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Optimizing Abrasive Water Jet Machining for Enhanced Machining of 316 Stainless Steel

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Abstract

Abrasive Water Jet Machining (AWJM) is a non-traditional machining process renowned for its versatility and ability to cut a wide range of materials precisely. This research article presents an in-depth analysis of the optimization of AWJM parameters for machining 316 stainless steel, aiming to enhance surface quality and machining efficiency. Through a comprehensive experimental setup, the study explores the effects of varying the speed, standoff distance (SOD), and flow rate on the surface roughness (Ra) of the machined workpiece. The Taguchi method's L9 orthogonal array is employed to design the experiments, and a signal-to-noise (S/N) ratio analysis, alongside an analysis of variance (ANOVA), is utilized to discern the most significant machining parameters. Response tables for S/N ratios and means are created to summarize the effects, and main effects plots are generated to visualize trends in the data. Furthermore, a regression model is developed to correlate the machining parameters with the surface roughness, which is validated by a high coefficient of determination. Residual plots and diagnostics for unusual observations are utilized to ensure the robustness of the model. The study concludes that SOD is the most influential parameter, followed by speed and flow rate. The optimization results provide a quantitative understanding that can significantly contribute to the industrial application of AWJM for 316 stainless steel, ensuring optimal surface integrity and operational cost-effectiveness. The findings of this research offer pivotal insights for manufacturing industries that seek to integrate AWJM into their production processes.

Keywords: Abrasive Water Jet Machining, Surface Roughness, Optimization, 316 Stainless Steel, Taguchi Method

1 Introduction

Stainless steel 316 is a material known for its excellent corrosion resistance and robust mechanical properties, making it indispensable in sectors that demand high durability and resilience, such as marine engineering, biomedical devices, and chemical processing equipment [1, 2]. Despite its widespread use, machining stainless steel 316 can be challenging due to its high work hardening rate and considerable toughness, often resulting in accelerated tool wear and poor surface quality [3–5]. These challenges necessitate the exploration of non-conventional machining techniques that can mitigate the limitations posed by traditional machining. Abrasive Water Jet Machining (AWJM) has emerged as a potent solution, offering a non-contact and versatile cutting process that circumvents the thermal and mechanical stresses typically associated with conventional machining methods [6].

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Table 1: Chemical composition of Stainless Steel 316.

Element	Composition (%)
Iron (Fe)	Balance
Chromium (Cr)	16.0 - 18.0
Nickel (Ni)	10.0 - 14.0
Molybdenum (Mo)	2.0 - 3.0
Manganese (Mn)	<2.0
Silicon (Si)	<1.0
Carbon (C)	<0.08
Phosphorus (P)	<0.045
Sulfur (S)	<0.03

The core mechanism of AWJM involves a high-pressure jet of water mixed with abrasive particles directed at the workpiece to effect material removal through erosion. This technique is particularly beneficial for cutting intricate shapes and handling tough materials like stainless steel 316, as it eliminates thermal distortion and reduces tool wear, while improving surface quality of the machined surface [7–9]. However, to fully exploit the capabilities of AWJM, it is crucial to optimize the machining parameters, such as jet speed, standoff distance (SOD), and abrasive flow rate, to achieve the desired surface integrity and dimensional accuracy. The complexity of the interactions between these parameters and their effects on the machining outcomes necessitates a systematic approach to their study and optimization [10]. Extensive research has been conducted in recent times to explore the effects of AWJM parameters on the surface quality and machining efficiency of various steel. For instance, Singh et al. [11] conducted a study to optimize process parameters for machining marine grade Inconel using abrasive water jet machining (AWJM) to improve surface properties and productivity. They applied Taguchi-based Grey analysis to optimize parameters for minimum surface roughness and higher material removal rate (MRR, identifying standoff distance (SOD), abrasive flow rate (AFR), and jet traverse speed (JTS) as the most influential parameters. Machining at specific values of SOD, AFR, and JTS resulted in maximum MRR and minimum surface roughness, with SOD being identified as the most significant parameter. Gawade and Jatti's [12] study focused on optimizing process parameters for minimizing taper angle in abrasive water jet machining of 304 stainless steel. They used response surface methodology, design of experiments, and ANOVA to determine the optimal parameters (traverse rate, abrasive flow rate, stand-off distance) leading to a high desirability model (0.9195) with validation results showing low percentage error (<6%) for taper angle. Rammohan's [13]study on AWJ machining of armour steel highlights that higher traverse speed and water jet pressure lead to wider kerf width and higher material removal rate. The research emphasizes the importance of these parameters for achieving optimal machining results, especially in terms of surface finish and material removal rate.

While the literature provides a solid foundation for understanding AWJM processes, there remains a need for targeted research that addresses the specific characteristics of stainless steel 316. This study aims to fill this gap by optimizing AWJM parameters to improve surface roughness and overall machining performance for this material. The study's objectives are to identify the most influential AWJM parameters on the surface roughness of stainless steel 316 and to develop a comprehensive regression model that can predict surface quality based on these parameters. The subsequent sections of this paper detail the methodology adopted for the experimental design, present the results of the machining trials and discuss the implications of the findings in the context of the existing literature. By doing so, the study contributes a nuanced understanding of AWJM parameter optimization for stainless steel 316, with the potential to inform industrial practices and future research in this domain.

2 Materials and Methods

2.1 Materials

The study employed Stainless Steel 316 (SS316), an austenitic alloy celebrated for its excellent corrosion resistance, high tensile strength, and robust mechanical properties across a wide temperature range. The choice of SS316 was driven by its prevalent use in demanding environments such as marine, chemical processing, and pharmaceutical sectors. The alloy's composition includes iron, chromium, nickel, and molybdenum, offering superior corrosion and oxidation resistance. The specific chemical composition sourced from the supplier is detailed in Table 1 to ensure reproducibility and relevance in industrial applications.

2.2 Equipment Setup

The experimental setup was centered around a high-precision AWJM system. This system comprised a high-power pump (37 kW) designed to generate a pressurized water stream mixed with abrasive particles directed through a precision-engineered nozzle. A CNC controller augmented the machine's cutting capabilities, ensuring meticulous control over the machining process. Key specifications include a working table dimension and a high-capacity abrasive feeder, facilitating continuous operation. The selection of SS316 as the workpiece material further underscores the study's industrial relevance.

2.3 Experimental Design Using L9 Orthogonal Array

Adopting the Taguchi L9 orthogonal array, the experimental design was structured to analyze the effects of three pivotal AWJM parameters: traverse speed, stand-off distance, and abrasive flow rate. This design choice allowed for a comprehensive investigation with minimal experimental runs, focusing on efficiency and effectiveness. The parameters were chosen based on an extensive literature review and preliminary experiments to bridge the gap between theoretical knowledge and practical application.

2.4 Surface Roughness Measurement

The quantification of surface roughness, a critical quality attribute in machining, was meticulously conducted using a Surtronic 3+ profilometer. This instrument, known for its precision, measures the texture of machined surfaces through a diamond-tipped stylus. The procedure involved multiple measurements across different surface areas to ensure accuracy and reproducibility. Based on these measurements, the calculation of Ra values provides a reliable metric for assessing the machining process's impact on surface integrity.

Table 2: L9 Orthogonal Array for AWJM Parameters

Experiment No.	Speed [mm/min]	SOD [mm]	Flow rate [g/min]
1	30	2	200
2	30	5	500
3	30	8	800
4	50	2	500
5	50	5	800
6	50	8	200
7	70	2	800
8	70	5	200
9	70	8	500

3 Results

3.1 Influence of AWJM Parameters on Surface Roughness

The experimental data obtained from the Taguchi L9 orthogonal array are presented in Table 3, which showcases the interplay between the abrasive water jet machining parameters and the resultant surface roughness (Ra) of the machined 316 stainless steel samples.

Table 3: Experimental Results for AWJM on 316 Stainless Steel

Speed (mm/min)	SOD (mm)	Flow rate (g/min)	Ra (μm)
30	2	200	1.8
30	5	500	2.1
30	8	800	2.5
50	2	500	2.0
50	5	800	2.4
50	8	200	3.0
70	2	800	1.7
70	5	200	2.9
70	8	500	3.2

The data elucidate the effect of traverse speed, stand-off distance (SOD), and abrasive flow rate on the surface roughness of the material. Initial observations suggest that an increase in SOD and abrasive flow rate tends to correlate with an increase in Ra, indicating a rougher surface finish. In contrast, higher traverse speeds appear to contribute to a finer surface finish, as the lowest Ra value was observed at the highest speed of 70 mm/min with a SOD of 2 mm and an abrasive flow rate of 800 g/min. This trend is consistent with the understanding that higher speeds reduce the interaction time between the abrasive particles and the workpiece, resulting in a smoother surface. Further statistical analysis was conducted to quantify these parameters' effects and identify optimal settings for minimal surface roughness in AWJM of 316 stainless steel.

3.2 Analysis of Signal-to-Noise Ratios

The Taguchi method's signal-to-noise (S/N) ratio, which adopts the "smaller-is-better" characteristic for surface roughness, is utilized to determine the robustness of the AWJM process. The main effects plot for S/N ratios (Figure 1) indicates the influence of each machining parameter on the quality characteristic. The response table for S/N ratios

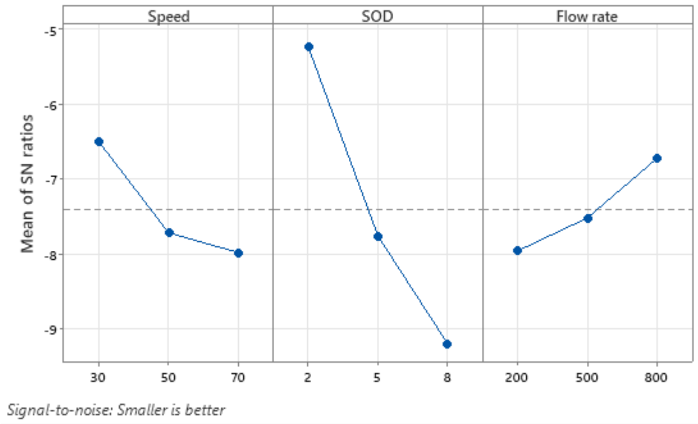

Figure 1: Main Effects Plot for S/N Ratios

Table 4: Response Table for Signal to Noise Ratios

Level	Speed	SOD	**Flow rate**
1	-6.503	-5.245	-7.965
2	-7.722	-7.766	-7.523
3	-7.987	-9.201	-6.724
Delta	1.484	3.956	1.241
Rank	2	1	3

(Table 4) further complements the plot by quantifying the effect of each parameter level. The delta value represents the range between the highest and lowest S/N ratio for each parameter, indicating its impact on surface roughness. A higher delta signifies a more significant effect on the quality characteristic. According to the data, the SOD exhibits the highest delta value, suggesting it is the most influential parameter affecting surface roughness, followed by speed and flow rate, in that order. This preliminary analysis implies that to achieve a finer surface finish; the SOD should be carefully controlled, while the speed and flow rate can be adjusted to fine-tune the process.

3.3 Regression Model and Statistical Analysis

The regression model and its summary, presented in Table 5, provide a robust statistical framework for understanding the relationship between the AWJM parameters and the surface roughness of 316 stainless steel.

Table 5: Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
0.158114	94.70%	91.53%	0.491323	79.18%	17.05	-1.96

The Analysis of Variance (ANOVA), detailed in Table 6, highlights the significance of the regression model. The F-values and P-values indicate that the model terms are statistically significant predictors of surface roughness.

Table 6: Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	3	2.2350	94.70%	2.2350	0.74500	29.80	0.001
Speed	1	0.3267	13.84%	0.3267	0.32667	13.07	0.015
SOD	1	1.7067	72.32%	1.7067	1.70667	68.27	0.000
Flow rate	1	0.2017	8.55%	0.2017	0.20167	8.07	0.036
Error	5	0.1250	5.30%	0.1250	0.02500		
Total	8	2.3600	100.00%				

Unusual observations, potentially outliers or influential points are diagnosed with Cook's D measure, as shown in Table 7. A single observation with a high Cook's D value, observation 7, is excluded from the analysis to improve the model's accuracy.

Table 7: Fits and Diagnostics for Unusual Observations

Observation	Ra	Fit	SE Fit	95% CI	Resid	Std Resid	Del Resid	HI	Cook's D
7	1.700	1.917	0.124	(1.599, 2.234)	-0.217	-2.20	-10.61	0.611111	1.90

Residual plots are instrumental in verifying the assumptions of the regression analysis. As depicted in Figure 2, the normal probability plot of residuals indicates normality, and the absence of patterns in the residuals versus fits and versus order plots suggests that the residuals are randomly distributed, satisfying the assumptions of homoscedasticity and independence.

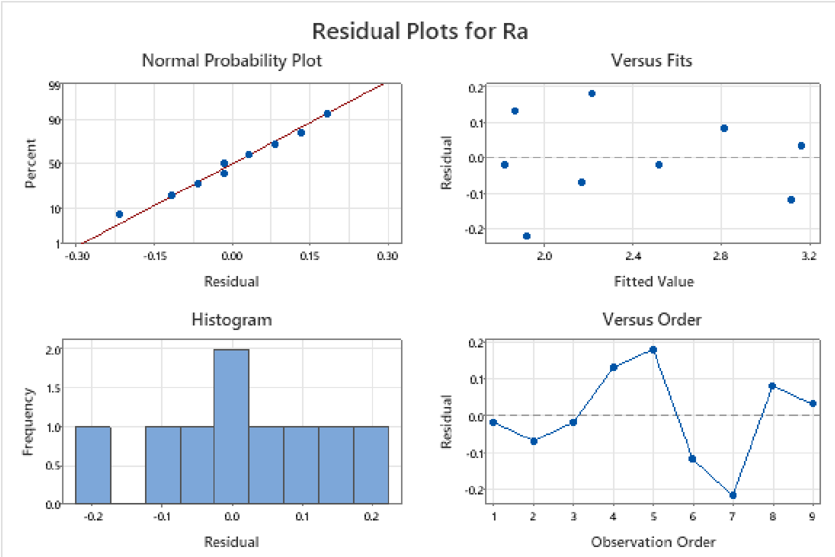

Figure 2: Residual Plots for Surface Roughness (Ra)

The regression equation, given below, encapsulates the quantitative relationship between the machining parameters and the surface finish, enabling predictions of surface roughness for given sets of parameters:

$$Ra = 1.233 + 0.0167 \times \text{Speed} + 0.1778 \times \text{SOD} - 0.000611 \times \text{Flow rate} \tag{1}$$

This equation, derived from the regression analysis, serves as a predictive model for determining the expected surface roughness (Ra) for a given combination of AWJM parameters, facilitating the optimization of the machining process.

