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Effect of Abrasive Water Jet Turning AWJT Parameter Setting on Surface Finish of Inconel 718

Kasim, M. S [1*], Kasman Z. [1], Jefri, A. S [1], Mohamad, W. N. F. [1], Hambali, A.[1], Hafiz[1], M. S. A., Husshini[1], N. H. N., Mohamed, S. B [2], Izamshah, R.[1], and Ito, T. [3]

[1]Advance Manufacturing Center, Fakulti Kejuruteraan Pembuatan, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia
[2]Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, 21300 Kuala Terengganu, Terengganu Darul Iman, Malaysia
[3]Faculty of Computer Science and Systems Engineering, Okayama Prefectural University, Okayama, 719-1197 Japan

ABSTRACT

This research article aims at comparing the cutting performance of Inconel 718 during abrasive waterjet turning (AWJT). In this study, the various combination processing parameters were performed namely; depth of cut (DOC), traverse speed, and rotational speed. Three factors and two levels of full factorial involving 8 experimental runs were done during this study. This design of the experimental approach is to establish a correlation between controlled parameters input and experimental outputs. The response to be evaluated is surface roughness. The significance of AWJT parameters on this surface roughness was determined statistically using the analysis of variance method. The experimental results have revealed the surface quality of the cylindrical surface was extremely affected by the depth of cut followed by interaction between traverse speed and rotational speed. The optimum parameter set in minimizing surface finish is DOC 0.3 mm, traverse speed of 3 mm/min, and rotational speed of 90 RPM. This knowledge obtained from these results and optimization provides information for industrial applications.

Keywords: Abrasive waterjet turning, Inconel 718, surface roughness, full factorial

1. INTRODUCTION

Inconel 718 (IN718) is a nickel-chromium-based austenitic superalloy. This material is prominently known as a hard material. It exhibits the best mechanical and chemical characteristics that withstand harsh environments make it the chosen material in various industrial applications. The turning process is the traditional method of producing a cylindrical shape. However, the hard particle content and gummy property of Inconel 718, leads to rapid tool life during removing processes. These were numerous cutting strategies toward refining the efficiency of operation and improving the quality and productivity [1], [2].

The conventional cutting especially turning process having limited MRR, which is controlled by feed rate, depth of cut, and width of cut as to compensate with tool life and surface finish [3]–[5]. Many researchers have contributed their studies on improving the surface finish of Inconel 718 by optimizing process parameters, study by [6] indicated the surface roughness with the minimum surface finish of 0.33 µm. As the limitation of conventional is tool wear and surface roughness issues due to the heat generated and friction, several strategies have been proposed to improve the machinability of this material [7]. Abrasive waterjet is another removing process by the erosion process where the material is removed physically by multiple high-velocity water streams with the aid of abrasive particle. Nowadays, abrasive water jet (AWJT) machining techniques have gained high interest among researchers as an alternative for conventional

* shahir@utem.edu.my

turning. AWJT process is a method that uses waterjet technology and is integrated with the turning mechanism to enable produce cylindrical shapes [8]. This approach was introduced for solving various issues especially cutting machining hard-to-machine materials. Abrasive water jet (AWJ) cutting process can be used in industrial applications where require no microstructure deformation or minimum machine affected zone [9]. Abrasive water jet machine enables the production of intricate part profiles with high levels of precision requirement, surface quality and productivity dimensional accuracy and productivity of Inconel 718 [10].

There were major process parameters in the AWJ machining process; material to be cut, waterjet pressure, traverse rate, abrasive configuration, abrasive flow rate, nozzle stand-off distance, and angle [11]. Additional parameters for AWJT are rotational speed and depth of cut. A review done by Llanto et.al. indicated that nozzle motion speed greatly affects cutting performance, followed by the flow rate of abrasive particles and water jet pressure [12]. Similar to the turning process, increasing the depth of cut reduces the surface quality. Some researchers used angle impact terminology indicating the water stream away from the workpiece periphery. The extreme position is a normal impact condition where the jet nozzle position above the axis of rotational part; means 100% depth of cut; where low angle impact when the jet stream tangential cut at the periphery of the round workpiece. A study by Manu and Babu indicated the AWJ stream with a low angle of impact better surface finish than a high impact angle. The normal impact produces a poor surface finish but improves productivity [13]. A study by Ravi et. al. using response surface methodology on aluminum/tungsten carbide composite indicated that the MRR is greatly affected by transverse speed, material composition, and standoff distance [14].

