EXPERIMENTAL ANALYSIS OF ABRASIVE WATER JET MACHINING ON INCONEL 718 USING RESPONSE SURFACE METHOD

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Abstract - *Abrasive water jet machine (AWJM) is a nonconventional machining technique in which, material removal takes place from the work piece by impact erosion. High pressure and high velocity water jet mixed with abrasive material to provide smooth surface finish. Abrasive Waterjet (AWJ) cutting has proven to be an effective technology for material processing with the distinct advantages of no thermal distortion, high machining versatility, high flexibility and small cutting forces. In the current study, a Box–Behnken design of the response surface methodology (RSM) was used to investigate the performance of the abrasive water jet machining (AWJM) of INCONEL 718.The nozzle traverse speed, abrasive mass flow rate and standoff distance were selected as AWJM variables, whereas the material removal rate (MRR), kerf width and kerf taper angle (θ) were considered as output responses. Statistical models were developed for the response, and Analysis of variance (ANOVA) was executed for determining the robustness of responses.*

Key Words: Abrasive waterjet machining (AWJM); Response surface methodology (RSM); Box-Behnken; ANOVA; Optimization; Material removal rate (MRR); Kerf width; Kerf taper angle.

1. INTRODUCTION

It is very difficult to machine an alloy using traditional machining methods because of its high strength and work hardening nature. Hence non-traditional methods like electrochemical machining, ultrasonic machining, electro discharge machining (EDM), Wire cut Electro Discharge Machining (WEDM), water jet machining (WJM), Abrasive water jet machining (AWJM), Ultrasonic Machining(USM), Electron beam machining (EBM), Laser beam machining (LBM) etc. are used [1, 2] IRJET. Inconel-718 is one among the family of nickel-chromium based super alloys which are having high strength, corrosion-resistant used at -217°C to 704°C extreme temperatures [3]. Inconel-718 having 8mm thickness is studied in the present investigation.

The suitable process model to machining nickel-chromium based super alloys was found to be Abrasive water jet machining, because it has no thermal influence on machining material. Abrasive water jet can machine a various range of materials such as metal matrix composites (MMC), super alloys, Titanium alloys, stainless steel, ceramics, and plastics etc. The Cutting time is faster but cost per cutting is relatively high. Abrasive waterjet machining (AWJM) is one of the most widely used non-traditional processes in industries for the machining of hard materials [4.5,6]. AWJM has a high cutting speed, ensures high accuracy and flexibility, has no heat-affected zone, and is eco-friendly [7,8]. Some of the other advantages include the low machining cost, ease in programming, and conservation of properties due to a lower temperature during machining and the wide range of machinable materials [9,10,11]. In AWJM, the high velocity and pressured water jet mixed with abrasives target the workpiece leading to erosion of the material. Some of the limitations of AWJM include the development of surface roughness, kerf taper, delamination, abrasive embedment, etc., which results in poor quality of the machined part [7]. The use of optimized AWJM process parameters can reduce these limitations. A considerable amount of work has been conducted in recent years to study the mechanism of AWJ cutting and to develop kerf geometry and surface roughness models for process control and optimization. These have involved the processing of ductile and brittle materials, leathers, woods and rubbers, as well as composites and layered composites.

1.1 Literature Review

B. Satyanarayana et al. optimized the value of MRR and kerf width simultaneously of AWJM process on INCONEL 718 alloy using Taguchi grey relational analysis accurately. Minitab 17 was used for analysis purpose. Water pressure is the most influencing process parameter for MRR and Kerf width [12].

Reddy et al. [13] investigated multi objective optimization using WASPAS and MOORA techniques for input controllable parameters of AWJM such as TS, AFR and SOD which influences performance characteristics of MRR, kerf width, and SR. They performed experiments on the Inconel-625 workpiece. They found that MRR was positively varying with TS and AFR. SR was increasing with an increase in AFR and decreasing with an increase in TS.

Thakkar et al. worked on optimization of machining parameters on Material removal rate and Surface roughness of work piece of Mild Steel [14], Stainless Steel 403 [15], red mud reinforced banana/polyester hybrid composite [16], Inconel 718 [17,18], Inconel 800H [19], mild steel [20], ductile material such as AISI 4340, Aluminum 2219 [21] using Taguchi's method.

