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An Experimental Study on Submerged AWJ Turning and its Influence on castamide Machining

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Abstract

This study focuses on the application of submerged abrasive water jet turning (AWJT) to enhance the machinability of castamide, a polymer widely used in industrial components. The research investigates the influence of three primary machining parameters—traverse speed (TS), abrasive flow rate (AFR), and spindle speed (SS)—each tested at three levels within a full factorial experimental design. This approach allowed both the independent effects and the interactions of these parameters to be examined comprehensively. To evaluate process performance, two responses were selected: surface roughness (Ra), as an indicator of surface quality, and material removal rate (MRR), representing machining productivity.

The collected data were subjected to statistical analysis using analysis of variance (ANOVA) and visualized through three-dimensional surface plots to better illustrate parameter interactions. In addition, multi-criteria decision-making methods, namely TOPSIS and VIKOR, were applied to determine the optimum machining conditions. Regression models were also developed to establish predictive relationships between the process variables and responses.

The results demonstrated that submerged AWJT significantly improved machining outcomes compared to conventional AWJT. Specifically, the process reduced noise levels from 108.8 dB to 86.1 dB, improved surface roughness by approximately 15%, and resulted in a slight 5.22% reduction in MRR. ANOVA revealed that traverse speed was the most influential factor, contributing 83.11% to Ra and 85.56% to MRR. Based on the optimization results, the best machining conditions were obtained at TS = 40 mm/min, AFR = 310 g/min, and SS = 300 rpm. These findings highlight the potential of submerged AWJT as an effective and environmentally friendly method for machining castamide and similar materials.

Keywords:* *Submerged turning Abrasive water jet Castamid TOPSIS VIKOR

1. Introduction

Abrasive water jet (AWJ) machining has become one of the most effective non-traditional manufacturing processes for handling hard and brittle engineering materials. Unlike conventional cutting methods, which rely on thermal or mechanical stresses, AWJ removes material primarily through high-pressure erosion, enabling precise shaping of ceramics, glass, hardened steels (>60 HRC), and composites without introducing heat-related distortion [1–7].

The erosive effect of abrasive particles carried by a high-pressure water jet enhances its cutting capability, while the absence of thermal influence prevents microstructural alteration, mechanical softening, and distortion of the machined surface [8–14]. This advantage is particularly critical when machining polymer-based materials, where heat sensitivity often leads to severe processing challenges. Despite these strengths, AWJ machining still faces disadvantages, such as excessive noise generation (often >100 dB), pressure-dependent water splashing, and conical edge formation within the kerf [15,16].

In most machining processes, friction between the tool and workpiece, along with atomic bond separation during deformation, results in high operating temperatures.

Metallic materials, with their superior thermal conductivity, dissipate this heat more effectively, thereby reducing thermal damage. Polymers, by contrast, are significantly more vulnerable; elevated temperatures can cause undesirable effects such as distortion, adhesion of molten material to the tool, surface roughness deterioration, and build-up edge formation [17–20]. Although optimization of process parameters can minimize these issues to some extent [21], parameter control alone is insufficient to address the thermal challenges in polymer machining.

Traditionally, cutting fluids are applied to reduce heat and improve surface quality. However, mineral- and semi-synthetic-based coolants pose environmental hazards and occupational health concerns [22–24]. Even vegetable-based alternatives have limited applicability due to poor thermo-oxidation resistance at elevated temperatures, resulting in reduced tribological performance [25,26]. Consequently, there is growing interest in machining methods that eliminate the need for cutting fluids altogether. The AWJ process, which performs cutting with minimal heat generation, provides a promising alternative for improving polymer machinability and achieving better surface integrity [13,27–30].

Previous research has confirmed the potential of AWJ in polymer machining. For example, Kartal et al. [31] studied low-density polyethylene and identified optimum parameter settings for minimizing surface roughness and maximizing material removal rate (MRR), concluding that AWJ is a viable process for polymers. Their experiments demonstrated that careful parameter selection (TS = 5 mm/min, AFR = 350 g/min, SS = 2500 rpm) could yield favorable surface quality (Ra = 1.67 µm) and high MRR (14,072.02 mm^3/min). These results emphasized that eliminating thermal effects during AWJ machining significantly enhances machinability [32]. Nevertheless, challenges remain regarding surface finish and ergonomic factors such as excessive noise [33].

