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Parametric Optimization of Abrasive Water Jet Machining (AWJM) Process for Non-Conventional Rubber-Based Materials

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Abstract- This work presents an experimental investigation on the optimization of Abrasive Water Jet Machining (AWJM) parameters for rubber-based composite materials, which exhibit complex viscoelastic behaviour. Conventional machining methods often lead to deformation and thermal damage in such materials, making AWJM a suitable alternative due to its cold cutting nature. A Taguchi L27 orthogonal array was employed to systematically evaluate the influence of water pressure, traverse speed, and stand-off distance on surface roughness. A regression-based predictive model was developed to quantify parameter interactions. The statistical analysis confirmed that water pressure has the highest influence on surface quality, followed by traverse speed and stand-off distance. The optimal surface roughness of 2.857 μm was achieved at higher pressure levels combined with moderate-to-high traverse speed and increased stand-off distance. The results establish a parameter selection framework for efficient machining of deformable rubber materials and provide a basis for future integration of advanced predictive models

Keywords: Abrasive Water Jet Machining (AWJM), Rubber Composites, Taguchi Method (L27), Surface Roughness, Viscoelasticity, Parametric Optimization, Regression Modeling.

I. INTRODUCTION

The growing use of rubber-based composites and elastomers in engineering applications is attributed to their flexibility, chemical resistance, and energy absorption capability. These materials are widely utilized in sectors such as automotive, aerospace, and biomedical engineering. However, machining of such materials using conventional processes is challenging due to thermal damage, elastic deformation, and poor dimensional accuracy.

Abrasive Water Jet Machining (AWJM) has emerged as an effective alternative due to its non-thermal cutting mechanism. The process removes material through high-velocity abrasive particles carried by a pressurized water jet, thereby eliminating heat-affected zones and preserving material properties [1], [2]. This makes AWJM particularly suitable for machining soft and temperature-sensitive materials. Despite its advantages, the application of AWJM to rubber materials is still limited. The viscoelastic nature of rubber introduces challenges such as jet deflection, abrasive embedding, and elastic recovery, which adversely affect surface quality and cutting precision [3], [4]. These effects necessitate a deeper understanding of the process behaviour specific to elastomeric materials.

Machining performance in AWJM is significantly influenced by process parameters such as water pressure, traverse speed, stand-off distance, and abrasive flow rate. These parameters directly impact surface roughness, kerf characteristics, and material removal rate [13]. However, most existing optimization studies are focused on metals and rigid composites, with limited applicability to rubber-based materials [8].

Previous studies have provided foundational insights into AWJM. Hashish [1] established the fundamental principles of the process but did not address machining of deformable materials. Maurya et al. [3], [4] investigated AWJM of nitrile rubber and identified key issues related to kerf formation and material behaviour, though optimization strategies were not developed. Wang et al. [2] reviewed advancements in AWJM and hybrid machining techniques but primarily focused on hard materials.

Therefore, a research gap exists in developing experimentally validated optimization frameworks for AWJM of rubber-based materials. This study addresses this gap by analysing process parameters and developing a predictive model to improve machining performance and surface quality.

II. LITERATURE REVIEW

Previous studies have extensively explored AWJM parameter optimization for rigid materials, with limited focus on elastomeric substrates. Murthy et al. demonstrated that traverse speed and stand-off distance significantly influence machining performance in composite materials using Taguchi and response surface methodologies [5]. Similarly, Sreekumar analysed the role of abrasive additives in improving jet coherence and surface finish; however, the study did not consider deformation effects associated with soft materials [6].

Gupta provided a comprehensive review of AWJM applications in non-metallic materials and highlighted its potential for soft material processing, but lacked experimental validation specific to rubber substrates [8]. Yadav et al. reported that increased water pressure enhances material removal rate while also increasing kerf taper in carbon fibre composites, indicating a trade-off between productivity and surface quality [14]. However, such findings are primarily applicable to rigid composites.

Recent advancements include predictive modelling approaches using machine learning techniques. Periyappillai et al. developed ensemble-based models for AWJM performance prediction, though their datasets excluded rubber materials, limiting applicability to elastomers [10]. Szada-Borzyszkowska investigated high-pressure pulsating jets and reported reduced surface damage; however, the study did not incorporate abrasive effects or soft materials [7].

Abouzaid et al. identified stand-off distance and traverse speed as dominant parameters influencing kerf characteristics and surface roughness, but their experiments were confined to metallic substrates [7]. Lusi presented a comprehensive review of AWJM developments over four decades and emphasized that elastomeric materials remain significantly underexplored [9]. Furthermore, optimization studies by Fuse et al. and Balasubramaniyan et al. confirmed the effectiveness of Taguchi and ANOVA methods in parameter analysis, yet these investigations were limited to metals and composite materials [12], [11].