4 Discussion

The optimization of AWJM parameters for the machining of 316 stainless steel is a complex interplay of process variables that directly influence the surface roughness of the finished workpiece. The experimental data indicate that both the speed of the abrasive water jet and the standoff distance (SOD) significantly affect the surface quality, with the flow rate of the abrasive mixture playing a lesser yet notable role. The physics underlying the AWJM process involves the conversion of pressure energy into kinetic energy as the water and abrasive mixture exits the nozzle. The abrasive particles, propelled by the water jet, strike the material surface with significant force, leading to material erosion primarily by micro-cutting and deformation wear mechanisms. An increase in the traverse speed of the jet results in a reduction of interaction time between the abrasive particles and the target surface, which tends to produce a finer finish. This is corroborated by the inverse relationship between speed and surface roughness observed in the experimental data. The kinetic energy imparted to the abrasive particles is a function of the square of their velocity, as described by $\frac{1}{2}mv^2$, where m is the mass of the particles and v is their velocity. Hence, a higher traverse speed translates to increased kinetic energy and a greater capacity for the particles to deform and erode the workpiece material. The SOD plays a pivotal role in the quality of the machined surface. With an increased SOD, there is a notable dispersion of the jet, which leads to a decrease in the energy density as the particles spread over a larger area. This dispersion results in a reduction of the localized impact forces, hence a diminished erosion efficiency and a rougher surface texture. The experimental results, reflecting the SOD as the most significant factor, align with the principles of jet dispersion and its impact on the energy delivered to the target material. The abrasive flow rate determines the number of particles available to erode the material.

At an optimal flow rate, the balance between particle mass and velocity is maintained, allowing for maximum energy transfer to the material surface without significant interference from particle collisions or agglomeration. However, if the flow rate is too high, it can result in a crowding effect, where the particles interfere with each other, reducing the efficiency of the cutting action. This phenomenon explains the negative coefficient for the flow rate in the regression equation, suggesting that beyond a certain threshold, an increase in flow rate can adversely affect surface finish. The formation of surface roughness in AWJM is governed by the mechanics of abrasive particle impact, where each particle acts as a micro-cutting tool that chips away minute fragments of the material. The quality of the surface finish is therefore a cumulative effect of these microscopic interactions, which are influenced by the parameters discussed. It is evident from the analysis that a delicate balance between speed, SOD, and flow rate is required to achieve a surface finish that meets the stringent requirements of industries employing 316 stainless steel. Understanding the mechanics behind the AWJM process is critical for its application in industry. The ability to predict the outcome of varying parameters allows for better control and optimization of the machining process, leading to improved efficiency, reduced costs, and enhanced quality of the machined parts. The discussion presented here provides a theoretical basis for the observed effects and underscores the importance of precise control over AWJM parameters to achieve desired machining outcomes.

5 Conclusion

In this study, the optimization of abrasive water jet machining (AWJM) parameters for the machining of 316 stainless steel was systematically investigated to enhance surface quality. The experimental results and subsequent analysis have elucidated the significant influence of process parameters on the surface roughness of the machined specimens. The standoff distance (SOD) emerged as the most impactful factor, followed by the traverse speed of the jet, and lastly, the abrasive flow rate. These findings are in line with the underlying mechanics of AWJM, where the energy density of the abrasive particles and their interaction with the workpiece surface determine the machining quality. A higher SOD was observed to disperse the jet, reducing the energy density and leading to a rougher surface, while a higher speed reduced the surface roughness due to increased kinetic energy imparted to the abrasive particles. The flow rate's inverse relationship with surface roughness underscores the need for a balanced abrasive supply to maintain cutting efficiency. The regression model developed provides a predictive capability for determining the surface roughness for given machining parameters, offering a valuable tool for process optimization in industrial applications. Future research may explore the integration of real-time monitoring and adaptive control systems in AWJM to dynamically adjust parameters and further improve surface integrity. Additionally, the extension of this study to other materials and the investigation of other AWJM parameters could provide broader insights into the versatile nature of this machining process.

Declaration of Competing Interests

The authors declares that they has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Author Contributions

Ritesh Bhat: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Supervision, Project Administration; **Vipin Tandon**: Data Curation, Formal Analysis, Investigation, Visualization, Writing - Review & Editing; **Syed Azuan Syed Ahmad**: Software, Validation, Resources, Writing - Review & Editing.

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