Surface finish is one of the issues during AWJ cutting besides geometrical issue; barrelling effect, the taper on the kerf profile. Further investigation on the process parameters, these undesirable surface quality, and geometrical defects caused by abrasive water-jet cutting mechanism. This is mainly attributed to the water-jet energy characteristics as well as the features of the material to be cut. The error is caused by the waterjet spreading profile which having different regions in the water jet stream. Roughness is a manifestation of the quality during the cutting process that may influence the service performance, since irregularities on the surface may form the initial location for cracks or corrosion. In tribology, good surfaces surface finish promotes the wear process more slowly and may have lower coefficients of friction than rough surfaces. For some applications, a high coefficient of friction may be favourable to improve adhesion for the finishing process [15], [16]. Based on the anatomy of the waterjet stream, it can be divided into two sections; axial (horizontal) distances consist of the potential core region, main region, and diffused droplet region. On the radial (vertical) distance, it consists of the water droplet zone, water mist zone, and highly diffused water droplet zone. Each zone possesses different abrasive cutting energy to erode the workpiece. The pressure is maximum at the nozzle centreline and its distribution is Gaussian in the radial (vertical) direction [17], [18]. Water and particle velocities decreased as the radial and axial increases [19], [20]. The surface finish and V shape of kerf width formation are due to the lost kinetic energy due to workpiece-nozzle distance and nozzle centreline-kerf edge distance. The standoff distance greatly affects the kerf width [21].

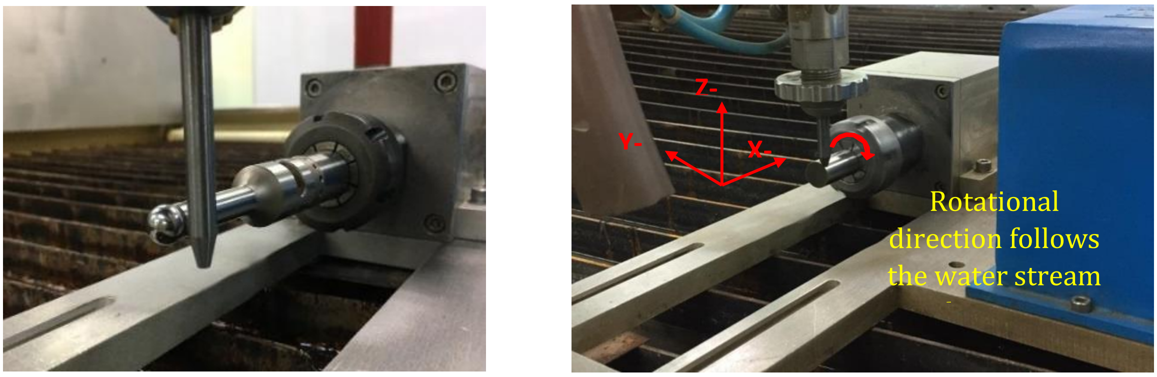
2. EXPERIMENTAL PROCEDURE

To investigate the surface quality and dimensional accuracy of AWJT cutting of Inconel 718. A Flow-March 2b CNC abrasive water jet machine was pumped with high pressure of 400 MPa. The samples were cut 20 mm length at a nozzle traverse speed of 1-3 mm/min. This computer-controlled nozzle having straight accuracy of ±0.07 mm and repeatability of ±0.06 mm. The nozzle used was 76.2 mm in length, and the orifice used was 0.25 mm in diameter. The working pressure for this nozzle is 400 MPa. It is a service life of up to 200 hours. A tiny orifice made of very hard material such as sapphires 6. The standoff distance was set at 8 mm; consider within the continuous jet region.

