# Performance of Cutting Parameters for Surface Excellence on 304 Stainless Steel Using Abrasive Water Jet Technique

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# Performance of cutting parameters for surface excellence on 304 stainless steel using abrasive water jet technique

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## Abstract

Advanced machining techniques are extensively being adopted for machining of high strength materials such as stainless steels. However, these materials are difficult to be machined out due to properties such as high work hardening rate and low thermal conductivity, work hardening and poor machinability. The manufacturing requirements such as production of high precision and surface finished components has led the researchers to study abrasive water jet (AWJ) machining and its applications in industrial sectors. As the AWJ is multi-operational and can produce high precision components. The carried-out work mainly intended to involve technical parameters such as water pressure, cutting speed, abrasive flow. These parameters were analyzed with respect to kerf taper and surface roughness on 304 stainless steel. Two critical variables namely cutting speed and outlet pressure were varied from 100 to 200 mm /min and 100 to 200 MPa, respectively. In additional based on the setup flow rate was altered from 360 to 540 g/min. The experimental results indicate kerf taper and surface roughness were strongly deflect by varying cutting rate, water pressure, and flow rate. Optimization of process parameter was performed by adopting response surface methodology as well as central composite design method. Finally, mathematical models and set of contour graphs for tested surface quality along the kerf taper angle was carried out using ANOVA analysis.

Keywords: Abrasive water jet; ANOVA; Response Surface Methodology; Kerf Taper

## Declarations

**Author contributions:** Isam Qasem: original draft preparation, validation, and software. Ahmed A. Hussien: writing, discussion and methodology. Pramodkumar S. Kataraki: reviewing and editing. Ayub Ahmed Janvekar: review and editing.

**Data availability:** the data in this research has not been associated and will not be deposited.

**Ethical approval** the manuscript is an original work of authors, and this work has not been submitted to any other publication.

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## 1 Introduction

One simple way of representing water jet machining in common terms is a simple high velocity water jet machining process. It finds application to manufacture metallic and non-metallic materials. In addition, it can be considered for abrasive high-pressure water jet machining process, since it can cut high strength and hard materials by directing a high-pressured water. The water jet process offers reduction of cost due to elimination of toxic fumes, recast layers, slag and thermal stresses that do exist in other manufacturing processes. Recent trends of manufacturing indicate the application of water jet machining process to manufacture stone, glass, metals in addition to the manufacturing of paper products, wood, clothes, plastics etc., [1-4]. There is enormous research going on in development of new and effective high-performance materials, and products are being developed. The challenging aspect is to enable new raw materials for manufacturing process. The main hurdles involved are getting premium surface finish and fulfill all the customer requirements [5]. It is very evident that in case of water jet with super high pressure helps to remove materials in desired qualities, to achieved this feature the jet can be enabled with various micro sized particles such as silica, garnet, aluminum oxide and Silicon carbide. The common form of wear can be notices namely; cutting wear and deformation wear. This type of activity will lead to erosion phenomenon at smaller impact angle [6].

Stainless steel is the most and the best material an industrial market has received from decades. There is massive advantage of using stainless steel because of its excellent properties such as high work hardening, corrosion resistance and low thermal conductivity, but a lot of challenges have been faced during machining and cutting of these stainless-steel materials especially while machining by dry cutting tools. The main challenge was to overcome overheating caused mainly because of low thermal conductivity parameter of stainless steel. Therefore, researchers focused more on developing fluid cutting machine such as abrasive water jet [7-10].

