To Study and Optimize the Effects of Process Parameters on Taper Angle of Stainless Steel by Using Abrasive Water Jet Machining

Meghna K. Gawade and Vijaykumar S. Jatti

Abstract Abrasive water jet machining (AWJM) is a non-conventional manufacturing process, has a potential to cut wide range of materials. For processing various engineering materials abrasive water jet cutting has been proven to be an effective technology. The motive of the paper is to analyze the process parameters on taper angle in abrasive water jet machining having grade type of 304 stainless steel material. Design of experiment were conducted according to response surface methodology (RSM), based on Box-Behnken design. Influence of process parameters on taper angle is shown by main effect plots and 3D surface plots. Evaluation of process parameters were done by ANOVA technique. For optimization of process parameters so as to achieve minimum taper angle, multi-objective response methodology is used which resulted desirability 0.9195 of the developed model. The optimal process parameters obtained were traverse rate 80 mm/min, abrasive flow rate 300 gm/min, and stand-off distance 1 mm. For validation of results, confirmation analysis is performed and resulted percentage error showed is less than 6% for taper angle.

Keywords Abrasive water jet machining · Response surface methodology · Taper angle

Nomenclature

AWJM	Abrasive water jet machining
RSM	Response surface methodology
TS	Traverse speed
ANOVA	Analysis of variance
AFR	Abrasive flow rate
DOE	Design of experiment
SOD	Stand-off distance

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1 Introduction

Abrasive water jet machining (AWJM) is a non conventional machining process and is proven effective technology to cut various materials. Stainless Steel is one of the popular materials in automobile sector due to their heat resistance, corrosion, strength, durability, high hardness, fabrication flexibility, and low maintenance characteristics. The purpose of stainless steels used in the areas of automobile and various manufacturing field have been demonstrated many studies. During machining of stainless steels with conventional method face many problems such as poor chip breaking, work hardening, huge amount of coolant supply and these results in increased in production cost and time. They mainly get prone to edge chipping due to vibrations occurred by machines, chattering of tool, and o traditional tools. To overcome this problem, operations carried out by abrasive water jet machining (AWJM) is an effectively proven method and have several advantages such as any manufacturing of intricate shapes with precision, also fine finishing surface of the material can be obtained [1]. Hardness of abrasives plays important in cutting of the material. Garnet abrasives produces small width of cut compared with other abrasives material such as silicon carbide, aluminium oxide [2]. A open tapered slot was investigated, it was observed that width of top is wider as compared to width of bottom and normally known as kerf taper angle and is represented as 'θ 'as a characteristic [3].

2 Materials and Methods

The material used is iron based alloy, which is manufactured commercially having grade type 304 stainless steel sheet with dimension 330 mm × 100 mm × 6 mm. Its yield strength is 205 MPa, tensile strength is 515 MPa, hardness 92 HRB. Chemical composition of type 304 stainless steel specification is shown in Table 1.

Experiment was performed on Water Jet German—3015 Machining facilitated with CNC equipment. Table 2 shows process machining parameters. The experiments were carried under water pressure 3100 bar and the abrasive material was garnet 80 mesh size. Figure 1 shows the abrasive water jet machine.

The DOE is a systematized technique to establish the correlation between control factors and final response. Table 3 shows the 3 control factors levels.

RSM (response surface methodology) is a statistical method used to find the relationship of control factors on response process. RSM is used to design with

Table 1 Chemical composition of 304 steel

C%	S%	P%	Ni%	N%	M%	Si%	C%
0.08	0.03	0.05	8	0.1	2	0.75	18

Table 2 Parameters of AWJM machine

Sr No.	Parameters	Values
1	Diameter of nozzle	1.1 mm
2	Orifice diameter	0.35 mm
3	Water pressure	2500–3100 bar
4	Abrasive flow rate	100–300 g/min
5	Traverse speed	50–200 mm/min

Fig. 1 Abrasive water jet machine

Table 3 Control factors and their levels

Symbol	Parameters	Level 1	Level 2	Level 3
A	Traverse speed (mm/min)	80	120	160
B	Abrasive flow rate (g/min)	100	200	300
C	Stand-off distance (mm)	1	2	3

minimum number of experiments performed and also used to obtain optimum conditions to produce desirable responses. Box-Behnken design (BBD) model were used for 3 level and 3 factors based on the experiments were performed. The relationship between the independent variables and response variables [4] is given in Eq. 1.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_{ii}^2 + \sum_{i,j=1,i \neq j}^{k} \beta_{ij} X_i X_j \quad (1)$$

where Y is represented as variable response; Xi, X^2, and $Xi\ Xj$ are input variables; β_0 are coefficient of intercept model; β_0, βi, βij and βii are regression coefficients of linear, quadratic, and second-order terms, respectively. Design of experiment is generated by using RSM approach in MINITAB 19 software. The response obtained during the experimental trials is listed in Table 4.