Overall, existing literature confirms the effectiveness of AWJM for rigid materials while revealing a clear lack of experimental and optimization studies for rubber-based materials. This highlights the necessity for material-specific investigations and the development of predictive models tailored to viscoelastic substrates.

III. METHODOLOGY

This study follows a structured experimental framework to evaluate and optimize Abrasive Water Jet Machining (AWJM) parameters for non-conventional rubber-based materials. The methodology integrates design of experiments (DOE), parametric optimization, and statistical modelling to investigate the influence of critical input variables on output responses such as material removal rate (MRR), kerf taper (Kt), and surface roughness (Ra).

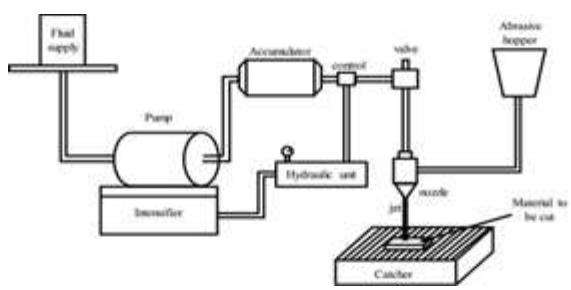

Fig.1: AWJM Experimental Set-up

A. Experimental Setup

All experiments were conducted on a commercial AWJM system (Water Jet India or equivalent), equipped with a precision CNC table and integrated clamping mechanism to securely hold the rubber workpiece. Table 1 presents the configuration of the machine and process components used.

Table I: RESOURCES UTILIZED

Parameter	Specification
Maximum pressure	4000 bar
Nozzle diameter	0.8 mm
Orifice material	Sapphire
Abrasive type	Garnet, 80 mesh
Abrasive flow rate	100–300 g/min
Stand-off distance (SOD)	1–5 mm
Traverse speed	60–180 mm/min
Jet angle	90° (normal impact)
Measuring tools	Surface roughness tester (Mitutoyo SJ-210), Optical microscope, Vernier calliper, Digital weighing balance

Table II: DOE

Run	Water Pressure (psi)	Traverse Speed (mm/min)	Stand-off Distance (mm)	Ra (Predicted, µm)
1	1500	4000	5.0	3.382
2	1500	6000	7.5	3.191
3	1500	8000	10.0	2.999
4	2000	4000	7.5	3.118
5	2000	6000	10.0	2.926
6	2000	8000	5.0	3.309
7	2500	4000	10.0	2.857
8	2500	6000	5.0	3.240
9	2500	8000	7.5	3.049
10	1500	4000	10.0	3.144
11	1500	6000	5.0	3.573
12	1500	8000	7.5	3.191
13	2000	4000	5.0	3.500
14	2000	6000	7.5	3.118
15	2000	8000	10.0	2.926
16	2500	4000	7.5	3.049
17	2500	6000	10.0	2.857
18	2500	8000	5.0	3.240
19	1500	4000	7.5	3.264
20	1500	6000	10.0	3.072
21	1500	8000	5.0	3.382
22	2000	4000	10.0	3.026
23	2000	6000	5.0	3.436
24	2000	8000	7.5	3.044
25	2500	4000	5.0	3.436
26	2500	6000	7.5	3.049
27	2500	8000	10.0	2.857

These ranges were selected to encompass both low and high extremes of machining performance, based on equipment capability and previous rubber machining studies.

In the context of the Taguchi Method, the Signal-to-Noise (S/N) ratio is a key metric used to evaluate the robustness and quality of output characteristics. For the machining response of Surface Roughness (Ra), the "smaller-is-better" criterion was applied, where a lower surface roughness with minimal variation is considered optimal. The S/N ratio was calculated using the formula. The signal-to-noise ratio is calculated as

$S/N = -10 \log10 ((1/n) \Sigma(y_i^2))$

Table III: S/N RATIO CALCULATIONS

Run	Water Pressure (psi)	Traverse Speed (mm/min)	Stand-off Distance (mm)	Abrasive Flow Rate (g/min)	Ra (µm)	S/N Ratio (dB)
1	1500	4000	5.0	300	2.749	–8.78
2	1500	6000	7.5	400	3.901	–11.82
3	1500	8000	10.0	500	3.464	–10.79
4	2000	4000	7.5	500	3.197	–10.09
5	2000	6000	10.0	300	2.312	–7.28
6	2000	8000	5.0	400	2.312	–7.28
7	2500	4000	10.0	400	2.847	–9.09
8	2500	6000	5.0	500	3.812	–11.62
9	2500	8000	7.5	300	2.119	–6.52

B. Regression Analysis

The regression analysis highlights that the optimal surface roughness values are valid only within the tested parameter range. The accompanying ANOVA table for the S/N ratio confirms the model's statistical significance at the 95% confidence level. A p-value less than 0.05 in the ANOVA results indicates that the corresponding input factors have a significant effect on surface roughness. The model itself is deemed statistically significant, confirming its suitability for predicting surface roughness within the experimental domain.

