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Influence of Process Parameters on Kerf Width in Abrasive Waterjet Machining of GFRP Composites

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ABSTRACT

This study investigates the influence of process parameters on kerf width in abrasive waterjet (AWJ) machining of glass fiber reinforced polymer (GFRP) composites. The experimental analysis was conducted using a Taguchi L27 orthogonal array to optimize the machining parameters: pressure, feed rate, abrasive flow rate, and standoff distance. The top kerf width (TKW) and bottom kerf width (BKW) were measured to evaluate the impact of these parameters. Results indicate that higher pressures and abrasive flow rates generally increase both TKW and BKW due to enhanced material removal rates. Conversely, increased feed rates tend to reduce kerf widths, highlighting the importance of optimizing cutting speeds. Standoff distance exhibited a less pronounced effect but still influenced the kerf widths. The optimal parameters for minimizing TKW and BKW were identified, providing valuable insights for improving precision and efficiency in AWJ machining of GFRP composites. These findings contribute to the development of more effective manufacturing practices for high-performance composite materials.

Keywords: Abrasive waterjet cutting, optimization, reinforced composite, GFRP, machining parameters, kerf width.

GFRP Kompozitlerin Aşındırıcı Su Jeti ile İşlenmesinde Proses Parametrelerinin Kerf Genişliğine Etkisi

Araştırma Makalesi

Süreç

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ÖZ

Bu çalışma, cam elyaf takviyeli polimer (GFRP) kompozitlerin aşındırıcı su jeti (AWJ) işlenmesinde işlem parametrelerinin kerf genişliği üzerindeki etkisini araştırmaktadır. Deneysel analiz, işleme parametrelerini optimize etmek için bir Taguchi L27 ortogonal dizisi kullanılarak gerçekleştirilmiştir: basınç, ilerleme hızı, aşındırıcı akış hızı ve ara mesafe. Bu parametrelerin etkisini değerlendirmek için üst kerf genişliği (TKW) ve alt kerf genişliği (BKW) ölçülmüştür. Sonuçlar, daha yüksek basınçların ve aşındırıcı akış hızlarının, artan malzeme çıkarma hızları nedeniyle genellikle hem TKW'yi hem de BKW'yi artırdığını göstermektedir. Tersine, artan ilerleme oranları kerf genişliklerini azaltma eğilimindedir ve bu da kesme hızlarını optimize etmenin önemini vurgulamaktadır. Ara mesafe daha az belirgin bir etki göstermiştir ancak yine de kerf genişliklerini etkilemiştir. TKW ve BKW'yi en aza indirmek için optimum parametreler belirlenmiş ve GFRP kompozitlerin AWJ işlenmesinde hassasiyet ve verimliliği artırmak için değerli bilgiler sağlanmıştır. Bu bulgular, yüksek performanslı kompozit malzemeler için daha etkili üretim uygulamalarının geliştirilmesine katkıda bulunmaktadır.

Anahtar Kelimeler: Aşındırıcı su jeti kesimi, optimizasyon, takviyeli kompozit, GFRP, işleme parametreleri, kesme genişliği.

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Introduction

Glass fiber reinforced polymer (GFRP) composite materials are extensively utilized in various sectors, including space, automotive, machinery, and electronics industries, primarily due to their exceptional properties. These materials are known for their high hardness and resistance, low thermal expansion, and superior damping properties, which make them ideal for a broad range of applications (Agarwal and Broutman, 2017). Despite being manufactured in the desired geometrical configurations, composite structures often require additional cutting during the assembly process (Mallick, 2007). In the context of manufacturing processes, cutting operations represent a significant portion, accounting for approximately 40% of all machining activities (Davim, 2012). However, drilling composite materials poses several challenges, notably surface damage to the holes, such as delamination and fiber breakage (Singh and Bhatnagar, 2006). Such damage is a critical issue as it can significantly impair the structural integrity and performance of the composite materials. Preventing these damages necessitates a meticulous selection of the workpiece, cutting tools, and cutting parameters (Davim, 2012). Research has consistently highlighted that the quality of the machined surface is heavily dependent on factors such as cutting parameters, tool geometry, and cutting forces (Singh and Bhatnagar, 2006; Kartal and Kaptan, 2024; Abrão, 2008; Kartal and Kaptan, 2023). Polymer matrix composite materials, due to their advantageous engineering properties, are not only common in daily applications but also prominent in the aerospace industry. Nevertheless, the inherent complexity of these materials can lead to adverse effects on their engineering properties during machining operations. The assembly of composite parts often involves the use of pin connections, which necessitates an increased frequency of drilling operations. Extensive research in the literature has focused predominantly on the drilling process, investigating surface damages at the inlet and outlet of holes while considering variables such as cutting tools, cutting parameters, and tool geometry.

