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OPTIMIZING THE PROCESS PARAMETERS OF AWJM USING TAGUCHI METHOD AND ANOVA ON INCONEL 625

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ABSTRACT

Inconel 625 has a wide range of applications because of its high resistance to corrosion cracking, pitting, and crevice formation and to a variety of mineral and organic acids along with high thermal fatigue resistance. However conventional machining of Inconel 625 is not so economical and ease, on the other hand non conventional processes like laser cutting, Abrasive Water Jet Machining (AWJM), Electric Discharge Machining (EDM), etc have a very good potential in overcoming these machining difficulties. Among these AWJM is commonly employed for very hard and brittle materials due to its economical and technical significance. In this work, research oriented experimentation on the AWJM of Inconel 625 is planned and being carried out successfully to optimize the input process parameters for fine Surface finish (SR) and high Material removal rate (MRR). Optimization was carried out by these phases SR and MRR are individually optimized as per Taguchi method by Analysis of variance (MINI TAB).

Keywords: AWJM, inconel 625, MRR, SR, Taguchi method, MINITab.

INTRODUCTION

Inconel 625 is one among the family of austenite nickel-chromium-based super alloys which are having high resistance to corrosion and stabilized mechanical properties even at extreme temperatures. Specifically Inconel 625 is highly resistant to inter crystalline corrosion, pitting, crevice corrosion, chloride induced stress corrosion cracking and oxidative stress at high temperatures of up to 1050^{0}C. Hence it is employed for the manufacture of components that are in continuous exposure to sea water and high mechanical stresses such as oil and gas extraction machinery, aerospace industry, marine appliances, chemical processing, nuclear reactors, pollution control equipment etc. As the alloy is having high strength and work hardening nature it cannot be machined with conventional machining processes. Therefore non conventional machining techniques like Laser cutting and abrasive water jet machining etc are employed. From economic perspective laser cutting is very good for cutting Inconel 625 plates of up to 4mm thick, for Inconel-625 plates beyond 4mm thick AWJM is commonly used. Further AWJM has the capability of machining the least slot widths over the complex components.

Extensive studies over optimization of AWJM of grey cast iron, aluminium, composites, steel, hard polymers and tiles reveals that water pressure and abrasive jet traverse speed are the significant factors influencing MRR on the other hand water pressure and abrasive flow rate mostly determine the quality of surface finish. Remaining parameters like abrasive grit size and standoff distance are sub significant in determining MRR and SR. It was observed that comparatively high abrasive flow rates are required for ferrous materials followed by non ferrous materials and hard polymers. Till now optimization of AWJM parameters for Inconel 625 did not gained much attention despite the prevalence of AWJM of Inconel-625. So the present work concentrates on the optimization of AWJM parameters for good MRR and SR based on Taguchi method for optimization technique. In this work, Water pressure, standoff distance, abrasive jet traverse speed and abrasive flow rate were optimized for two quality characteristics namely material removal rate (MRR) and surface roughness.

El-Domiaty *et al.* study that Drilling of glass sheets with different thicknesses have been carried out by Abrasive Jet Machining process (AJM) in order to determine its machinability, under different controlling parameters of the AJM process.

J. John Rozario Jegaraj *et al.* had worked on strategy for efficient and quality cutting of materials with abrasive water jets considering the variation in orifice and focusing nozzle diameter in cutting 6063-T6 aluminium alloy. They have assessed performance in terms of different parameters such as depth of cut, material removal rate cutting efficiency. This variation is based on three different jet pressures and abrasive flow rate.

A.A. Khan *et al.* had worked on Performance of different types of abrasive materials like garnet, aluminium oxide and silicon carbide during abrasive water jet machining of glass. They have used varying parameter as Abrasive flow rate (gm/min), work feed rate (mm/min), SOD (mm) and analyze for Taper of cut and average width of cut with different abrasive materials. Increases with SOD with abrasive materials like garnet, aluminium oxide and silicon carbide.

M.A. Azmir *et al.* conducted experiment to assess the influence of abrasive water jet machining (AWJM) process parameters on surface roughness (Ra) of glass fibre reinforced epoxy composites. It has been found that the type of abrasive materials, hydraulic pressure, standoff distance and traverse rate were the significant control factors and the cutting orientation was the insignificant control factor in controlling the Ra.