Surface roughness, in particular, plays a decisive role in determining fatigue life for components operating under cyclic loads. In AWJT, surface deterioration arises from scattering of the water jet as it exits the nozzle. The turbulence and dispersion of abrasive particles reduce jet rigidity, leading to irregular cutting and poor surface quality. Additionally, noise levels produced by high-pressure jets (≈110 dB) are often unacceptable for industrial environments [34,35]. Addressing these limitations requires improved control over jet scattering and acoustic emissions.

The application of hydrostatic pressure is expected to suppress jet scattering, stabilize abrasive particle trajectories, and reduce hypersonic noise during cutting.

Accordingly, a submerged AWJT setup was developed to investigate the machinability of castamide, a widely used engineering polymer known for its mechanical strength and broad application in machine design [36].

The novelty of this research lies in the application of submerged AWJT for polymer turning, which remains scarcely explored in the literature.

Castamide was selected as the test material due to its engineering relevance and industrial importance. A full factorial experimental design was employed to evaluate the effects of traverse speed (TS), abrasive flow rate (AFR), and spindle speed (SS). The machining outcomes were assessed in terms of Ra and MRR, and statistical tools—including analysis of variance, regression modeling, and multi-criteria optimization methods (TOPSIS and VIKOR)—were used to analyze and optimize the result.

2. Materials and Methods

2. 1Workpiece Material

The material selected for this study was castamide, a commonly used engineering plastic. Its main mechanical and thermal properties are summarized in Table 1.

Castamide is favored in industrial applications for its relatively high tensile strength (~90 MPa), hardness (Shore D: 84), and durability under wear.

However, in conventional machining, the high temperatures generated often cause melting, surface damage, and increased roughness. Melted fragments may even adhere back to the work surface, which makes achieving good surface quality difficult (Fig. 1).

Therefore, machining techniques that minimize heat generation are essential for improving its workability. Abrasive water jet turning (AWJT) is particularly suitable since it eliminates the thermal effects usually observed in conventional cutting processes.

Table 1

Engineering properties of cast-polyamide [36].

Property	Unit	Value
Density	g/cm3	1.15
Water absorption	%	6–7
Tensile strength	MPa	90
Modulus of elasticity	Gpa	4
Tensile elongation	%	>20
Impact strength(Izod, notched)	kJ/m2	5.6
Hardness (Shore D)	Shore D	84
Melting temperature	°C	220
Thermal elongation	1/K.105	8–9

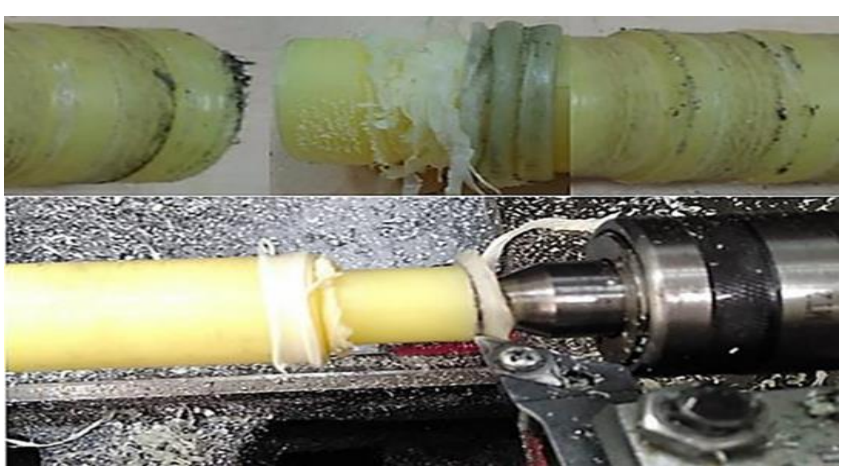

Fig. 1. Surface quality deterioration due to melt spinning

2. 2 Submerged AWJT System

To address these limitations, a submerged AWJ turning system was developed (Fig. 2). The setup was constructed by combining a conventional lathe with a water-jet cutting unit. In this system, the rotating workpiece is cut by a high-pressure jet carrying abrasive particles. By operating under hydrostatic pressure, the jet expansion is reduced, which improves stability and surface finish (Fig. 3).

The system consists of a 0.37 kW electric motor with an ATV 12 control unit that regulates spindle rotation at constant torque and speed. A belt-pulley mechanism transmits power to a chrome-plated spindle supported by roller bearings, and the workpiece is held in a 100 mm three-jaw chuck. A digital dial gauge (0.001 mm accuracy) was used to verify system alignment, which was within 0.001 mm.