Lot of researchers have discussed the effects of parameters such as depth of cut, type of material, taper angle, surface roughness, wear, kerf taper, abrasive performance and characteristics etc. The researchers utilized the empirical models as well as experimental approaches to find the optimal machining parameters range for abrasive water jet machining processes [11]. Sanghani and Korat [12] took up research work on the performance testing of abrasive water jet machine by considering AISI 304 stainless steel. Technical parameters involved were water pressure, traverse speed, stand-off distance and abrasive flow rate. All the variables were focused with respect to kerf taper, surface roughness, and power consumption. It was concluded that the direct proportionality relation exists between kerf taper and surface roughness with respect to traverse speed, stand-of distance and abrasive flow. In addition, they noted that increasing of water pressure caused decreasing of kerf taper and increase in power consumption. A parametric model of cutting depth was established by Miao and Wu [13]. The authors analyzed the process parameters and built the simulation of erosion process of abrasive water jet by using finite element and smoothed particle hydrodynamics methods. Next the volume of material removal was studied. After verifying the model experimentally, it was concluded that parametric model can be used to fetch optimal process parameters as well as to predict cutting depth. Löschner et al.[14] worked by considering two important parameters namely cutting speeds on surface roughness. The materials used by them was stainless steel of 10mm size which undergoes abrasive water jet cutting. The roughness parameters were taken for cutting surface geometry at different locations and depth. The results regarding the variation of speed on surface roughness were validated. In addition, authors considered surface quality and occurrence of machining marks. Qiang et al. [15] made research work by considering effect of water pressure, mass fraction of abrasive and size of abrasive on cutting speed. In addition, energy utilization was also involved. The stainless steel was considered as source material and the authors established a mathematical model to study the cutting speed. While energy utilized rate during processing was enabled by abrasive water jet. The concept was based on two areas; inelastic impact mechanics and hydrodynamics. Next, experiments were conducted for the verification of developed model. The results revealed that increasing of cutting speed and decreasing of energy could be done by increasing the water pressure. While the other way is by decreasing of mass fraction with respect to size, which can be considered as negligible.

Selvan et al. [16] took up challenge to work with process factors. These factors include abrasive mass flow rate, nozzle traverse speed, water pressure as well as standoff distance. The intension was to deal with depth of cut on cast iron by utilizing abrasive waterjet cutting. The main intension of the author was to focus on the depth of cut rather than other parameters. They ensure and validate the data with modified empirical model for get information about the depth of the cut. It was concluded that the modified empirical technique can be used to predict the cutting depth of cast iron within the range of their experiment. Furthermore, there exist direct dependency between depth of cut and mass flow rate. While decrease in depth of cut shall increase standoff distance and nozzle traverse speed. Recently, Alsoufi et al. [17] worked with two parameters namely surface roughness and micro-hardness. There team worked with performance of abrasive water jet cutting and outcome reports were compared with laser beam technology. The output data for abrasive water jet cutting method showed good performances as compared with other cutting methods especially for metals.

The vast spread of literature indicates the importance and significance of optimizing the effect of process parameters over various commercial materials. The most popular choice made by researcher was stainless steel 304 using abrasive water jet technology. Hence, the present research work takes up the challenge to enhance on similar lines by considering experimental study of performance with water pressure, cutting speed and abrasive flow rate on kerf taper and surface roughness. Moreover, the better a methodology was adopted such as response surface methodology along with central composite design method so that best values of process parameters can be generated. To get further accuracy and clear understanding of various parameters ANOVA analysis was integrated to come up with set of contour graphs for tested surface quality and kerf taper angle.

## 2 Experimental procedure and methodology

### 2.1 Material preparation

Firstly, based on the literature study, AISI 304 which is an austenitic stainless steel was shortlisted to undergo various processes. It was selected since it possesses superior properties over conventional materials. It has low thermal conductivity and high work hardening rate. The consideration of stainless steel is also due to its vast applications such as in fabrication, chemical processing and in food processing equipment thereby fulfilling the needs of high corrosion resistance [8]. Some of the key mechanical properties of considered stainless steel 304 are reforested in Table 1.

**Table1.** Mechanical properties of stainless steel 304

| Property | Value |
|---|---|
| Yield strength, MPa | 230 |
| Tensile strength, MPa | 540–750 |
| Elongation, % | 45 |

The samples arranged for experimental tests with 7mm thickness, where the chemical composition of AISI 304 austenitic stainless-steel material is represented in Table 2.

**Table 2.** Weight percentage (wt.%) of chemical composition of AISI 304 austenitic stainless steel

| Chemical composition | wt.% | Chemical composition | wt.% |
|---|---|---|---|
| C | 0.05487 | Al | 0.00 |
| Si | 0.64 | V | 0.046 |
| Mn | 1.66 | W | 0.048 |
| Cr | 18.2 | Co | 0.40 |
| Ni | 9.11 | Nb | 0.013 |
| Mo | 0.092 | Pb | 0.015 |
| Cu | 0.14 | Sn | 0.00 |
| Ti | 0.006 | Fe | 69.7 |

### 2.2 Machine preparation

The machining operations are performed using an abrasive water jet cutting machine, which has accuracy and repeatability of ±0.1mm. The lateral speed is ranged from 0 to 15 m/min. The pumping system produces a high-velocity water jet by pressing water up to 200MPa. The machine with the worktable is shown in Fig. 1, while the details of abrasive material is shown in Table-3.

