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OPTIMIZATION OF SURFACE ROUGHNESS AND CONE ANGLE IN AWJ MACHINING OF AIRCRAFT MATERIAL USING RSM

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Abstract

Abrasive water jet machining (AWJM) of aircraft material is a difficult process using conventional machines. Machined parts of Inconel 718, a nickel-based alloy (aircraft material) are widely used in the aerospace industries. However, these alloys are expensive and difficult to machine. The objective of this article is to optimize AWJM process parameters. Response Surface Methodology (RSM) is planned with travel speed, abrasive flow rate, and stand-off distance as inputs. The response models of surface finish and cone angle show the correlation coefficient `$R^2$` of 96.94% and 96.67%, respectively. 3D surface plot with analysis of variance (ANOVA) is presented to distinguish significant AWJM parameters. The work revealed that travel speed is a significant factor for surface finish and cone angle. Multi-response optimization results in the best optimal values of traverse speed; abrasive flow rate and standoff distance are 200 mm/min, 460 g/min, and 4 mm respectively. This research outcome showed more than 90 % of accuracy for both the responses. This article is helpful to the AWJM centers to select optimal machining parameters for achieving the desirability in the machining of Inconel 718. The obtained novel results confirmed that such a technique can be implemented to identify optimal parameters in the machining of different materials.

Keywords

Abrasive Water Jet Machining (AWJM), Inconel 718, Surface Finish, Cone Angle, Response Surface Methodology (RSM)

1. Introduction

In advanced manufacturing processes, to meet the high-quality surface finish demands of various parts in aerospace, unconventional machines have been widely utilized, especially for the "difficult to machine" super-alloys (Saha, 2016 and Junwei-Wang et al., 2019). The technology of Abrasive water jet machining (AWJM) not only ensures quality parts but also considerably simplifies the complex processes and controls the machining cost. In AWJM, the abrasives are permitted to entrain in a water jet to form an abrasive water jet with a velocity of 800 m/s. Such a high velocity of the abrasive jet can machine all materials. In this process, the material is eradicated by the erosive wear process, in which the material is exposed to a high-speed water jet that accelerates the abrasive particles. Therefore, it shows many advantages, like no thermal damage, high flexibility to machining, minimal cutting forces, etc over other machining processes (Madankar, Dumbhare, Deshpande, Andhare & Barve, 2021; Dumbhare, Dubey, Deshpande, Andhare & Barve, 2018).

Surface roughness is a significant factor directly linked to the functional requirements of the components being machined. Component damage usually begins at the surface due to remote manufacturing. Therefore, surface roughness study is essential for several applications related to friction, fatigue, and part wear control reported by Blau, 2008 and Deshpande, Andhare & Sahu, 2017. At AWJM, good surface quality is achieved with low material thickness at high cutting speed and vice versa, which is why surface roughness is a dominant factor in determining the quality of a product. This factor also influences the manufacturing costs due to the high demands on a fine surface quality (Madankar et al. 2021; Çaydaş U, Hascalık 2008).

2. Literature Review

Researchers predict the significance of AWJ machining parameters on responses such as cone angle, surface finish, material removal rate, etc. in the machining of metals. Modelling and optimization techniques are usually preferred to estimate the optimum process parameters (Deshpande, Andhare, Padole, 2018). Therefore, recently reported studies on AWJM are discussed in the subsequent paragraph.