(a) (b)

Figure 1 (a) shows the coordinate setting for vertical and horizontal positions before the cutting process. The coordinate value obtain requires compensation for the radius of the jet stream.
(a) (b)

Figure 1(b) shows the sample setup with oblique jet impact cutting configuration. The waterjet moves along the axial of the rotating cylindrical specimen. Garnet sand is categorized as silicate minerals. In this project, the type of garnet with silicon carbide mesh size 80 was used in the experiment.



(a) (b)

Figure 1. Machining setup. (a) Zero position of Y-axis by using an electronic edge finder; (b) sample of the tested material.

Olympus BX51M metallurgical microscope equipped with a digital camera was used to capture the microscopic image of AWTJ specimens. This microscope has 7 levels of magnification. Full factorial is employed to describe the correlation between AWJT parameters and responses. There are 8 samples with a diameter of 16 mm and a length of 50 mm. All the levels were set in small value to dedicate to turn Inconel 718 round bar. Traverse speed beyond 7 mm/min for AWJT forms a striation on cut surfaces (treaded-like shape) on the specimen. The details of variable and fixed input parameters are detailed in Table 1. Whereas the responses to be measured are surface roughness, roundness, eccentricity, and dimensional accuracy. The data gathered will be evaluated by Analysis of Variance (ANOVA). ANOVA is a technique for check the adequacy of the models developed by full factorial. ANOVA also to be used to analyse variation in response. The significance of the model and parameter can be determined when the p-value less than 0.05.

Table 1 Experimental Parameters of AWJT Settings

Input	**Parameter**	**Value**
Variable parameters	Depth of cut, ap (A)	0.1 mm - 0.3 mm
	Traverse speed, f (B)	1 mm/min - 3 mm/min
	Rotational Speed, N (C)	60 rpm - 90 rpm
Fixed parameters	Stand-off distance, z	8 mm
	Surface distance	20 mm
	Jet angle	90˚
	Water pressure, P	340 MPa
	Water velocity	4.116 x 107 mm/min
	Rotational direction	Clockwise

The response to be measured namely surface roughness. Surface roughness is a component of cutting quality and plays an important criterion in determining how an object will perform during operation especially interaction between mating parts. Workpiece surface roughness (Ra) was measured using a stylus type profilometer, Mitutoyo Surftest 301. The stylus traversing distance, L, was set to 1.25 mm with cut-off, λc, at 0.25 mm which complies with JIS 1994. Measurements were taken along the sample axis, parallel to the cutting traverse direction. Each specimen result is based on the average of five total roughness measurements were taken for each cutting parameter at a random location.

3. RESULTS AND DISCUSSION

The results of the sample under different AWJT conditions are measured and listed in Table 2. The surface roughness, Ra, from the whole data set exhibited a good surface finish equivalent to N8 grade. Based on the result of the previous study, the result shows the turned surface is comparable to the abrasive water jet [10] [10] and conventional turning process [22]. The Ra value ranging from 4.002 – 4.504 µm with the standard deviation (STD) 0.20-0.51 µm among the five measurement areas for each sample. Roughness is the importance that contributes to function and performance. Friction between both mating components is unavoidable. The process to keep to the minimum surface roughness to reduce energy losses due to friction.

The image of maximum sample Ra values is given in Table 2. It can be seen the surface profile for sample 5 much smoother than sample 3. Figure 2 shows the surface profile where no striations mark on the AWJT surface event during the highest traverse speed (3 mm/min).

Table 2 Experimental Result from Surface Roughness Testing

Run	DOC, ap (mm)	Traverse Speed, f (mm/min)	Rotational Speed, N (rpm)	Roughness, Ra (µm)	
				Average	Std. Dev
1	0.3	1	90	4.086	0.50
2	0.1	3	60	4.314	0.51
3	0.3	1	60	4.504	0.24
4	0.1	1	90	4.002	0.20
5	0.1	1	60	3.792	0.46
6	0.3	3	90	4.088	0.34
7	0.1	3	90	4.212	0.32
8	0.3	3	60	4.196	0.30