Importance of Composite Materials in Various Industries

Composite materials, particularly glass fiber reinforced composites, are indispensable in modern industry due to their unique combination of high strength and low weight. These materials exhibit superior mechanical properties, including high stiffness and durability, which are critical for aerospace applications where weight reduction is paramount (Kaw, 2005). In the automotive sector, the use of composites contributes to the production of lighter vehicles, thereby improving fuel efficiency and reducing emissions (Friedrich and Almajid, 2013). Similarly, in the electronics industry, composites are favored for their excellent thermal stability and electrical insulation properties, making them suitable for various components and housings (Hegde and Sharma, 2008).

Challenges in Machining Composite Materials

Despite their advantages, machining composite materials, especially drilling, presents numerous challenges. Delamination, which refers to the separation of layers within the composite, is a common issue that occurs during drilling and can compromise the structural integrity of the material (Hegde and Sharma, 2008). Fiber breakage is another prevalent problem that leads to rough hole surfaces and reduced material strength (Hocheng and Tsao, 2003). These defects are influenced by several factors, including the type of cutting tool used, the cutting parameters (such as feed rate and spindle speed), and the geometry of the cutting tool (Khashaba, 2004).

Influence of Cutting Parameters and Tool Geometry

The relationship between cutting parameters and the quality of the drilled holes in composite materials has been a focal point of numerous studies. Optimal cutting parameters are crucial for minimizing surface damage and ensuring a high-quality finish. For instance, appropriate feed rates and spindle speeds can reduce the forces exerted on the material, thereby mitigating delamination and fiber breakage (Rahme et al., 2011). Additionally, the geometry of the cutting tool, including its point angle and helix angle, plays a significant role in the drilling process. Tools with specific geometries designed for composite materials can enhance cutting performance and reduce damage (Isbilir and Ghassemieh, 2013).

Advances in Drilling Techniques for Composite Materials

Recent advancements in drilling techniques have aimed to address the challenges associated with machining composite materials. Innovations such as the use of special coatings on cutting tools, the development of hybrid drilling methods, and the implementation of automated drilling systems have shown promising results in improving the quality of drilled holes (Sarasini et al., 2009). Furthermore, ongoing research continues to explore the effects of different tool materials, cutting fluids, and cooling methods to optimize the drilling process for composite materials (Rubio et al., 2008).

Material and Methods

Material Preparation

The material used in the experiments was glass fiber reinforced polymer (GFRP), characterized by its high strength-to-weight ratio and resistance to corrosion. Prior to machining, samples were prepared to standard dimensions of 100x100 mm with a thickness of 10 mm to ensure uniformity across all tests. The surface of each sample was cleaned and dried to remove any contaminants that could affect machining outcomes. The mechanical properties of the composite material used in this study are outlined in Table 1.

Table 1. Mechanical properties of the GFRP material.

Tensile strength [MPa]	Youngs modulus [GPa]	Elongation [%]	Hardness [VHN]
255	8	3	30

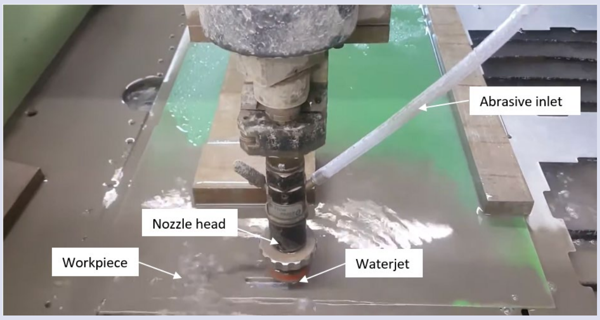

Figure 1. GFRP composites machining with AWJ.