Madankar et al., (2021) examined the effect of traverse speed on the surface finish for plate thicknesses of 4 mm, 6 mm and 8 mm in AWJ machining of AISI 1030 steel. RSM is used to develop response models which showed more than 90% accuracy. Dumbhare et al., (2018) investigated the effect of - traverse speed, abrasive flow rate and standoff distance on surface roughness and kerf taper angle during AWJM of mild steel. Taguchi approach is used for planning the experiment. It is reported that traverse speed is the most significant factor for surface roughness and kerf taper angle followed by stand-off distance and abrasive flow rate. Later on, optimum values of abrasive flow rate, standoff distance and traverse speed are predicted at 420 g/min, 3 mm and 85 mm/min respectively using Response surface methodology (RSM). Samson et al., 2020, accomplished the Taguchi method in abrasive jet machining of Inconel 718. The flow rate of abrasive, pressure and standoff distance are selected as machining input parameters. Surface finish, taper angle, material removal rate and roundness are measured to establish the qualities of the washer. VIKOR method is used to recognize the optimum parameters like the flow rate of abrasive, pressure and standoff distance are 0.42 kg/min, 180 MPa and 2 mm respectively. Uthayakumar, Khan, Thirumalai-Kumaran, Adam, & Zajac, 2016, performed the machining of Inconel 600 with an abrasive water jet cutter. The machining parameters such as water jet pressure, traverse speed and standoff distance are used to analyze kerf width, kerf wall inclination and MRR. Water jet pressure is the most significant factor for material morphology and surface quality. It is reported that AWJ machining of Inconel 600 can offer a superior surface finish at high pressure with moderate traverse speed. Bhandarkar Singh, & Gupta, 2020, presented AWJ machining of Inconel 718 using traverse speed and pressure to obtain the desired surface quality. It is reported that abrasive particles are infused on the machined surface at low speeds resulting in a good surface finish. Tripathi et al., 2021, study examined the influence of the AWJ machining parameters. The correlation of input parameters such as traverse speed, and flow rate of abrasive with surface finish, material removal rate, roundness and cylindricity are presented. The optimal machining condition for traverse speed and flow rate of abrasive is established as 100 cm/min and 300 gm/min respectively

3. Research Finding and Work Scope

From the literature studies, it is noticed that researchers used various techniques like regression, Taguchi, RSM, etc. for modelling of AWJM parameters. To assure accurate geometries and exceptional performance of Aircraft material, Inconel 718, as it is promptly used in aircraft applications. However, the low thermal conductivity of such alloy poses a very high temperature during the machining which affects the surface quality. Therefore, the machining of Inconel 718 is a common challenge to the shop floor industries (Junwei-Wang et. 2019; Samson et al., 2020; Uthayakumar et al., 2016; Li et al., 2015; Deshpande et al., 2019).

A very few studies have been reported in AWJM of aircraft material, Inconel 718, to estimate and optimize surface finish and cone angle based on the computation techniques. In the present study, AWJM of Inconel 718, involving modelling and optimization of surface finish and cone angle is characterized systematically. A novel optimized result is proposed. The research methodology of the AWJ machining process is presented in the following flow chart for easy outlook.