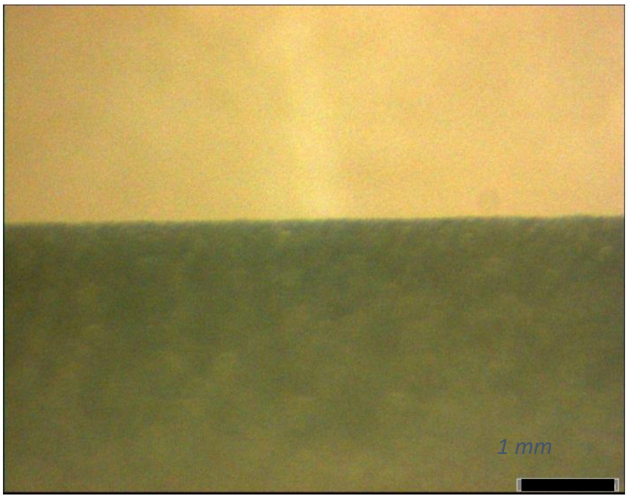
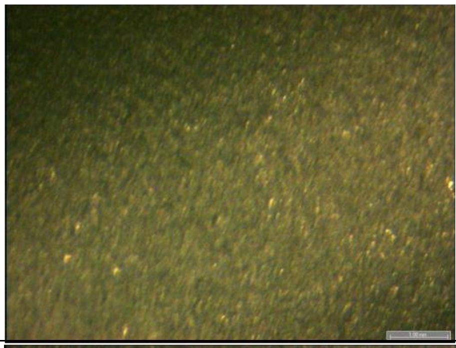
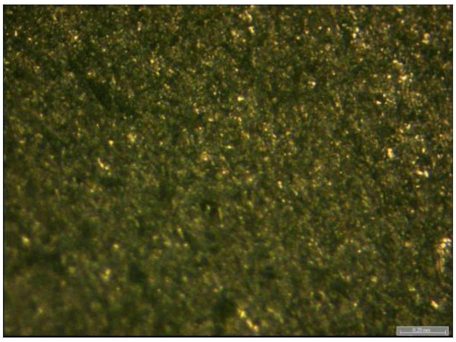
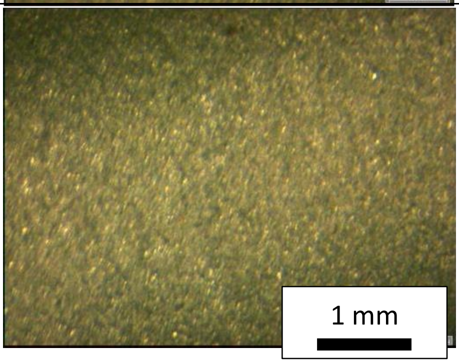
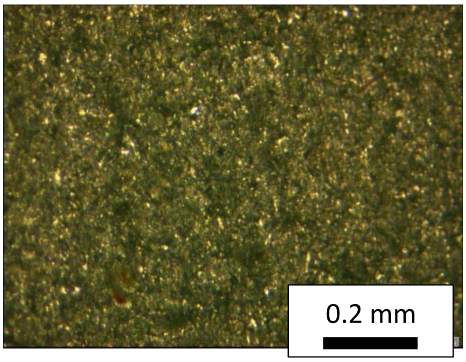


Figure 2. No striations mark presents on the specimen at a traverse speed of 3 mm/min.

Table 3 The Results of Surface Roughness Picture by Using the Optical Microscope

Surface Roughness	Scope 1x	Scope 5x
Minimum Ra value, 3.792 µm (Specimen 5; DOC= 0.1 mm, traverse speed= 1 mm/min, rotational speed= 60 rpm)		
Maximum Ra value, 4.504 µm (Specimen 3 DOC= 0.3 mm, traverse speed= 1 mm/min, rotational speed= 60 rpm)		

ANOVA for surfaced roughness is shown in Table 4. The P-Value 0.0401 implies the linear model is significant against regression. Among the parameter inputs, it can be seen that all the single and two-factor interaction (2FI) factors having a p-value less than 5% which means significant. The only interaction between DOC and traverse speed slightly beyond 0.05 to be marginally significant. Based on the F-value, the depth of cut factor (A) found the most major contribution on the surface finish, followed by interaction between term traverse speed and rotational speed (BC), the interaction between DOC and rotational speed (AC), traverse speed (B), rotational speed (C) and interaction between DOC and traverse speed (AB). There is a 4.10 % chance F-Value model could happen due to noise. It was supported with the R^2 of 0.99 where is a very good correlation.