Cutting was performed using a KMT SL-V 50 pump delivering water at 3800 bar. An ~80 mesh garnet abrasive was employed due to its non-toxic, non-corrosive properties. The sharp multi-edged structure of garnet, as shown in the SEM images (Fig. 4), enhances cutting efficiency. Proper sealing was ensured by protective covers and liquid gaskets to safeguard electronic and mechanical components.

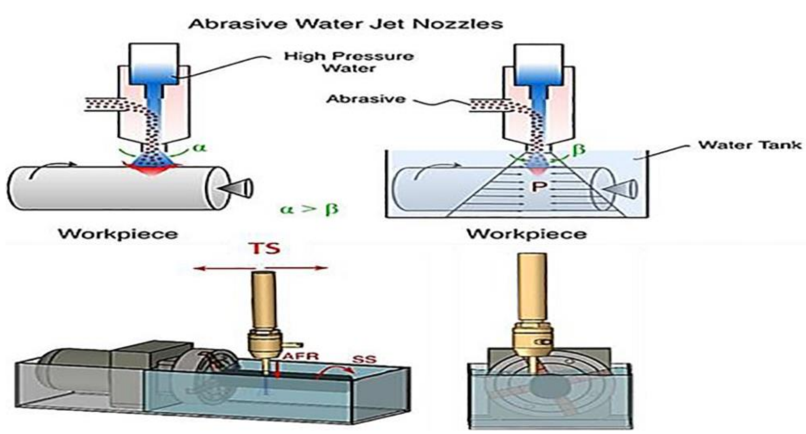

Fig 2. Behaviour of water jet in submerged cutting conditions and 3d drawig of submerged abrasive water jet process (Perspective and front side).

Fig. 3. Submerged abrasive water jet experimental setup.

2. 3 Experimental design

Three machining parameters were investigated: traverse speed (TS), abrasive flow rate (AFR), and spindle speed (SS). Each parameter was tested at three levels, as shown in Table 2, resulting in 27 experimental runs designed using a full factorial approach (3^3). The stand-off distance between nozzle and workpiece was fixed at 2 mm (Fig. 5).

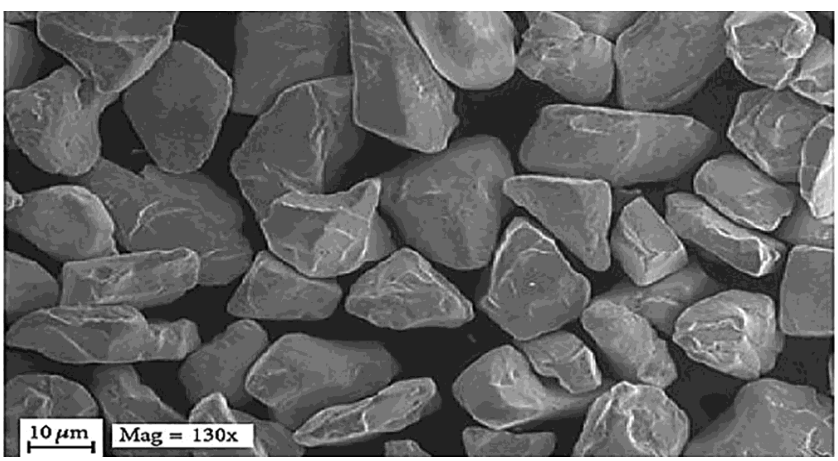

Fig. 4. SEM image of the garnet abrasive material.

Surface roughness (Ra) was measured using a Mitutoyo SJ-301 profilometer with a 0.8 mm cut-off length, taking three readings per sample. Material removal rate (MRR) was calculated from the difference in workpiece diameter before and after machining, using Equation (1):

$$MRR_i = p.\ D_i^2 - D_{i+1}^2\ /4.h \qquad (1)$$

where Di and Di+1 are the initial and final diameters, and h is the cutting length.Noise levels were measured. Statistical evaluation of results was carried out through ANOVA and regression analysis to determine the significance of each input parameter. Optimization was performed using multi-criteria decision-making methods TOPSIS and VIKOR, with equal weighting (0.5) given to Ra and MRR.

Table 2

Experimental input and output parameters.