**Table 3.** Quick Details of Garnet

| Specification | Details |
|---|---|
| Place of Origin | Jiangsu, China (Mainland) |
| Material | Almandine garnet |
| Color | Red |
| Bulk Density | 1.96-2.15 g/cm$^3$ |
| Brand Name | Jin Hong |
| Hardness | 7.5-8.0 Mohs Scale |
| Abrasive Grain | 80 mesh |

Various parameters considered along with the value are indicated in Table 4. The shortlisting for the parameter was based on the type and thickness of the material. Further the selection of the procedure was based on the available built in library in the adopted CNC machine.

Fig.1. Abrasive water jet cutting machine.

**Table 4.** Constant process parameters

| Parameter | Value |
|---|---|
| Thickness, mm | 7 |
| Stand of distance, mm | 3 |
| Abrasive type | Garnet |
| Abrasive grain size | 80 mesh |
| Nozzle diameter, mm | 0.79 |
| Impinging angle, degree | 90 |
| Orifice diameter, mm | 0.25 |

### 2.3 Measurements procedure

The surfaces produced during abrasive water jet cutting can be divided into three zone. These zones can be distinguished geometrically depending on material properties and cutting process settings. Hloch and Valíček [18] gave suitable naming to the various zones. The team identified zones as initial, the surface cut, and the bottom. The approximate location of the smooth zone was indicated by surface cut region. With the experiment, surface roughness Ra value was considered. This was intended to portion on the cut surface of the smooth cutting zone, which was 3mm in the depth. More information can be notices in Fig.2. A quantitative approach was made to ensure the outcome of surface roughness using selected water jet variables. It includes static characteristics, including the roughness average (Ra). The roughness tester RT10 with measure range ±150 µm and resolution of 5 nm is utilized to measure Ra. Every measurement has been repeated at least three times to calculate the average values of Ra with a cutoff of 0.8 mm. Samples of cutting AISI 304 stainless steel using abrasive water jet machine are shown in Fig.3 wherein the figure signifies the cut profile of work pieces and denotes the top kerf angle.

Fig. 2. Topography of cut surface

Fig. 3. Photograph of the stainless steel work piece (top view)

It characterizes the complete geometry of a cut which is as shown in Fig. 4. Further, Kerf taper angle was computed from kerf width values using Eq. ( 1) [19]:

$$T = tan^{-1}(\frac{w_{top} - w_{bottom}}{2t}) \quad (1)$$

In above expression $T$ refers to kerf taper angle (°), while metal thickness is represented by $t$ (mm). Further $w_{top}$ and $w_{bottom}$ implies to top and bottom kerf width in terms of mm, respectively. Fig. 4 indicates a cut profile of material by focusing on top kerf angle. The Kerf taper is one of the parameters that describes the geometry of a cut produced by abrasive water jet, using the taper definition.

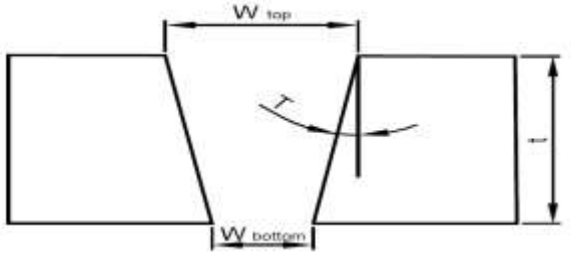

Fig. 4. Abrasive water jet cut profile

2.3 Utilized parameters and its impact

Present work enables one of the popular methodologies known as RSM i.e, Response Surface Methodology. It is adopted by various researchers to assess the outcomes and performance of manufacturing operations [20]. RSM with central composite design (CCD) experiment is being adopted. The concept of CCD involves factorial design by considering center points. This will boot a group of axial points, which are known as star points. With the use of these information curvature can be made in much better way. The RSM is also a technique for optimizing that is used to integrate multiple independent variables and analyze how their dynamic interactions affect responses.

With available of various methodologies, RSM was shortlisted due to presence of optimal settings for each factor. Thus, the proposed model's makes success in demonstrating various critical information using analysis of variances. The variable levels were restricted to only three levels because of machine configuration. Table 5 shows the information from Level 1 to 3 across factors considered.