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Ahmet Hascalik *et al.* had worked on Effect of traverse speed on abrasive water jet machining of Ti-6Al-4V alloy. They have used varying traverse speeds of 60, 80, 120, 150, 200, and 250 mm/min by abrasive water jet (AWJ) machining. After machining, the profiles of machined surfaces, kerf geometries and micro structural features of the machined surfaces were examined using surface profilometry and scanning electron microscopy (SEM).

Chidambaram Narayanan et al. modelling of abrasive particle energy in water jet machining. They took process parameter with wide variations in cutting-head geometry, operating pressure, and abrasive mass flow rates.

ABRASIVE WATER JET CUTTING MACHINE

Abrasive Water jet Cutting [AWJC] has various distinct advantages over the other non-traditional cutting technologies, such as no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces and has been proven to be an effective technology for processing various engineering materials. It is superior to many other cutting techniques in processing variety of materials and has found extensive applications in industry. In this method, a stream of small abrasive particles is introduced in the water jet in such a manner that water jet's momentum is partly transferred to the abrasive particles. The main role of water is primarily to accelerate large quantities of abrasive particles to a high velocity and to produce a high coherent jet. This jet is then directed towards working area to perform cutting. It is also a cost effective and environmentally friendly technique that can be adopted for processing number of engineering materials particularly difficult-to-cut materials such as ceramics. However, AWJC has some limitations and drawbacks. It may generate loud noise and a messy working environment. It may also create tapered edges on the kerf, especially when cutting at high traverse rates.

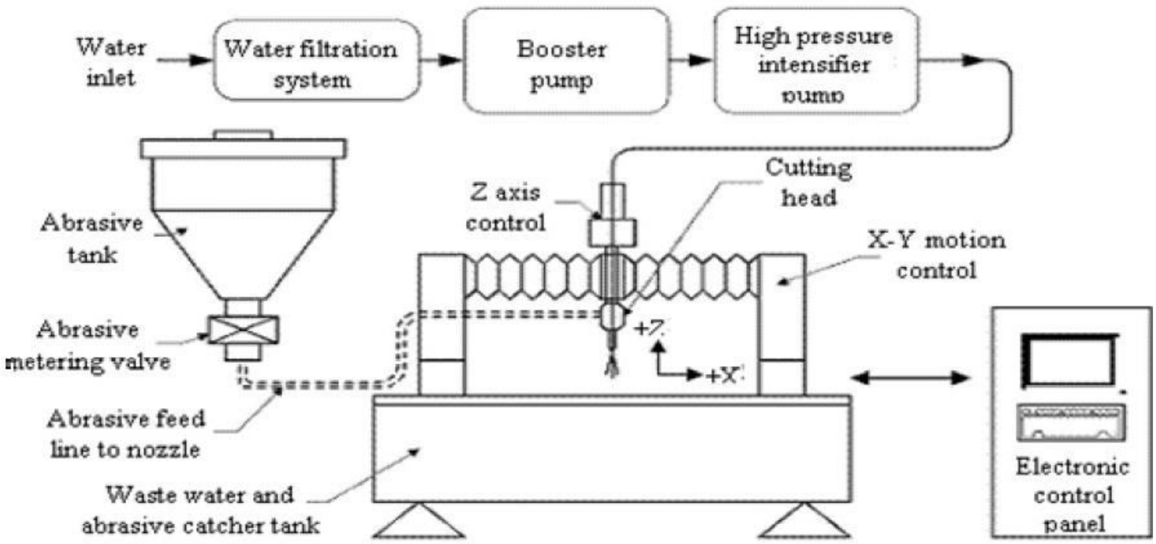

Figure-1. Abrasive water jet machining process.

The rate of cutting in water jet machining, particularly while cutting ductile material, is quite low. Cutting rate can be achieved by mixing abrasive powder in the water to be used for machining. In Abrasive Water Jet Cutting, a narrow, focused, water jet is mixed with abrasive particles. This jet is sprayed with very high pressures resulting in high velocities that cut through all materials. The presence of abrasive particles in the water jet reduces cutting forces and enables cutting of thick and hard materials (steel plates over 80-mm thick can be cut).The velocity of the stream is up to 90 m/s, about 2.5 times the speed of sound.

Abrasive Water Jet Cutting process was developed in 1960s to cut materials that cannot stand high temperatures for stress distortion or metallurgical reasons such as wood and composites, and traditionally difficult-to-cut materials, e.g. ceramics, glass, stones, titanium alloys.