Figure 2 shows square slots was cut having dimension as 20 × 20 mm using AWJM After the experiment the width at top of material and width at the bottom of each slot is calculated by digital vernier caliper. Taper angle is calculated by formula [5]

$$\text{Taper angle}(\theta) = \tan^{-1}\left(\frac{\text{Wt} - \text{Wb}}{2 * t}\right)\text{degree} \quad (2)$$

where, Wt is width cut at top in mm, Wb is width cut at bottom in mm, t- thickness in mm.

Table 4 Responses obtained for Trials

Trials	Parameters			Taper angle
	A	B	C	
1	80	200	1	1.59
2	80	300	2	1.49
3	80	200	3	1.6
4	80	100	2	1.55
5	120	200	2	1.63
6	120	300	1	1.41
7	120	200	2	1.62
8	120	100	1	1.66
9	120	100	3	1.7
10	120	200	2	1.62
11	120	300	3	1.51
12	160	200	3	1.6
13	160	300	2	1.5
14	160	100	2	1.69
15	160	200	1	1.66

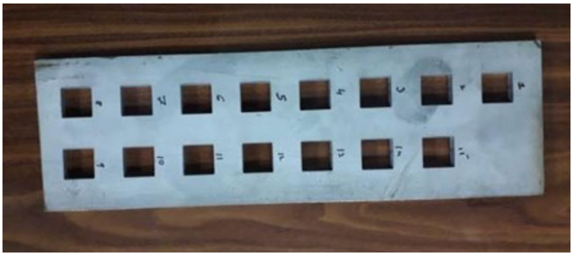


Fig. 2 Stainless steel machined by AWJM

3 Results and Discussion

3.1 Statistical Analysis of Stainless Steel for Taper Angle

The mathematical relationship between independent parameters and taper angle regression equation is obtained and is presented in Eq. (3).

$$\text{Taper angle}(\theta) = 1.6562 + 0.000687\,\text{A} - 0.000863\,\text{B} + 0.0113\,\text{C} \tag{3}$$

From Eq. (3), it has been observed that parameter SOD and TS have positive effects and AFR has the negative effect on taper angle.

Further, to check the most significant parameter affecting on taper angle is determined by ANOVA (Analysis of Variance) about 95% confidence interval (CI). It is a computational method helps us to evaluate the significance of every control factor on response factor.

Table 5 shows the ANOVA results. The F value is the fisher's statistical test and P value is the probability of significance acts in accordance with coefficient of R-sq and R-sq (adj) is determined. This coefficient implies the acceptability and suitability of the model. It is observed that, process variables having lager F value and P value less than 0.05 implies that the variable is significant. For the value of AFR, P value less than 0.05 implies that the variable is significant statistically. The value of R-sq is 89.47% and R-sq (adj) is 70.53% for taper angle implies accuracy and fitness of model. Higher the value of R-sq satisfies the accuracy and fitness of model.

