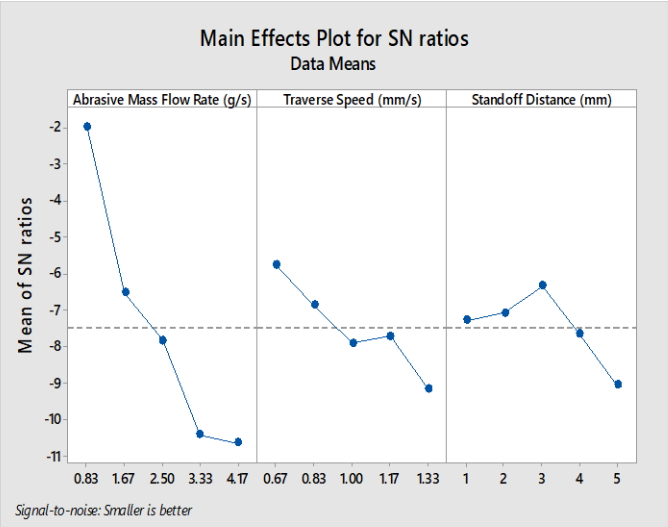

Fig. 10. Main effect plot of Signal to Noise ratio for abrasive mass flow rate, traverse speed, standoff distance

Table 6. Signal to Noise ratio – finding delta, ranking of abrasive mass flow rate, traverse speed & standoff distance

Level	Abrasive Mass Flow Rate (g/s)	Traverse Speed (mm/s)	Standoff Distance (mm)
1	-1.981	-5.778	-7.295
2	-6.529	-6.866	-7.071
3	-7.835	-7.902	-6.341
4	-10.432	-7.731	-7.666
5	-10.653	-9.153	-9.056
Delta	8.671	3.376	2.715
Rank	1	2	3

The signal to noise ratio and the main effect plot for the SN ratio was analyzed for 5 different levels. The abrasive mass flow rate was varying from -1.981 to -10.653, the traverse speed is varying from -5.778 to -9.153, and standoff distance is varying from 7.295 to 9.056. By this we have found that the delta value for the mass flow rate is 8.671 which ranks 1st, for traverse is about 3.376 which ranks 2nd and for standoff distance is 2.715 which ranks 3rd. The ranking is based on the highest delta value and the range of smaller is better assumption which was fixed before the experiments were conducted. The signal to noise ratio main effect plot was also plotted for mass flow rate, traverse speed and standoff distance, as per smaller is better assumption.

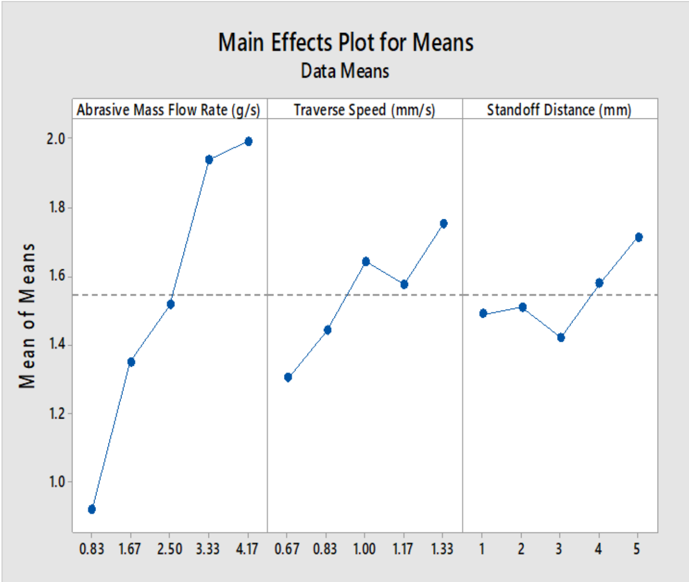

Fig. 11. Main effect plot of means for abrasive mass flow rate, traverse speed, standoff distance

Table 7. Means – finding delta, ranking of abrasive mass flow rate, traverse speed & standoff distance

Level	Abrasive Mass Flow Rate (g/s)	Traverse Speed (mm/s)	Standoff Distance (mm)
1	0.9170	1.3047	1.4913
2	1.3496	1.4405	1.5100
3	1.5174	1.6436	1.4220
4	1.9400	1.5765	1.5801
5	1.9936	1.7522	1.7142
Delta	1.0765	0.4475	0.2922
Rank	1	2	3

The mean and the main effect plot for means was analyzed for 5 different levels. The abrasive mass flow rate is varying from 0.9170 to 1.9936, traverse speed is varying from 1.3047 to 1.7522, and the standoff distance is varying between 1.4913 and 1.7142. By this we have found that the delta value for the mass flow rate is 1.0765 which ranked 1st, for traverse speed is about 0.4475 which ranked 2nd, for standoff distance is about 0.2922 which ranked 3rd. The ranking is based on the highest delta value and the lowest delta value which was found in the experiment. The mean main effect plot was also plotted for mass flow rate, traverse speed and standoff distance.