**Table 5**. AWJM cutting parameters their factor and levels.

| Symbol | Factors | L1 | L2 | L3 |
|---|---|---|---|---|
| $P_1$ | Traverse speed, mm/min | 100 | 150 | 200 |
| $P_2$ | Abrasive flow rate, g/min | 360 | 450 | 540 |
| $P_3$ | Water pressure, MPa | 100 | 150 | 200 |

In this research, AWJM process characteristics have been investigated (surface roughness, Kerf taper angel) using a recommended number of experimental trials. MINITAB 19.0 statistical software is utilized for this experimental investigation [21].

Based on the experimental data, a regression analysis and statistical analysis have been obtained. Using MINITAB 19 software an optimum option was selected to ensure the multilinear stepwise regression analysis to occur. With this prediction was made for the surface roughness as well as for kerf taper. The 2nd order polynomial regression model was adopted for better results [22, 23], which indicated below.

$$Y_n = \beta_0 + \sum_{i=1}^{k} \beta_i P_i + \sum_{i=1}^{k} \beta_{ii} P_i^2 + \sum\sum_{i<j} \beta_{ij} P_i P_j + \epsilon_i$$

Where $Y, P,\ \beta_0\ , \beta_i,\ \beta_{ii}$ and $\beta_{ij}$ are variables for response, factor, free term, linear effect, squared effect, and interaction effect respectively. While the $k$ and $n$ represents the number of factors and response, respectively.

## 3 Results and discussion

The main intension was to explore the effect of process factors on considered materials. In present case AISI 304 austenitic stainless steel was subjected to abrasive water jet machine. Three aspect where closely monitors namely; traverse speed, abrasive flow rate and water pressure. The impact of parameters influenced on surface roughness as well as kerf taper angle. Table 6 List out experimental data for process parameters based on CCD.

**Table 6.** Experimental outcomes for surface roughness and Kerf taper angel

| $P_1$ | $P_2$ | $P_3$ | Surface roughness Ra (µm) | Kerf taper angel (°) |
|---|---|---|---|---|
| 200 | 360 | 200 | 10.93 | 1.97 |
| 150 | 450 | 150 | 12.04 | 2.10 |
| 150 | 450 | 150 | 11.94 | 2.08 |
| 200 | 540 | 200 | 9.76 | 2.57 |
| 150 | 450 | 150 | 12.15 | 2.13 |
| 200 | 450 | 150 | 13.13 | 2.34 |
| 150 | 360 | 150 | 12.62 | 1.78 |
| 150 | 450 | 150 | 12.25 | 2.08 |
| 150 | 450 | 200 | 8.95 | 2.01 |
| 150 | 450 | 150 | 12.09 | 1.98 |
| 100 | 450 | 150 | 9.10 | 1.83 |
| 200 | 360 | 100 | 13.50 | 2.11 |
| 100 | 540 | 100 | 11.03 | 2.20 |
| 150 | 540 | 150 | 11.47 | 2.38 |
| 150 | 450 | 100 | 14.53 | 2.15 |
| 100 | 360 | 100 | 12.15 | 1.60 |
| 200 | 540 | 100 | 13.35 | 2.71 |
| 100 | 540 | 200 | 6.44 | 2.06 |
| 150 | 450 | 150 | 12.31 | 2.05 |
| 100 | 360 | 200 | 8.59 | 1.46 |

### 3.1 Analysis of variance and fitted regression models

The CCD provides nearly the same results as three-level factorial. A CCD was used for a series of tests, as shown in Table 7 & 8. Other Numerical data such as standard error of estimate, sum of squares of the errors, F statistics and, p value for Surface roughness and Kerf taper in AWJM was also investigated. Using 5% significance levels, If the p value was less than 0.05, the model was considered important (significance probability value), the effects of $P_1$, $P_2$, $P_3$ statistically significant.

According to the analysis, the best model to match the response data is the quadratic model results are validated using a coefficient $R^2$, adjusted $R^2$, and the Predicted $R^2$. These values for a surface roughness are 96.1%, 92.56%, and 70.58% respectively. Table 7 indicate data from ANOVA simulation using quadratic model for surface roughness. Further regression model adopted after narrowing insignificant variables, which can be seen in Eq. (2). This model matches the data very well, as shown in Fig. 5.

$$Ra(\mu m) = 5.46 + 0.1058P_1 + 0.0003P_2 + 0.0143P_3 - 0.000395P_1^2 \quad (2)$$

**Table 7**. ANOVA for Quadratic model - Surface roughness

| Source | DF | Adj SS | Adj MS | F-Value | p-value | |
|---|---|---|---|---|---|---|
| Model | 9 | 70.328 | 7.8143 | 27.40 | 0.000 | Significant |
| $P_1$ | 1 | 17.849 | 17.849 | 62.58 | 0.000 | Significant |
| $P_2$ | 1 | 3.2948 | 3.2948 | 11.55 | 0.007 | Significant |
| $P_3$ | 1 | 39.561 | 39.561 | 138.70 | 0.000 | Significant |
| $P_1^2$ | 1 | 2.6755 | 2.6755 | 9.38 | 0.012 | Significant |
| $P_2^2$ | 1 | 0.0087 | 0.0087 | 0.03 | 0.865 | |
| $P_3^2$ | 1 | 0.3591 | 0.3591 | 1.26 | 0.288 | |
| $P_1P_2$ | 1 | 0.4753 | 0.4753 | 1.67 | 0.226 | |
| $P_1P_3$ | 1 | 0.4950 | 0.4950 | 1.74 | 0.217 | |
| $P_2P_3$ | 1 | 0.5253 | 0.5253 | 1.84 | 0.205 | |

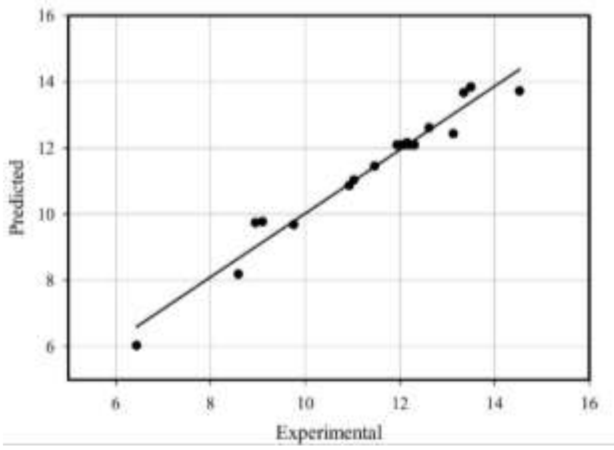


Fig. 5. Variation of data points for predicted and experimental measurements

Analysis of variance of Kerf taper angel shows high accurate model with significant level (0.05). Where the $R^2$ equal to 99.17%, an adjusted $R^2$ is 98.42%, and the Predicted $R^2$ 98.90% as shown in table 8. The quadratic regression model, which containing the significant terms, is in Eq. (3). In addition, Fig. 6 illustrated the good agreement between the predicted values of kerf taper angle with the measurements data.

$$T(°) = 0.180 + 0.00417P_1 + 0.00303P_2 - 0.00173P_3 \quad (3)$$

**Table 8**: ANOVA for Quadratic model - Kerf taper angel

| Source | DF | Adj SS | Adj MS | F-Value | p-value | |
|---|---|---|---|---|---|---|
| Model | 9 | 1.6000 | 0.1778 | 132.92 | 0.000 | Significant |
| $P_1$ | 1 | 0.6502 | 0.6502 | 486.18 | 0.000 | Significant |
| $P_2$ | 1 | 0.9000 | 0.9000 | 672.92 | 0.000 | Significant |
| $P_3$ | 1 | 0.0490 | 0.0490 | 36.64 | 0.000 | Significant |
| $P_1^2$ | 1 | 0.0002 | 0.0002 | 0.12 | 0.733 | |
| $P_2^2$ | 1 | 0.0000 | 0.0000 | 0.02 | 0.904 | |
| $P_3^2$ | 1 | 0.0000 | 0.0000 | 0.02 | 0.904 | |
| $P_1P_2$ | 1 | 0.0000 | 0.0000 | 0.00 | 1.000 | |
| $P_1P_3$ | 1 | 0.0000 | 0.0000 | 0.00 | 1.000 | |
| $P_2P_3$ | 1 | 0.0000 | 0.0000 | 0.00 | 1.000 | |

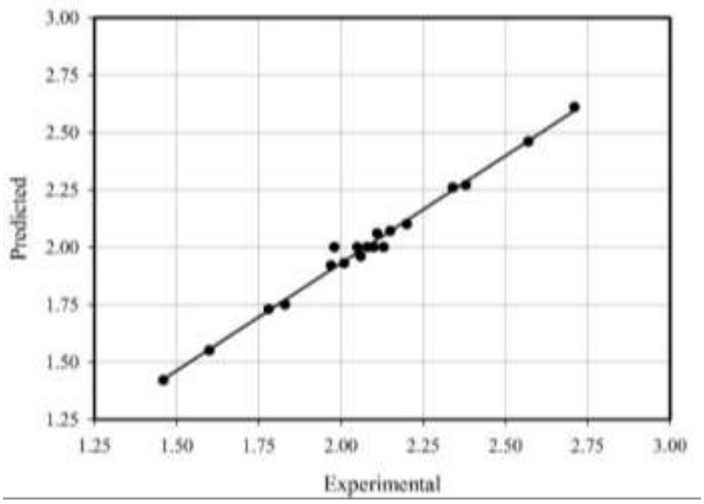


Fig. 6. Comparison of predicted kerf taper angle with experimental measurements

### 3.2 Impact of process parameters

The variation of surface roughness across three prearrest are indicated with the help of Fig. 7. From the plot it can be inferenced that variation of water pressure of abrasive water jet moves inversely to surface roughness. This parameter has a significant effect comparing to flow rate and cutting speed. For example, when water pressure was varied from 100 to 200 MPa the mean of surface roughness dips from 13 µm to 9 µm. These results occur due to increase of kinetic energy of the water particles which hit the working metals, so the cutting become perfect with less cavitation and waviness pattern on the cutting surfaces[24]. The same trend can be seen for the effect of flow rate on surface roughness, Fig. 7. However, the increase of cutting speeds produced low surface quality. When cutting process was carried out especially at high cutting rate it was noticed that small quality of materials was behaving very unstable in nature. This action leads to propagation of more uneven and irregular cavities, further significate holes was also observed, over the cutting surfaces [25]. Thus, it can be inferenced that higher cutting rate can lead to more surface roughness. This kind of behavior was noticed immaterial to the stacking configuration [26].

In order to find the optimum settings of the process parameters to reach the best surface roughness (minimum value of Ra), contour plots shown in Fig. 8 illustrated a relation between surface roughness and other two process factors. For example, Fig. 8-b shows that the best value of Ra in the upper left region where travers speed is at minimum value and at high abrasive flow rate.

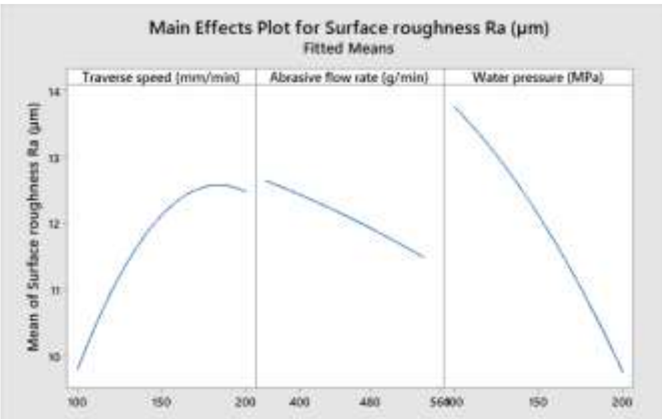


Fig. 7. Variation process parameters with mean of surface roughness

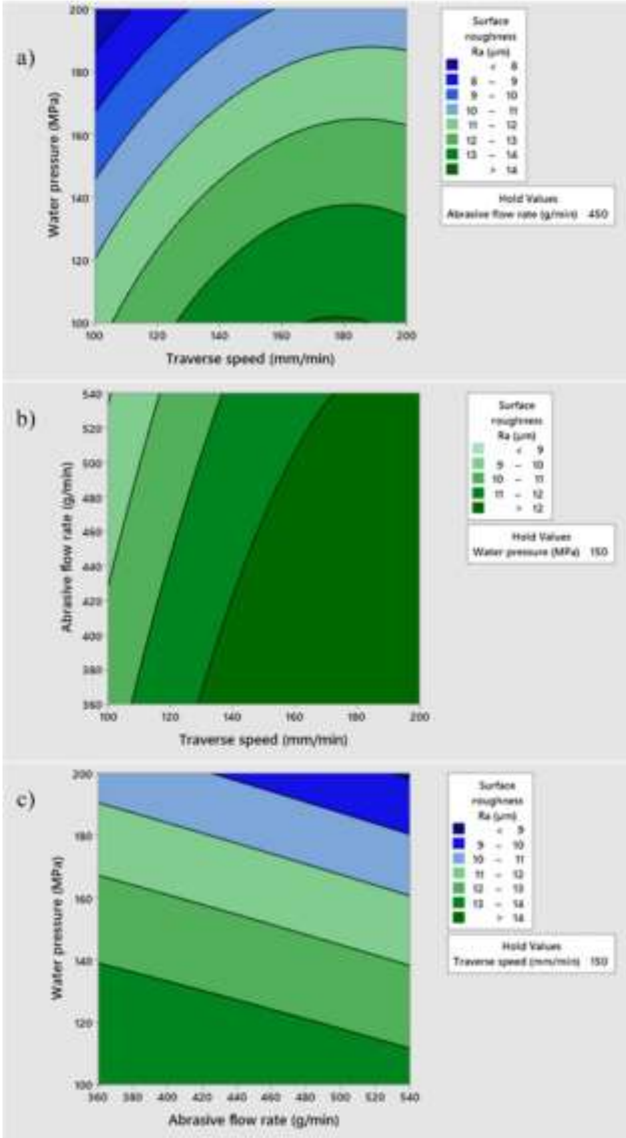


Fig. 8 Contour plot of surface roughness with a) water pressure and traverse speed , b) abrasive flow rate and traverse speed, and c) water pressure and abrasive flow rate.

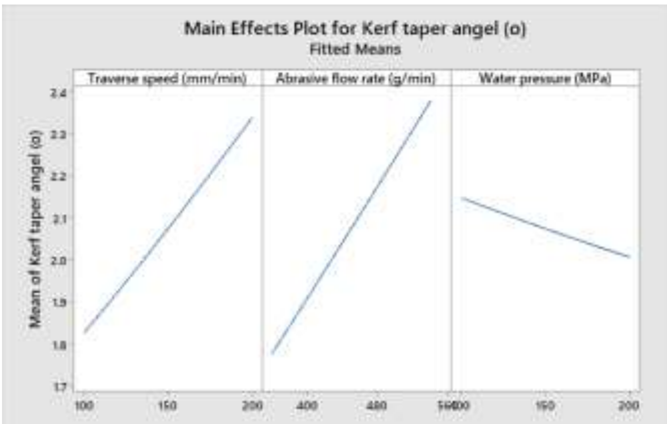


Fig. 9. Variation of process parameters across Kerf taper

### 3.3 Performance of process parameters with respect to Kerf taper angle

One of the main objectives of this research was to consider the investigation of effect along the process parameters. This was also intended to include AWJ cutting on kerf taper angle. It can be shown from Fig. 9 that high traverse speed is applied to material cutting it leads to higher kerf taper angle than the mean value of kerf taper angle, because of increase in probability of jet deflection [19]. Also, the higher mass flow rate and pressure of water particles led to decrease in kerf taper angle for example, the mean of kerf taper decreases from 2.15° to 1.65° when the water pressure raised from 100 MPa to a value of 200 MPa. Next, both water pressure and abrasive flow rate was found out to be more significant impact on kerf taper angle. These results occur because of higher kinetic energy of fluids which hit on the working metals. Gnanavelbabu [24] took lower kerf taper at high water pressure by trimming of Aluminum metal matrix composites. In addition, Fig. 10 presents the effect of combination of different two-process factors to kerf taper as a contour plot. This can lead to find the optimum grouping process parameters setting.

The validation of the predecting models has been done using response optimazer, as shown in Fig.11. The target values for surface roughness and kerf taper angel are 10 μm and 2°, respectivily. The diviation between predicted and experiment values were ± 8% which is acceptable range of the suggested model. The deviations are due to the influence of the high pressure, cousing wearing of mixing tubes, and particle fragmentation before they escape from the nozzle in the cutting machine.