Vinod B Patel [22], investigated the influence of AWJM process parameters on response MRR and Ra of EN8 material based on Taguchi's method and analysis of variance. They found that varying parameters are affected in different way for different response

Pravin R. Kubade, Pranav Potdar, Ravindranath G. Kshirsagar [23] worked on optimization of the process parameters on abrasive water jet machining for Inconel-718 material by taking Material removable rate (MRR) and surface roughness (SR) as responses. Traverse Speed (S) plays a vital role on influencing material removable rate (MRR) by 90.27% as observed in ANOVA test. Then the major contribution on MRR is abrasive Flow Rate which is about 5.97%. We also observed that Standoff distance is sub significant in influencing MRR. In case of surface Roughness Abrasive Flow Rate major significance of about 42.51%. Traverse speed and Standoff distance having sub significance influence on SR by 25.49% and 22.09 % respectively. The confirmation experiments were conducted using the optimum combination of the machining parameters obtained from Taguchi analysis.

The material removal rate (MRR) increases with increase in standoff distance because of abrasive jet particles impacts deeper on work surface which creates craters [24]. Lower traverse speed also influences in higher material removal rate (MRR)[25].

2. Experimental Procedure

In this investigation, the work material Inconel 718 was used. The workpiece was procured from BHARAT AEROSPACE METALS, Mumbai, India. The chemical composition of the workpiece examined by spectroscopic analysis is given in Table 1.

Table -1: Chemical Composition of INCONEL 718

Ni	Fe	Cr	Nb	Mo	Ti	Al	Co	Si	Mn
52.330	19.420	17.690	4.980	3.090	0.770	0.490	0.370	0.260	0.190

The Abrasive Water Jet Machining has been conducted on 3-axis machine (ADTECH CNC4640) with CNC programming at BALAJI Enterprise, vatva GIDC, Ahmedabad. The machine used for samples was Water Jet Model: DWJ1525-FA which is equipped with SL-V50 PLUS pressure pump with the designed pressure of 3900 bar. The machine is equipped with a gravity feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve and a work piece table with dimension of 3000 mm x 3000 mm. Sapphire orifice was used to transform the high-pressure water into a collimated jet, with a carbide nozzle to form an abrasive water jet.

Figure-1:Experiential setup of AWJM process used in current study

2.1 AWJM process parameters

Constant Parameters :

- Nozzle material : ROCTEC 100 Composite Carbide
- Nozzle diameter : 1.02 mm
- Orifice material : Sapphire
- Orifice diameter : 0.33 mm
- Impact angle of jet : Neutral nozzle position (90°)
- Water Pressure (P) Bar : 3900 Bar
- Type of abrasive material : Garnet
- Mesh size of abrasive : 80 mesh

Table-2: Levels of Parameters Used in Experiment

Levels	Stand-off distance (S_d), mm	Abrasive flow rate (A_f), g/min	Traverse speed (T_V), mm/min
Low	2	200	80
Intermediate	3	250	90
High	4	300	100

2.2 Selection of Response Parameters

In most of the literature surveyed, two performance parameters, namely, MRR or cutting rate and Kerf width, were the most important performance measure for investigating the machinability of a material by AWJM. In the present study, Kerf taper angle is also included as a performance measure. Thus, in this experimental work MRR, Kerf width and Kerf taper angle are considered as response parameters.

❖ Material Removal Rate (MRR)

The material removal rate (MRR) of the work piece is the amount of the material removed per minute. MRR and Cutting speed capabilities of AWJM have increased enormously over the years. MRR is measured on weight bases or volume bases.

The MRR (g/min) is the quantum of material removed per unit of time and is calculated using following equation,

$$\text{MRR} = \frac{W_{bm} - W_{am}}{t}$$

The weight of the job before machining (W_{bm}) and after machining (W_{am}) was determined using a digital weighing machine with a precision of ± 0.001 g. The time (t) required for cutting the slot of the defined size is measured using a stopwatch with an approximate precision of ±1 s.

❖ Kerf Width

It is the measure of the amount of the material that is removed during machining and determines the dimensional accuracy of the finishing part.

❖ Kerf taper angle

The kerf taper angle was calculated using following equation,

$$\theta = tan^{-1}\left(\frac{W_t - W_b}{2t}\right)$$

where W_t is the width at the top, W_b is the width at the bottom, and t is the depth of penetration.

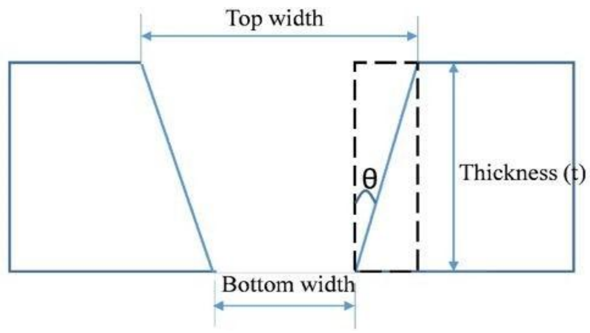

Figure-2: Representation of the Kerf taper angle

2.3 Preparation of DOE Table

The experiments were systematically designed using the design of experiments (DOE) technique. The DOE arranges the experiments such that the maximum amount of information can be collected by performing fewer experiments.

