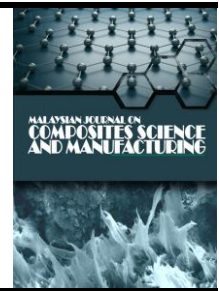




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Taguchi Method-Based Optimization of Single-Pass Abrasive Waterjet Cutting of Thick Aluminium

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ABSTRACT

Cutting force attenuation in AWJ induces surface defects (high Ra, large Θ°) in metals and delamination in composites, especially in thick sections that limiting industrial adoption and requiring post-processing. A robust Taguchi experimental design was employed to optimize AWJ cutting parameters to minimize these issues when cutting thick aluminium blocks. An L8 orthogonal array with three factors; waterjet pressure (WP), stand-off distance (SOD), and traverse speed (TS), each at two levels, was used and analyzed via Minitab software. Other parameters remained constant: nozzle diameter (1.0 mm), abrasive size (80 mesh), and abrasive flow rate (0.3 kg/min). Traverse speed was found to be the most critical factor affecting Ra and Θ° , though waterjet pressure and stand-off distance also had significant impacts. The optimal parameters, higher waterjet pressure (315 MPa), lower traverse speed (38 mm/min), and lower stand-off distance (3 mm), yielded the best results for both Ra (4.2 μm) and Θ° (1.24°). In conclusion, the interaction of optimized AWJ parameters enhances kinetic energy and momentum transfer, improving material removal efficiency and cutting surface quality. The study systematically evaluates critical abrasive waterjet parameters to optimize cutting strategies, demonstrating applicability for thick aluminium and diverse material types.

1. Introduction

Aluminium and its alloys are extensively used in many automotive and aerospace industries due to their excellent strength-to-weight properties. The lightweight nature of aluminium is crucial for reducing greenhouse gas emissions and promoting a sustainable environment. Additionally, recycling aluminium is much simpler than recycling other common metals like steel, which is another critical factor in reducing the carbon footprint [1-2]. Despite these advantages, achieving the closest cutting

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tolerances for fitting and other applications remains a significant challenge. Popular non-conventional methods such as laser and electrical discharge machining can lead to thermal damage, including heat-affected zones that introduce internal stress, recast layers, and shorten product life [3]. These adverse impacts can be mitigated by using abrasive water jet (AWJ) machining technology [4-6].

AWJ machining uses high-velocity water entrained with abrasive particles to cut a wide range of materials, including composites [7-8]. It offers numerous benefits over other cutting technologies, such as no thermal distortion, high machining versatility, high flexibility, and low cutting forces [9-11]. The system employs an intensifier technique to pump water to extremely high pressures, typically between 30,000 and 90,000 psi, which passes through an aperture to generate a high-velocity water jet. As the water jet passes through a mixing chamber, it creates a vacuum that pulls in abrasive particles through a separate entrance, transferring high momentum of water and abrasive out of a narrow nozzle to the workpiece [12].

Surface quality and taper angle are crucial factors in the precise machining of materials using AWJ [13-14]. Surface quality in AWJ refers to the uniformity, irregularity, and integrity of the cut surface. These flaws not only hinder the functional performance of the machined components but also increase costs by necessitating additional surface improvement operations. Additionally, the taper angle, which refers to the gradual change in cutting kerf width from the start to the exit of the cut, is critical. Excessive taper angle results in dimensional inaccuracies, risking the functionality and fitting of machined parts, especially in applications requiring high precision. Achieving a low and consistent taper angle is essential for maintaining the dimensional accuracy and geometric precision of the cut surfaces.

The Taguchi method is a reliable, simple, and cost-effective technique widely applied in industries to optimize AWJ parameters [15-16]. This technique involves an orthogonal array experiment to establish the actual scatter of in-control and beyond-control values, known as signal (S) and noise (N), respectively. The ratio of S/N is used to obtain the optimal parameter settings depending on the study's aim, whether "bigger is better," "smaller is better," or "nominal is best" [17]. Joel and Jeyapooan [18] combined Grey Relation Analysis and the Taguchi method to optimize the multi-responses of abrasive feed rate (AFR), stand-off distance (SOD), and traverse speed (TS) of AWJ parameters on an AA7075 aluminium alloy. The smallest surface roughness was obtained with 250 g/min (AFR), 3 mm (SOD), and 36 mm/min (TS). Similarly, Gowthama *et al.* [19] conducted a Taguchi experiment on these factors for Al7071 aluminium alloy surface roughness, finding that TS was the most influential factor, followed by AFR, with SOD having the least impact.