Input parameters	Units	Level 1	Level 2	Level 3	Output parameters	Units
Traverse speed (TS)	mm/min	40	140	240	Surface roughness (Ra)	mm
Abrasive flow rate (AFR)	g/min	110	210	310	Material removal rate (MRR)	mm3/min
Spindle speed (SS)	rpm	100	200	300		

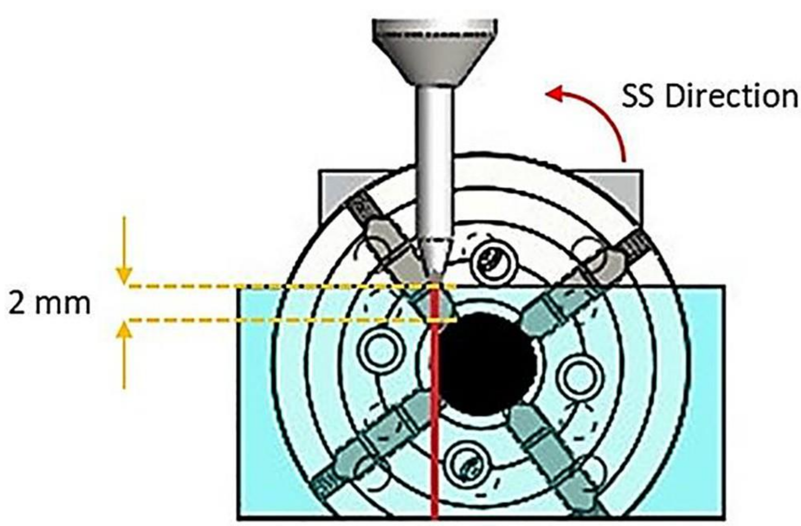

Fig.5. Schematic of nozzle stand-

off distance parameter.

3. Results and Discussion

3.1 Noise and Splash Suppression

One of the most visible advantages of submerged AWJT was the significant reduction in environmental disturbances. Compared with conventional AWJT, which produced both heavy splashing and noise levels up to **108.8 dB**, the submerged system reduced the sound to **86.1 dB** and eliminated splash from the machining zone (Fig. 6a–b). This improvement not only enhanced operator safety but also ensured a more stable and consistent machining environment.

