Experimental Investigation of Surface Roughness Parameter of 25mm Thick Ss304 using Abrasive Waterjet Machine

Akshay Bharate[1], Sagar Bhagwat[2], Akshay Chavan[3], Rushikesh Bande[4], Aniket Jadhav[5]

[1]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,* ***bharate.akshay@gmail.com***
[2]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,* ***sagar.b6565@gmail.com***
[3]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,*
akshaychavan2577@gmail.com
[4]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,* ***rushibande12@gmail.com***
[5]*Department of Mechanical Engineering, Smt. Kashibai Navale College of Engineering,* ***jadhavaniketb@gmail.com***

ABSTRACT

Abrasive jet and Water Jet technology has been around for years, but abrasive jet equipment has just recently entered the machining tool market. This is extremely high-tech machining method, and there are only a handful of early innovators making a lot of money replacing and complementing conventional machining types like laser cutting, plasma cutting, etc. with abrasive waterjet cutting methods. Abrasive Waterjet technology has demonstrated to be an interesting manufacturing process for space and research equipment, aircraft, marine and automotive sectors due to its specific advantages such as high quality surface finish, no heat affected zones, and is rarely affected by the material being cut. Stainless Steel is one of the most used materials in today's world. Machining of stainless steel is very important task in consideration to the industrial sector and many manufacturing processes can be used to do the same. AWJM is one of the important processes to machine Stainless Steel with high surface finish and having desired thickness and shape. Hence the aim of this research paper is to study effect of AWJM machining on a specific process parameter i.e. surface roughness of a SS304 25mm thick plate. The variation in surface roughness with varying process parameters are studied with Design of Experiment Software. Optimization is done using Response surface methodology (RSM) by implementing three levels Box-Behnken design.

Keywords: Abrasive Water Jet, Surface Roughness, Box-Behnken, Optimization, etc.

---

1. INTRODUCTION

In the 1950s, forestry engineer Dr. Norman Franz experimented with an early form of water jet cutter to cutting wood. The technique of cutting relatively softer materials using high pressure jet of water was first time patented in 1968 by Dr. Norman Franz, Associate Professor of Forestry and researcher at University of Michigan, USA [1]. However, the technology did not advance notably until the 1970s. First introduced in the late 1980s, this technology allows harder and more exotic materials to be machined efficiently at reasonable speeds. Currently AWJs are used to cut a wide range of engineering materials including ceramics, metal alloys, and composites [2]. Among the methods of cutting metallic and non-metallic materials, abrasive waterjet cutting techniques have a distinct advantage because of their versatility, no heat affected zone and speed. They can cut all materials, including hard-to-machine materials such as super alloy, stainless steel, Kevlar, and boron carbide. They can also easily cut aerospace materials such as graphite composite and titanium, and brittle materials such as advanced ceramics, granite, marble and glass.

The high speed jet of water transfers the kinetic energy to the abrasive particles and the mixture (water and abrasives) impinges on the work piece material. The performance of AWJM process is dependent on erosion of material by pressurized water-abrasive mixture and mechanical properties of work piece material along with various other process parameters [3].

The set up consists of a pump, abrasive hopper, high pressure tube, cutting head, catcher, etc. AWJM cuts 10 times faster than the conventional machining methods. The system uses a high-speed water jet to accelerate abrasive particles at extremely high speeds so that it will erode (shearing) the work piece material at impact.

High pressure water starts at the pump, and is delivered through special high pressure plumbing to the cutting head. The pump or an intensifier elevates the fluid to desired nozzle pressure while the accumulator smoothes out the pulses in the fluid jet. Flow out, of the pump is turbulent (high Reynolds number) at a pressure of the order of 50,000 PSI. The fluid enters a mixing tube, a section of which contains a sapphire orifice. The orifice is made of sapphire because the design specifications require that the orifice remain at a constant, size and shape in spite of the high pressure forces and wear and tear. The fluid is forced through the orifice at a speed on the order of about Mach 3. The pressure of the flow at the location of the orifice is lower than atmospheric (increase of fluid speed across the orifice and there is an accompanying pressure drop with the increased fluid velocity). At this point, the abrasive is sucked into the stream of fluid, in what is called a "mixing chamber." See Fig. 1 for a cross section of the insides of the mixing chamber and the tubing surrounding the sapphire orifice [4].