Therefore, it is important to investigate and resolve the root cause factors that contribute to poor surface quality and taper angle in single-pass AWJ [20-22]. Several process parameters, such as abrasive flow rate, stand-off distance, traverse speed, and orifice diameter, influence the quality of these characteristics [23-24]. According to a statistical finding by Llanto *et al.* [25], based on studies conducted by researchers worldwide from 2017 to 2020, 27% concluded that traverse speed is the most influential input parameter in the AWJ cutting process, followed by waterjet pressure, abrasive mass flow rate, and stand-off distance, with 22%, 20%, and 19% contributions, respectively. Although few studies have considered abrasive size, nozzle and orifice diameter, abrasive material, and jet impact angle, the effects of these input parameters cannot be justified due to limited attention from researchers and infrequent use in experimental studies [26-27].

This study investigates three key factors influencing surface quality and taper angle in single-pass abrasive waterjet (AWJ) machining of aluminium blocks: traverse speed, waterjet pressure (WP), and stand-off distance. A Taguchi L8 orthogonal array design of experiments (DoE) was employed for

process optimization. The results indicate that the optimal parameter combination consists of high waterjet pressure coupled with low traverse speed and low stand-off distance.

2. Methodology

2.1 Material and equipment

This study selected a pure aluminium block with dimensions of 32 mm in thickness and 100 mm in width as the primary material, as illustrated in Figure 1. The choice of aluminium was due to its widespread industrial applications and relevance in cutting industries. A mineral abrasive with a mesh size of 80, derived from almandine garnet, was utilized in the Abrasive Water Jet (AWJ) cutting process. Almandine garnet was chosen for its hardness and effectiveness in cutting a variety of materials, including steel, aluminium, and marble.

The AWJ cutting operations were performed using a Flow Mach 2 waterjet machine, depicted in Figure 2. This machine is equipped with a fixed cutting nozzle of 1.0 mm in diameter, ensuring precision in the cutting process. The Flow Mach 2 is known for its reliability and accuracy in industrial cutting applications.



Fig. 1. Aluminium block

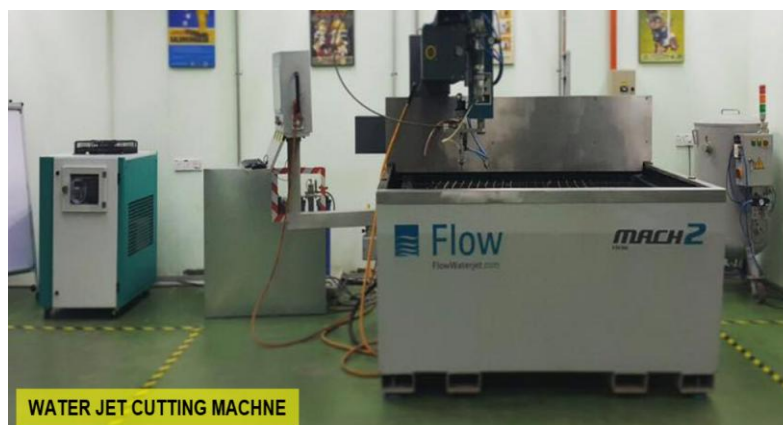


Fig. 2. Abrasive waterjet machine

2.2 Taguchi method: Design of experiment

This research employed Taguchi's L8 orthogonal array, consisting of 8 experiments with 3 factors at 2 levels each. The experiments were designed and analyzed using Minitab software. The signal-to-noise (S/N) ratio was utilized to optimize the outputs, aiming for smaller, better results.

The variable factors considered in the experiments were waterjet pressure (WP), stand-off distance (SOD), and traverse speed (TS), each at low and high levels as detailed in Table 1. Other parameters were kept constant, including the nozzle diameter (1.0 mm), abrasive size (80 mesh), and abrasive flow rate (0.3 kg/min) [28]. Each experiment involved a series of straight cuts (90 mm) on the same aluminium block. The setup for the Taguchi L8 experiments is shown in Table 2.

Table 1
Variable factors at low and high parameters setting

Factor	Waterjet pressure, MPa	Transverse speed, mm/min	Stand-off distance, mm
High	315	76	6
Low	245	38	3

Table 2
Taguchi L8 orthogonal array

Exp. No.	Waterjet pressure, MPa	Transverse speed, mm/min	Stand-off distance, mm
1	245	38	3
2	245	38	6
3	245	76	3
4	245	76	6
5	315	38	3
6	315	38	6
7	315	76	3
8	315	76	6

2.3 Testing and Analysis

The surface roughness (Ra) of the cutting surface was evaluated using a Mitutoyo surface roughness analyzer, following the ISO 4287:1997 standard. The average Ra value was calculated from 10 measurements for each experiment.