PROCESS PARAMETERS

Water Jet pressure

Relationship between pressure and depth of cut for different abrasive flow rates and nozzle diameters will observe on experimental work. The effect of water jet pressure on the depth of cut for various abrasive flow rates makes an observation. There is minimum pressure (critical pressure) below which no machining takes place. The critical pressure exists because a minimum abrasive particles velocity is required to cut a particular material. Critical pressure is obviously different for different work piece materials.

Water flow rate

In abrasive jet machining where gas (usually air) is used as a propelling fluid, only small mass flow rates of

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abrasives can be achieved. In AWJM, water is used as a propelling fluid which enables high abrasive flow rates to be achieved, and makes it possible to accelerate abrasives to high velocities.

Abrasive particle size

Commonly used abrasive size ranges from 100-150 grit. There is an optimum particle size for a particular work piece material and also for a particular nozzle mixing chamber configuration. Recently efforts made to quantify the effect of abrasive particle size on depth of cut. Results have shown that an optimum particle size range exists for cutting different types of materials. Mesh size 60 is more effective for relatively shallow depth of cut.

Abrasive material

Garnet, silica and silicon carbide are commonly used abrasive in AWJC. Type of abrasives to be used is determined after knowing hardness of the work piece material. Higher the hardness of the work piece material, harder should be the abrasives to be used. While selecting a type of abrasive for a particular application, one should consider cost, nozzle rate, environmental constraints, machining rate, and strength of the particles.

Cutting speed

Cutting speeds are a function of the material to cut, the geometry of the part, the software and controller doing the motion, the power and efficiency of the pump making the pressure, and a few other factors such as the abrasive used.

Stand-off-distance

An increase in Standoff distance rapidly decreases machined depth. This has been explained by arguing that the liquid phase of the jet breaks up into droplets resulting in free abrasive particles. These free abrasive particles rebound upon impact that leads to a shallower penetration. There is an upper value of SOD beyond which the process will no longer do the cutting.

TAGUCHI APPROACH

Taguchi's approach was built on traditional concepts of design of experiments (DOE), such as factorial and fractional factorial designs and orthogonal arrays; he created and promoted some new DOE techniques such as signal-to-noise ratios, robust designs, and parameter and tolerance designs.

Design of experiments is a power full statistical technique introduced by R.A. fisher in England in the 1920‟s to study the effect of multiple variables simultaneously. These techniques are useful for the effective and efficient collection of data for a number of purposes. Design of experiments can be employed in both the product design phase and production phase. Robust designs are based on the use of DOE techniques for finding product parameter settings (e.g., temperature settings or drill speeds), which enable products to be flexible to changes and variations in working environments.

The objective of the robust design is to find the controllable process parameter settings for which noise or variation has a minimal effect on the product's or processes functional characteristics. It is to be noted that the aim is not to find the parameter settings for the uncontrollable noise variables, but the controllable design variables. To attain this objective, the control parameters, also known as inner array variables, are systematically varied as stipulated by the inner orthogonal array.

Taguchi method focuses on Robust Design through use of

a) Signal-To-Noise ratio

b) Orthogonal arrays

Steps in Taguchi methodology

Taguchi method is a scientifically disciplined mechanism for evaluating and implementing improvements in products, processes, materials, equipment, and facilities. These improvements are aimed at improving the desired characteristics and simultaneously reducing the number of defects by studying the key variables controlling the process and optimizing the procedures or design to yield the best results. Taguchi proposed a standard procedure for applying his method for optimizing any process.

a) Determine the Quality Characteristic to be Optimized
b) Identify the Noise Factors and Test Conditions
c) Identify the Control Parameters and Their Alternative Levels
d) Design the Matrix Experiment and Define the Data Analysis Procedure
e) Conduct the Matrix Experiment
f) Analyze the Data and Determine the Optimum Levels
g) Predict the Performance at these Levels

MINITAB

When you start Minitab, a new, empty project is opened for you. You will see three windows:

a) Data window
b) Session window
c) Project Manager (minimized at startup)

MINITAB Environment

Everything about your work is contained in a Minitab *Project* file. The *project* file contains

- Worksheets that contain your data. You can have multiple worksheets in one project.

- One or more Data windows that display any open worksheet files. Your data will be displayed as columns. There is one Data window for each worksheet in the project. You can enter and edit data directly in the Data window.

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METHODS AND FORMULAS

Table-1. Minitab provides methods and formulas for the following areas.

General statistics	Design of experiments (DOE)	Quality and process improvement	Reliability and survival analysis
Basic statistics	Factorial designs	Control charts	Test plans
Regression	Response surface designs	Measurement systems analysis	Distribution analysis
Analysis of variance (ANOVA)	Mixture designs	Process capability	Warranty analysis
Multivariate analysis	Taguchi designs	Quality planning tools	Repairable system analysis
Random data and probability	Optimal designs	Acceptance Sampling	Profit analysis

EXPERIMENTAL PROCEDURE

Abrasive Water Jet machine is used for conducting the experiment. Duplex stainless steel (SAF 2304) is used as a work material. In this we have measured the material removal rate of duplex steel. The experimentation for this work was based on Taguchi's design of experiments (DOE) and orthogonal array. A large number of experiments have to be carried out when the number of process parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal array to study the entire parameter space with a small number of experiments only. In this work, four machining parameters namely, Water pressure (P), Abrasive Mass Flow Rate (AMFR), Stand Off Distance (SOD) and Cutting Speed (CS) were considered for experimentation. Accordingly there are four input parameters and for each parameter three levels were assumed. For a four factors, three level experiments, Taguchi has specified L9 orthogonal array for experimentation. The response obtained from the trails conducted as per L9array experimentation was recorded and further analyzed.

WORK PIECE MATERIAL

Inconel-625 is used as a work piece for the machining. Inconel-625 is used in many marine engineering, aerospace engineering etc. The dimension of work piece is 150x150x5. The chemical compositions and mechanical properties are shown in Tables 2, 3 & 4.

Table-2. Chemical compositions.

Element	% Present
Chromium(Cr)	23
Nickel(Ni)	58
Molybdenum (Mo)	10
Manganese (Mn)	0.5
Titanium (Ti)	0.4
Carbon(C)	0.1
Aluminum (Al)	0.4
Ferrous (Fe)	5.0
Silicon (Si)	0.5
Sulphur (S)	0.015
Phosphorous (P)	0.015

Table-3. Mechanical properties.

Property	Value
Yield Strength	72.0Mpa
Tensile Strength	138.8Mpa
Elongation	38%

Table-4. Physical properties.

Property	Value
Density	8.44 g/cm^3
Specific Heat	560J/kg –c
Electrical Resistance	1.32micro Ω m
Thermal conductivity	21.3 W/M- C
Thermal Expansion	13.7 x10^-6 /K
Thermal Conductivity	19.0 W/m.K

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MACHINE DETAILS

Abrasive Water Jet Machining on Duplex stainless steel was performed in ALIND WATER JET LTD, Ambattur on KMT's Streamline SL-V 50 Plus.

Table-5. Machine details.

Nominal power rate	50hp (37 KW)
Maximum continuous pressure	60,000 psi (4,137 bar)
Maximum Water Flow Rate	1.0 gpm (3.79L/min)
Maximum single orifice Dia.(full pressure)	0.014inches (0.355 mm)
Control voltage & power supply	24V DC; 10Amps DC
Ambient Operating Temperature	Min. 40^0F (5^0C), Max. 104^0F(40^0C)
Hydraulic Reservoir Capacity	28 gal (106 L)
Cooling Water Flow@75 (24^0C) water Temperature	3 gpm (11.4 L/min)
Length	1.7 m
Width	914 mm
Height	1,453 mm
Weight	2,900 lbs
Abrasive type	Garnet Sand
Abrasive size	80 Mesh
Orifice diameter	0.30 mm
Nozzle diameter	1.00 mm
Nozzle length	82.4 mm
Jet impact angle	90^0
Average diameter of abrasives	0.20 mm

TAGUCHI EXPERIMENTAL DESIGN APPROACH

Degrees of Freedom (V_f)

The number of factors and their interactions and levels for each factor determine the total degrees of freedom required for entire experiments. Table-6.6 shows the degrees of freedom of each factor along with total degrees of freedom for experiments. The degrees of freedom for each factor are given by number of levels minus one.

Degrees of freedom, V_f = Number of levels (k) - 1

Where

$V_{f,}$ is degrees of freedom of factor levels.

k, is the number of levels for each factor.