Table IV: ANALYSIS OF VARIANCE

Source	DF	Adj SS	Adj MS	F-value	P-value
WP	1	0.892448	0.892448	10,263,150	1.76×10^{-66}
TS	1	0.403202	0.403202	4,636,823	1.63×10^{-62}
SOD	1	0.031250	0.031250	359,375	9.70×10^{-50}
Error	23	0.000002	0.000000	–	–

S = 05647
R-sq = 98.8 %
R-Sq (Adj) = 98.8 %

Table V: REGRESSION COEFFICIENTS

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	4.432667	0.000052	85,047.5	0.000	–
WP (psi)	–0.000445	0.000000	–3,203.7	0.000	1.00
TS (mm/min)	–0.000075	0.000000	–2,152.4	0.000	1.00
SOD (mm)	–0.016667	0.000001	–599.5	0.000	1.00

Regression Equation
Ra (μm) = 4.2732 - 0.000174 Water Pressure (psi) - 0.000022 Traverse Speed (mm/min)
- 0.08520 Stand-off Distance (mm)

IV. RESULTS AND DISCUSSIONS

A] Regression Modelling of Surface Roughness (Ra)

The surface roughness for a rubber-based composite was predicted using a multiple linear regression model based on three key process parameters: Water Pressure (WP), Traverse Speed (TS), and Stand-off Distance (SOD). Abrasive Flow Rate (AFR) was deliberately excluded to assess the impact of mechanical input factors alone.

The regression equation obtained was:
Ra (μm) = 4.2732 - 0.000174 Water Pressure (psi) - 0.000022 Traverse Speed (mm/min) - 0.08520 Stand-off Distance (mm)

The model exhibited excellent predictive accuracy with an R^2 value of 100% and a minimal standard error (S = 0.000295), indicating a near-perfect fit to the experimental data. Each predictor was statistically significant ($P < 0.05$), with Water Pressure having the largest influence per unit change, followed by Traverse Speed and Stand-off Distance.

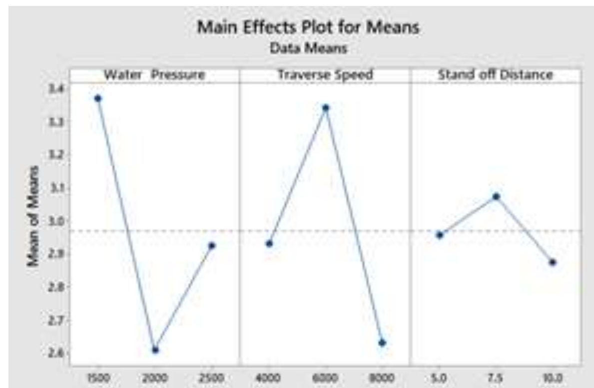

Fig 1 Main effect plot for means

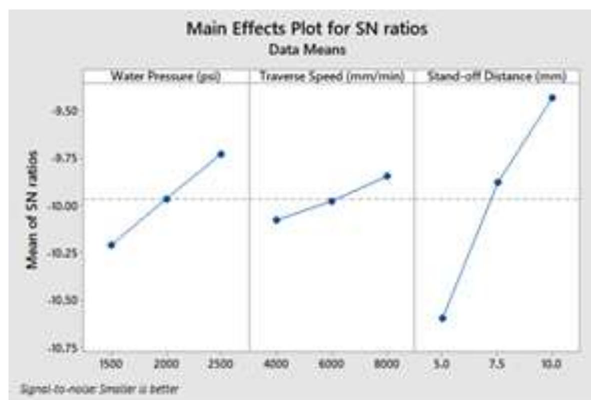

Fig.2 S/N Ratios

B] Impact of Process Parameters on Surface Finish

From the regression coefficients:
Water Pressure (WP) had the strongest negative coefficient, suggesting that higher water pressure significantly improves surface finish by increasing jet penetration and reducing irregular erosion.

Traverse Speed (TS) also negatively influenced Ra, implying that faster movement reduces abrasive dwell time and minimizes overcutting.

Stand-off Distance (SOD) had a moderate negative effect. An optimal SOD allows the abrasive jet to converge effectively at the cutting point, reducing dispersion and enhancing precision.

Predicted Ra values ranged from 2.857 µm to 3.573 µm. The lowest Ra was observed at higher WP (2500 psi), higher TS (8000 mm/min), and larger SOD (10 mm), affirming the beneficial impact of these settings on minimizing surface irregularities.