Additionally, the cutting taper angles (θ°) were measured using a Mitutoyo vertical optical comparator model 20-4600, as shown in Figure 3. The average value of 5 taper angle measurements was used for each experiment.

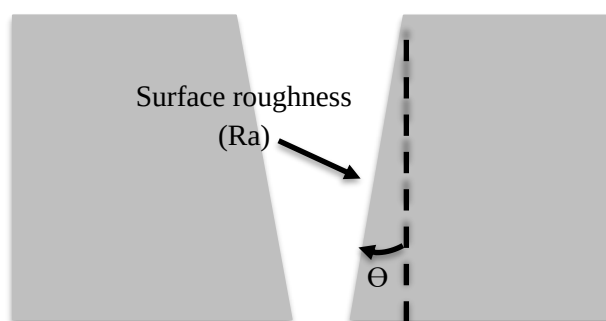


Fig. 3. Surface roughness (Ra) and taper angle (θ°) measurements

3. Results

3.1 Analysis of Taguchi on surface roughness

The L_8 experimental data reveal that Exp. 5 (high WP: 315 MPa, low TS: 38 mm/min, low SOD: 3 mm) yields the lowest average Ra (4.22 μm), whereas Exp. 8 (high WP: 315 MPa, high TS: 76 mm/min, high SOD: 6 mm) results in the highest Ra (5.14 μm), as illustrated in Table 3 and Figure 4. This contrast highlights the significant role of traverse speed (TS) and stand-off distance (SOD) in surface roughness, despite both experiments sharing the same high waterjet pressure (WP). The 21.8% increase in Ra for Exp. 8 suggests that higher TS and SOD exacerbate striations and particle embedment, while the lower TS and SOD in Exp. 5 promote smoother cutting due to prolonged abrasive interaction and reduced jet dispersion.

Table 3

Surface roughness, Ra (μm) at 10 locations on each sample

Data	Exp. No.							
	1	2	3	4	5	6	7	8
1	4.81	4.84	4.81	4.94	4.28	4.83	5.31	5.28
2	5.05	5.59	4.20	4.40	3.72	4.68	5.22	4.11
3	5.08	4.71	4.87	5.73	3.60	5.08	5.03	5.89
4	5.12	5.50	4.89	5.39	4.13	5.18	4.99	4.59
5	5.01	5.17	4.79	4.98	4.71	4.37	4.86	4.72
6	4.91	4.86	4.26	6.30	4.11	4.05	4.41	5.51
7	4.64	4.92	5.08	5.01	4.60	4.69	5.17	5.18
8	5.41	4.80	5.12	4.90	4.55	4.65	5.34	4.81
9	5.20	4.65	4.42	4.91	4.24	4.08	4.62	6.07
10	4.80	4.70	5.34	5.06	4.23	4.88	4.90	5.20
Ave.	5.00	4.97	4.78	5.16	4.22	4.65	4.99	5.14

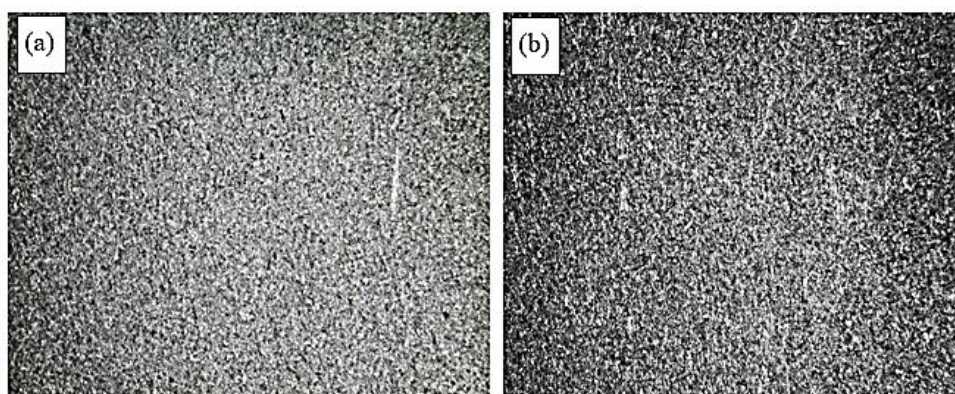


Fig. 4. Surface roughness of (a) Exp.5 and (b) Exp. 8

Taguchi analysis shows all factors in the studies significantly impact the cutting surface roughness. The traverse speed (TS) has the most significant impact. Moreover, the stand-off distance (SOD) and waterjet pressure (WP) have an almost similar impact on Ra, as shown in Figure 5. The Ra decreases with TS decreased as a slower speed gives the waterjet more time to remove material efficiently and provide a smoother surface. Likewise, the Ra increases as SOD increases; at higher SOD, an air

resistance causes the waterjet pressure and velocity to drop significantly. Hence, its kinetic force is reduced and provides less impact to remove material from the cutting area as compared with a lower SOD [29]. This observation agrees with the WP impact in which Ra improves at higher WP, resulting in a smoother cutting surface. Slower traverse rates enable the water jet more time for the water and abrasive particulates to remove material efficiently and provide a smoother surface. However, excessively slow traverse velocities may result in excessive attrition or material deformation, resulting in a rougher surface. On the other hand, extremely high traverse speeds can affect the cutting action, resulting in poor surface quality and increased irregularity.

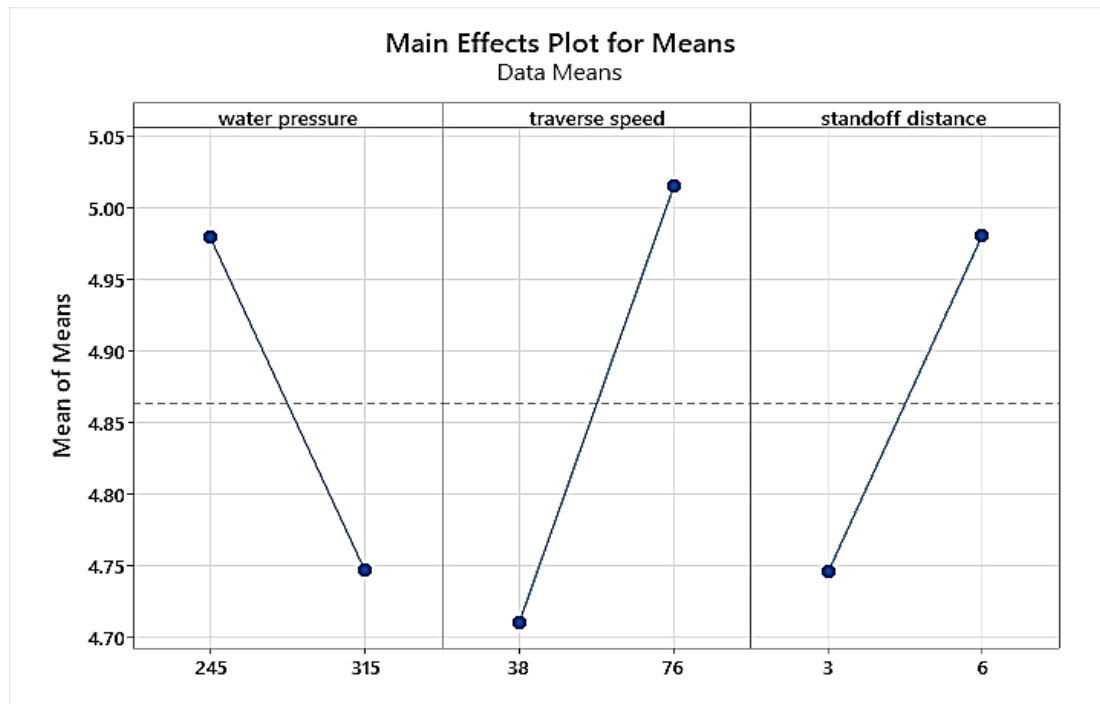


Fig. 5. Main effects plot for means of Ra

3.2 Analysis of Taguchi on cutting taper angle

The taper angle in abrasive water jet cutting greatly impacts fitting machined parts such as gears. Table 4 shows the results of average taper angles based on the Taguchi L8 experiments. Again, Exp. 5 has produced the smallest average taper angle (Θ°) of 1.24° . On the other hand, the Exp. 3 with low WP (245 MPa), high TS (76 mm/min) and low SOD (3 mm) have given the largest Θ° of 1.55° .