E. Interaction Plot for Surface Roughness vs Abrasive Mass Flow Rate (g/s), Standoff Distance (mm), Transverse Rate (mm/s)

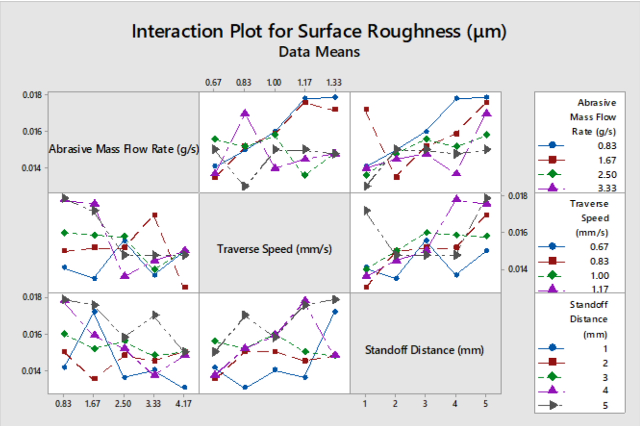

Fig. 12. Interaction Plot for Surface Roughness vs abrasive mass flow rate, traverse speed & standoff distance

In the interaction plot for surface roughness, we will be able to analyze the combined interactions between each process parameters in four different colors, such as the abrasive mass flow rate (g/s) is between 0.83 and 3.33, traverse speed (mm/s) is between 0.67 and 1.17 and the standoff distance (mm) the varying between 1 and 5, in total of 6 different graphs, that means for each varying process parameters consists of 2 graphs of combined interaction between all the experimental values which was found during conducting of the design of experiments.

IV. CONCLUSIONS AND FUTURE SCOPE OF WORK

Experimental investigations have been carried for the surface roughness in abrasive waterjet cutting of hastelloy. The effects of different operational parameters such as, abrasive mass flow rate, traverse speed and nozzle standoff distance on surface roughness have been investigated.

As a result of this study, it is observed that these operational parameters have direct effect on surface roughness. It has been found that mass flow rate has the most effect on the surface roughness. Surface roughness constantly decreases as mass flow rate increases. It is recommended to use more mass flow rate to increase surface smoothness. As nozzle traverse speed increase, surface roughness increases. This means that low traverse speed should be used to have smoother surface but is at the cost of sacrificing productivity. An increase in standoff distance is associated with an increase in surface roughness. These findings indicate that the use of low standoff distance is preferred to obtain surface smoothness. Among the process parameters considered in this study traverse speed and standoff distance have the similar effect on surface roughness. This research also experimentally demonstrated that if the cutting parameters are not selected properly, AWJC can reduce the major cutting performance measure which is surface roughness. Finally, it is recommended that a combination of more abrasive mass flow rate, low traverse speed and short standoff distance be used to produce less surface roughness.

REFERENCES

1. Muath Al-Falahi, B. T. Baharudin, Tang Sai Hong & Khamirul Amin Matori, “Surface Defects in Groove Milling of Hastelloy- C276 Under Fluid Coolant”, Taylor & Francis - Materials and Manufacturing Processes, 1-9, 2016.
2. Sk.Khadar Basha, Murahari Kolli, M.V.Jagannadha Raju, “Parametric optimization of Edm on Hastelloy C-276 Using Taguchi L18 Technique”, International Journal of Engineering & Technology, vol.7, 714-716, 2018.
3. Chithirai Pon Selvan M, Sahith Reddy Madara, Sampath S, Sarath Raj N S, “Effects of Process Parameters on Depth of Cut in Abrasive Waterjet Cutting of Phosphate Glass”, IEEE Xplore, 1-6, 2018.
4. S.Jaya Kishore, K.Siva Kumar, Dr.M.Narayana Rao, “Experimental Parametric Studies on Hastelloy Using Abrasive Water Jet Machining”, International Conference on Precision, Mesco, Micro and Nano Engineering – Indian Institute of Technology Madras, 1-5, 2017.
5. Guo Y, Wu D, Ma G, “Trailing heat sink effects on residual stress and distortion of pulsed laser welded Hastelloy C-276 thin sheets”, Journal of Materials Processing Technology, vol.214, iss.12, 891-2899, 2014.

*Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication*