INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 5 (2024) 187-200
https://publisher.uthm.edu.my/ojs/index.php/ijie

Multi-Objectives Optimization of Abrasive Water Jet Machining (AJWM) on Mild Steel

Nurul Hayati Abdul Halim[1], Izdihar Tharazi[1]*, Farrahshaida Mohd Salleh[1], Mohd Firhan Morni[1], Muhammad Ilham Khalit[2], Muhammad Azri Arifin Abdullah[1]

[1] *School of Mechanical Engineering, College of Engineering,*
Universiti Teknologi MARA, 40450 Shah Alam, MALAYSIA

[2] *Department of Mechanical Engineering,*
School of Engineering, Bahrain Polytechnic, Isa Town 33349, KINGDOM OF BAHRAIN

*Corresponding Author: izdihar92@uitm.edu.my

DOI: https://doi.org/10.30880/ijie.2024.16.05.015

Article Info

Received: 23 November 2023
Accepted: 2 June 2024
Available online: 1 August 2024

Keywords

Abrasive water jet, full factorial, ANOVA, optimization

Abstract

Abrasive waterjet machining (AWJM) is an advanced machining technology that is commonly used to machine hard materials that are difficult to machine using traditional methods. AWJM with a narrow stream of high-velocity water and abrasive particles offers a low-cost and environmentally friendly machining approach with a high rate of material removal. Some issues that were usually highlighted while cutting the metal are poor appearance cutting due to visible stream lagging particularly when working at high-speed cutting. This can lead to decreased accuracy and precision in the cutting process. Past literatures are mostly focused on improving the machining performances through intensive experimental works, thereby not many studies are concerned on process optimization through design of experiment approach. In this regard, this study aims to statically analyze how the controlled machining factors; transverse speed and cutting geometry influence surface roughness, and dimensional accuracy of a mild steel plate under the AWJC process. A two level Full Factorial method was applied to design the experiment that entailed 6 sets of parameters. Through the Analysis of Variance (ANOVA) on the experimental results, it was found that the dimensional accuracy are significantly influenced by the changes of cutting geometry. The factor also interacts with transverse speed to affect surface roughness. For optimization, the ANOVA suggest a transverse speed of 40% as the optimum value to produce a surface at 2.85 μm of roughness and a dimension accuracy of 0.177% for the circular geometry-controlled factor.

1. Introduction

Due to the competitive nature of the manufacturing industry, the latest technology is required to cut materials faster and more efficiently. Recently, non-traditional machining of abrasive water jet cutting (AWJC) has become one of the demands for industries in the cutting sector with the quickest growth in technologies [1]. This technology is used by various industries to cut soft and hard materials such as stainless steel, aluminum, mild steel, and other metals as it offers precise cutting with fewer excessive materials and no additional finishing phase [2]. Aside from that, this process also does not generate dangerous residues such as fumes, gas, dust, or other contaminants that might harm the environment and machine operators during or after the cutting. Thus, this cutting technology is regarded as a clean, environmentally benign, cost-effective, and good alternative to traditional cutting [3].

The AWJM procedure takes inspiration from the idea of water erosion, which states that when fast water contacts a metal's surface, material removal occurs [4]. As explained by Yadav and Chavda [5], during the cutting process, a jet of water at high speed at approximately 600 m/s is supplied directly to the workpiece to generate high kinetic energy of water particles that are able to erode the metal in contact. The abrasive particle is mixed with the stream of water in a mixing tube before passing through the nozzle. However, when utilizing AWJC to cut the material, some difficulties were reported with one of the stream laggings. A phenomenon that can happen while using an abrasive water jet for cutting is referred to as stream lagging, also known as jet lag or stream wandering. It speaks about the water jet stream's movement or diversion from the cutting route or target region that was intended [6]. Stream lagging can negatively affect the cutting process, resulting in decreased cutting accuracy, dimensional errors, and decreased overall cutting efficiency. It might lead to lower-than-expected cut quality, more scrap, and an increased need for finishing operations. According to Mertz [1] and Akkurt et al. [7], stream lagging happened due to the power beginning to drop while cutting through a material block during high-speed cutting and may sweep out of the arcs. The cutting accuracy changes from a straight line to a corner or sharp angle which caused dimensional inaccuracies in the product [7]. While by referring to Waheed et al. [8], cutting speed and pressure settings also play a role in stream lagging. High cutting speeds or excessively high pressures can cause the stream to lose stability and wander off course.

For water jet technology, an intensifier and a hydraulic pump are used to pressurize the water to a very high pressure, forming around 4000 to 6000 bar of water in an extremely high-pressure stream [9]. The pressurized stream then concentrates through the orifice. The orifice is commonly made of sapphire, diamond, or ruby material [7], [9]. While for the control factors for abrasive water jet cutting (AWJC) are normally set based on the machine's technical constraints and the open system of AWJC [10]. Cutting parameters such as grit size, transverse speed, waterjet pressure, nozzle diameter, and stand-off diameter are among the significant factors that affect process performance and product quality [11]. When referring to Korat and Acharya [12], water pressure and transverse speed were found to dominate influencing the product quality produced by the abrasive water jet process. Meanwhile, nozzle diameter and orifice were reported as less significant. The optimization of this process usually focuses on the responses such as kerf shape, surface roughness, material removal rate, and others [12].

To carry out a systematic investigation, this study applied a statistical method of Analysis of Variance (ANOVA) to analyze the influences of AWJC parameters on machining performances of surface roughness, straightness tolerance, and dimensional accuracy when cutting a mild steel plate. A design of experiment (DOE) was conducted by using the two-level Full Factorial method, to design the experiment that generated six sets of parameters.

2. Methodology

Fig. 1 illustrates the project methodology with activities that were involved in the implementation. The design of experiment (DOE) approach was applied to design and analyze the performances of the abrasive waterjet cutting process under controlled parameters.