Table 2. AWJ machining parameters

Parameters	Levels		
	1	2	3
Pressure [MPa]	200	250	300
Feed rate [mm/min]	200	300	400
Abrasive flow rate [g/min]	100	150	200
Standoff distance [mm]	2	4	6

Experimental Setup and Parameters

The abrasive waterjet (AWJ) machining was conducted using a precision AWJ machine capable of exerting a maximum pressure of 400 MPa. The machine was equipped with a 0.3 mm diameter nozzle and utilized garnet abrasive particles of 80 mesh size. The operational parameters adjusted during the experiments included. Figure 1 shows the machining process of GFRP composite material using AWJ.

A Taguchi L27 orthogonal array was utilized to design the experiments, allowing for an efficient exploration of the parameter space with a minimized number of experimental runs. The effects of the parameters on kerf width were analyzed using analysis of variance (ANOVA), which helped in identifying the statistically significant factors. The interaction effects between parameters were also explored to understand their combined influence on the outcomes. The experimental setup involves varying four parameters: Pressure (P), abrasive flow rate (m_v), feed rate (V), and standoff distance (d). Pressure is ranged from 200 to 300 MPa in increments of 20 MPa. Feed rate is set between 100 mm/min and 200 mm/min, with increments of 25 mm/min. Abrasive flow rate is adjusted from 150 g/min to 300 g/min in increments of 30 g/min. Standoff distance is varied from 2 mm to 6 mm in increments of 1 mm. This systematic variation allows for comprehensive analysis of the effects of these parameters on the desired outcomes.

To further understand the quantitative relationship between the machining parameters and the kerf widths, multiple linear regression analysis was conducted. The regression model was developed with kerf width as the dependent variable and pressure, feed rate, abrasive flow rate, and standoff distance as independent variables. This model provided coefficients that quantified the impact of each parameter on the kerf width, offering insights into how parameter adjustments could optimize machining performance.

Based on the regression model and the ANOVA results, response surface methodology was employed to find the optimal set of parameters for minimizing kerf width while maintaining the integrity of the machined surface. Contour plots were generated to visualize the relationship between parameters and their effects on kerf width, aiding in the decision-making process for parameter selection. Table 2 shows the processing parameters and levels.

Results

In the current work, the effect of the AWJ process parameters on the top and bottom slit widths was examined using an L27 orthogonal array. A total of 27 experiments were conducted, each with two recurrences. The operational parameters for each run are detailed in Table 3. During each run, a 20 mm length was cut from the test sample using a three-axis AWJ computer numeric control machine. The widths of the slits on the top and bottom surfaces are referred to as the TKW and the BKW, respectively. The kerf widths were measured using a digital caliper tool. For each sample, the kerf width was measured at seven equidistant points along the length of the cut, and the average values were recorded in Table 3. The analyze influence of four key AWJ process parameters on the TKW and BKW. These parameters are P, m_v, V and d. The goal is to understand how variations in these parameters affect the kerf widths and to identify optimal conditions for minimizing surface damage while achieving precise cuts. The Taguchi L27 orthogonal array was selected for its specific advantages in optimizing and understanding the influence of multiple parameters on kerf widths in abrasive waterjet machining of

GFRP composites. This array structure allows for a comprehensive analysis of three levels for each factor in fewer experimental runs than would be required in a full factorial design. Specifically, the L27 array supports the examination of up to 13 factors simultaneously, which provides significant efficiency and robustness in experimental design. The use of this orthogonal array enhances the reliability of the results by minimizing the effects of variability in the experiments. It systematically covers the interaction and main effects of the parameters, thereby providing a balanced view of the process factors under study. This design methodology not only reduces the time and resources needed but also improves the precision of the data obtained, facilitating a more effective optimization of the machining parameters. As a result, it is particularly valuable in industrial applications where time and cost efficiency are crucial, and it contributes substantially to the reproducibility and scalability of the findings.