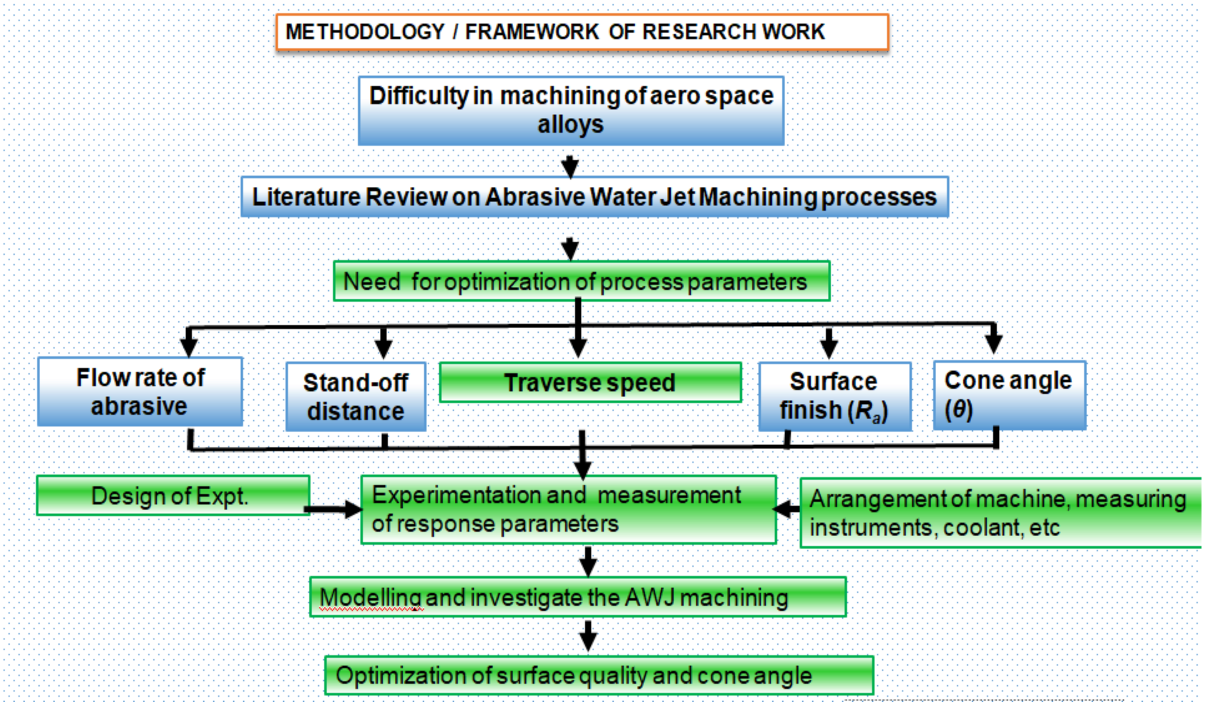


Figure 1: *AWJ machining process*

(Source: Author's own work)

4. Experimentation

In this work, Inconel 718 plates of dimension 50mm x 30mm having thickness 12 mm were machined through AWJM and used for experimentation. Inconel 718 is commonly used for industrial applications due to its desirable properties. Specifically, it is used in turbomachinery of aircraft systems. **Figure 1** shows the experimental set-up of AWJM made of TOPS (Model: SJA T300).

Figure 1: *AWJ machining set-up*

(Source: Compiled by author)

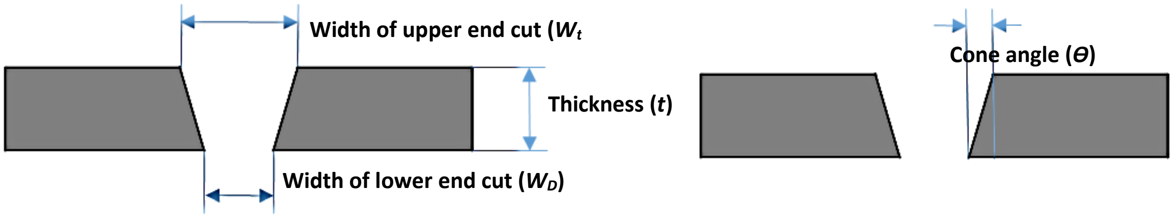
In this experimentation, the flow rate of abrasive, stand-off distance and traverse speed are preferred as input machining parameters and surface finish (R_a) and cone angle (θ) is for the responses. Five levels of all input parameters are selected as the flow rate of abrasives (370, 390, 420, 450, 470 g/min), stand-off distance (1.6, 3, 5, 7, 8.3 mm) and traverse speed (66, 182, 546, 910, 1158 mm/min) for the design of experiment using RSM.

Input design matrix to conduct the experimentation is generated in MINITAB 17 software. After experimentation, the machined part is measured with a surface finish tester (Make: Mitutoyo) as shown in **Fig. 2**. The cone angle is measured in terms of upper and lower kerf width with absolute digimatic calliper (Make: Mitutoyo). The measured responses with input parameters are tabulated in **Table 1**. **Figure 3** shows θ, W_t, W_d and t which represent cone angle (kerf taper angle), the width of upper end cut, the width of lower end cut and thickness of machined part using Equation (1) (Dumbhare et al., 2018a; Gupta, Gag, atra & Khanna, 2013).

$$\theta = tan^{-1}(\frac{W_t - W_d}{2t}) \qquad (1)$$

Figure 2: *Surface finish tester*

(Source: Compiled by author)



(a) **(b)**

Figure 3: *Schematic of cone angle measurement*

(Source: Compiled by author)