Figure-3: Machined workpiece

In this study, experiments were designed based on Box-Behnken design with three-level of Parameters. Table 3 shows the 15 experimental runs by considering the 3 factors at 3 levels along with experimentally measured values of responses.

Table-3: The BBD matrix of three variables along with experimentally measured values of responses

Exp. No.	Process Parameters			Response Parameters		
	SOD (mm)	AFR (g/min)	TS (mm/min)	MRR (g/s)	Kerf width (mm)	Kerf taper angle, θ (°)
1	2	200	90	0.067310	0.4649	1.6646
2	3	200	100	0.101400	0.7624	2.8352
3	3	250	90	0.106440	0.5929	2.1221
4	3	300	80	0.093860	0.5395	1.9312
5	3	300	100	0.107260	0.6215	2.2244
6	4	300	90	0.107400	0.4566	1.6346
7	2	250	80	0.086880	0.3173	1.1364
8	2	250	100	0.095380	0.3289	1.1779
9	4	250	80	0.094080	0.4249	1.5212
10	4	200	90	0.086280	0.4506	1.6131
11	3	250	90	0.100290	0.5572	1.9945
12	3	250	90	0.084273	0.5876	2.1030
13	2	300	90	0.110030	0.3443	1.2331
14	3	200	80	0.084510	0.6543	2.3417
15	4	250	100	0.098250	0.8449	3.0227

3. Results and Discussion

The AWJM process variables as per the Box-Behnken of Response surface methodology (RSM) are shown in Table 3. The measured values of the selected output response parameters of MRR, SR, and θ are also shown in Table 3. Mathematical regression models were generated using the RSM technique for the prediction of output responses. ANOVA analysis is carried out one by one on all the response parameter and then Regression equation is generated with significant terms based on response surface methodology. Confidence level of 95% (α = 0.05) was used throughout analysis of the experiment.

3.1 Material Removal Rate (MRR)

3.1.1 Main effects plot for MRR

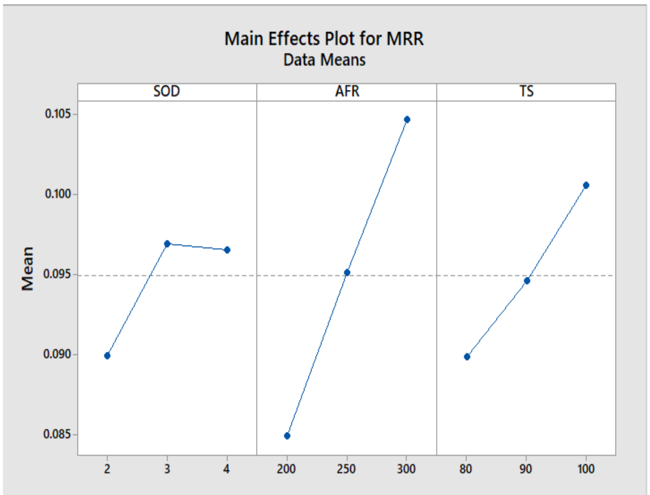

Figure-4: Main effects plot for MRR

Figure 4 represents the influence of various parameters on MRR. It can be observed that Traverse speed (T_V) increases the MRR. This is due to an increase in intermolecular forces and energy causing the sharing and erosion of more material from the parent material. As the number of abrasives increase with an increase in Abrasive flow rate, the number of sharp edges performing the cutting action increases, resulting in higher MRR. An increase in Stand-off distance (S_d) also enables higher MRR due to the divergence of the jet because the jet diameter increases due to divergence, which leads to the erosion of material from larger areas.