The line graphs presented elucidate the impact of various operational parameters on the mean cutting thicknesses (TKW and BKW) in a controlled experimental setting. From the analysis, it is evident that increasing pressure correlates with an increase in both TKW and BKW, suggesting that higher pressures enhance the material's removal rate, possibly due to intensified jet penetration capabilities (Figure 2.a). Conversely, as the abrasive flow rate rises, there is a noticeable reduction in the thickness measurements, indicating improved cutting efficiency and precision, attributable to the increased availability of abrasive particles to erode the material more effectively (Figure 2.b). Similarly, an increase in feed rate leads to a decrease in both TKW and BKW, which could be attributed to reduced interaction time between the abrasive jet and the material, resulting in thinner cuts (Figure 2.c). However, the variation in standoff distance shows a less pronounced effect on the cutting thickness, implying that its influence might be overshadowed by the other more dominant operational parameters (Figure 2.d). This analysis highlights the intricate balance and interplay between different machining conditions that can be optimized for enhanced cutting performance in abrasive water jet machining processes.

Table 3. Experiment parameters and their levels

Exp. Number	Pressure [MPa] (P)	Abrasive flow rate [g/min] (m_v)	Feed rate (mm/min) (V)	Standoff distance [mm] (d)	TKW [mm]	BKW [mm]
1	200	100	200	2	1.01	0.98
2					1.00	0.98
3					1.01	0.92
4		150	300	4	0.98	0.95
5					0.95	0.95
6					0.97	0.95
7		200	400	6	0.95	0.93
8					0.94	0.93
9					0.95	0.93
10	250	100	300		1.10	1.00
11					1.10	1.05
12					1.00	1.05
13		150	400	2	1.03	1.04
14					1.06	1.01
15					1.03	1.04
16		200	200	4	0.98	0.93
17					0.99	0.93
18					0.99	0.93
19	300	100	400		1.18	1.14
20					1.18	1.14
21					1.18	1.14
22		150	200	6	1.11	1.03
23					1.11	1.03
24					1.11	1.03
25		200	300	2	1.06	1.01
26					1.06	1.01
27					1.02	1.01

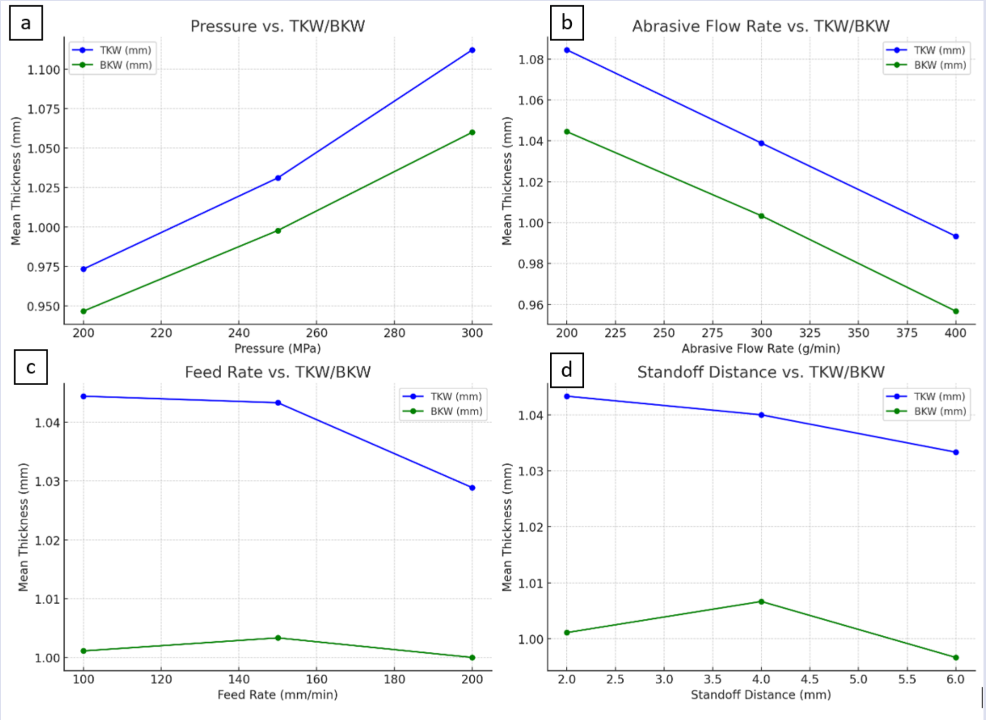

Figure 2. Effects of operational parameters on mean cutting thicknesses (TKW and BKW) in AWJ machining a.) Pressure b.) Abrasive flow rate c.) Feed rate d.) Standoff distance