Table-6. Degrees of freedom of factor levels.

S. No.	Factors /Parameters	Factor code	Degrees of freedom, (k-1)
1	Water pressure (MPa)	A	3-1=2
2	Standoff distance (mm)	B	3-1=2
3	Abrasive Mass flow rate (gm/min)	C	3-1=2
4	Cutting speed (mm/min)	D	3-1=2
Total			8

The degrees of freedom of a 3-level factor has two degrees of freedom. Four 3-level factors require 8 degrees of freedom.

Selection of an Orthogonal array

The smallest orthogonal array with at least 8 degrees of freedom is the L_9 orthogonal array. Table-7 shows the L_9 (3^4) orthogonal array for four 3-level factors. Therefore, it is possible to assign four 3-level factors to the four columns.

Table-7. L_9 (3^4) orthogonal array for four 3-level factors.

Experiment	Factors			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Array selector

Table-8 shows the array selection based on levels and factors. There are 4 parameters and each one has 3 levels. The highest number of levels is 3, so use a value of 3 when choosing our orthogonal array. Using the array selector above, find that the appropriate orthogonal array is L9.

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Table-8. Array selection based on levels and factors.

Number of levels	Number of factors/parameters													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	L_4	L_4	L_4	L_8	L_8	L_8	L_{12}	L_{12}	L_{12}	L_{12}	L_{16}	L_{16}	L_{16}	L_{16}
3	L_9	L_9	L_9	L_{18}	L_{18}	L_{18}	L_{18}	L_{27}	L_{27}	L_{27}	L_{27}	L_{27}	L_{36}	L_{36}
4	L_{16}	L_{16}	L_{16}	L_{16}	L_{32}	L_{32}	L_{32}	L_{32}	L_{32}					
5	L_{25}	L_{25}	L_{25}	L_{25}	L_{25}	L_{50}	L_{50}	L_{50}	L_{50}	L_{50}	L_{50}			

Degrees of freedom of an orthogonal array, V_{OA} = Number of experiments - 1
= 9-1
=8

Where,
V_f is degrees of freedom of factor levels,
V_{OA} is degrees of freedom of an orthogonal array.

Table-9. Design layout of L_9 orthogonal array for machining the work piece.

Exp. No.	**Water pressure** (MPa) **(A)**	**Standoff distance** (mm) **(B)**	**Abrasive Mass flow rate,** (gm/min) **(C)**	**Cutting speed** (mm/min) **(D)**
1	300	200	400	200
2	300	4	500	280
3	300	6	600	350
4	350	200	500	350
5	350	4	600	200
6	350	6	400	280
7	400	200	600	280
8	400	4	400	250
9	400	6	500	200

EXPERIMENTAL RESULTS AND DISCUSSIONS

Material removal rate

Material removal rate increases with increase in current density. As current density increases material removal rate also increases. Increase of current increase the temperature between the electrode and work-piece due to which more vaporization of work-piece takes place. Table-10 shows the MRR responses of machined plate
MRR is calculated using the relation

MRR = $h_t d_n Vt$

Where,
h_t = depth of penetration
d_n = diameter of the focusing tube or nozzle or the insert
V_t = cutting speed

And for measuring the Value of (h_t) depth of penetration, equation is

$h_t = \pi/4\ d_o^2\ R * (1/1+R) * (P^{3/2}/\mu_{job} d_{SOD} V_t) * (2/\rho_w)^{1/2}$

Where,

- d_o = orifice diameter in mm
- d_{SOD} = standoff distance in mm
- R = mass flow rate of abrasive (m_{abr}) / mass flow rate of water (m_w)
- ρ_w = density of water
- μ_{job}= specific energy of material in j/mm^3
- P = pressure in bar (psi)
- V_t = cutting speed in mm/min.

Surface roughness measurement

Surface roughness (Ra) of each machined surface was measured using a Talysurf SJ-201P surface roughness tester with a gauge range ±150 µm, resolution 0.014 µm, Stylus - 112/1502 diamond tip radius 2 µm and the cut-off length 0.8 mm. The direction of surface roughness measurements is perpendicular to the hole circumference.

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Table-10. Machining responses for machining Inconel 625.