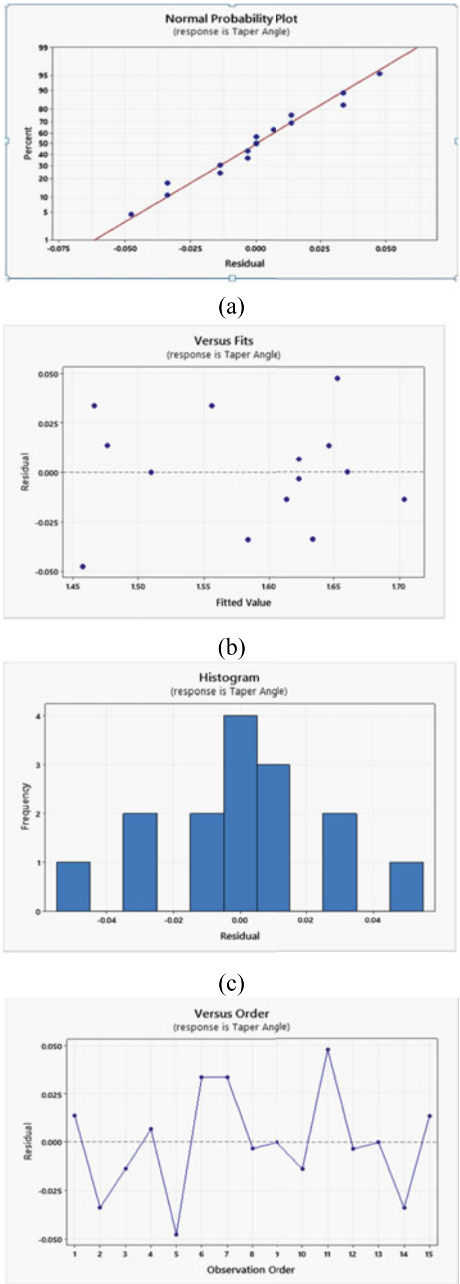
For better analysis, we have plotted the graphs of probability and residuals for taper angle of stainless steel material. The graph of normal probability shows that residual are distributed normally have a close fit to line. Versus fit graph implies there is randomly distribution of residuals. Versus order graph implies observation a constant variance. This graphs shows clarity that the observation are reliable and has 95% confidence interval (CI). Figure 3 shows the residual graph.

Figure 4 shows the effects of various process parameters on taper angle. It is observed that there is rise in taper angle as traverse rate increases this is because as traverse speed increases cutting action gets reduced at bottom width of cut this leads

Table 5 ANOVA for taper angle

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
A	2	0.00628	0.006553	0.003276	1.61	0.258
B	2	0.070436	0.070346	0.035173	17.32	0.001
C	2	0.001015	0.001015	0.000508	0.25	0.785
Error	8	0.016242	0.016242	0.00203		
Lack-of-fit	6	0.016175	0.016175	0.002696	80.88	0.012
Pure error	2	0.000067	0.000067	0.000033		
Total	14	0.093973				

Fig. 3 Residual graph plots



(a)

(b)

(c)

(d)

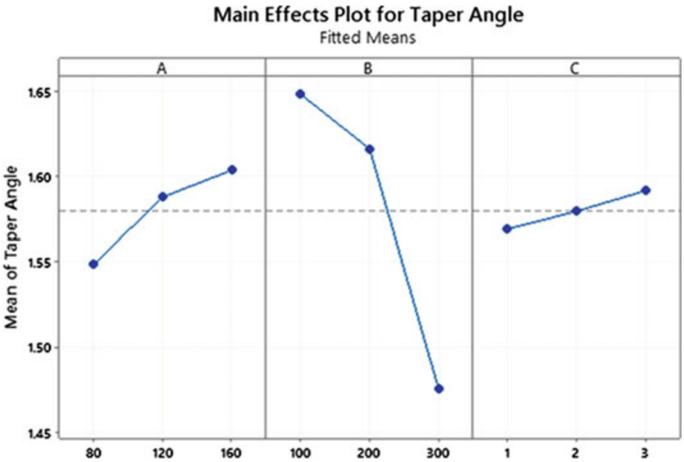


Fig. 4 Main effects plot for taper angle

to increases in the value of taper angle. It is observed that as flow rate of abrasives increases there is decrement in taper angle. Also, as stand-off distance increases there is increment in taper angle is due to increase in focus area of jet results increase in width of cut.

Figure 5 shows the surface plots, to find the effect of different control factors, surface plots are also generated. Figure 5a shows interaction between AFR and SOD keeping value constant of TS at 120 mm/min. It is noticed that for lower value of SOD and higher value of AFR there is decrement in angle of taper and similarly for higher SOD and lower AFR there is rise in angle of taper, this is due to abrasive particles which cannot pierce sufficiently inside the specimen material [6]. Figure 5b shows the interaction between SOD and TS keeping value constant AFR at 200 g/min. As there is increase in TS and SOD as there is rise in angle of taper. Similarly, at lower SOD and TS there is fall of angle of taper. Figure 5c shows that at higher TS and lower of AFR there is rise in the angle of taper keeping the value constant of SOD at 2 mm. Similarly, at the higher value of AFR and lower TS there is decrement in angle of angle of taper.