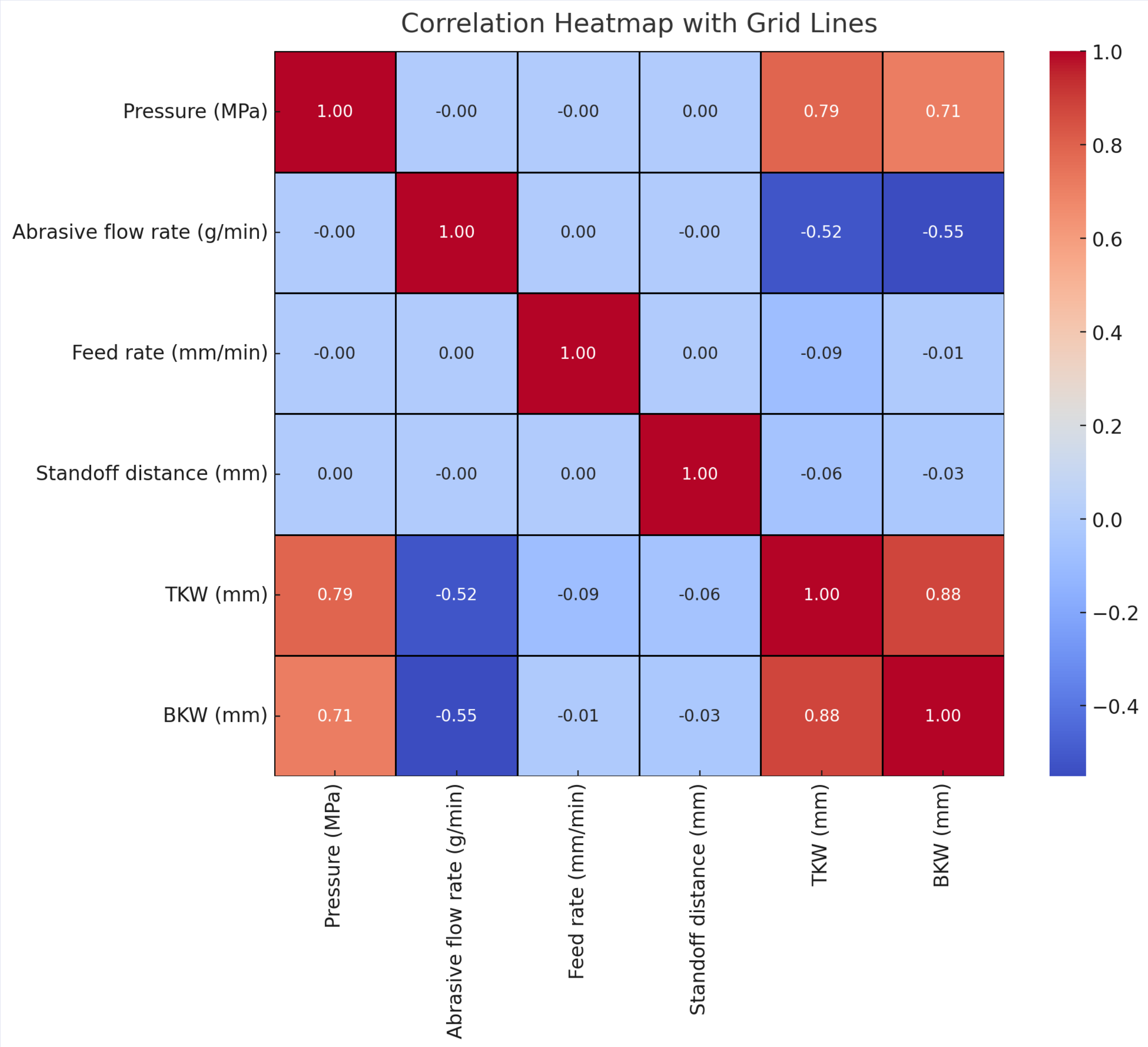

Figure 3. The heatmaps illustrate the combined effects of the parameters

The combined effects of these parameters can be analyzed using interaction plots, which show how two parameters together influence the kerf widths. Understanding these interactions is crucial for optimizing the AWJ process. Understanding the combined effects of multiple parameters on TKW and BKW is crucial for optimizing the AWJ process. The interplay between P, m_v, V, and d significantly influences machining performance. Higher pressure combined with increased abrasive flow rate generally results in greater kinetic energy and more effective material removal, widening both TKW and BKW due to the enhanced abrasive action. High pressure coupled with a lower feed rate often leads to increased exposure time of the material to the jet, resulting in wider kerf widths, whereas a high feed rate at high pressure might reduce the kerf width due to shorter interaction time. Increasing both pressure and standoff distance can significantly affect the kerf widths as high pressure ensures effective cutting, but a larger standoff distance may cause the jet to spread more, widening the kerf widths. A high abrasive flow rate paired with a low feed rate usually results in a wider kerf due to prolonged cutting action, while a high feed rate with a high abrasive flow rate may balance out, depending on the material's response to rapid cutting. Higher abrasive flow rates and increased standoff distances can lead to wider kerf widths as the spread of the jet and the quantity of abrasives erode the material more effectively. A low feed rate with a large standoff distance typically results in wider kerf widths due to extended exposure and jet spread, whereas a high feed rate with a small standoff distance may lead to narrower kerfs. Understanding these combined effects is crucial for optimizing the AWJ process, as each combination influences TKW and BKW differently, and the optimal settings depend on the specific machining task requirements, such as precision, material properties, and desired surface quality. In conclusion, careful consideration and optimization of P, m_v, V, and d can lead to improved machining performance and higher quality outcomes.

The heatmaps (Figure 3) illustrate the combined effects of pressure and abrasive flow rate on the TKW and BKW in the AWJ machining process. As observed in the heatmaps, both TKW and BKW tend to increase with higher pressure and abrasive flow rates. This trend is particularly evident at higher pressure levels, where the increased kinetic energy and abrasive particle flow contribute to wider cuts. The heatmaps also show that the BKW is generally narrower than the TKW, reflecting the jet's diminishing energy as it penetrates deeper into the material. These visualizations highlight the critical influence of operational parameters on the precision and quality of the machining process.