3.1.2 Surface Plot and Contour Plot of MRR

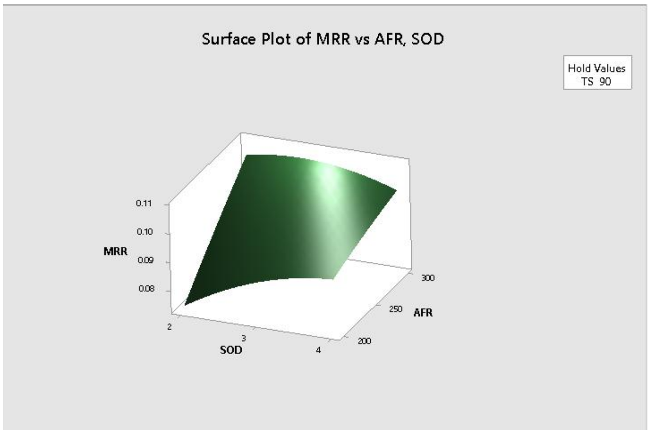

Figure-5: Surface Plot of MRR vs AFR, SOD

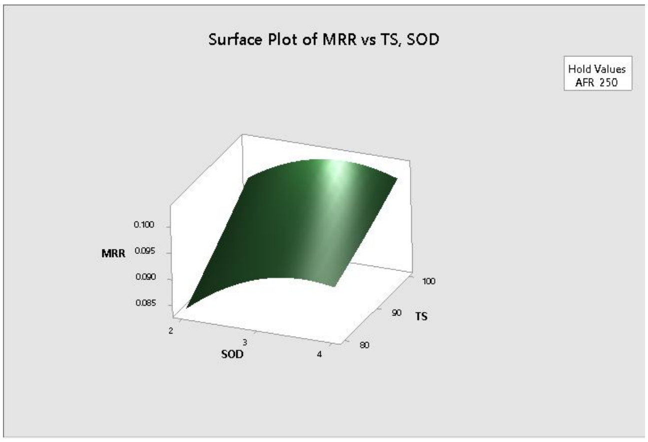

Figure-6: Surface Plot of MRR vs TS, SOD

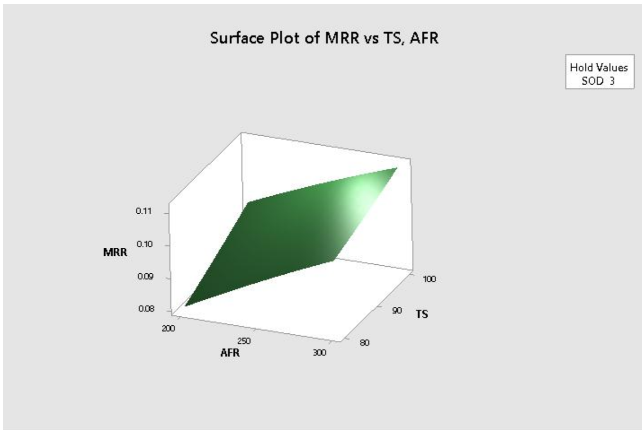

Figure-7: Surface Plot of MRR vs TS, AFR

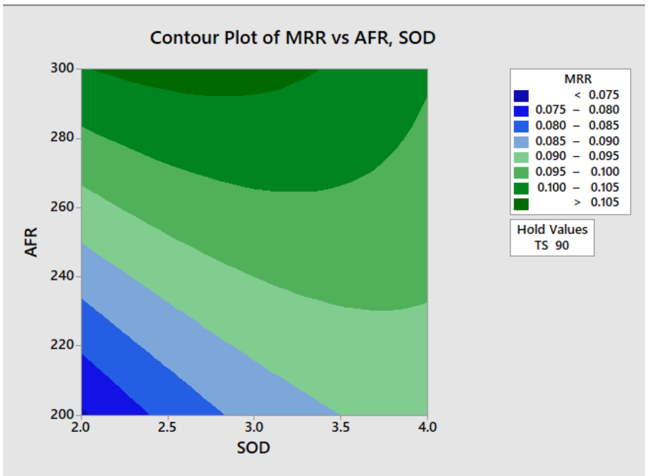

Figure-8: Contour Plot of MRR vs AFR, SOD

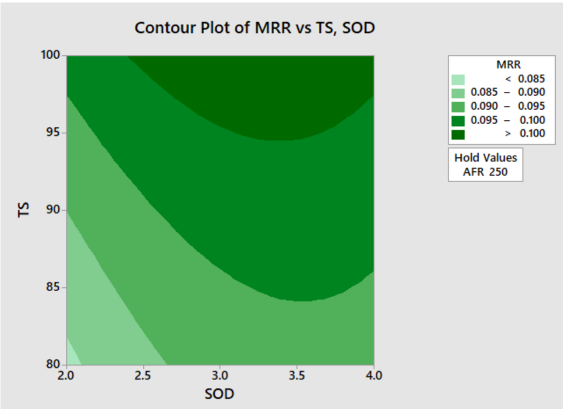

Figure-9: Contour Plot of MRR vs TS, SOD

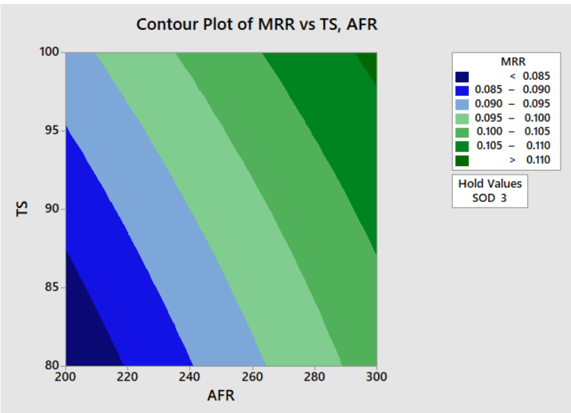

Figure-10: Contour Plot of MRR vs TS, AFR