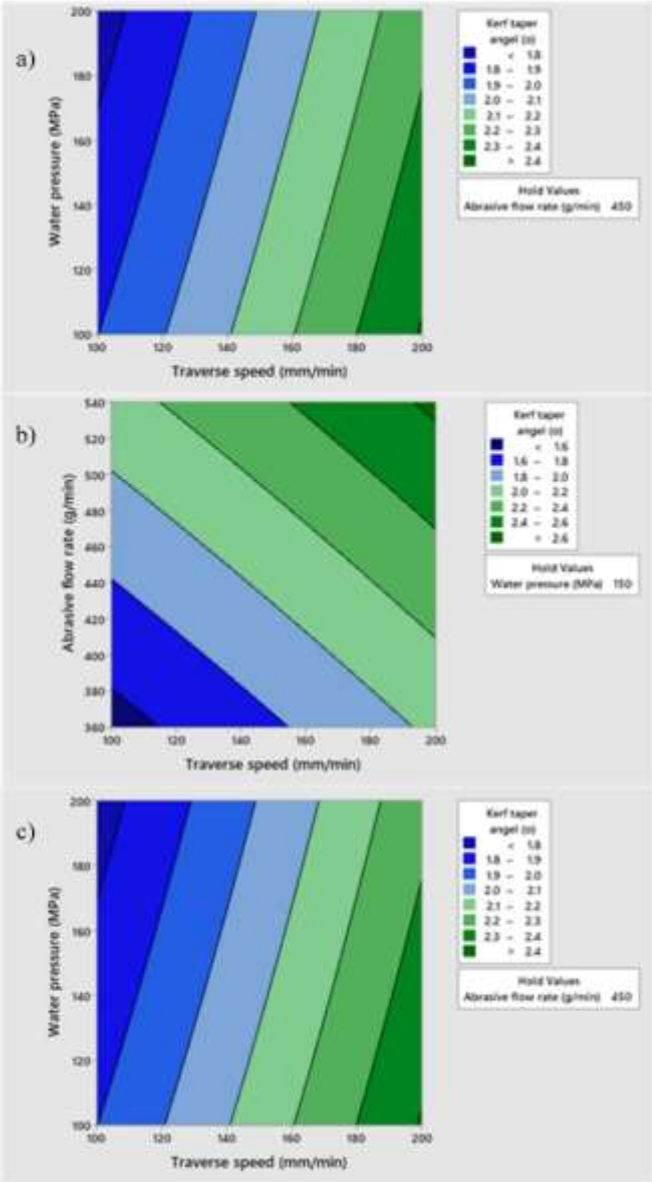


Fig. 10 Contour plot of kerf taper angle with a) water pressure and traverse speed, b) abrasive flow rate and traverse speed, and c) water pressure and abrasive flow rate.

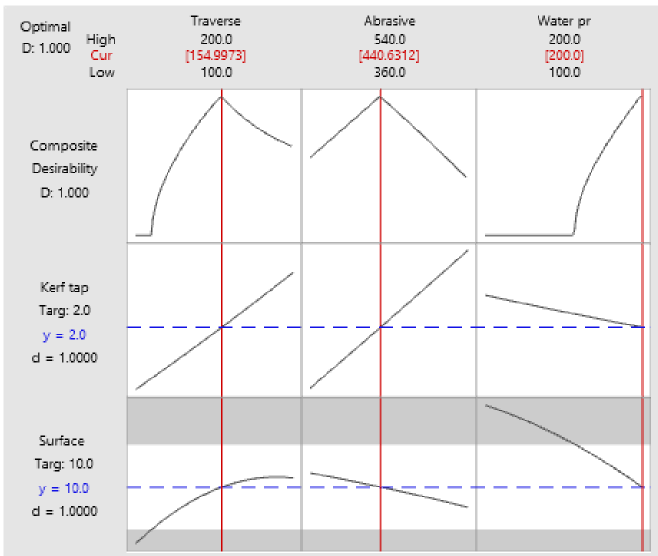


Fig. 11. Validation of quadratic model for surface roughness and kerf taper angle.

## 4. Conclusion

The experimental research was performed by studying behavior of process parameters over the cutting quality of AISI 304 austenitic stainless steel using abrasive water jet machine. Three main parameters namely; traverse speed, water pressure and abrasive flow rate affected to cutting surface quality were studied. In addition, the statistical optimization, mathematical models, and set of contour graphs for tested surface quality and kerf taper angle was performed using the response surface methodology and central composite design method, and ANOVA analysis, respectively. The major outbreak information indicates that water pressure and abrasive water flow rate during cutting metals was inversely proportional to kerf taper angle and mean of surface roughness. This possible reason can be due to increase in kinetic energy of water particles during cutting process. In addition to that, the effect of abrasive speed on kerf taper angle and mean of surface roughness was insignificant with a little negative effect. Finally, the quadratic models were validated.

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