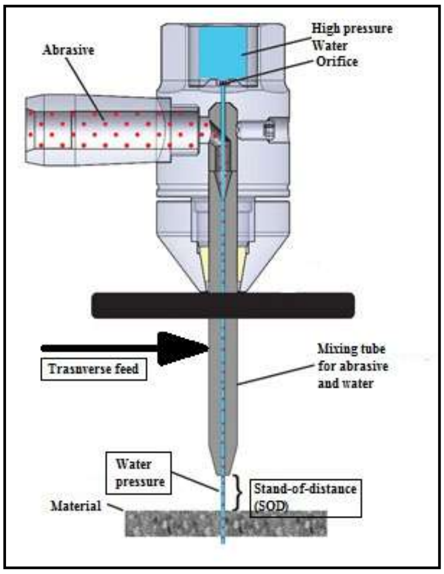


Fig- 1: Cross-section of the insides of the mixing chamber

The process parameters included in AWJM are transverse feed rate, waterjet pressure, SOD, abrasive mass flow rate, abrasive type, nozzle diameter, thickness of material, etc. and some performance parameters taken into consideration are surface roughness, kerf width, taper angle, taper ratio, etc [5]. So in this study we have considered three major process parameters such as transverse feed rate, waterjet pressure and SOD and performance parameters measured is surface roughness. The sample is a SS304 25mm thick plate. It is observed that surface roughness is one of the main ways of evaluating quality of cut surfaces obtained with AWJ cutting. It is also one of the most often specified end user requirements [6]. Process parameters such as traverse speed, material grade and thickness, abrasive flow rate and abrasive size directly affect surface roughness [7].

2. EXPERIMENTAL SETUP

The experiments were conducted with a commercial abrasive waterjet machine Omax 60120 which is illustrated schematically in Figure 1. The details of the machine and process parameters are listed in Table 1. The three major process parameters considered in this experiment are transverse feed rate of the nozzle, water jet pressure at nozzle exit and abrasive mass flow rate. The two responses were also considered such as surface roughness and taper ratio in this experiment. Stainless steel 304 is used as the work piece for experimentation having dimension of 400mmX100mmX25mm. Chemical composition of SS304 is given in Table 2.