4 RSM Optimization

Optimization of control parameters, multi-objective optimization is executed by the response surface optimization (RSO) technique with respect to response parameters. Table 6 shows constraints of parameters for optimization. A desirability (D) function is used in response surface optimization, to optimize the response factors. Desirability value changes in range of 0 to 1. If the value of d = 0, response value are unacceptable where as d = 1 shows desirability of the model. RSO technique is based on principle

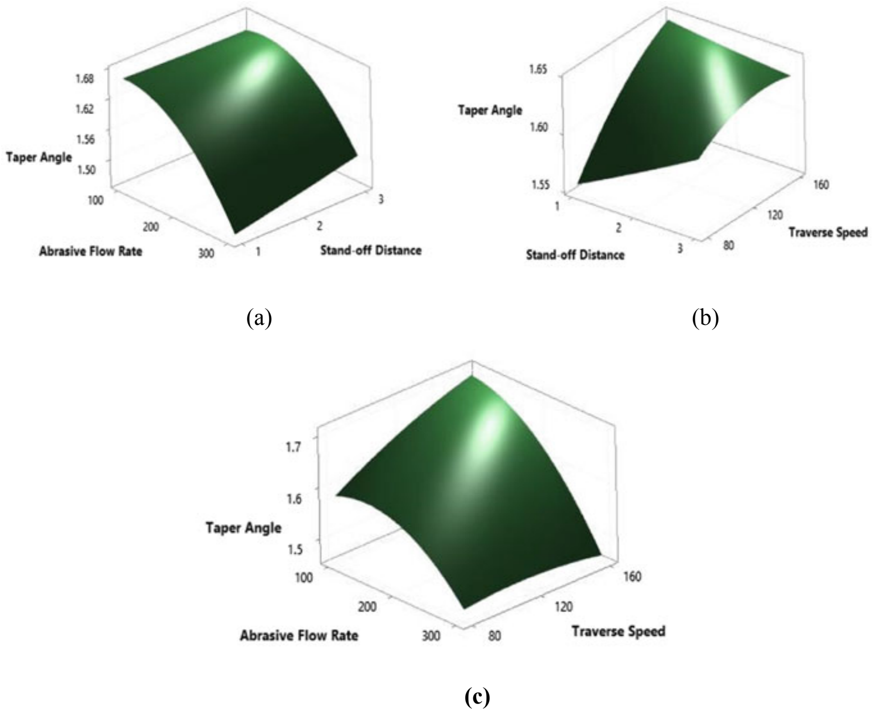


Fig. 5 Surface Plot for taper angle

Table 6 Constraints of parameters for optimization

Condition	Goal	Lower limit	Upper limit
Traverse speed, A	In range	80	160
Abrasive flow rate, B	In range	100	300
Stand-off distance, C	In range	1	3
Taper angle (degree)	Minimum	1.41	1.70

of calculating weights and individual desirability for every response. Higher the value of'd' implies higher desirables optimum values obtained for response parameter [6].

RSM optimization was performed for input parameters, multi-objective optimization were used for response parameter. Figure 6 shows plot for response optimization. It implies the composite desirability of 0.9195 for optimizing the taper angle. The desirability value 0.9195 indicates acceptance of the response parameter. Optimal values obtained TS 80 mm/min, AFR 300 gm/min, and SOD of 1 mm, so as to achieve minimum value of angle of taper.