Table 4 The Results of ANOVA for Surface Roughness

Sources	Sum of Squares (SS)	Degrees of Freedom (DF)	Mean Square (MS)	F value	Prob>F	
Model	0.320	6	0.053	364.51	0.0401	Significant
DOC (A)	0.130	1	0.130	875.46	0.0215	Significant
Traverse speed (B)	0.043	1	0.043	297.06	0.0369	Significant
Rotational speed (C)	0.025	1	0.025	175.17	0.0480	Significant
AB	0.023	1	0.023	156.99	0.0507	Marginally significant
AC	0.048	1	0.048	334.67	0.0348	Significant
BC	0.050	1	0.050	347.71	0.0341	Significant
Residual	1.445×10^{-4}	1	1.445×10^{-4}			
Total	0.320	7				

Based on ANOVA, a prediction equation in terms of actual units is generated. A prediction linear model of surface roughness, Ra model of AWJM can be denoted by Eq. 1.

$$Ra = 2.48 + (3.70\,ap) + (0.43\,f) + (0.025\,N) - (0.53\,ap \cdot f) - (0.052\,ap \cdot N) - (5.28 \times 10^{-3}\,f \cdot N) \qquad (1)$$

Where ap: depth of cut, f: traverse speed, N: rotational speed.

Figure 3 shows the response graph between the depth of cut and traverse speed on the AWJT surface quality. By looking at the graph, reducing the depth of cut will increase the surface roughness. It can be seen clearly during traverse speed of 3 mm/min. The graph also shows the surface roughness statistically slightly improved during faster traverse speed. However, this phenomenon was not too obvious to compare to the effect of the DOC. Increasing DOE will decrease the surface roughness. That is because the workpiece close to the cone zone which having more energy density and higher cutting pressure. The abrasive particle with kinetic energy is more intense produces an overlapping affects so that the material can be removed effectively. Therefore, the surface quality much better when the material exposes more toward the high-density zone rather than the mist zone (
Figure **4**).

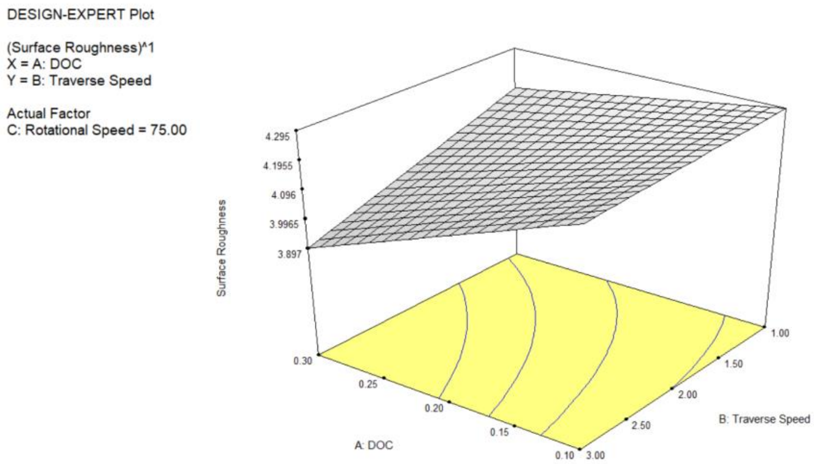


Figure 3. Response graph between depth of cut and traverse speed on surface roughness.