3.2 Kerf Width

3.2.1 Main effects plot for Kerf width

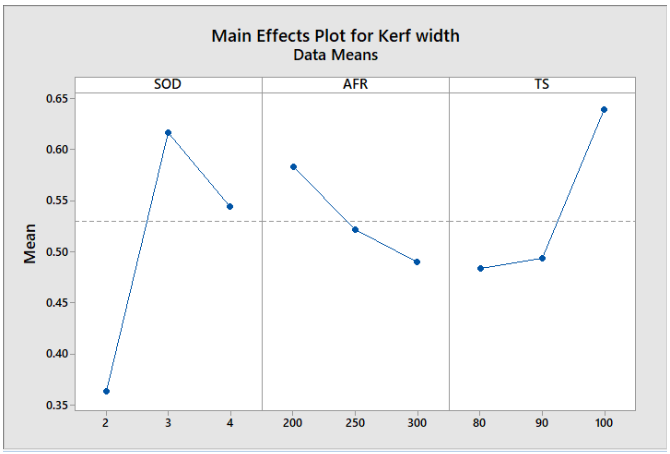

Figure-11: Main effects plot for Kerf Width

Figure 11 shows the main effect plot of MRR at different parameters like, Standoff distance, Abrasive flow rate and Traverse speed in Abrasive water jet machining of Inconel718 material. It can be observed that Traverse speed (T_V) increases the kerf width. It can be highlighted that when Abrasive flow rate (A_f) is increased from 200 to 300 g/min, it decreases the kerf width.