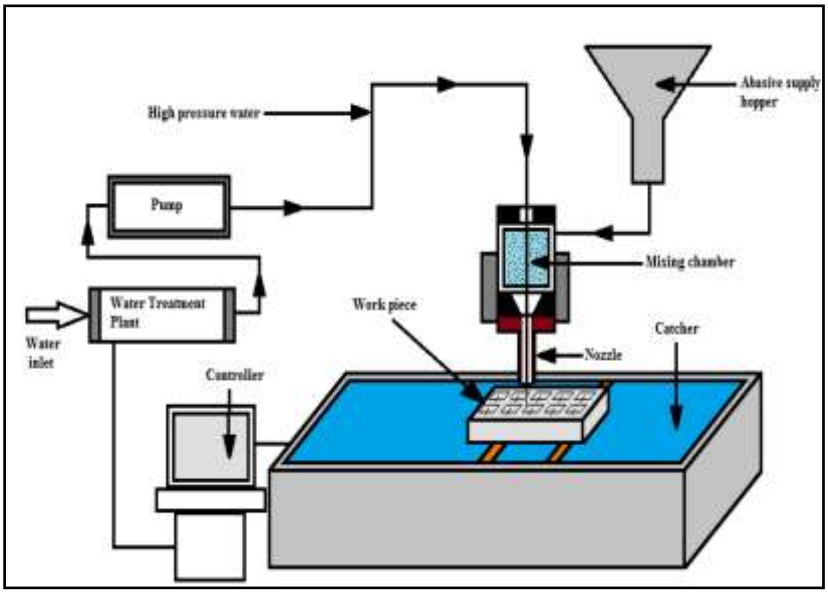


Fig- 2: Schematic representation of AWJM

MACHINE DIMENSIONS	
Footprint (with controller)	18’9” x 9’2” (5,715 mm x 2,794 mm)
Weight (tank empty)	6,200 lb (2,812 kg)
Height (with scissor plumbing)	9’7” (2,921 mm)
Operating Weight	23,200 lb (10,545 kg)
WORK ENVELOPE	
X-Y Cutting Travel	10’6” x 5’2” (3,200 mm x 1,575 mm)
Z-Axis Travel	8” (203mm)
Table Size	12’0” x 6’5” (3,658 mm x 1,956 mm)
STANDARD MODEL SPECIFICATIONS	
Material Support Slats	4" x 1/8" Galvanized Steel
Maximum Supported Material Load	400 lbs/sq ft (1,950 kg/sq meter)
Electrical Requirements	3-Phase, 380-480 VAC ±10%, 50-60 Hz
Noise Level	Below 80 dBA at one meter for submerged cutting
Speed	180 in/min (4,572 mm/min)
Linear Positional Accuracy	±0.001” (±0.025 mm)
Repeatability	±0.001” (±0.025 mm)

Table- 1: AWJ machine specification

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Fe
Percentage	0.08	10.368	1.74	0.018	0.019	19.04	7.93	1.24	Remaining

Table- 2: Chemical composition of SS304

2.1 Design of experiment (DOE)

Design of experiments is a series of tests in which purposeful changes are made to the input variables of a system or process and the effects on response variables are measured. Design of experiments is applicable to both physical processes and computer simulation models. Experimental design is an effective tool for maximizing the amount of information gained from a study while minimizing the amount of data to be collected. Factorial experimental designs investigate the effects of many different factors by varying them simultaneously instead of changing only one factor at a time. Factorial designs allow estimation of the sensitivity to each factor and also to the combined effect of two or more factors. In a highly competitive world of testing and evaluation, an efficient method for testing many factors is needed [8]. In the current study Response Surface Methodology (RSM) has been applied for the above mentioned process parameters, using statistical software, Design-Expert V8.

2.2 Response surface methodology (RSM)

Response surface methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building. By careful design of experiments, the objective is to optimize a response (output variable) which is influenced by several independent variables (input variables). An experiment is a series of tests, called runs, in which changes are made in the input variables in order to identify the reasons for changes in the output response.

The application of RSM to design optimization is aimed at reducing the cost of expensive analysis methods (e.g. finite element method or CFD analysis) and their associated numerical noise.

The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualize the shape of the response surface. Contours are curves of constant response drawn in the X_i, X_j plane keeping all other variables fixed. Each contour corresponds to a particular height of the response surface.

2.3 Box-Behnken design

A Box-Behnken design is a type of response surface design that does not contain an embedded factorial or fractional factorial design. For a Box-Behnken design, the design points fall at combinations of the high and low factor levels and their midpoints:

- Waterjet pressure: 50,000PSI, 52500PSI and 55,000PSI
- Transverse feed rate: 27mm/min, 38mm/min and 50mm/min
- SOD: 0.55mm, 0.8mm and 1.05mm

Box-Behnken designs have treatment combinations that are at the midpoints of the edges of the experimental space and require at least three continuous factors. The following figure shows a three-factor Box-Behnken design. Points on the diagram represent the experimental runs that are done:

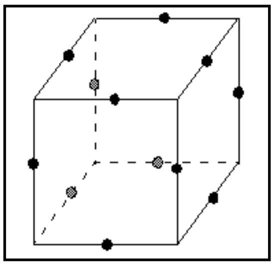
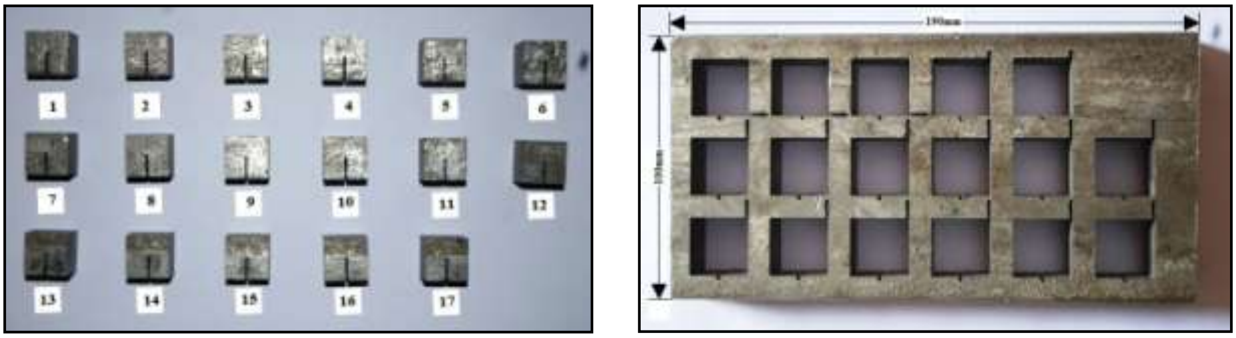