Table 1: *Design matrix and measured responses*

Exp. No.	*A_f (g/min)*	*S_d (mm)*	*T_v (mm/min)*	*R_a (µm)*	*θ (deg)*
1	420	8.3	546	3.5	1.9
2	420	5	546	3.3	1.8
3	420	5	546	2.9	1.75
4	450	3	182	1	1.3
5	420	1.6	546	2.2	1.6
6	420	5	546	2.8	1.7
7	390	3	910	3.8	2
8	450	7	182	2.5	1.6
9	370	5	546	3.9	2
10	470	5	546	2.1	1.5
11	420	5	66	2.2	1.5

12	390	7	910	4.3	2.1
13	420	5	546	2.5	1.65
14	420	5	546	3.1	1.8
15	420	5	1158	4.4	2.2
16	390	3	182	2.4	1.6
17	450	7	910	3.3	1.85
18	420	5	546	3	1.8
19	390	7	182	4	2
20	450	3	910	3.6	1.9

(Source: Compiled by author)

5. Results and Discussion

In this section, the effect of cutting parameters like flow rate of abrasive, stand-off distance and traverse speed on the surface finish (R_a) and cone angle (θ) is presented using main effect plots and surface plots developed by RSM. The multi-objective optimization of the cutting parameters with the aim of minimization of surface roughness and cone angle is established with the validation of optimum results.

5.1. Application of RSM

Response surface methodology (RSM) is a statistical technique that makes formative functional correlation among the dependent parameter (y) and a group of independent parameters Is presented in **Eq** P is the coefficients that are designed using the least squared method and RSM is performed by way of the fitted surface.

$$y = P_0 + \sum_{i=1}^{k} P_i X_i + \sum_{i=1}^{k} P_{ii} X_i^2 + \sum\sum_{i<j} P_{ij} X_i X_j + \varepsilon \qquad (2)$$

5.2. For Surface Finish

Analysis of variance (ANOVA) assists to assess the relative weights of all control factors. It presents an idea about the main effects, interaction effects as well as 3D effects of factors. A regression model for R_a is presented in **Eq. 3**, the details of ANOVA is tabulated in **Table 2**.

$$\boldsymbol{R_a} = 15.3 - 0.0553\,\mathrm{Af} + 1.295 - 0.00502\,\mathrm{Tv} + 0.000044\,\mathrm{Af} * \mathrm{Af} - 0.0034\,\mathrm{Sd} * \mathrm{Sd} + 0.000001\,\mathrm{Tv} * \mathrm{Tv} - 0.00188\,\mathrm{Af} * \mathrm{Sd} + 0.000019\,\mathrm{Af} * \mathrm{Tv} - 0.000498\,\mathrm{Sd} * \mathrm{Tv}$$
$$(\boldsymbol{R^2} = 96.67\,\%)(\boldsymbol{R^2}_{\boldsymbol{adj}} = 93.68\,\%) \tag{3}$$

Equation 3 (regression model) specifies derided values of F and p as 32.27 (high) and 0.0001 (low) respectively. Mean absolute inaccuracy (MSI) is obtained as 1.5 % for surface finish. Similarly, R^2 and R^2_{adj} values are 96.67 % and 93.68 % respectively, which offers a fine association between measured and expected values.

Table 2: *ANOVA for surface finish*

Parameters	DF	Adj. Sum of squares	Adj. Mean square	F-value	p-value
Model	9	13.04	1.48	32.27	<0.0001
Af	1	3.01	3.01	65.40	<0.0001
Sd	1	1.45	1.45	31.58	<0.0001
Tv	1	5.94	5.94	128.77	<0.0001
Af Af*	1	0.0224	0.0224	0.49	0.0502
*Sd*Sd*	1	0.0027	0.0027	0.06	0.813
Tv Tv*	1	0.1999	0.1999	4.33	0.064
*Af*Sd*	1	0.1013	0.1012	2.19	0.169
*Af *Tv*	1	0.3612	0.3612	7.83	0.019
*Sd*Tv*	1	1.0512	1.0512	22.77	0.001
		R^2			**96.67 %**
		R^2_{adj}			**93.68 %**

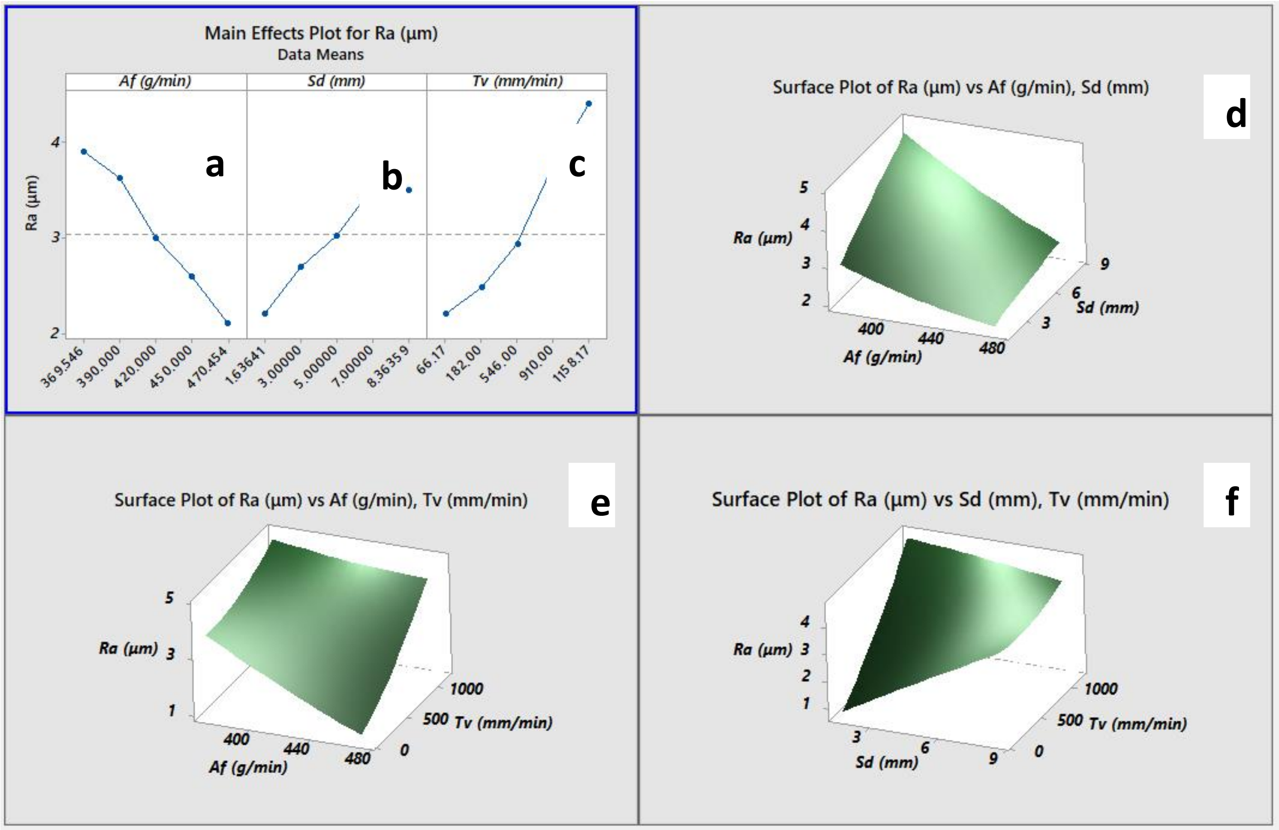


Figure. 4: *Main effect (a, b, c) and 3D plots for R_a (d, e, f)*

(Source: Compiled by author)