3.2.2 Surface Plot and Contour Plot of Kerf width

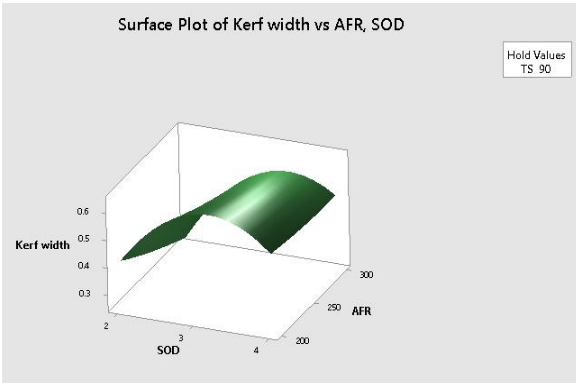

Figure-12: Surface Plot of kerf width vs AFR, SOD

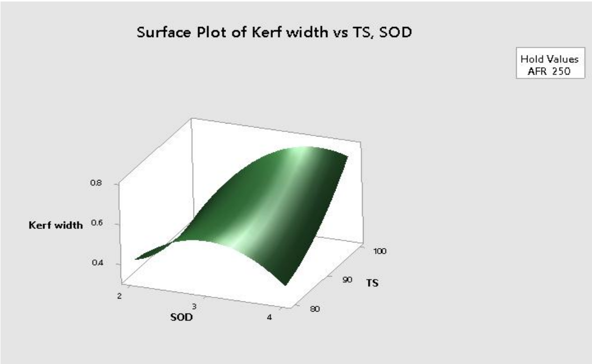

Figure-13: Surface Plot of kerf width vs TS, SOD

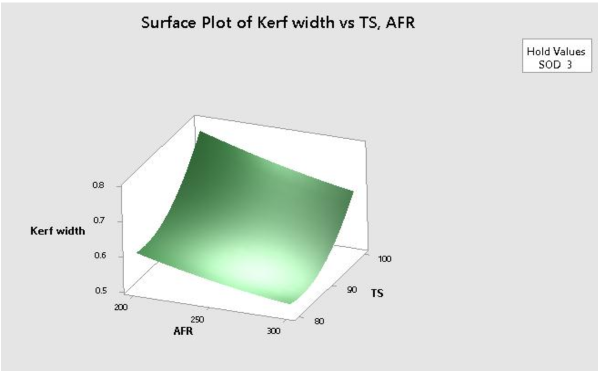

Figure-14: Surface Plot of kerf width vs TS, AFR

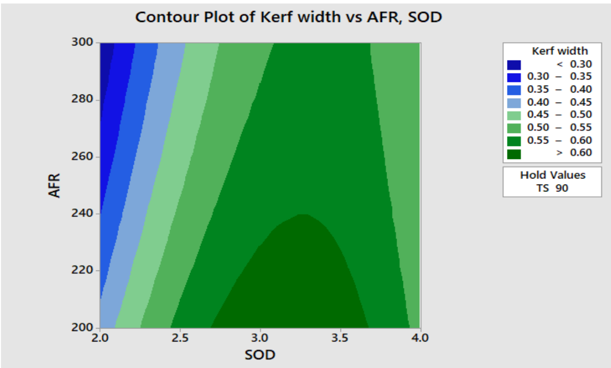

Figure-15: Contour Plot of kerf width vs AFR, SOD

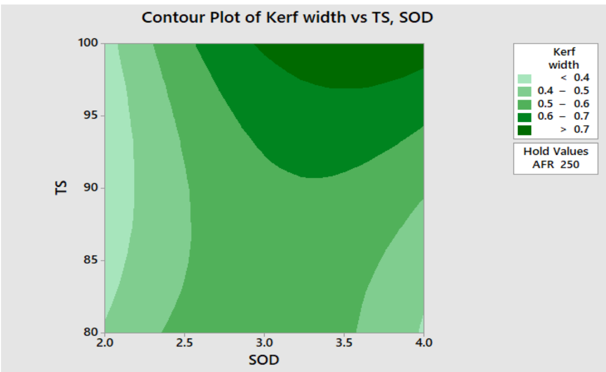

Figure-16: Contour Plot of kerf width vs TS, SOD

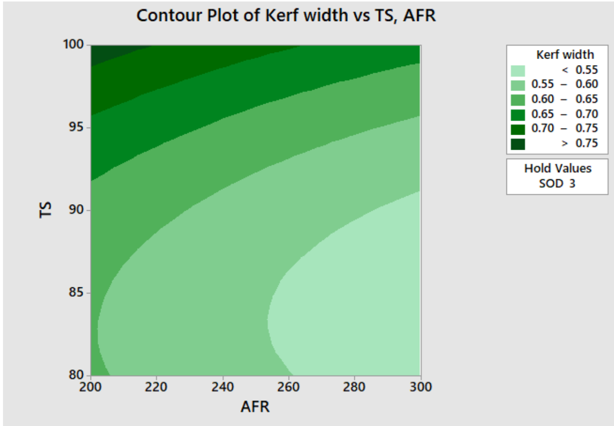

Figure-17: Contour Plot of kerf width vs TS, AFR

3.3 Kerf taper angle

3.3.1 Main effects plot for Kerf taper angle

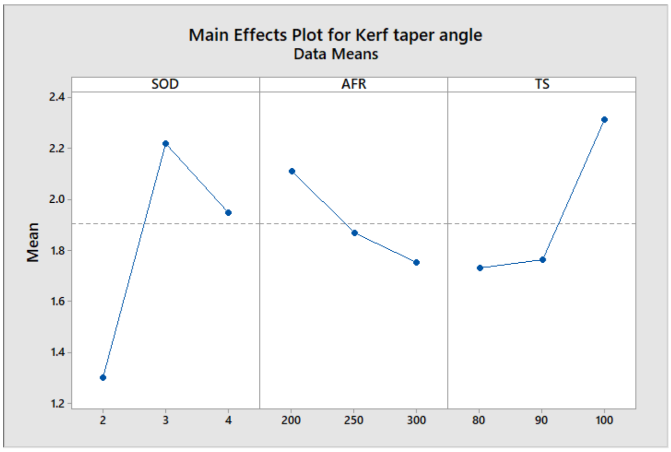

Figure-18: Main effects plot for Kerf taper angle

The kerf taper angle is a measure of the straightness of the machined slot cross-section. The main effect plot of the kerf taper angle as shown in Figure indicated a positive correlation between TS and the Kerf taper angle. Increasing the TS increases the kerf taper angle. This can be attributed to insufficient broadening of the bottom kerf width by the jet as TS increases. The increase in SOD was found to increase the taper angle. This can be attributed to the fact that at higher SOD, the jet is impacted by the flaring mode. Thus, eroding more material at the top causes a higher top kerf width and lower bottom kerf width. As Abrasive flow rate increases, the number of sharp edges performing the cutting action increases, resulting in lower kerf taper angle.