Fig- 3: Three-factor Box-Behnken design

Here we have taken 17 samples having dimensions 20x20 mm and 25 mm thick of SS304 with varying input parameters Waterjet pressure, transverse feed rate and SOD. The output parameters are then analysed according to the given data.

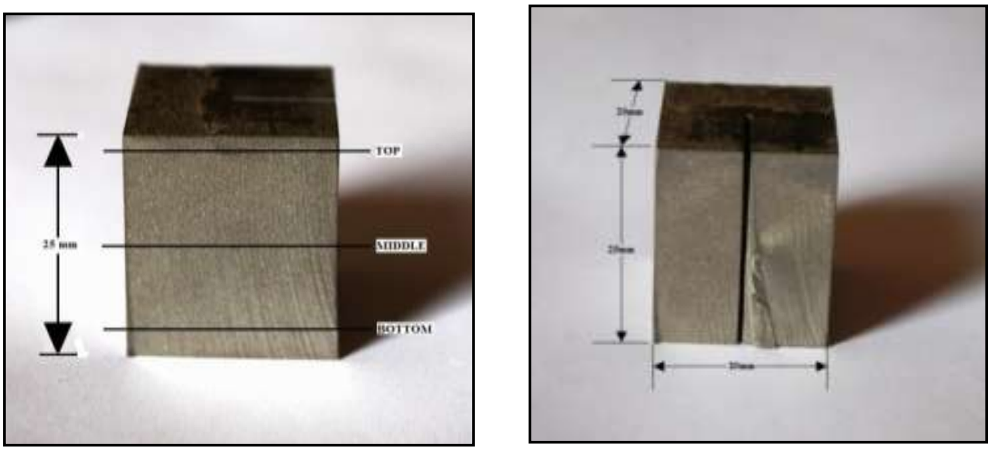


(a) **(b)**

Fig- 4: (a) Actual sample that were cut during experimentation and (b) Left over material from work piece

3. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

In this section, the effect of the process parameters such as waterjet pressure, transverse speed and SOD on the surface roughness at the top, middle and bottom of the work piece were analysed. The readings for surface roughness were taken at three different locations for every single work piece as shown in figure 5.



(a) **(b)**

Fig- 5: (a) Actual view of cut where roughness was measured for 25 mm work piece, (b) Dimension of individual sample

		Factor 1	**Factor 2**	**Factor 3**	**Response 1**	**Response 2**	**Response 3**
Std	**Run**	**A:Water Jet Pressure**	**B:Speed**	**C:SOD**	**Top**	**Middle**	**Bottom**
		psi	**mm/min**	**mm**	**micron**	**micron**	**Micron**
1	6	50000	27	0.8	2.232	2.657	2.987
7	9	50000	38.5	1.05	2.325	2.419	3.012
5	10	50000	38.5	0.55	2.456	2.527	2.923
3	13	50000	50	0.8	2.335	2.471	2.995
11	2	52500	27	1.05	3.254	3.265	3.757
15	3	52500	38.5	0.8	3.452	3.855	4.039
16	4	52500	38.5	0.8	3.596	3.855	4.238
14	5	52500	38.5	0.8	4.412	4.789	4.835
10	7	52500	50	0.55	3.781	3.956	4.012
12	12	52500	50	1.05	3.996	4.227	4.438
13	14	52500	38.5	0.8	4.003	4.123	4.238
17	15	52500	38.5	0.8	4.259	4.591	4.737
9	16	52500	27	0.55	2.457	2.752	4.006
8	1	55000	38.5	1.05	3.756	3.862	4.122
6	8	55000	38.5	0.55	3.154	3.249	3.431
4	11	55000	50	0.8	3.258	3.379	3.591
2	17	55000	27	0.8	3.552	3.822	4.059

Table- 3: Experimental data

3.1 Analysis of Surface Roughness at Top

Surface Roughness tester was used in the study for determining the surface roughness value of the machined samples in microns. Analysis of variance (ANOVA) was performed on experimental data for investigating the significance and contribution of the machining parameters on roughness. The ANOVA of surface roughness so obtained is given in Table 4.

Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		**Mean**	**F**	**p-value**	
Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
Model	0.55	9	0.062	4.52	0.0296	significant
A-Waterjet Pressure	0.21	1	0.21	15.25	0.0059	
B-Speed	0.035	1	0.035	2.54	0.1548	
C-SOD	0.021	1	0.021	1.55	0.2537	
AB	3.236E-003	1	3.236E-003	0.24	0.6410	
AC	0.010	1	0.010	0.77	0.4102	
BC	8.270E-003	1	8.270E-003	0.61	0.4615	
A^2	0.20	1	0.20	14.49	0.0067	
B^2	0.034	1	0.034	2.47	0.1603	
C^2	0.018	1	0.018	1.34	0.2855	
Residual	0.095	7	0.014			
Lack of Fit	0.052	3	0.017	1.57	0.3280	not significant
Pure Error	0.044	4	0.011			
Cor Total	0.65	16				

Table- 4: ANOVA for response surface quadratic model at Top

The Model F-value of 4.52 implies the model is significant. There is only a 2.96% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 1.57 implies the Lack of Fit is not significant relative to the pure error. There is a 32.80% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

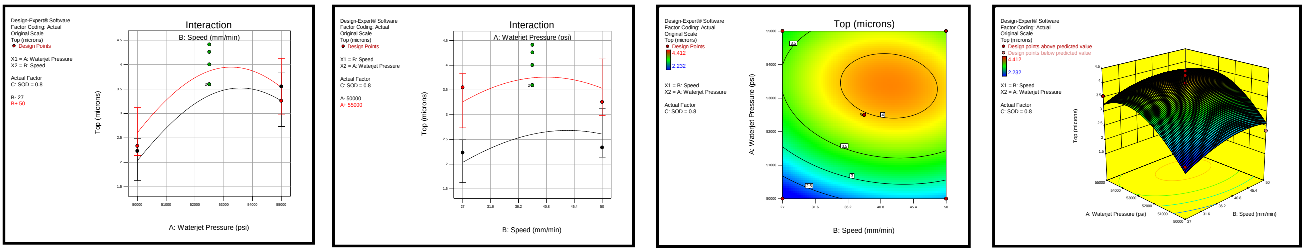
Std. Dev.	0.12	R-Squared	0.8533
Mean	1.81	Adj R-Squared	0.6647
C.V. %	6.45	Pred R-Squared	-0.3751
PRESS	0.89	Adeq Precision	6.270
-2 Log Likelihood	-39.87	BIC	-11.53
		AICc	16.80

Table- 5: Values of signal to noise ratio

A negative "Pred R-Squared" implies that the overall mean may be a better predictor of your response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 6.270 indicates an adequate signal. This model can be used to navigate the design space.

A negative "Pred R-Squared" implies that the overall mean may be a better predictor of your response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 6.270 indicates an adequate signal. This model can be used to navigate the design space.

Figure 6 (a) and (b) shows effect of waterjet pressure and transverse speed on surface roughness when SOD was at the centre point. Surface roughness increases with increasing waterjet pressure but after some time it starts to decrease slightly. This is seen at both the levels of speed i.e. high as well as low levels which are represented by red and black lines respectively in figure 7(a). Similar is the case with Transverse speed, in which the roughness increases with increase in speed, shown in figure 7(b). The contours and three dimensional response surfaces were plotted in figures 6(c) & (d), as a function of the interactions of any two of the factors by holding the other one at average value.



(a) (b) (c) (d)

Fig- 6: Effect of Waterjet pressure and speed on surface roughness when SOD was at centre point. (a) The effect of Waterjet pressure and Speed (fixed) on Surface roughness at top, (b) The effect of Waterjet pressure (fixed) and Speed on Surface roughness at top, (c) Contour plots of effects of Waterjet pressure and Speed and (d) Response surface plots of the effects of Waterjet pressure and Speed on Surface roughness.