Exp. No.	Material removal rate (g/s)	Surface roughness, (μm)
1	3.75	0.000576
2	3.70	0.000384
3	3.78	0.000576
4	3.00	0.000768
5	2.97	0.000960
6	3.20	0.000960
7	2.5	0.001152
8	2.32	0.000960
9	2.52	0.001152

Table-11. Taguchi analysis - Minitab 16.1 Software, L9 OA for MRR, S/N ratio, means.

Trial No.	Control parameter (Levels)				Result / Observed value	Taguchi analysis	
	Water pressure (Mpa)	Standoff distance (mm)	Abrasive Mass flow rate (gm/min)	Cutting speed (mm/min)	MRR (g/s)	S/N ratios	Means
1	300	2	400	200	3.75	11.4806	3.75
2	300	4	500	280	3.70	11.3640	3.70
3	300	6	600	350	3.78	11.5498	3.78
4	350	2	500	350	3.00	9.5424	3.00
5	350	4	600	200	2.97	9.4551	2.97
6	350	6	400	280	3.20	10.1030	3.20
7	400	2	600	280	2.5	7.9588	2.50
8	400	4	400	250	2.32	7.3098	2.32
9	400	6	500	200	2.52	8.0280	2.52

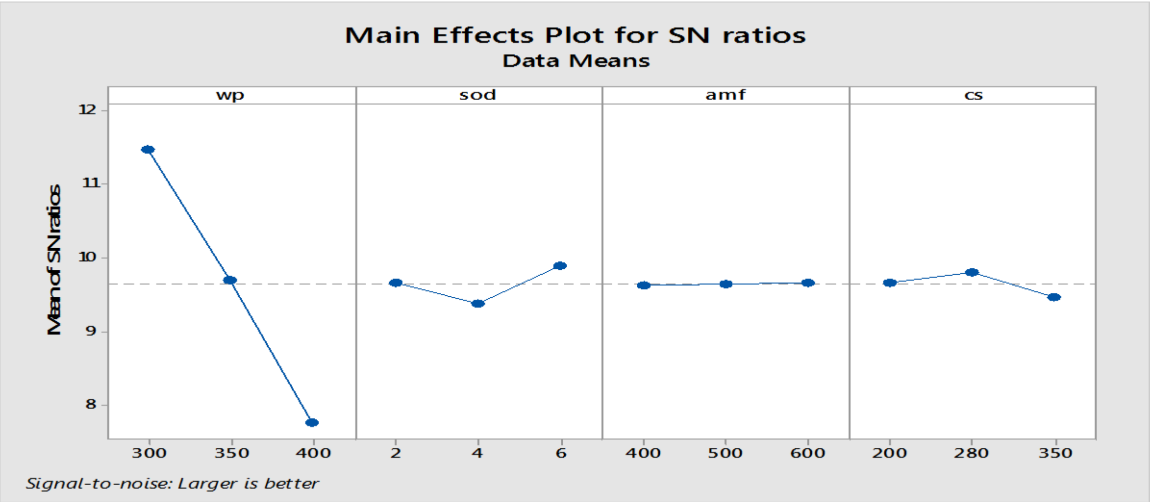

Figure-2. Graph for Material Removal Rate (MRR).

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Table-12. Response table.

Level	Pressure	Standoff distance	Abrasive mass flow rate	Cutting speed
1	11.465	9.661	9.631	9.655
2	9.700	9.376	9.645	9.809
3	7.766	9.894	9.655	9.467
Delta	3.699	0.517	0.023	0.341
Rank	1	2	3	4

Table-13. Taguchi analysis - MINITAB 16.1 Software, L9 OA for SR, S/N ratio, means.

Trial No.	**Control parameter** (Levels)				Taguchi analysis		
	Water pressure (Mpa)	**Standoff distance** (mm)	**Abrasive flow rate** (gm/min)	**Jet traverse speed** (mm/min)	**Surface roughness**	**S/N Ratios**	**Means**
1	300	2	450	90	0.000576	64.7916	0.000576
2	300	4	550	140	0.000384	68.3134	0.000384
3	300	6	650	200	0.000576	64.7916	0.000576
4	350	2	550	200	0.000768	62.2928	0.000768
5	350	4	650	90	0.000960	60.3546	0.000960
6	350	6	450	140	0.000960	60.3546	0.000960
7	400	2	650	140	0.001152	58.7710	0.001152
8	400	4	450	200	0.000960	60.3546	0.000960
9	400	6	550	90	0.001152	58.7710	0.001152