The main effects on TKW and BKW indicate that increasing pressure generally increases both TKW and BKW, suggesting that higher pressure results in wider cuts at both the top and bottom surfaces. Similarly, higher abrasive flow rates lead to increases in both TKW and BKW, implying that more abrasive material contributes to wider kerfs. Conversely, increasing feed rates tend to decrease both TKW and BKW, meaning faster feed rates result in narrower cuts. Additionally, a greater standoff distance generally results in wider TKW and BKW, as the increased distance between the nozzle and the workpiece affects the spread of the water jet. These insights into how each parameter individually influences the kerf widths are valuable for optimizing the machining process. The heatmaps provide a comprehensive visualization of the interactions between various operational parameters - P, m_v, V, and d - on the mean values of TKW and BKW in AWJ machining. The analysis reveals that higher pressures consistently result in increased cutting thicknesses for both TKW and BKW, indicating that greater pressure enhances the jet's penetration capability. However, the abrasive flow rate exhibits a more complex relationship: moderate levels of abrasive flow rate achieve optimal cutting thickness, while extremes (either too high or too low) result in suboptimal performance, likely due to inefficient material removal or excessive dispersion of the jet. Similarly, feed rate shows a negative correlation with TKW and BKW, where increased feed rates lead to reduced cutting thicknesses, suggesting a faster traversal speed limits the interaction time between the jet and material, thus reducing the cut depth. Standoff distance, though less influential than other parameters, still plays a role, with lower standoff distances generally favoring better cutting performance by maintaining the jet's focus and energy density. The interaction plots between pairs of parameters underscore the importance of balanced settings; for instance, combining higher pressure with moderate abrasive flow rate and feed rate yields the best results. These insights are crucial for optimizing the AWJ machining process, ensuring efficient material removal while maintaining precise control over the cut dimensions.