Final Equation in Terms of Coded Factors:

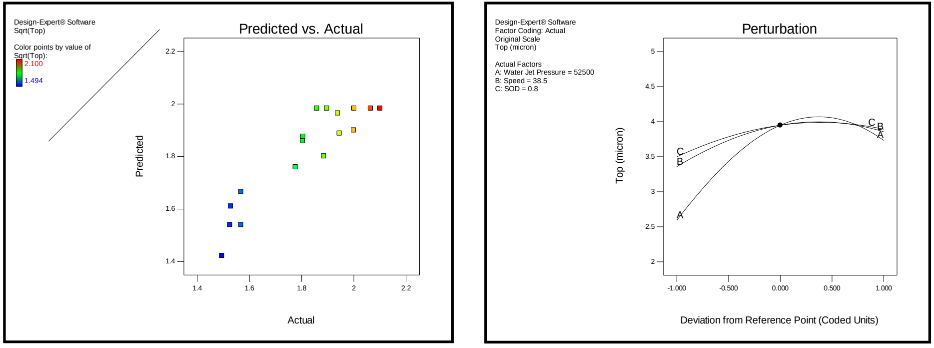
$$\mathrm{Sqrt}\ (Top) = +1.93 + 0.18 * A + 0.078 * B + 0.074 * C - 0.014 * AB + 0.051 * AC - 0.023 * BC - 0.22 * A^2 - 0.022 * B^2 - 0.066 * C^2$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Final Equation in Terms of Actual Factors:

$$\mathrm{Sqrt}\ (Top) = -98.01988 + 3.67550E{-}003 * \text{Water Jet Pressure} + 0.12233 * \text{Speed} - 1.79517 * \text{SOD} - 9.89258E{-}007 * \text{Water Jet Pressure} * \text{Speed} + 8.17831E{-}005 - 0.015816 * \text{Speed} * \text{SOD} - 3.46511E{-}008 * \text{Water Jet Pressure}^2 - 6.75576E{-}004 * \text{Speed}^2 - 1.05263 * \text{SOD}^2$$

The graphical representation of the above said surface roughness model is depicted below in figure 8.



(a) (b)

Fig- 7: (a) Graph of Predicted Vs Actual roughness and (b) Perturbation Graph of Surface Roughness

From figure 7 (a), it is observed that the surface roughness values for 8 runs lie above and 6 below origin line respectively and rest of the values are on the line. The effect of individual parameter on surface roughness was found by plotting the perturbation graph as shown in figure 7 (b).

The effect of machining parameters observed on surface roughness at Top are discussed below:

(a) Effect of Waterjet pressure

The curve with denotation (A) shows the effect of Waterjet pressure on surface roughness. It is revealed form the figure that with increase in waterjet pressure, the surface roughness firstly increases then it decreases slightly. This is because at higher waterjet pressure the kinetic energy of the individual particle inside the jet increases and enhances their capability for the material removal. However, higher waterjet pressure may also result in random collision between the particles due to the large acceleration and also due to more energy from the abrasive to the area bombarded by the water jet hence resulting in a rougher cut.

(b) Effect of Transverse Speed of cutting head

The curve with denotation (B) shows the effect of Transverse speed on surface roughness. It can be seen in the perturbation graph that as the transverse speed increases the roughness also increases this due to the fact that as the cutting head moves faster, less number of particles is available at the time of machining of sample per unit area of sample. Thus, less number of impacts and cutting edges will be available per unit area that results in rougher surface finish. Consequently, the surface roughness is higher at higher transverse speed of cutting head.

(c) Effect of Stand-off distance (SOD)