The parametric investigation to study the effects of A_f, S_d, and T_v on R_a are presented in **Fig. 4** using RSM. It shows the means for each set within a definite variable. As, the stream rate of abrasive rises, the surface finish increases. As, the stream rate of abrasive rises, the surface roughness decreases. It can be perceived from **Fig. 4a**, that a lower surface finish is achieved at a low flow rate whereas a good finish is attained at a high value of flow rate. Hence, it is noticed that a rise in flow rate offers a smoothening effect on the machined surfaces (Dumbhare, et al., 2018). For the case of stand-off distance, the surface finish is deteriorating when the stand-off distances increased from 1.6 to 8.3 mm shown in **Fig. 4b**. It means that stand-off distance permits the increase in jet diameter earlier to impingement which may rise predisposition to external drag from the touching location. So, an increase in the stand-off distance enhances the jet diameter as cutting is started. This marks a reduction of kinetic energy and jet density at impingement outcomes with uneven surfaces. However, at low density of abrasives at the exterior perimeter of the expanded jet (outer rim) produces peaks and valleys (Bhowmik and Ray, (2017). Henceforth, a lower stand-off distance is expected that might be produced better surface quality on the machined portion. **Figure 4c** shows an increase in traverse speed increases the roughness. It happens, because of less number of abrasives may pass over a unit area accompanied with less overlap machining action. Hence, a minimum impact on the cutting area results in uneven surfaces (Dumbhare, et al., 2018; Bhowmik and Ray, (2017). **Figure 4 (d, e, f)** specifies the combined effect of dual variables which are presented in association with 3D surface plots.

5.3. For cone angle

Given the cone angle, a developed regression model is presented in **Eq. 4. Table 3** shows the parametric analysis with desired F and p values using RSM. It displays an F-value of 35.14 (high) and p-value less than 0.0001, indicating that the used AWJ machining inputs (A_f, S_d and T_v) are significant**.** R^2 and R^2_{adj} values are 96.94 % and 94.18 % respectively, which indicates a good association between experimental and expected values.

$$\boldsymbol{\Theta} = 3.44 - 0.0072\,\mathrm{Af} + 0.318\,\mathrm{Sd} - 0.000931\,\mathrm{Tv} + 0.000004\,\mathrm{Af}*\mathrm{Af} + 0.00081\,\mathrm{Sd}*\mathrm{Sd} + 0.000000\,\mathrm{Tv}*\mathrm{Tv} - 0.000521\,\mathrm{Af}*\mathrm{Sd} + 0.000004\,\mathrm{Af}*\mathrm{Tv} - 0.000112\,\mathrm{Sd}*\mathrm{Tv} \quad (\boldsymbol{R^2} = 96.94\,\%)(\boldsymbol{R^2}_{\boldsymbol{adj}} = 94.18\,\%) \tag{4}$$

Table 3: *ANOVA for cone angle (Ɵ)*

Parameters	**DF**	**Adj. Sum of squares**	**Adj. Mean square**	**F-value**	**p-value**
Model	9	0.9377	0.1041	35.14	<0.0001
Af	1	0.2201	0.2201	74.26	<0.0001
Sd	1	0.0768	0.0768	25.91	<0.0001
Tv	1	0.4844	0.4844	163.41	<0.0001
Af Af*	1	0.0001	0.0001	0.05	0.0826
*Sd*Sd*	1	0.0001	0.0001	0.05	0.0826
Tv Tv*	1	0.0159	0.0159	5.37	0.043
*Af*Sd*	1	0.0078	0.0078	2.63	0.136
*Af *Tv*	1	0.0153	0.0153	5.16	0.046
*Sd*Tv*	1	0.0528	0.0528	17.81	0.002
$\boldsymbol{R^2}$				**96.94 %**	
$\boldsymbol{R^2_{adj}}$				**94.18 %**	

(Source: Compiled by author)