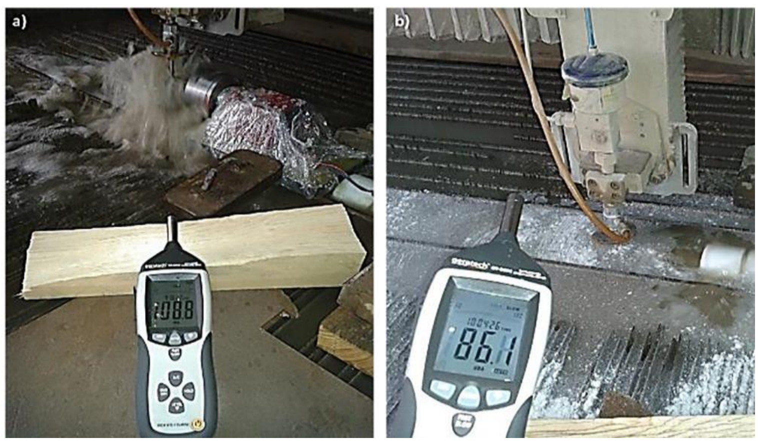

Fig 6. Process conditions of (a) Conventional AWJT and (b) Submerged AWJT

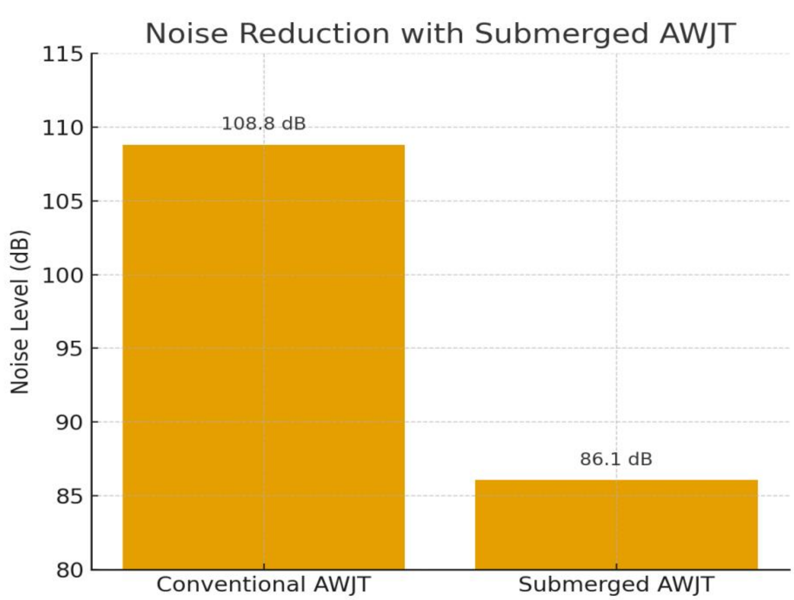

Figure 7. Comperssion of (a) Conventional AWJT and (b) Submerged AWJT

3.2 Surface Roughness and Material Removal Rate

The outcomes of the 27 factorial experiments are listed in Table 3. The **lowest Ra (1.46 µm)** was observed at **TS = 40 mm/min, AFR = 210 g/min, SS = 300 rpm (Run 6)**. By comparison, earlier work on conventional AWJT for castamide reported a best Ra of **1.73 µm**, meaning submerged cutting achieved ~15% better surface quality.

For productivity, the **highest MRR (200.93 mm³/min)** occurred at **TS = 40 mm/min, AFR = 310 g/min, SS = 300 rpm (Run 9)**. This value is slightly lower (−5.22%) than the **212 mm³/min** obtained in conventional AWJT, attributed to additional resistance caused by the surrounding hydrostatic medium. Considering that AWJ processes inherently exhibit up to **±20% variability** due to material heterogeneity, localized jet instabilities, and suction issues, this difference falls within the expected uncertainty band. Thus, submerged AWJT can be regarded as comparable to conventional AWJT in terms of productivity, while offering distinct advantages in surface quality and ergonomics.

Table 3
Experimental results.

Exp. No	Input parameters			Output parameters	
	TS (mm/min)	AFR (g/min)	Spindle speed (rpm)	R_a (mm)	MRR (mm³/min)
1	40	110	100	2.89	142.79
2	40	110	200	2.81	149.88
3	40	110	300	1.92	154.10
4	40	210	100	2.56	154.88
5	40	210	200	2.11	158.60
6	40	210	300	1.46	169.07
7	40	310	100	1.52	185.25
8	40	310	200	1.61	192.52
9	40	310	300	1.95	200.93
10	140	110	100	4.25	114.94
11	140	110	200	3.27	117.13
12	140	110	300	3.97	120.94
13	140	210	100	3.81	125.93
14	140	210	200	3.17	127.46
15	140	210	300	3.37	129.77
16	140	310	100	2.57	132.11
17	140	310	200	2.68	135.39
18	140	310	300	3.07	138.89
19	240	110	100	5.46	79.76
20	240	110	200	5.42	84.93
21	240	110	300	5.04	85.63
22	240	210	100	4.27	88.01
23	240	210	200	4.92	88.82
24	240	210	300	4.89	94.90
25	240	310	100	4.49	96.65
26	240	310	200	4.40	99.73
27	240	310	300	4.28	103.71

3.3 Influence of Process Parameters (ANOVA)

Analysis of variance revealed traverse speed (TS) **as the most influential variable on both responses. Its contribution reached** 83.11% for Ra **and** 85.56% for MRR**, confirming its primary role. In general,** higher TS values increased Ra and decreased MRR**, showing the trade-off between quality and productivity.**

Abrasive flow rate (AFR) and **spindle speed (SS)** had comparatively smaller influences: AFR affected MRR by ~10.26% and Ra by ~1.10%, while SS contributed ~1% to both responses. This indicates that while AFR can fine-tune productivity, TS remains the critical factor to control in order to balance machining quality and efficiency.

Regression analysis supported these findings, achieving **R^2 = 91.32% for Ra** and **R^2 = 99.89% for MRR**, demonstrating that the developed models adequately represent the experimental data.

3.4 Surface Integrity and SEM Observations

Microscopic examination provided further insight into the quality improvements. Under conventional AWJT, the expanding jet profile led to uncontrolled dispersion of abrasive particles. Many of these particles became embedded in the polymer surface, resulting in higher roughness (Fig. 8a). In contrast, submerged cutting restricted jet expansion, ensuring more focused particle impact and smoother surface features (Fig. 8b).

The improved finish also relates to the braking effect of abrasive particles in water compared to air. Larger particles tend to migrate outward to slower jet regions, while finer ones remain in the high-velocity core. In polymers, even lower-energy outer particles can damage the surface due to the material’s relatively low strength. Braking in water reduces their impact energy, minimizing surface gouging and consequently lowering Ra.