3.3.2 Surface Plot and Contour Plot of Kerf taper angle

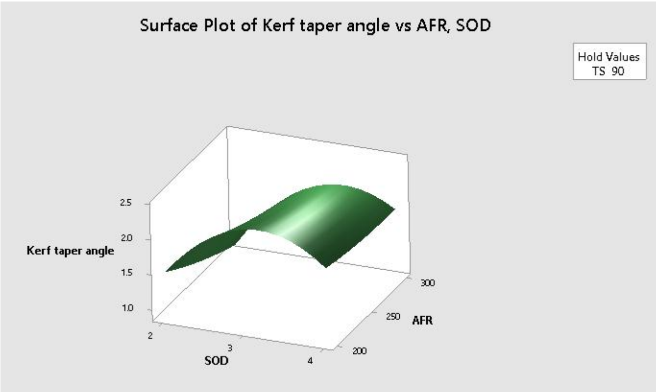

Figure-19: Surface Plot of kerf taper angle vs AFR, SOD

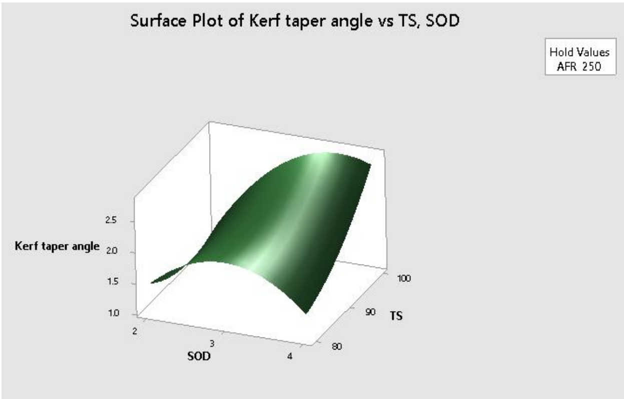

Figure-20: Surface Plot of kerf taper angle vs TS, SOD

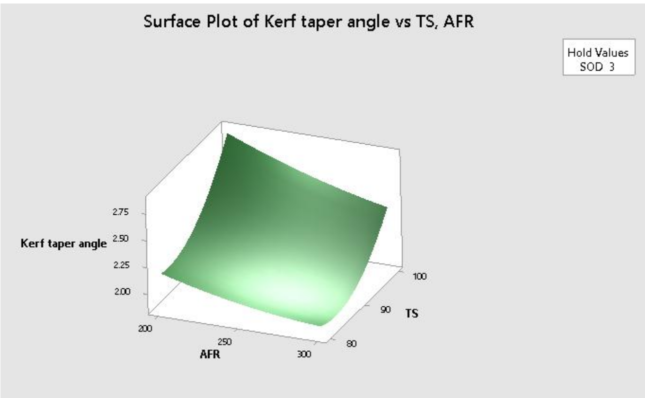

Figure-21: Surface Plot of kerf taper angle vs TS, AFR

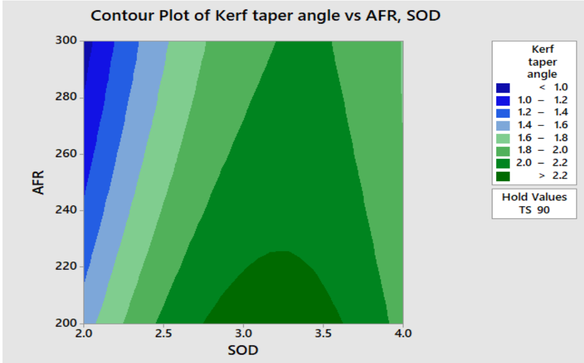

Figure-22: Contour Plot of kerf taper angle vs AFR, SOD

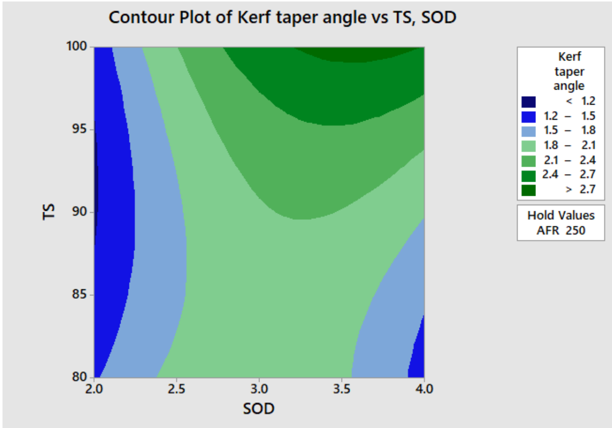

Figure-23: Contour Plot of kerf taper angle vs TS, SOD

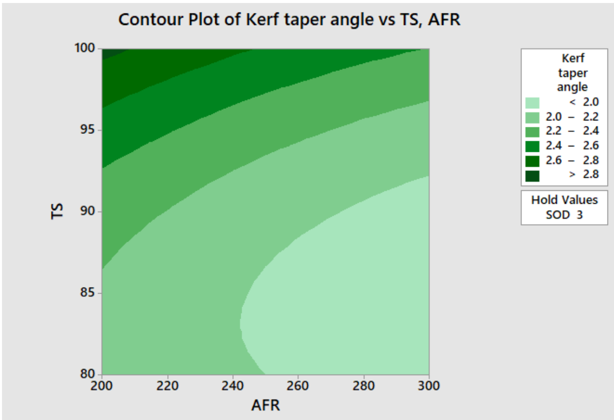

Figure-24: Contour Plot of kerf taper angle vs TS, AFR

3.4 Multi-objective optimization of responses

Table-4: Representation of parameters and their optimal levels

Solution	SOD	AFR	TS	MRR Fit	Kerf width Fit	Kerf taper angle Fit	Composite Desirability
1	2	300	100	0.110640	0.287596	1.01694	1

From optimization plot Figure 6.13 the optimized parametric values and the ranges of optimization are SOD (2 mm), AFR (300 g/min) an TS (100 mm/min).

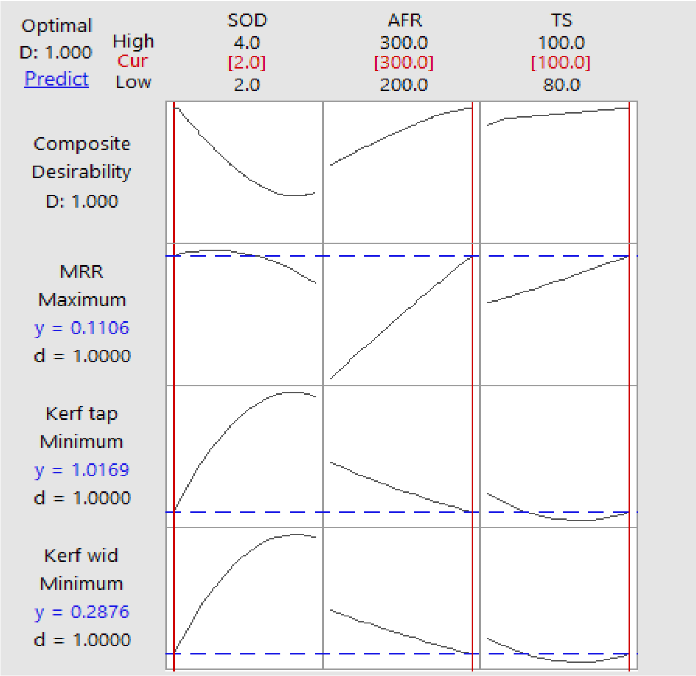

Figure-25: Optimization plot shows optimized values of parameters

4. CONCLUSIONS

The present study investigated the effect of AWJM parameters Stand-off distance, Abrasive flow rate and Traverse speed on responses of MRR, Kerf width and the Kerf taper angle for INCONEL 718. Based on the work, the following important conclusions can be drawn:

- Mathematical regression models were generated using the RSM technique, and ANOVA results have shown the adequacy of the developed models.
- Normal probability, the significance of model terms, and the insignificance of lack-of fit for all responses highlighted good prediction capabilities of the developed models of MRR, Kerf width and the kerf taper angle.