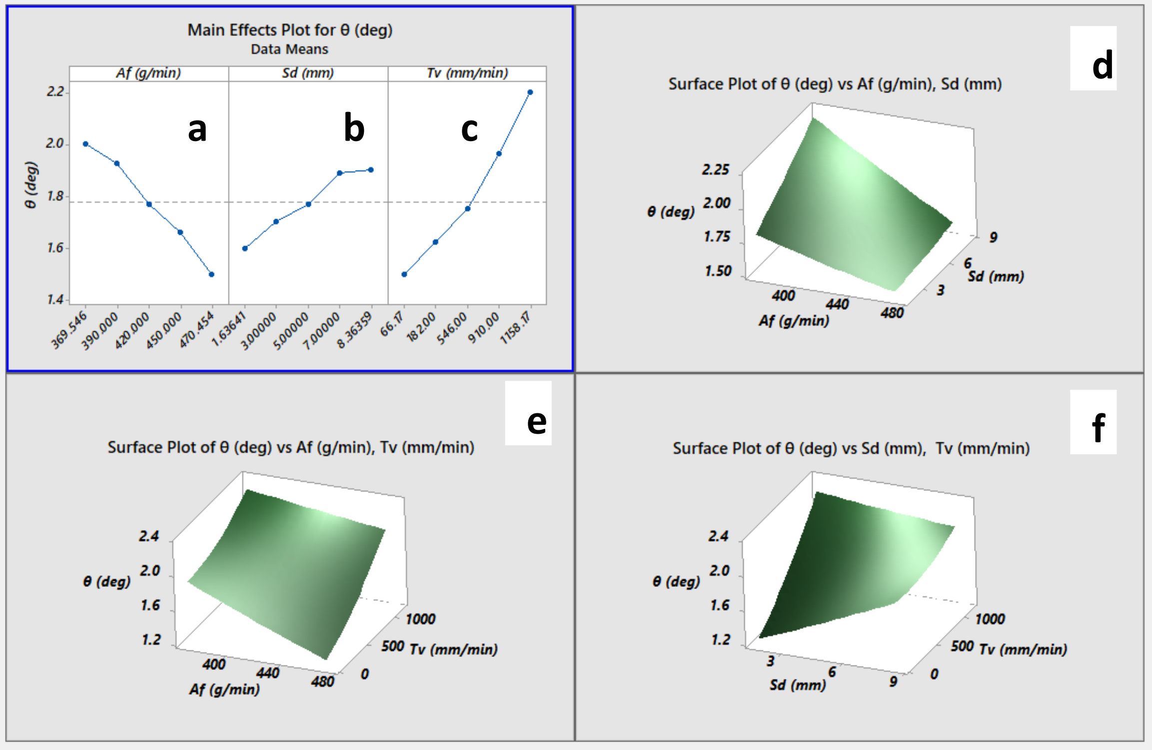


Figure 5: *Main effect (a, b, c) and 3D plots for Ɵ (d, e, f) *

(Source: Compiled by author)

Figure 5 shows the effect of the input AWJ machining parameters on the cone angle *(Ɵ)* in **Fig. 5**. As flow rate of abrasives increases, cone angle *(Ɵ)* decreases as shown in **Fig. 5a**. In case of an increase in stand-off distance, cone angle *(Ɵ)* increases as shown in **Fig. 5b**. **Figure 5c** shows increases in the cone angle by increasing traverse speed. It happened due to enlargement of the lower edge of kerf by the jet decreases. **Figure 5d** shows, at a minimum flow rate of abrasives and maximum standoff distance, cone angle increases. **Figure 5e** shows the maximum value of traverse speed and minimum flow rate, cone angle rises. **Figure 5f** presents, the greater value of S_d, and T_v which boosts the Θ keeping A_f value at 420 g/min. In the same way, lower values of S_d, and T_v result in lowermost Θ.

5.4. RSM optimization

Optimization algorithm methods are beginning by recording the different points to find the optimal parameters. Of all the local results, one of the best is the universal (global) result.

The RSM desirability function is used to optimize the response factors (R_a, Θ). **Eq. 5** demonstrates the complete objective desirability function (D).

$$D = \left(\prod_{i=1}^{n} d_i^{n}\right)^{\frac{1}{\sum ri}} \qquad (5)$$

Where, r indicates the importance of each response. In this investigation a multi-objective optimization with RSM is carried out in order to optimize the AWJM parameters with respect to maximization of surface finish (minimization of surface roughness) and minimization ssof cone angle. **Figure 6** shows the composite feasibility of 0.9622 to optimize the responses, indicating that the solution is satisfactory. The best parameters are predicted as A_f = 460 g / min, S_d = 4 mm and T_v = 200 mm / min.