The optimal parameters for minimizing kerf widths in AWJM machining. For the smallest BKW of 0.92 mm, (Figure 4.a) the ideal settings are 200 MPa pressure, 200 g/min abrasive flow rate, 200 mm/min feed rate, and a 6 mm standoff distance, which also resulted in a TKW of 1.01 mm. Conversely, the minimum TKW of 0.94 mm (Figure 4.b) was achieved with 200 MPa pressure, 400 g/min abrasive flow rate, 150 mm/min feed rate, and a 2 mm standoff distance, producing a BKW of 0.93 mm. These findings emphasize the necessity of fine-tuning process parameters to enhance cutting precision and efficiency in AWJM, highlighting that different optimal settings are required to minimize upper and lower kerf widths (Table 4).

The regression analysis for TKW (Table 5) shows that none of the process parameters (P, m_v, V, and d) are statistically significant predictors at the 0.05 level, as indicated by their high p-values. The ANOVA results for TKW (Table 6) support this, with none of the factors having a significant effect on TKW, as all p-values exceed 0.05. Similarly, the regression analysis for BKW (Table 7) indicates that only Pressure is marginally significant (p=0.051048), while other parameters are not significant predictors. The ANOVA for BKW (Table 8) confirms this, showing a near-significant effect of Pressure on BKW (p=0.051048), with other parameters not having significant effects. In summary, pressure has a marginal impact on BKW but not on TKW, while abrasive flow rate, feed rate, and standoff distance do not significantly influence either kerf width.

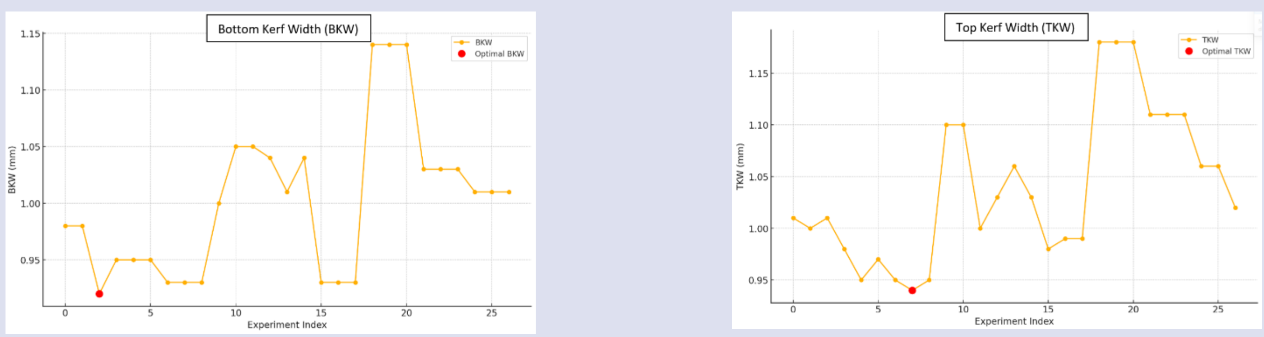

Figure 4. Optimum value of experiment number for a.) BKW and b.) TKW

Table 4. Optimum kerf width parameters and their values.

AWJ Parameters	Optimum parameters	
	TKW	BKW
Pressure [MPa]	200	200
Feed rate [mm/min]	150	200
Abrasive flow rate [g/min]	400	200
Standoff distance [mm]	2	6
Optimum kerf width	0.94	0.92

Table 5. Regresion analysis table for TKW.

	sum_sq	df	F	PR(>F)
Intercept	0.008411	1	2.129423	0.158627
Pressure	0.002468	1	0.624916	0.437665
Abrasive_Flow_Rate	0.002936	1	0.74331	0.397903
Feed_Rate	0.005498	1	1.392021	0.250665
Standoff_Distance	0.086895	22		

Table 6. ANOVA for TKW.

	sum_sq	df	F	PR(>F)
Pressure	0.008411	1	2.129423	0.158627
Abrasive_Flow_Rate	0.002468	1	0.624916	0.437665
Feed_Rate	0.002936	1	0.74331	0.397903
Standoff_Distance	0.005498	1	1.392021	0.250665
Residual	0.086895	22		

Table 7. Regresion analysis table for BKW.