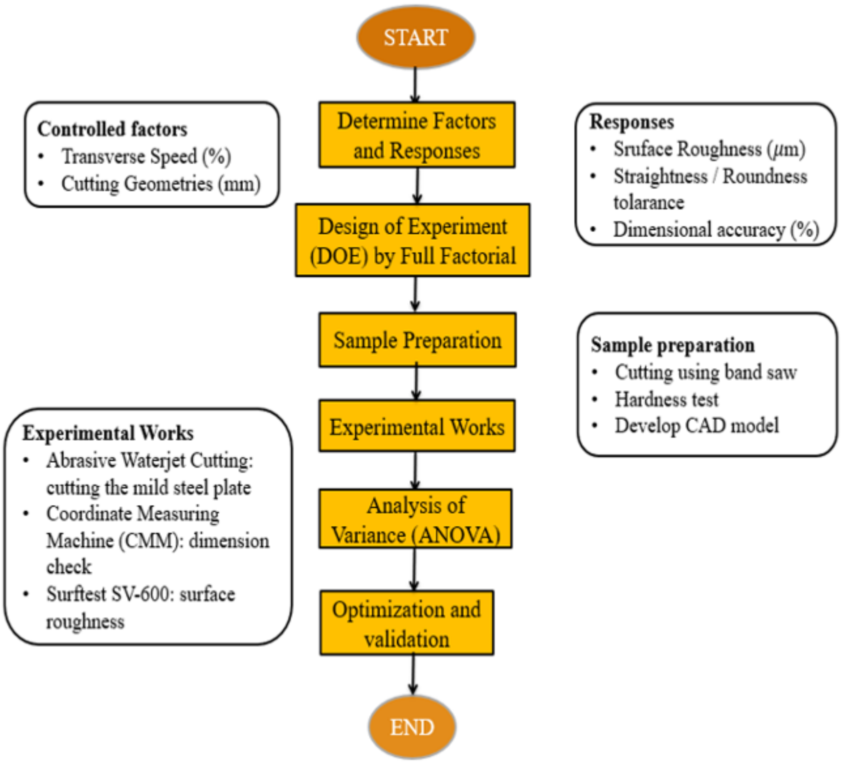


Fig. 1 *Detail flowchart*

2.1 Materials

For the experimental works, a plate of mild steel with an average hardness value of 39.4 HRA was selected as the workpiece. Before the experiment, the workpiece was face milled at 0.3 mm to remove the top surface, which tends to have surface irregularities and residual stress from the previous machining processes. Mild steel is categorized as a material with medium to poor machinability, but with high corrosion resistance that suits it well in industries such as vehicle construction, chemical, medical/pharmaceutical, and building construction. Its chemical composition (wt.%) according to the DIN of this steel is C ≤ 0.03%, Cr 16.5–18.5%, Ni 10.5–13.0%, Mo 2.0–2.5%.

2.2 CAD Models

Fig. 2 shows the CAD model that was generated using CATIA V5, with detailed geometries for the rectangle and circle shapes of the mild steel plate. In this study, these two cutting contours were cut to analyze the impacts of contour profiles on the machining performances. As opposed to straight-slit cutting, contour cutting is more commonly used in the metalworking industry to form a particular geometry [13].

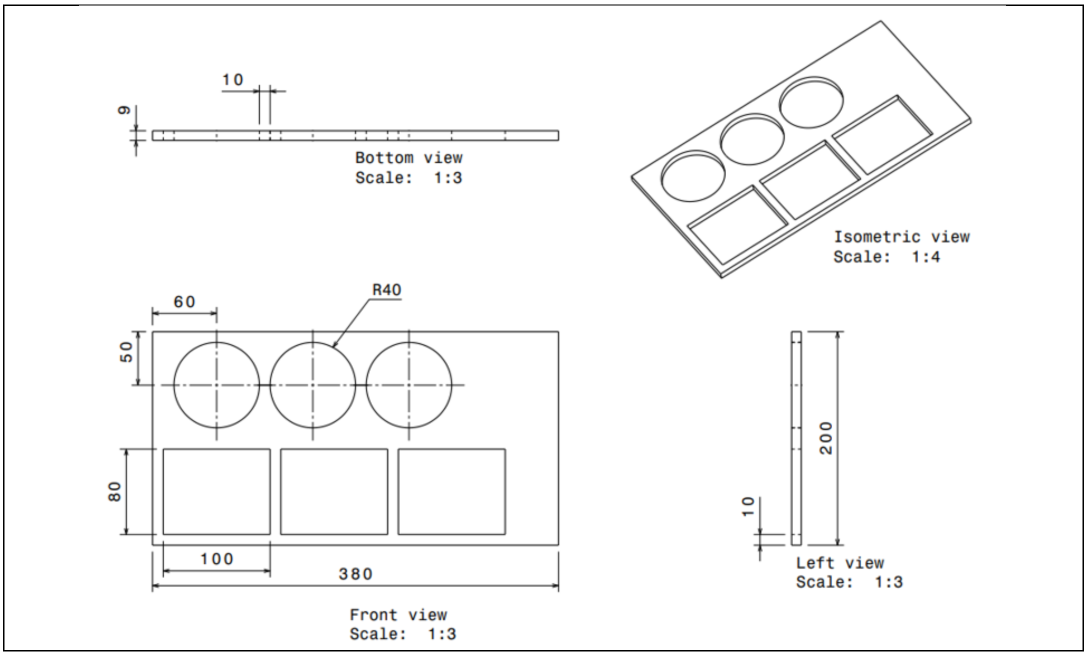
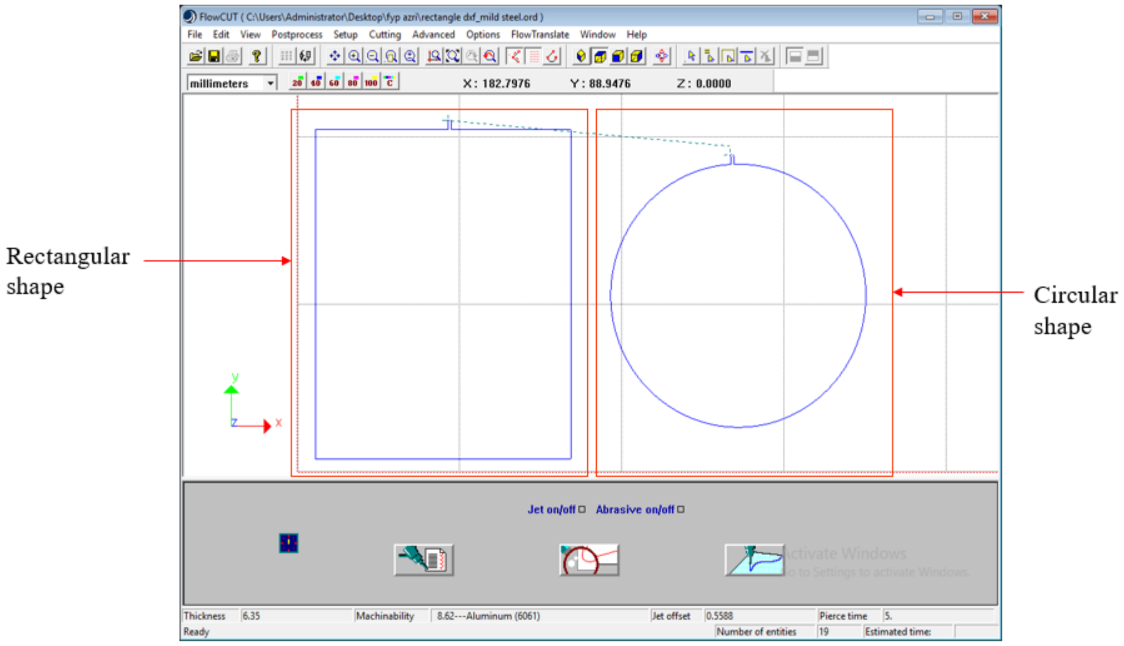