Table 4
Taper angle (Θ°)

Data	Exp. No. ($^\circ$)							
	1	2	3	4	5	6	7	8
1	1.14	1.55	1.48	1.26	1.03	1.27	1.26	1.18
2	1.18	1.11	1.50	1.10	1.05	1.41	1.37	1.38
3	1.23	1.37	1.43	1.51	1.06	1.29	1.40	1.36
4	1.27	1.43	1.55	1.32	1.24	1.34	1.43	1.25
5	1.33	1.27	1.45	1.40	1.26	1.20	1.35	1.27
Ave.	1.23	1.35	1.48	1.32	1.13	1.30	1.36	1.29

Taguchi's analysis of the kerf taper angle shows a similar trend to the cutting surface roughness. The traverse speed (TS) has the most significant impact. However, this time the waterjet pressure (WP) has more impact as compared with the stand-off distance (SOD), as shown in Figure 6.

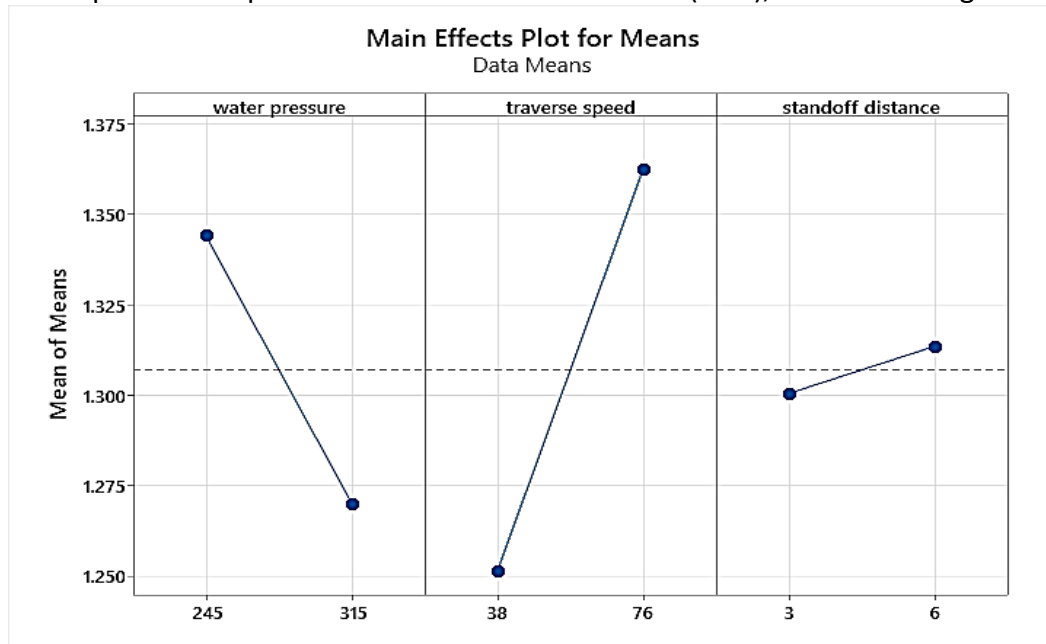


Fig. 6. Main effects plot for means of taper angle (Θ°)

Lower traverse speed typically produced smoother cuts with decreased taper angles. This is because slower traverse rates give abrasive particulates more time to erode the material uniformly. Unlike at higher traverse velocities, the cutting action becomes less precise and not concentrated, resulting in greater taper angles. When water pressure is increased, the jet kinetic energy increases, leading to a high momentum transfer of the abrasive and a decrease in kerf taper angle [30]. The kerf angle generally tends to increase as the stand-off distance increases. As the distance between the nozzle and the part's surface increases, the stream of water and abrasive particulates spreads out and disperses more.

4. Conclusions

A robust Taguchi L_8 orthogonal array was employed to optimize abrasive waterjet cutting parameters for surface quality (R_a) and kerf angle (Θ°) in aluminium blocks. Traverse speed emerged as the most influential factor, accounting for the greatest variance in both surface finish and taper angle. While waterjet pressure and stand-off distance exhibited comparatively lesser impacts on R_a and Θ° , their contributions remained statistically significant. The optimal results were achieved in Exp. 5, which combined high waterjet pressure (315 MPa), low traverse speed (38 mm/min), and low stand-off distance (3 mm). This configuration enhances cutting precision by maximizing the kinetic energy of water molecules and abrasive particles, thereby promoting efficient material removal with minimal surface irregularities. These findings establish a foundational framework for future optimization and advancement of abrasive waterjet cutting processes. These findings provide actionable insights for manufacturing applications requiring high-precision aluminium cutting, particularly in aerospace and automotive components where surface integrity is critical. The established parameter-property relationships serve as a foundation for future research in adaptive AWJ process control and multi-objective optimization.

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