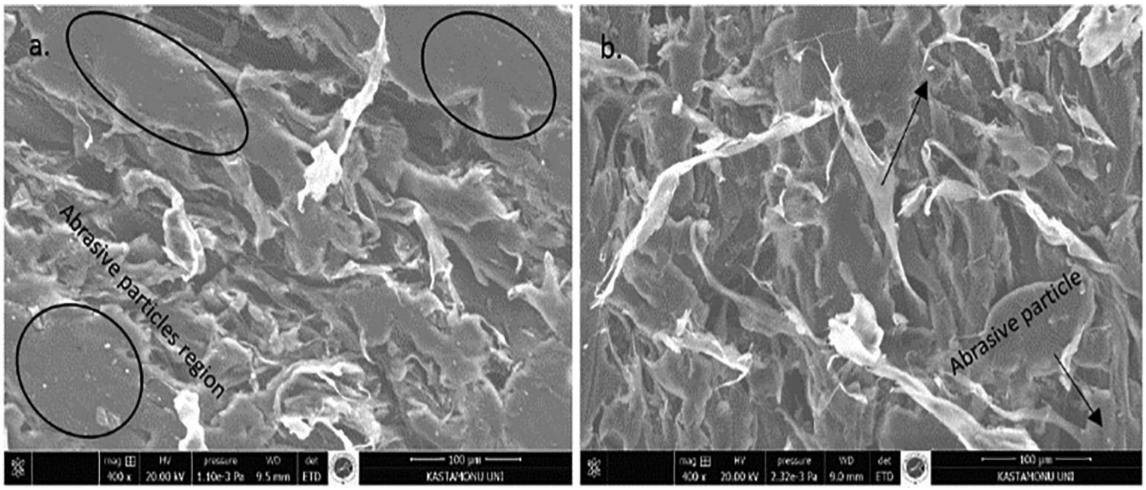

Fig. 8. Surface SEM images of (a) Conventional AWJT, (b) Submerged AWJT

(In conditions of 240 mm/min TS, 110 g/min AFR and 100 rpm Spindle Speed).

3.5 Multi-Criteria Optimization

Considering Ra minimization and MRR maximization simultaneously, **TOPSIS** and **VIKOR** analyses both converged on the same optimal setting: **TS = 40 mm/min, AFR = 310 g/min, SS = 300 rpm**. Validation experiments confirmed this solution, with prediction errors staying within **20%**, which is acceptable for AWJT processes.

3.6 Discussion of Key Findings

Overall, submerged AWJT demonstrated the following:

- **Superior surface quality** (Ra down to 1.46 µm vs. 1.73 µm in conventional AWJT).
- **Comparable productivity**, with only minor MRR reduction (−5.22%).
- **Significantly improved ergonomics**, reducing hazardous noise and eliminating splash.

These results confirm submerged AWJT as a practical and environmentally friendly method for machining castamide and potentially other polymers, especially in applications where surface finish and workplace safety are critical.

4. Conclusions

This experimental study examined the performance of submerged abrasive water-jet turning (AWJT) in machining castamide. The key conclusions are:

1. Ergonomic improvement: Operating under submerged conditions reduced the sound level from 108.8 dB (conventional AWJT) to 86.1 dB, while also eliminating splash and creating a more stable machining zone.
2. Surface finish: The minimum surface roughness achieved was 1.46 μm, representing a ~15% improvement compared to the best reported conventional AWJT result (1.73 μm).
3. Material removal rate (MRR): The maximum MRR under submerged conditions was 200.93 mm^3/min, slightly lower (−5.22%) than the 212 mm^3/min achieved in conventional AWJT. This reduction is attributable to hydrostatic resistance but remains within the typical ±20% variability of AWJ processes.
4. Factor significance: Traverse speed (TS) was the dominant parameter, influencing both Ra (83.11%) and MRR (85.56%). AFR and SS contributed less significantly, though higher AFR generally supported higher MRR.
5. Model adequacy: Regression models explained the data well, with R^2 = 91.32% for Ra and R^2 = 99.89% for MRR, confirming statistical reliability.
6. Optimization outcome: Multi-criteria analysis (TOPSIS and VIKOR) identified the best compromise condition as TS = 40 mm/min, AFR = 310 g/min, SS = 300 rpm, validated with prediction errors below 20%.
7. Overall, submerged AWJT proved effective in enhancing surface quality and reducing workplace hazards while maintaining comparable productivity to conventional AWJT. This positions it as a practical, environmentally favorable method for machining polymers such as castamide.

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