Fig. 2 *The CAD model of the mild steel*

Then, the CAD file was exported into Flowpath software that is connected to the abrasive waterjet machine. This software is a specialized computer program used specifically to regulate the flow of water and abrasive particles to cut the workpiece. From the Flowpath program, the cutting parameters which are transverse speed, cutting path, and dimension check were set. These inputs then were used by the software to determine how much water and abrasive should be sent to the nozzle at any given time in order to achieve the best cutting performance and efficiency. Finally, the geometries file was exported to the FlowCut software to set up the water pressure, abrasive flow rate value, and material thickness before operating the machine as shown in Fig. 3.



X: 182.7976 Y: 88.9476 Z: 0.0000

Thickness 6.35 Machinability 8.62---Aluminum (6061) Jet offset 0.5588 Pierce time 5.
Ready Number of entities 19 Estimated time:

Fig. 3 *FlowCut software*

2.3 Design of Experiments

Table 1 shows the controlled factors and their levels, while Table 2 shows the experimental set-up of AJWM during the experiment. To design the experiment, a 2-level Full Factorial method was applied. This entailed a total of 6 sets of parameters for the experimental works as indicated in Table 3. The responses measured were surface roughness and dimensional accuracy.

Table 1 *Controlled factors of AJWM*

Variables	**Level**	
Cutting Geometry	Circle	Rectangle
Speed of Machining	40%	80%

Table 2 *Experimental set-up of AJWM*

Parameter	**Value**
Type of cutting material	Mild steel
Thickness of material (mm)	6
Water Pressure (psi)	55,000
Abrasive Type	Garnet 80 Mesh
Abrasive Flow Rate (lb/min)	0.7
Stand Off Distance (mm)	5
Nozzle Diameter (mm)	0.8-1
Orifice Diameter (inch)	0.2540
Mixing Tube Diameter (inch)	1.0160

Table 3 *Experimental runs of AJWM*

Number of experiments	**Controlled parameters**	
	Transverse speed (%)	**Cutting geometry (mm)**
1	40	Circle
2	40	Rectangle
3	60	Circle
4	60	Rectangle
5	80	Circle
6	80	Rectangle

2.4 Equipment

An abrasive waterjet machine model M100 1313 with a system of FlowCut software was applied to conduct the experiments. The machine has the capability of operating up to 10 m/min with a linear straightness accuracy of ±0.13 mm/m when cutting any type of material. By using the FlowCut software, the simulation works at the controlled parameters were generated to avoid any errors before physical experimental works took place. At the same time, a weighting block was placed on the mild steel plate to prevent the plate from moving while cutting. Each parameter was carried out once, and Fig. 4 presents the sample geometries after the cutting process.

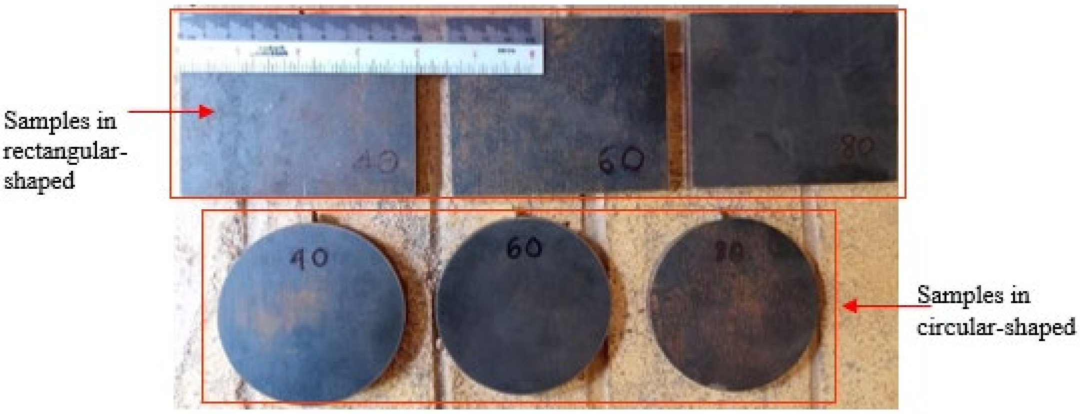


Fig. 4 *The cutting samples at rectangular and circular shaped at 40%, 60%, and 80% of transverse speeds*

The Surftest SV-600 Series was used to measure surface roughness. The measuring device provided a high-accuracy and high-level analysis of the rectangular and circular shapes' fine contours and the conventional type of surface roughness measurement [14]. SURFPAK was the software used to enhance various control functions by using a detector. The surface roughness measurement was divided into 3 sections, which are from the top, middle, and bottom of the specimen's cross-section. Subsequently, the arithmetic mean of these 3 measured results was computed. The travel of the roughness sensor was 4 mm, perpendicular to the direction of the abrasive jet. The factor representing the traverse speed was selected such as to allow cutting at minimum pressure, using a minimum diameter tube and an abrasive of smaller grain (grit size), while positioning the cutter head at maximum stand-off distance. After that, machined surfaces of each sample were observed by using a microscope.

To identify the dimensional accuracy, a coordinate measuring machine (CMM) Mitutoyo Beyond 707 was used to do the measuring processes. For the rectangular-shaped workpieces, each of them was checked for dimensional accuracy percentage errors. There are 3 points of the specimen's length and height were determined, respectively. Then, the circular-shaped workpieces were checked in terms of dimension accuracy. The origin of the circle and eight points of its radius were determined before taking the measurement reading. CMM has the advantage of measuring difficult items with high accuracy compared to any hand tool or other optical compactor [15]. For dimensional accuracy, the measured values were compared with the CATIA V5 sketch as in Fig. 1.

3. Results and Discussion

3.1 Experimental Results of AJWM

Fig. 5 and Fig. 6 present the experimental results for surface roughness and dimensional accuracy, respectively. The results show that the highest value of surface roughness was 4.12 μm at the transverse speed of 60% of circular geometry. Meanwhile, the 40% transverse speed resulted in the lowest value at 2.82 μm of circular geometry. Thus, it can be said that the increase of transverse speed increases surface roughness and this is parallel with Begic-Hajdarevic et al. [16], as they also reported a minimal change occurred at lower transverse speeds.

For dimensional accuracy response, the highest percentage error was 3.83% for rectangle geometry at 40% transverse speed. On the contrary, circular geometry resulted in the same dimension accuracy at 60% and 80% transverse speeds, which both were the lowest percentage error for dimension accuracy response.

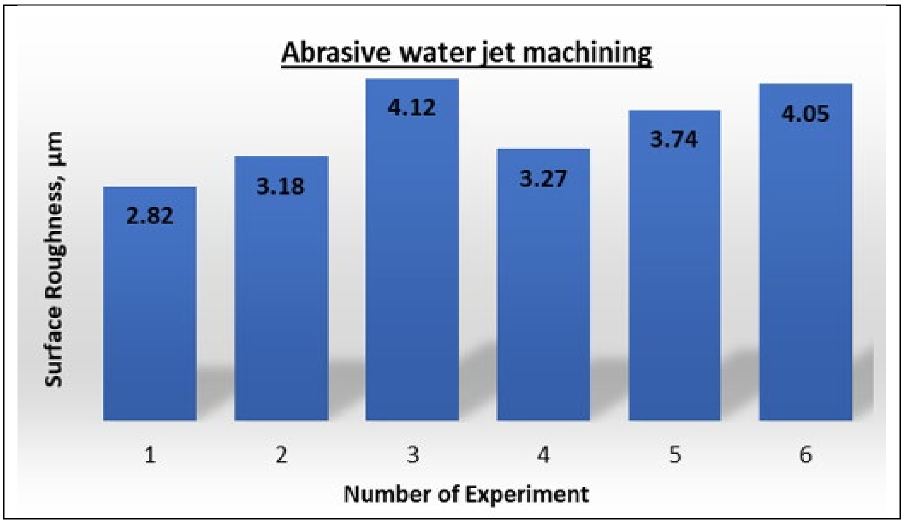


Fig. 5 *Experimental results of AJWM – surface roughness*

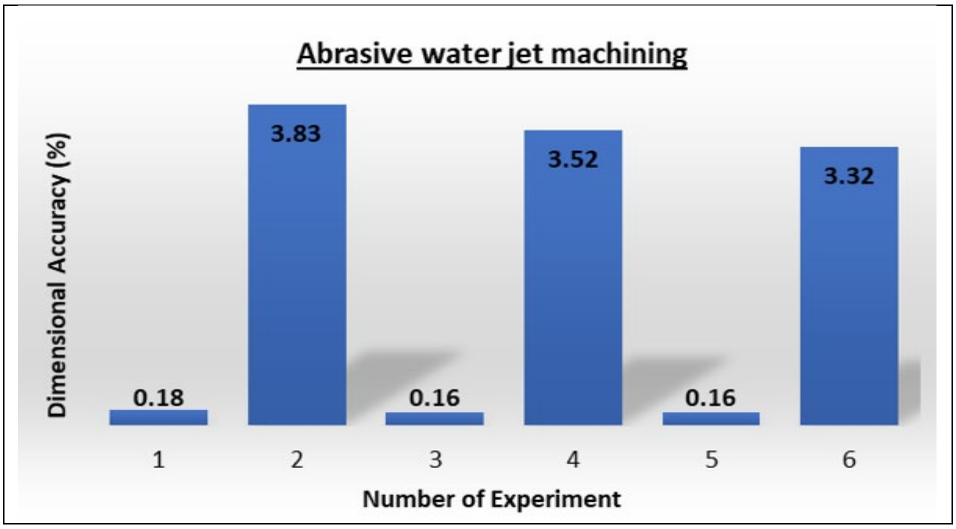


Fig. 6 *Experimental results of AJWM – dimensional accuracy*

3.2 Statistical Analysis Using ANOVA

An analysis of variance (ANOVA) was performed using Design Expert to evaluate the influence of each factor on the responses. According to Halim et al. [17], ANOVA is a powerful statistical method that is also able to determine the degree of significance of each factor and optimum condition. In this study, the experimental works value and the responses' optimal value were compared for surface roughness and dimensional accuracy.

3.2.1 ANOVA Table for Surface Roughness

ANOVA was done to analyze the influence of controlled factors on surface roughness. Based on the ANOVA result as shown in Table 4, the model's F-Value is 87.19, and the P-Value is less than 0.05. This implies that the model is significant with only a 0.22% chance that the F-value this large could occur due to noise. For the controlled factors, it was found that factors A-transverse speed and B-cutting geometry are significant model terms. There is no interaction between factors found for this response. Furthermore, the predicted R^2 of 0.9406 is in reasonable agreement with the adjusted R^2 which is 0.9718. The adequate precision shows the measurement of the signal-to-noise ratio. A sufficient signal is indicated by a precision of 22.8338, which is greater than 4 and is regarded to be acceptable [2].

Table 4 *ANOVA table for surface roughness*

Source	Sum of square	DF	Mean square	F-value	Prob-F	
Model	0.9131	3	0.4565	87.19	0.0022	Significant
A-Transverse speed	0.8010	1	0.8010	152.98	0.0011	
B-Cutting shape	0.1121	1	0.1121	21.40	0.0190	
Residual	0.0157	1	0.0052			
Cor Total	0.9288	5				
Std. Dev	0.0724					
Mean	3.43					
C.V. %	2.11					
R^2	0.9831					
Adjusted R^2	0.9718					
Predicted R^2	0.9406					
Adeq. Precision	22.8338					

3.2.2 ANOVA Table for Dimensional Accuracy

For dimensional accuracy, ANOVA shows that the model is significant with a P-value of 0.0002 as shown in Table 5. Other than that, the predicted R^2 of 0.9984 is in reasonable agreement with the adjusted R^2 of 0.9997 where the differences are less than 0.2. The adequate precision at 138.6975 which is larger than 4 is considered as fit with an adequate signal ratio [18]. The significant factors are B-cutting shape, followed by factor A-transverse speed, and the interaction between both factors.

Table 5 *ANOVA table for dimension accuracy*

Source	Sum of square	DF	Mean square	F-value	Prob-F	
Model	17.37	3	5.79	5557.89	0.0002	Significant
A-Transverse speed	0.0702	1	0.0702	67.42	0.0145	
B-Cutting shape	17.24	1	17.24	16548.62	< 0.0001	
AB	0.0600	1	0.0600	57.62	0.0169	
Residual	0.0021	1	0.0007			
Cor Total	17.37	5				
Std. Dev	0.0323					
Mean	1.86					
C.V. %	1.73					
R^2	0.9999					
Adjusted R^2	0.9997					
Predicted R^2	0.9984					
Adeq. Precision	138.6975					

Fig. 7 shows the interaction between factor A-transverse speed and B-cutting shape for dimensional accuracy. It can be observed that the lowest error is achieved when factor A is at the highest value of 80% transverse speed with a rectangular shape of cutting. While at the rectangular shape, there is no interaction with the changes of transverse speed value. This finding is in line with Wang et al. [19], as they found in their process optimization study that the transverse speed provided a substantial effect on the cutting front profile accuracy. They also added that the water pressure and abrasive flow rate as not significant in the measured response.

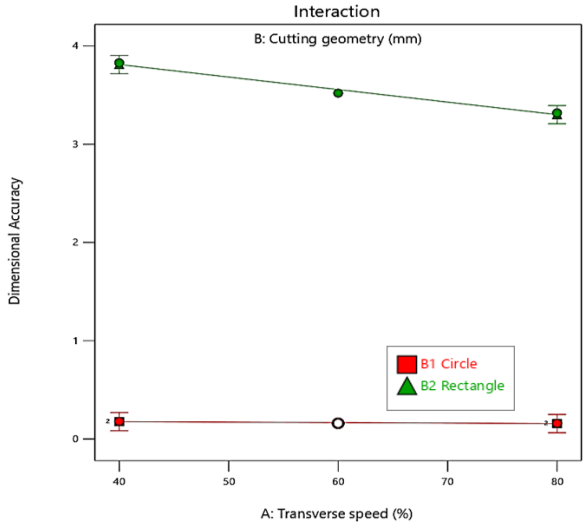


Fig. 7 *Interaction Plot of AB for dimensional accuracy*

3.3 Development and Validation of The First-Order Model

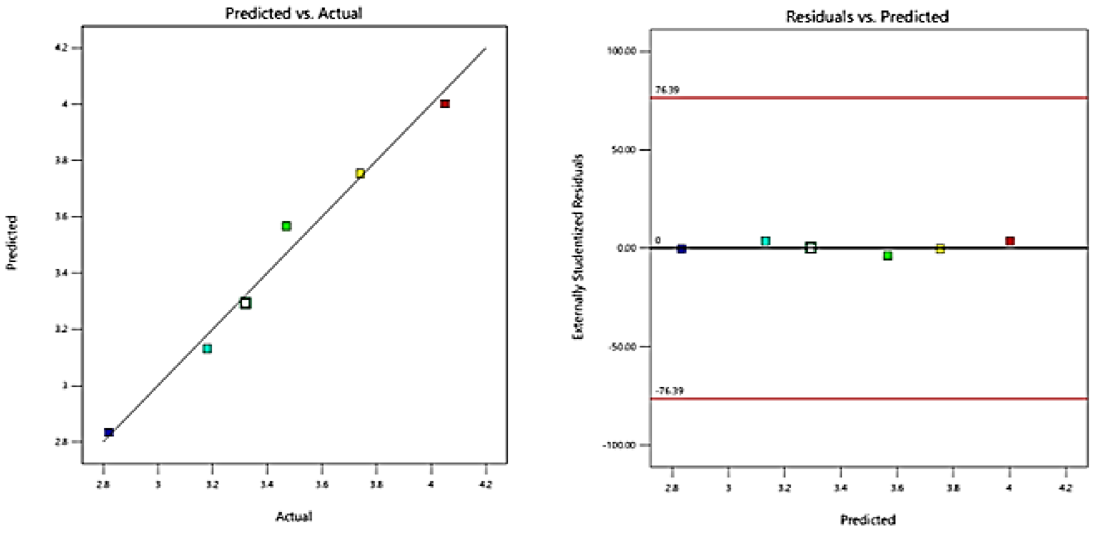
Full Factorial design constructed first-order model equations for both responses based on the experimental findings, as shown in Equation (1) and Equation (2):

$$\text{Surface Roughness} = 3.43 + 0.4475\,A + 0.1367\,B \tag{1}$$

$$\text{Dimensional Accuracy} = 1.86 - 0.1325\,A + 1.70\,B - 0.1225\,AB \tag{2}$$

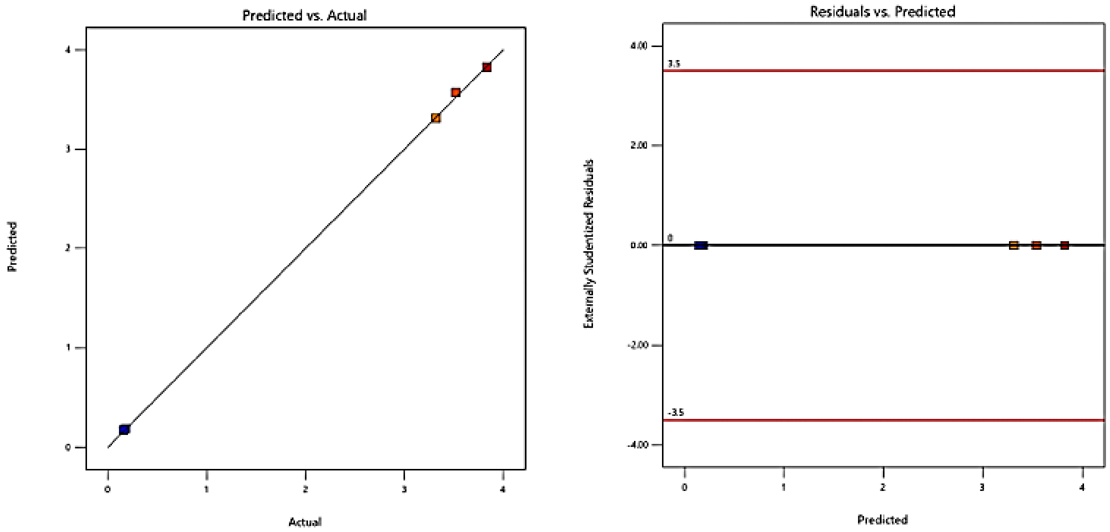
These first-order statistical model equations can be used to develop predictions on the responses of each value and term, within the controlled ranged. When the percentage error is less than 10%, the model's optimization solution is acceptable [2].

The diagnostic graph plots of predicted versus actual and residual versus predicted for surface roughness and dimensional accuracy were generated as illustrated in Fig. 8 and Fig. 9, respectively. As shown, the residuals suited the data well and followed a normal distribution. The predicted and actual values as in Fig. 8a and Fig. 9a are relatively close to the straight line, indicating that the errors were regularly distributed. Besides that, all the data in the fit position, which is the predicted and actual values are in a straight line. There are also no unusual patterns and structures for both residual versus predicted graphs (refer to Fig. 8b and Fig. 9b), and all the data is within the limit boundary.



(a) **(b)**

Fig. 8 *Diagnostic; (a) Predicted vs actual; (b) Residuals vs predicted for surface roughness*



(a) **(b)**

Fig. 9 *Diagnostic; (a) Predicted vs actual; (b) Residuals vs predicted for dimensional accuracy*

3.4 Optimization of Abrasive Waterjet Cutting Parameters

The Design Expert application allows ANOVA to generate the optimum parameters based on statistical analysis. The optimum parameters represent the values that are predicted to yield the best performance. Table 6 illustrates the optimum parameters evaluated by ANOVA with the transverse speed of 40% and circular-shaped geometry were selected as the optimum condition to produce a surface roughness of 2.833 and a dimensional accuracy of 0.177%. This solution gave the highest desirability at 0.992. The ramp view in Fig. 10 clearly shows the point of optimum value, which can be compared with the experimental value.

From the machining productivity point of view, the optimum parameter with minimum transverse speed is acceptable as according to Veerappan and Ravichandran [20], waterjet pressure and abrasive mass flow rate are more dominance in influencing the material removal rate of the process. Analyzing the transverse speed was reported as more important for the aspect of machined surface quality as also found in this study.

Table 6 *Optimization solution for abrasive waterjet cutting*

Number	Transverse Speed	Cutting Shape	Surface Roughness	Dimension Accuracy	Desirability	
1	40.00	Circle	2.846	0.177	0.987	Selected

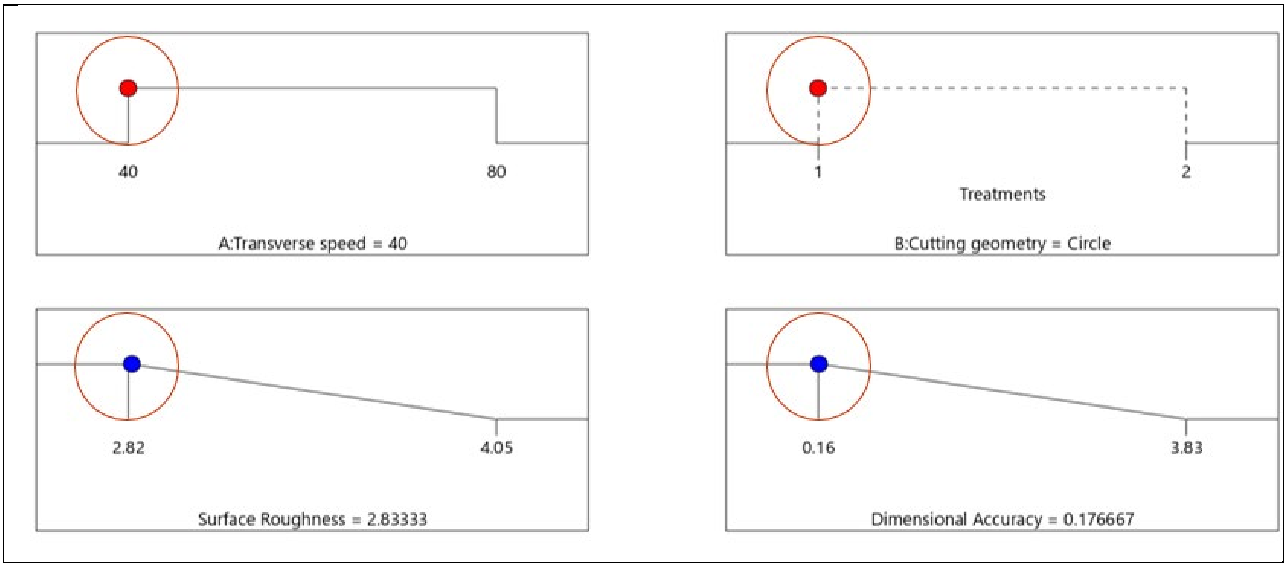


Fig. 10 *Ramps view of optimum parameters for abrasive waterjet cutting*

3.4.1 Result Validation

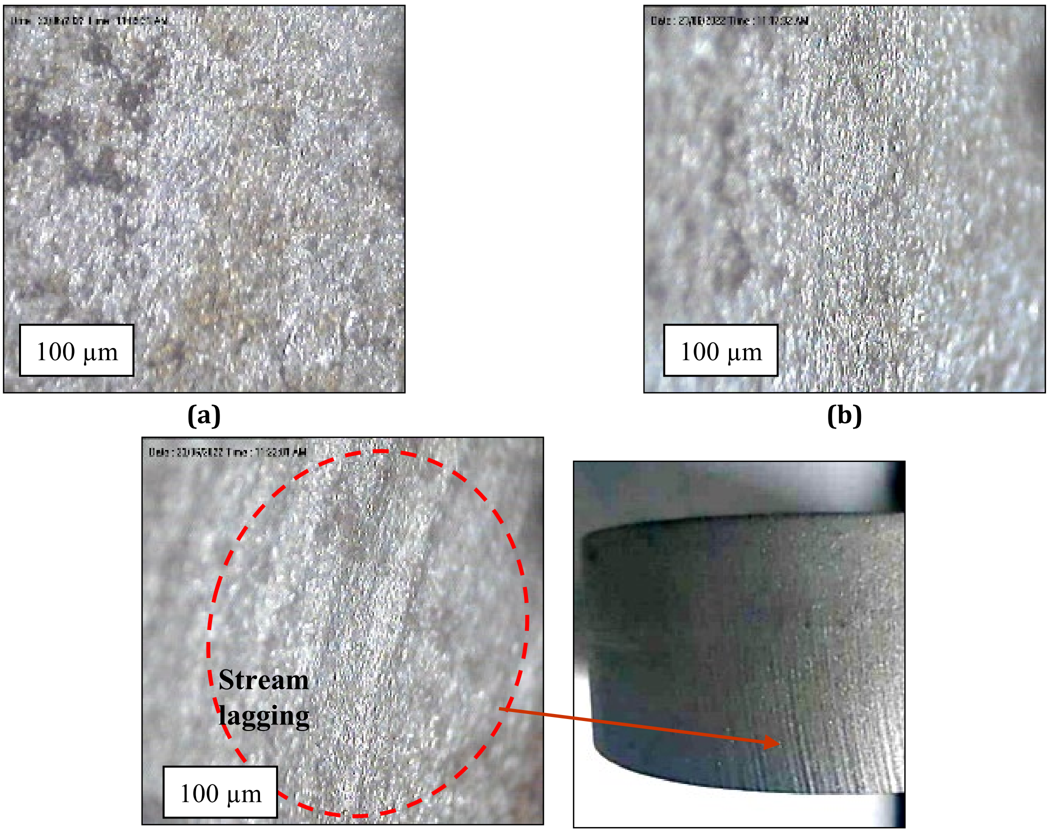
As for validation of the mathematical model, the predicted value and the actual value of experimental work were compared by using Equation (1) and Equation (2) for surface roughness and dimensional accuracy responses, respectively. By referring to Table 7, the error for surface roughness is 3.51% which is considered acceptable and valid as the error is less than 10% [2]. Similarly, the dimensional accuracy also resulted in an acceptable error value of 6.84%.

Table 7 *Result validation*

Response	Actual	Predicted	Error (%)
Surface Roughness (µm)	2.95	2.846	3.51
Dimension accuracy (%)	0.19	0.177	6.84

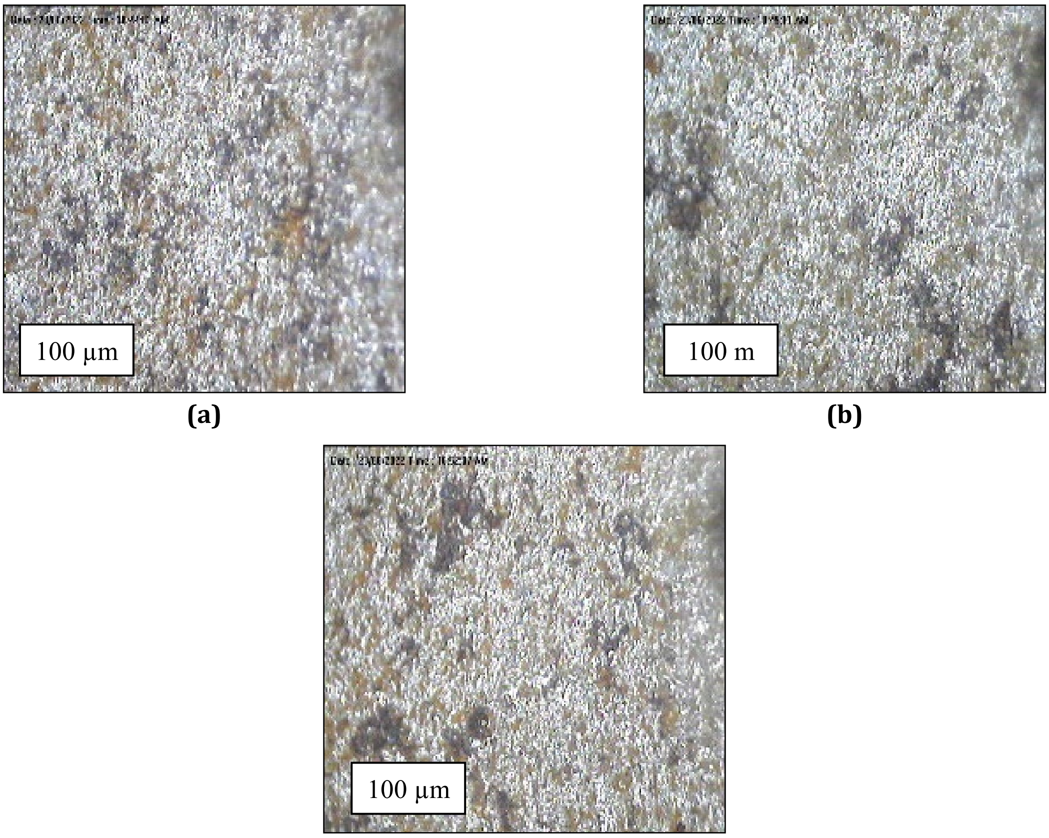
3.4.2 Machining Surface Quality

One of the main criteria for the finished machining parts is the level of surface quality. According to Jerman et al. [21], surface quality is highly influenced by cutting parameters. Thus, choosing the right value for the parameter is very important. Fig. 11 and Fig. 12 compare machined surface quality at different transverse speeds for circular and rectangular geometries, respectively. It was found that there were no obvious visible machining marks at transverse speeds of 40% and 60% for both circular and rectangular geometries. However, at the transverse speed of 80%, the stream lagging marks were found developed on the machined surface, with the circular shape geometry generating the obvious one as in Fig. 11c. Generally, this finding is parallel with Oh et al. [22], as they also noticed that the smoother surface roughness can be produced by reducing the cutting speed of the abrasive waterjet machine. By referring to Sasikumar et al. [23], the cutting process loses the number of abrasive particles with the increase of transverse speed, which then lead to a rougher surface as well as stream lagging marks. As in this study, the optimization solution suggested that a cutting speed of 40% on circular geometry produces excellent surface roughness visibility.



(a) (b) (c)

Fig 11 *Machined surface quality at the transverse speed of; (a) 40%; (b) 60%; (c) 80% for circular geometry*



(a) (b) (c)

Fig. 12 *Machined surface quality at the transverse speed of; (a) 40%; (b) 60%; (c) 80% for rectangular geometry*

4. Conclusion

The objective of this project is to analyze the influence of transverse speed and cutting geometry on surface roughness and dimensional accuracy using abrasive waterjet cutting on mild steel. The Full factorial and ANOVA have proved to be suitable and practical techniques that can be used to properly design the experiments, identify factors that significantly affect the responses as well as predict the value of the responses under the optimal parameters. Results from the ANOVA found that the optimization value is a transverse speed of 40% with circular geometry. The optimization for circular geometry would produce a surface roughness of 2.85 μm and a dimensional accuracy of 0.177%. The results of this study offer a variety of useful applications for future study and practice. Other than that, a suitable transverse speed such as 40% speed could be recommended as common industry use due to the time machining is not taking too long and able to offer a good finishing cutting.

Acknowledgement

The authors are grateful to the College of Engineering, Universiti Teknologi MARA, Shah Alam for funding and supporting the research fund.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurul Hayati Abdul Halim, Izdihar Tharazi, Muhammad Azri Arifin Abdullah;* ***data collection:*** *Muhammad Azri Arifin Abdullah, Mohd Firhan Morni;* ***analysis and interpretation of results:*** *Izdihar Tharazi, Nurul Hayati Abdul Halim, Farrahshaida Mohd Salleh, Muhammad Ilham Khalit;* ***draft manuscript preparation:*** *Izdihar Tharazi, Nurul Hayati Abdul Halim. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] T. Mert, "Water Jet Cutting Technology and Its Comparison With Other Cutting Methods in Some Aspects," *Academia Journal of Science*, vol. 1, no. 13, pp. 275–282, 2012.

[2] M. S. Alsoufi, "State-of-the-Art in Abrasive Water Jet Cutting Technology and the Promise for Micro- and Nano-Machining," *International Journal of Mechanical Engineering and Applications*, vol. 5, no. 1, p. 1, 2017, doi: 10.11648/j.ijmea.20170501.11.

[3] Y. Natarajan, P. K. Murugesan, M. Mohan, and S. A. Liyakath Ali Khan, "Abrasive Water Jet Machining process: A state of art of review," *Journal of Manufacturing Process.*, vol. 49, no. January 2019, pp. 271–322, 2020, doi: 10.1016/j.jmapro.2019.11.030.

[4] S. OKE and U. S. NWANKİTİ, "Optimal Cutting Conditions of Abrasive Waterjet Cutting for Ti-6Al-2Sn-2Mo Alpha-Beta Alloy Using EDAS and DFA Methods," *Gazi University Journal of Science Part A Engineering and Innovation*, vol. 9, no. 3, pp. 233–250, 2022, doi: 10.54287/gujsa.1135609.

[5] N. S. Yadav and N. K. Chavda, "Using Advanced Computational method to Investigate the reduce Kerf angle in Abrasive water jet cutting Machine for Aluminum 6082–t6 and SS304," *Kalaharijournals.Com*, vol. 7, no. 5, pp. 974–5823, 2022.

[6] V. Marušić, J. Baralić, B. Nedić, and Ž. Rosandić, "Effect of machining parameters on jet lagging in abrasive water jet cutting," *Tehnicki Vjesnik*, vol. 20, no. 4, pp. 677–682, 2013.

[7] A. Akkurt, M. K. Kulekci, U. Seker, and F. Ercan, "Effect of feed rate on surface roughness in abrasive waterjet cutting applications," *Journal of Materials Processing Technology*, vol. 147, no. 3, pp. 389–396, 2004, doi: 10.1016/j.jmatprotec.2004.01.013.

[8] W. Sami Abushanab, E. B. Moustafa, M. Harish, S. Shanmugan, and A. H. Elsheikh, "Experimental investigation on surface characteristics of Ti6Al4V alloy during abrasive water jet machining process," *Alexandria Engineering Journal*, vol. 61, no. 10, pp. 7529–7539, 2022, doi: 10.1016/j.aej.2022.01.004.

[9] J. Folkes, "Waterjet-An innovative tool for manufacturing," *Journal of Materials Processing Technology*, vol. 209, no. 20, pp. 6181–6189, 2009, doi: 10.1016/j.jmatprotec.2009.05.025.

[10] A. Deaconescu and T. Deaconescu, "Response surface methods used for optimization of abrasive waterjet machining of the stainless steel x2 crnimo 17-12-2," *Materials (Basel).*, vol. 14, no. 10, 2021, doi: 10.3390/ma14102475.

[11] Y. Ozcelik, M. Gursel, R. Ciccu, G. Costa, and A. Bortolussi, "Optimization of working parameters of water jet

cutting in terms of depth and width of cut," *Proceeding of the Institution of Mechanical Engineers Part E Journal of Process Mechanical Engineering*, vol. 226, no. 1, pp. 64–78, 2012, doi: 10.1177/0954408911407706.

[12] M. M. Korat and G. D. Acharya, "A Review on Current Research and Development in Abrasive Waterjet Machining," *Journal of Engineering Research and Applications*, vol. 4, no. 1, pp. 423–432, 2014.

[13] J. M. Llanto, A. Vafadar, M. Aamir, and M. Tolouei-Rad, "Analysis and optimization of process parameters in abrasive waterjet contour cutting of aisi 304l," *Metals (Basel).*, vol. 11, no. 9, 2021, doi: 10.3390/met11091362.

[14] M. S. Alsoufi, D. Suker, S. Azam, D. K. Suker, and A. S. Alsabban, "Experimental Study of Surface Roughness and Micro-Hardness Obtained by Cutting Carbon Steel with Abrasive WaterJet and Laser Beam Technologies Environmental sustainability and energy conservation during machining processes View project 4 Point Probe View," *American Journal of Mechanical Engineering*, vol. 4, no. 5, pp. 173–181, 2016, doi: 10.12691/ajme-4-5-2.

[15] I. Puertas, C. J. Luis Pérez, D. Salcedo, J. León, R. Luri, and J. P. Fuertes, "Precision study of a coordinate measuring machine using several contact probes," *Procedia Engineering*, vol. 63, pp. 547–555, 2013, doi: 10.1016/j.proeng.2013.08.260.

[16] D. Begic-Hajdarevic, A. Cekic, M. Mehmedovic, and A. Djelmic, "Experimental study on surface roughness in abrasive water jet cutting," *Procedia Engineering*, vol. 100, no. January, pp. 394–399, 2015, doi: 10.1016/j.proeng.2015.01.383.

[17] N. H. A. Halim, C. H. C. Haron, J. A. Ghani, and M. F. Azhar, "Prediction of cutting force for milling of Inconel 718 under cryogenic condition by response surface methodology," *Journal of Mechanical Engineering*, vol. 16, no. 1, 2019.

[18] A. Perec, "Multiple response optimization of abrasive water jet cutting process using Response Surface Methodology (RSM)," *Procedia Computer Science*, vol. 192, pp. 931–940, 2021, doi: 10.1016/j.procs.2021.08.096.

[19] S. Wang, F. Yang, D. Hu, C. Tang, and P. Lin, "Modelling and analysis of abrasive water jet cutting front profile," *The International Journal of Advanced Manufacturing Technology*, vol. 114, no. 9–10, pp. 2829–2837, 2021, doi: 10.1007/s00170-021-07014-5.

[20] G. Veerappan and M. Ravichandran, "Experimental investigations on abrasive water jet machining of nickel-based superalloy," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 41, no. 11, pp. 1–12, 2019, doi: 10.1007/s40430-019-2031-1.

[21] M. Jerman, J. Valentinčič, A. Lebar, and H. Orbanić, "The study of abrasive water jet cutting front development using a two-dimensional cellular automata model," *Strojniski Vestnik/Journal of Mechanical Engineering*, vol. 61, no. 5, pp. 292–302, 2015, doi: 10.5545/sv-jme.2014.2179.

[22] T. M. Oh, G. W. Joo, Y. Cha, and G. C. Cho, "Effect of garnet characteristics on abrasive waterjet cutting of hard granite rock," *Advances in Civil Engineering*, vol. 2019, 2019, doi: 10.1155/2019/5732649.

[23] K. S. K. Sasikumar, K. P. Arulshri, K. Ponappa, and M. Uthayakumar, "A study on kerf characteristics of hybrid aluminium 7075 metal matrix composites machined using abrasive water jet machining technology," *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture*, vol. 232, no. 4, pp. 690–704, 2018, doi: 10.1177/0954405416654085.