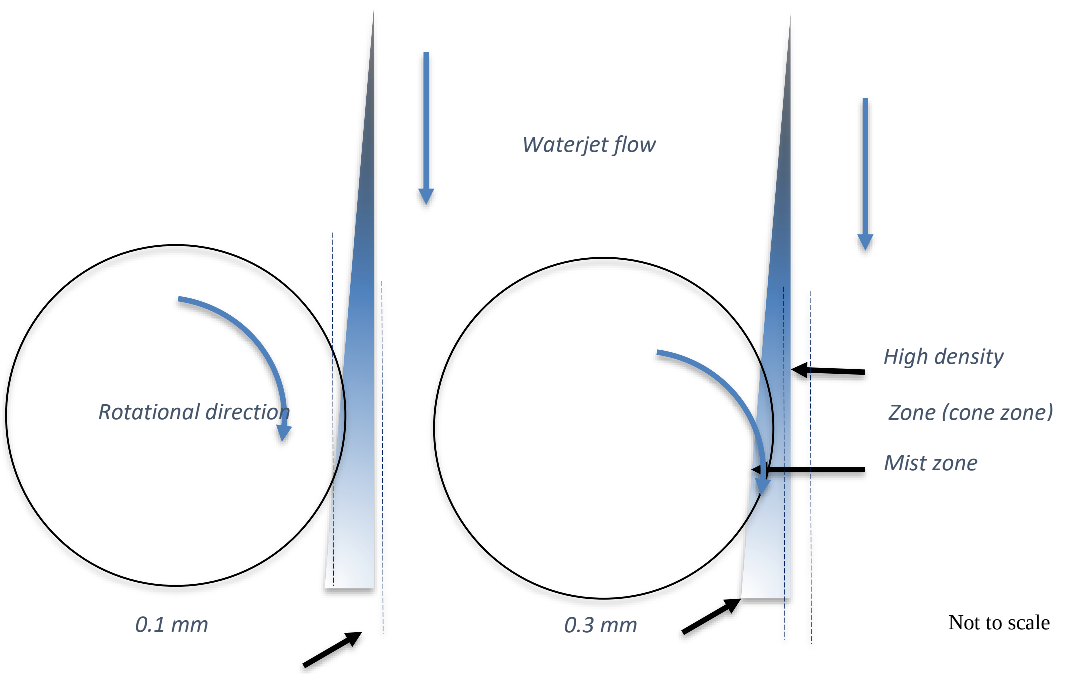


Figure 4. Schematic diagram showing half of the waterjet spreading profile; the energy density distribution of waterjet mixture varied along the radial direction that effect on surface finish.

Figure **5** shows the response graph of a relationship between depth of cut and rotational speed on the surface roughness. Increasing rotational speed will increase surface roughness. It can be more obvious during DOC of 0.1 mm. Conversely, during DOC 0.3 mm. The surface roughness slightly decreases as the rotational speed increases.

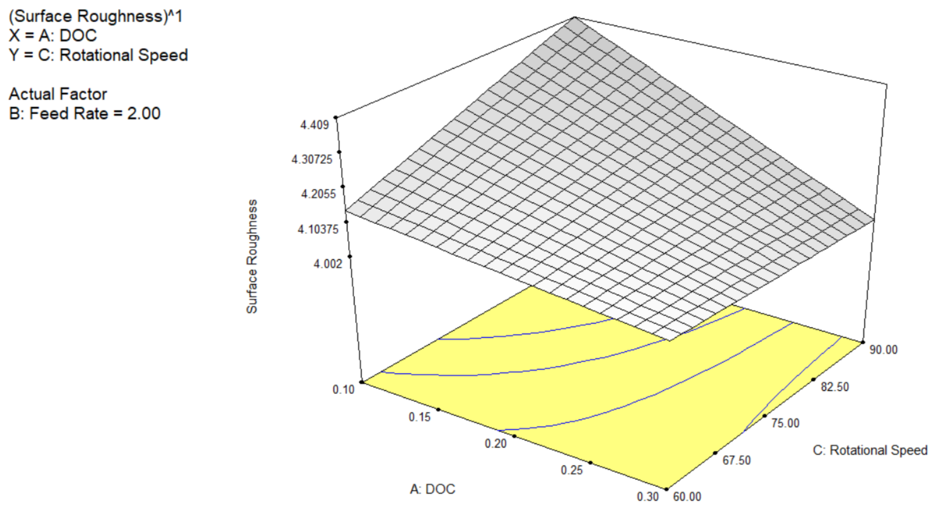


Figure 5. Response graph of a relationship between depth of cut and rotational speed on surface roughness.