	Coef.	Std.Err.	t	P>|t|
Intercept	0.858518	0.085631	10.02579	1.15E-09
Pressure	0.000788	0.000382	2.063618	0.051048
Abrasive_Flow_Rate	5.82E-06	0.000157	0.037028	0.970797
Feed_Rate	-9.7E-05	0.000176	-0.55128	0.587001
Standoff_Distance	0.003621	0.00733	0.493988	0.626211

Table 8. ANOVA for BKW.

	sum_sq	df	F	PR(>F)
Pressure	0,015045	1	4,25852	0,051048
Abrasive_Flow_Rate	4,84E-06	1	0,001371	0,970797
Feed_Rate	0,001074	1	0,303905	0,587001
Standoff_Distance	0,000862	1	0,244024	0,626211
Residual	0,077723	22		

Discussions

The findings of this study reveal that while pressure marginally impacts the bottom kerf width (BKW), other parameters such as abrasive flow rate, feed rate, and standoff distance do not significantly influence either the top kerf width (TKW) or BKW. These results align partially with previous research, where pressure has been noted to play a crucial role in abrasive waterjet machining, enhancing material removal rates and affecting kerf geometry (Agarwal & Broutman, 2017; Mallick, 2007). However, the insignificant effect of abrasive flow rate and feed rate contrasts with some studies that highlight their importance in optimizing cutting performance (Singh & Bhatnagar, 2006; Isbilir & Ghassemieh, 2013). These discrepancies could be attributed to differences in experimental setups, material properties, and specific machining conditions. The lack of significance for standoff distance is consistent with findings from Davim (2012), who noted its secondary role compared to other parameters. Further research incorporating a broader range of parameters and more advanced statistical analyses, such as interaction effects, could provide deeper insights into the complex dynamics of AWJ machining of GFRP composites.

Conclusion

AWJM is a precise and efficient method for cutting various materials, including metals, composites, and polymers. This study investigated the effects of different process parameters on the TKW and BKW, aiming to identify optimal settings for minimizing these widths. This study demonstrates that by carefully optimizing AWJ machining process parameters, it is possible to achieve desirable kerf characteristics. Specifically, achieving smaller kerf widths, both upper and lower, can significantly enhance precision and material efficiency in AWJM processes. The identified optimal settings—200 MPa pressure, 200-400 g/min abrasive flow rate, 150-200 mm/min feed rate, and 2-6 mm standoff distance—

provide a useful guideline for improving cut quality and minimizing material waste in various cutting applications.

- *Top kerf width (TKW):* The smallest TKW of 0.94 mm was achieved with a *P=200* MPa, an $m_v = 400$ g/min, a $V = 150$ mm/min, and a $d = 2$ mm. This indicates that lower pressure and higher abrasive flow rates are effective in reducing the upper kerf width.
- *Bottom kerf width (BKW):* The smallest BKW of 0.92 mm was achieved with a *P=200* MPa, an $m_v = 200$ g/min, a $V = 200$ mm/min, and a $d = 6$ mm. This suggests that lower abrasive flow rates and higher feed rates are beneficial for minimizing the lower kerf width.
- *Water Pressure (P):* Higher water pressure generally helps in reducing kerf taper by maintaining a uniform energy distribution, but beyond a certain point, it may increase kerf widths. Optimal TKW and BKW were found at 200 MPa, showing the significance of balancing pressure.
- *Abrasive Flow Rate (m_v):* Optimal abrasive flow rates were 400 g/min for TKW and 200 g/min for BKW. This highlights the complex influence of AFR on kerf widths, necessitating careful optimization.
- *Feed rate (V):* Higher traverse speeds were effective in minimizing BKW. The optimal BKW was achieved at a feed rate of 200 mm/min, indicating the importance of optimizing feed rates for better cut quality.
- *Standoff Distance (d):* Smaller standoff distances significantly reduce kerf widths and improve cut precision. Optimal TKW was achieved with a standoff distance of 2 mm, but very small distances should be managed to avoid excessive nozzle wear and cut irregularities.

In future studies, researchers can focus on determining the optimum kerf width for composite materials with different components. On the other hand, as the size of the workpiece increases, the optimization of the kerf width becomes more important. Therefore, within the framework of the limitations of the abrasive water jet process, the optimization of the kerf width can be achieved by evaluating the material thickness together.

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