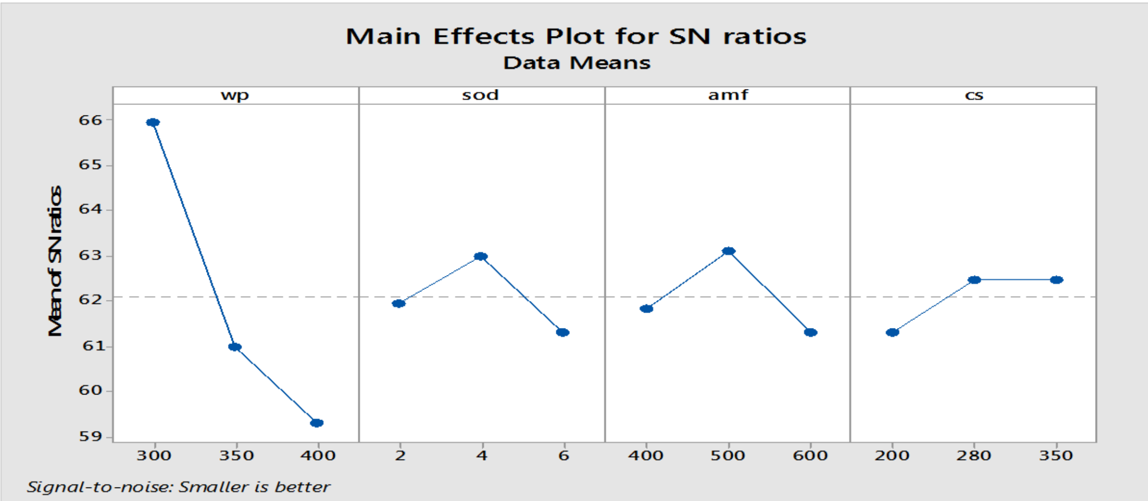

Figure-3. Graph for Surface Finish (SR).

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Table-14. Response table.

Level	Pressure	Standoff distance	Abrasive mass flow rate	Cutting speed
1	65.97	61.95	61.83	61.31
2	61.00	63.01	63.13	62.48
3	59.30	61.31	61.31	62.48
Delta	6.67	1.70	1.82	1.17
Rank	1	3	2	4

CONCLUSIONS

The Abrasive Water Jet Machining (AWJM) is the preeminent process for machining Inconel 625 metal. The main advantage of Taguchi method is that there is no need to calculate complex modelling formulations or simulations of process, which takes a lot of time and hardware to find out the optimum solution. Instead of the complex modelling formulations, a simple statistical calculation has been used to get the appreciable result. This approach also gives much more reliable solutions as exact experimental values are used to represent the process. When the results are concluded it is found that the Material Removal Rate (MRR) and Surface Roughness (SR) which are influenced over AWJM parameters of Cutting speed, Abrasive mass flow rate, Standoff distance and water pressure. It is observed that the experimented values for higher MRR and fine SR was found through the analysis of variance (MINITAB) gives a graphical form of optimal setting results. Thus the response approach using Taguchi approach is capable of solving optimization problem.

REFERENCES

[1] A.A. Khan, M.M. Hague. 2007. Performance of different abrasive material during abrasive water jet machining of glass. Journal of Materials Processing Technology. 191: 404-407.

[2] Ahmet Hascalik, Ulas C aydas, Hakan Guru. 2007. Effect of traverse speed on abrasive water jet machining of Ti–6Al–4V alloy. Materials and Design. p. 28.

[3] Chidambaram Narayanan, Reto Balz, Daniel A. Weiss, Kurt C. Heiniger. 2013. Modelling of abrasive particle energy in water jet machining. Journal of Materials Processing Technology. 213: 2201-2210.

[4] El-Domiaty, H. M. Abd El-Hafez and M. A. Shaker study that. 2009. Drilling of glass sheets with different thicknesses have been carried out by Abrasive Jet Machining process (AJM). World academy of science, Engineering and technology 56: 2009.

[5] J. John Rozario Jegaraj, N. Ramesh Babu. 2005. A strategy for efficient and quality cutting of materials with abrasive water jets considering the variation in orifice and focusing nozzle diameter. International Journal of Machine Tools & Manufacture. 45: 1443-1450.

[6] M.A. Azmir, A.K. Ahsan. 2008. Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining. Journal of materials processing technology. 198: 122-128.