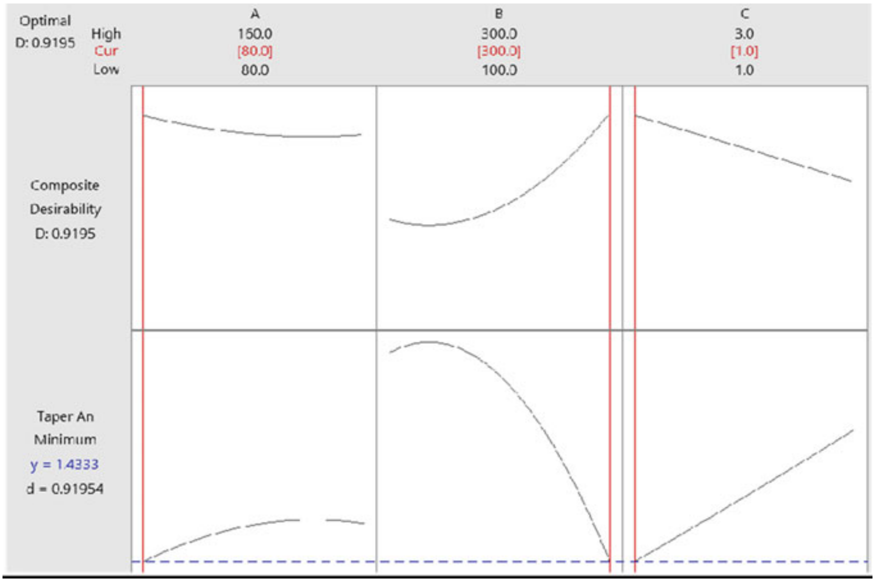


Fig. 6 Plot of optimization of process parameters

5 Confirmation Analysis

Confirmation analysis is the analysis is used to analyze the accuracy of the model performed by RSM. Table 7 is referred to plot the value of experiment and predicted results. Percentage error is calculated between experimental and predicted results. It is observed that percentage error is less than 6% within the limit of permissible. The predicted values of RSM model show a high level of accuracy.

Figure 7 shows the difference between experimental results and modeling results. It can be concluded to get low value of the angle of taper for the input parameters such as TR, AFR and SOD the obtained RSM model is fulfilled.

6 Conclusions

The analysis reveals the impact of input parameters on angle of taper of stainless steel material and thus we conclude as follows—

(i) The mathematical model is formulated for the taper angle showed the correlation between the flow rate of abrasive, traverse speed and SOD. The most significant parameter is AFR influencing on angle of taper significant statistically followed by TS and SOD. The value of R-sq is 89.47% and R-sq (adj)

Table 7 Confirmation analysis

Exp No.	A	B	C	Experimental result of taper angle	Modelling result of taper angle	% Error
1	80	300	2	1.47	1.47	0
2	160	200	3	1.6	1.62	−1.25
3	80	200	3	1.6	1.57	1.87
4	120	200	2	1.63	1.59	2.45
5	120	300	1	1.41	1.49	−5.67
6	160	300	2	1.5	1.52	−1.33
7	80	200	1	1.59	1.55	2.51
8	120	200	2	1.62	1.59	1.85
9	120	100	1	1.66	1.66	0
10	160	100	2	1.69	1.70	−0.59
11	120	100	3	1.7	1.68	1.17
12	120	200	2	1.62	1.59	1.85
13	120	300	3	1.51	1.51	0
14	80	100	2	1.55	1.64	−5.80
15	160	200	1	1.66	1.60	3.61

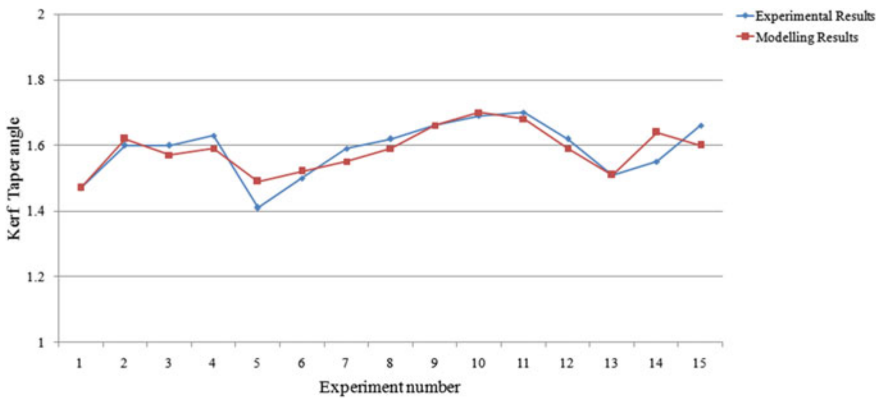


Fig. 7 Comparison experimental results and modeling results

is 70.53% for taper angle implies accuracy and fitness of model by ANOVA technique

(ii) Main plots and 3D surface plots were studied for the influence of control parameters on angle of taper. AFR is comparably slighter influential on angle of taper.

(iii) Optimization of process parameter using multi-objective RSM for minimum taper angle which results the desirability of 0.9195. Optimal values obtained for TS 80 mm/min, AFR 300 gm/min, and SOD of 1 mm, so as to achieve minimum value of angle of taper.

(iv) Confirmation analysis of the model was performed showed percentage error less than 6% for taper angle is in limit of permissible. Comparison of the experimental and predicted values is shown by graph.

Thus it is concluded that mathematical model is developed and optimization for prediction of response parameter for stainless steel is almost significant.

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