A similar trend occurs in the response between traverse speed and rotational speed as shown in Figure 6. During traverse speed 1 mm/min, the surface finish increases more significantly as the rotational speed increases. However, the value does not change significantly when the traverse speed 3 mm/min.

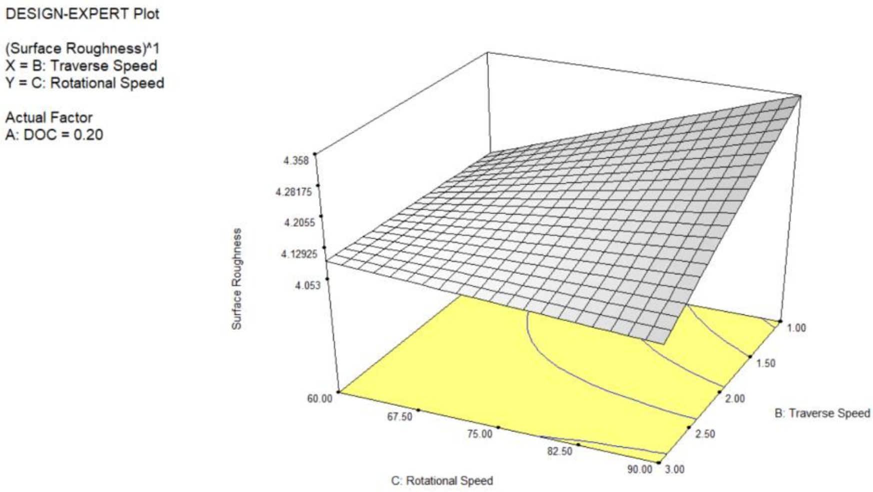


Figure 6. Interaction graph for surface roughness by the effect of traverse speed and rotational speed.

Figure 7 shows the perturbation plot for multi-objective optimization. As to achieve minimum surface roughness (3.796 µm). The suggested parameters are; DOC 0.30 mm, traverse speed 3 mm/min, and rotational speed 90 RPM.

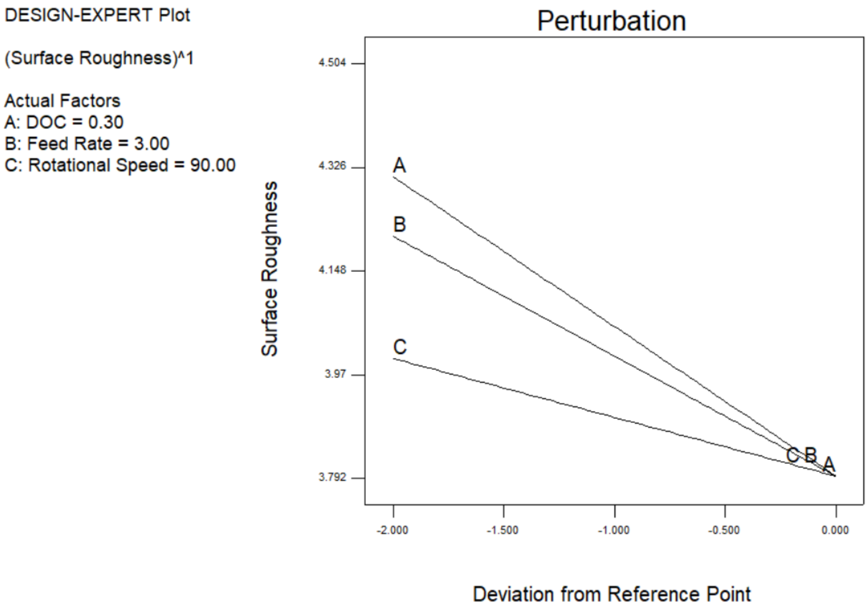


Figure 7. Perturbation plot for surface finish optimization.

4. CONCLUSION

The surface finish and dimensional accuracy of AWJT Inconel 718 were carried out. Based on the experiment, several conclusions can be rendered:

- Abrasive waterjet turning of Inconel 718 results shows a finished quality equivalent to smooth machining, N8 grade.
- All the input parameters are significant on surface roughness.
- The combination parameters were suggested to achieve the minimum surface finish.

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