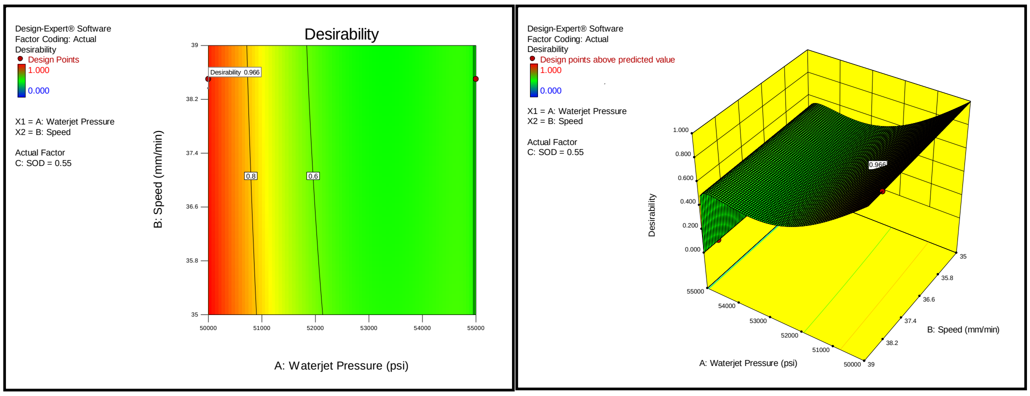
The curve with denotation (C) shows the effect of SOD on surface roughness. The graph shows a rise in surface roughness with increase in SOD in first half but then remains almost constant. This increase in the roughness can be justified by the fact that as the SOD increases the jet diverges more which results in reduced effective jet diameter.

3.2 Parametric Optimization

The optimum solution was obtained by DOE software Design Expert 10 by considering the relation between the three input parameters and response variables. The optimum parameter settings so obtained are given below in Table 6.

Space Parameter	Optimum value
Waterjet pressure	50000.012 psi
Transverse speed	38.363 mm/min
Stand-off distance	0.550 mm
Top	2.379 microns
Middle	2.518 microns
Bottom	2.987 microns

Table- 6: Optimum Values of Parameters in Design



(a) **(b)**

Fig- 8: (a) Optimization contours on surface roughness and (b) Surfaces of possible optimum solutions

4. CONCLUSION

A total 17 experiments were conducted using AWJ machining on 25mm thick SS304 sample. The conclusions based on the experimental results are as follows:

(i) Minimum surface roughness at Top obtained was 2.379 microns.
(ii) Minimum surface roughness at Middle obtained was 2.518 microns.
(iii) Minimum surface roughness at Bottom obtained was 2.987 microns.

(iv) The optimal combination of input parameters is Waterjet pressure 50000.012 psi, Transverse speed 38.363 mm/min and Stand-off distance 0.550 mm.

(v) It was found that waterjet pressure had greater effect on surface roughness at all three positions i.e. top, middle and bottom followed by transverse speed of cutting head and stand-off distance.

(vi) Increase in waterjet pressure and transverse speed of cutting head significantly affected the surface roughness parameter which increased with increase in both the parameters. Whereas change in SOD had just marginal significance on surface roughness which increased the surface roughness with increase in SOD.

REFERENCES

[1] Birtu C., & Avramescu V. (2012), *"Abrasive Water Jet Cutting - Technique , Equipment , Performances, Nonconventional Technologies Review",* (Romanian Association of Nonconventional Technologies Romania, March-2012), pp. 40–46

[2] Sheikh-Ahmad J. Y.," *Non-traditional Machining of FRPs, Machining of Polymer Composites"* (Springer Science + Business Media, 2009), pp. 237-289.

[3] Hascalik A., Caydas U., Gurun H., "*Effect of traverse speed on abrasive water jet machining of Ti-6Al-4V alloy"* (Materials and Design, 28, 2007), pp. 1953-1957.

[4] Sheikh-Ahmad J. Y., "*Non-traditional Machining of FRPs, Machining of Polymer Composites"* (Springer Science + Business Media, 2009), pp. 143-231.

[5] Kolahan F., Khajavi A. H., "*Modelling and Optimization of Abrasive Waterjet Parameters using Regression Analysis"* (World Academy of Science, Engineering and Technology, 35,2009), pp. 488–493

[6] Begic-Hajdarevic B., Cekic A., Mehmedovic M., Djelmic A., "*Experimental Study on Surface Roughness in Abrasive Water Jet Cutting"*, (Procedia Engineering 2015), pp. 100:394–399.

[7] Holmqvist G.,.Honsberg U., "*Sensitivity analysis of abrasive waterjet cutting economy",* (Proceeding of 19th International Conference on Water Jetting, Nottingham University, UK, 2008), pp. 273–287.

[8] Jacqueline K. Telford, "A Brief Introduction to Design of Experiments", (Johns Hopkins APL Technical Digest, Volume 27, Number 3 2007), pp. 224