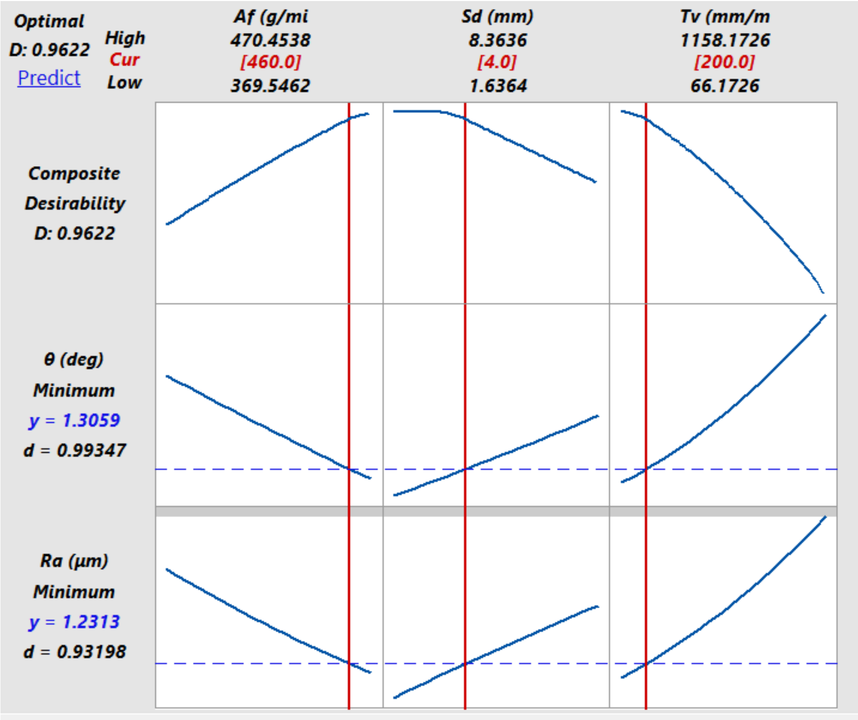


Figure 6: *Prediction of responses by RSM optimization*

(Source: Compiled by author)

5.5. Validation of models

To confirm the **Eq. (3)** and **Eq. (4)**, with optimal values reached for the cutting parameters, as shown in **Table 4**. The precision of the models is examined as a function of the percentage of error. These errors were determined to be 8.89% and 9.72% for surface finish and cone angle respectively. This clearly shows that there is a fine association among the measured and estimated results.

Table 4: *Validation of AWJM variables*

Variables	Experimental values	Predicted by RSM	Error
A_f (g/min)	460	460	-
S_d (mm)	4	4	-
T_v (mm/min)	200	200	-
R_a (μm)	1.35	1.23	8.89
Θ(deg)	1.44	1.30	9.72

(Source: Compiled by author)

6. Conclusions

1. RSM modeling of AWJM, showed fine association between measured and estimated values, based on prediction capability.
2. The effects of the AWJM parameters are examined for both responses. The performance of S_d factor is relatively less important to surface finish and cone angle followed by A_f, and T_v. It showed that T_v is the most influential parameters for surface roughness and cone angle.
3. It was found that an increase in the values of the distance and the travel speed result in minimum surface finish and maximum cone angle and vice versa.
4. Multi-target optimization is performed using RSM, resulting in a combined desirability of 96.22 %. Optimal values for A_f, S_d, and T_v are recorded as 460 g / min, 4 mm, and 200 mm/min, respectively. In this investigation maximization of surface finish (minimization of surface roughness) and minimization of cone angle are presented as 1.23 μm and 1.30 deg respectively.
5. The confirmation test showed error of 8.89% and 9.72% for the surface finish and the angle of the cutting cone which provide evidence for more than 90 % of accurate results. It is also, accomplished that the prediction of the response parameters is perfect as a function of the precision of the estimate in AWJM. Hence, the present result can be useful during AWJM of aircraft material at shop floor industries.

6. Scope of Future Research: Aircraft materials such as Titanium, Aluminum, etc can be machined on AWJM and its process parameters may be modeled and optimized for the betterment of manufacturing society.
7. Research Limitations: More response parameters may be considered for further evaluations. Also, other modeling and optimization technique can be used for comparison of existing results.

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