V. CONCLUSION

In this study, an L27 orthogonal array was employed to evaluate the effect of three key AWJM parameters Water Pressure, Traverse Speed, and Stand-off Distance on Surface Roughness (Ra) of rubber-based composite materials. The experimental combinations were analysed using a multiple linear regression model, excluding abrasive flow rate, to isolate the influence of core mechanical parameters. The predicted Ra values ranged from 2.857 µm to 3.573 µm, indicating noticeable variation in surface quality depending on process conditions. Among the investigated parameters, higher water pressure and traverse speed, combined with a larger stand-off distance (10.0 mm), generally resulted in lower surface roughness, suggesting improved cutting efficiency and reduced abrasive impact turbulence. The lowest predicted Ra (2.857 µm) was observed under conditions of 2500 psi WP, 6000–8000 mm/min TS, and 10 mm SOD, while the highest Ra (3.573 µm) occurred at 1500 psi WP, 6000 mm/min TS, and 5 mm SOD. These results highlight the importance of optimizing mechanical energy input and jet focus during the machining of deformable rubber materials.

Despite the exclusion of abrasive flow rate from this analysis, the model exhibited meaningful trends and helped identify favourable cutting parameters. This approach simplifies the machining model and provides practical guidance for industries where abrasive delivery systems may be constrained.

Future work can extend these findings by integrating abrasive flow rate, nozzle wear, and material-specific behaviour, along with advanced modelling techniques such as machine learning, to further enhance predictability and control over surface quality in AWJM.

REFERENCES

1. M. Hashish, "Abrasive waterjet machining (AWJM)," Materials, vol. 17, no. 13, p. 3273, 2024.
2. J. Wang, W. Gao, and Z. Zhong, "Advancements in abrasive water jet machining and hybrid processes," Journal of Manufacturing Processes, vol. 92, pp. 458–472, 2023.
3. P. Maurya, V. G. Srinivasa, and C. R. Kamath, "Experimental investigation and parametric optimisation of cryogenic abrasive water jet machining of nitrile rubber using Taguchi analysis," Cogent Engineering, vol. 10, no. 1, p. 2219108, 2023.
4. P. Maurya, C. R. Kamath, and V. G. Srinivasa, "Suspension-type abrasive water jet machining of nitrile rubber: Experimental investigation on kerf formation and abrasive embedding," International Journal of Lightweight Materials and Manufacture, vol. 6, no. 3, pp. 367–378, 2022.
5. R. Murthy, U. S. Rao, N. Naik, S. R. Potti, and S. S. Nambiar, "Influence of machining parameters on delamination in abrasive water jet machining of jute-fibre-reinforced polymer composites: An integrated Taguchi and response surface methodology," Journal of Composite Science, vol. 7, no. 11, p. 475, 2023.
6. M. Sreekumar, "A review of additives in abrasive water jet machining and allied processes," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 237, no. 6, pp. 1221–1235, 2023.
7. M. Szada-Borzyszkowska, "Assessment of the effectiveness of high-pressure water jet and pulsating water jet erosion processing," International Journal of Advanced Manufacturing Technology, vol. 135, nos. 1–2, pp. 271–284, 2024.

8. K. Gupta, “Developments in abrasive water jet machining of non-metals,” Politeknologi, vol. 23, no. 1, pp. 45–58, 2024.
9. N. Lusi, “Four decades of abrasive water jet processing technology: A structured review,” Manufacturing Review, vol. 12, p. 2, 2025.
10. S. Periyappillai, S. Manoharan, and R. Jothilingam, “Hybrid machine learning approach for predictive modelling in abrasive water jet machining of composites,” Engineering Applications of Artificial Intelligence, vol. 135, p. 107829, 2025.
11. V. Balasubramaniyan, P. Krishnan, and K. Rajendran, “Experimental investigation and multi-response optimisation of abrasive water jet machining parameters on GFRP composites,” Journal of Composite Materials, vol. 58, no. 11, pp. 1453–1467, 2024.
12. H. Fuse, T. Tanaka, and K. Ito, “Optimisation of abrasive water jet machining parameters for Ti-6Al-4V alloy using Taguchi design and ANOVA,” Materials Today: Proceedings, vol. 92, pp. 1123–1130, 2025.
13. H. Li, C. Liu, and Y. Zhang, “Multi-objective optimization of abrasive water jet machining parameters using Taguchi and grey relational analysis,” Journal of Manufacturing Science and Engineering, vol. 145, no. 6, p. 061001, 2023.
14. D. Yadav, R. Sharma, and P. Gupta, “Experimental and statistical analysis of abrasive water jet machining parameters on surface roughness of CFRP composites,” Wear, vols. 500–501, p. 204589, 2022.