- Single-objective optimization results yielded a maximum MRR of 0.11003 g/s (at SOD of 2.56566 mm, AFR of 300 g/min, and TS of 100 mm/min), a minimum Kerf width of 0.3173 mm (at SOD of 2 mm, AFR of 300 g/min, and TS of 92.7273 mm/min), a minimum Kerf taper angle of 1.1364 θ (◦) (at SOD of 2 mm, AFR of 300 g/min, and TS of 92.7273 mm/min).

❖ **Future Scope**

From the investigations carried out and reported in this thesis, a few possible future avenues of research derived from this work can be suggested.

- A similar study can be done on different materials, composite materials and different material thickness.
- A similar study can be done on the other process parameters which are not covered in this study for investigating effect on response parameters like water pressure, Orifice Diameter, Focusing Tube Diameter, Abrasive particle size etc.
- Use different Design Of Experiment techniques for planning of experiments such as Taguchi, Central Composite Design (CCD), Full Factorial etc.

ACKNOWLEDGEMENT

It is my proud privilege and duty to acknowledge the kind of help and guidance received from my research supervisor **Mrs. Sheetal S. Soni** in preparation of this research work. I consider myself privileged to express gratitude and respect towards my research supervisor who guided me through the completion of the entire research work. I would also like to extend my thanks to the technicians of the BALAJI Enterprise for their help in offering me the resources to complete the experiment. I would like to thank my parents for helping me out and also for inspiring and motivating me throughout my work.

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