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Machinability Assessment of Hole-Making in Rubberwood–Plastic Composites Using Abrasive Waterjet Cutting

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ABSTRACT

The application of wood-plastic composites (WPCs) in industrial and structural applications has increased; however, the secondary machining process of hole-making for assembly remains challenging due to tool wear, dimensional inaccuracy, and surface defects in conventional drilling. Therefore, this study examines the machinability of abrasive waterjet (AWJ) cutting as an alternative approach for creating holes in single-layer and three-layer WPCs. Experiments were conducted using different cutting parameters, including water pressure, traverse speed, abrasive mass flow rate, and hole diameter. The effect on hole characteristics, roundness, and surface quality was analyzed. The results indicated that AWJ achieved through-cuts in both single-layer and three-layer WPCs, providing greater hole roundness and surface polish, while WJ produced complete cuts mainly at 350 MPa. The recommended AWJ parameters are abrasive flow rate of 6.67 g/s, water pressure of 350 MPa, and traverse speed of 30 mm/s, results in a roundness of 0.351 mm. A regression model was created to predict roundness, attaining an acceptability of 84.8%. A comparison with drilling bit suggested that AWJ cutting enabled shorter processing times, more flexibility, and without tool changes, although yielding lower roundness values. The results indicate that AWJ is a feasible and efficient alternative for hole fabrication in WPCs for manufacturing purposes.

1. Introduction

Wood plastic composites (WPCs) are increasingly used in furniture and construction industries due to their durability, dimensional stability, and possibility for sustainable raw materials. WPCs can be made almost any form, but assembly still requires secondary machining operations like cutting and hole-making. Conventional machining techniques are frequently utilized as secondary processes, with cutting, drilling and milling being the most common. These techniques utilize precise cutting tools to remove unwanted material as chips; however, they frequently experience tool wear,

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thermal degradation, delamination, and dimensional inaccuracy, particularly with multi-layer composites [1-3]. These challenges indicate the necessity for unconventional machining methods. Recent research has shown the advantages and disadvantages of nontraditional machining processes, including laser machining and abrasive waterjet (AWJ) machining. In laser machining, feed rate and gas pressure significantly affect penetration, edge quality, and the size of the heat-affected zone; optimum parameters can minimize thermal deterioration and enhance cutting consistency [4-5]. Nevertheless, heat-affected zones continue to exist despite optimal conditions, causing thermal damage to WPCs. The AWJ cutting, on the other hand, has become an acceptable alternative because of it has less heat impacts and adaptability in creating complex shapes [6]. Several investigations have confirmed its efficacy in composites [7-10], indicating that traverse speed, abrasive flow rate, and water pressure represent crucial factors for achieving quality cuts. Nonetheless, adjustments specified to the unique characteristics of each composite material are essential for further improving cutting quality and performance [6].

For hole making, AWJ can operate in drilling (piercing) or circular cutting modes. Previous research indicated that AWJ drilling usually attains greater roundness compared to circular cutting, which experiences jet instability along curved trajectories [11-12]. In contrast, traditional drilling of WPCs is at risk of delamination and dimensional error, with results significantly influenced by the drilling method [1]. Despite these developments, there remains few thorough investigations on AWJ hole machining of WPCs. The impacts of water pressure, cutting speed, abrasive mass flow rate, and hole diameter on roundness and cut quality have not been extensively studied. Comparative assessments with traditional drilling are necessary to evaluate the commercial potential of AWJ. Therefore, this study addresses these gaps by experimentally investigating AWJ hole machining of WPCs in single and three layers. The cutting parameters were considered for their impact on hole characteristics, roundness, and surface quality. Regression model was constructed and validated, and the results were compared with traditional drilling to explain the advantages and limitations of AWJ in WPC machining.

2. Methodology

2.1 Wood plastic composites

Wood–plastic composites (WPCs) with a thickness of 10 mm were fabricated using a polypropylene (PP) matrix, rubberwood flour (RWF), a UV stabilizer, maleic anhydride-grafted polypropylene (MAPP), and paraffin. Table 1 presents the characteristics of the WPCs. Further details on the development and testing of the WPCs are provided by Srivabut et al. [13]. The fabrication process began with extrusion of the composite strands into pellets, followed by sheet formation through compression moulding. Two types of WPCs were produced: a single-layer model with a thickness of 10 mm (Figure 1a), and a three-layer model consisting of WPC–PP–WPC with thicknesses of 2–6–2 mm, respectively (Figure 1b).

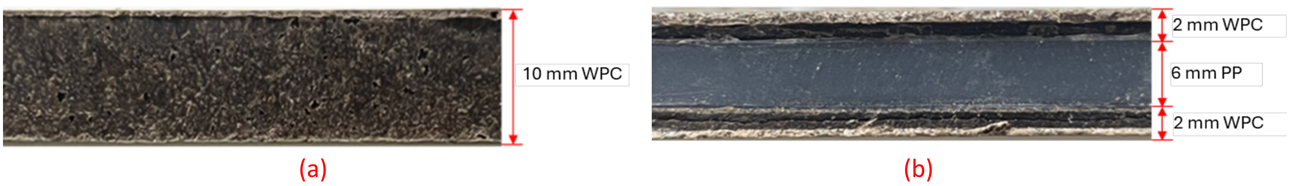


Fig. 1. Lateral perspective of WPCs: (a) single-layer WPCs and (b) three-layer WPCs

Table 1
Properties of WPCs [13]

Material	Thickness (mm)	Hardness (N/m^2)	Tensile (MPa)	Impact (J)	Water absorption (%)
1-layer	10	64.30	6.57	0.09	19.53
3-layers	10 (2-6-2)	79.24	24.26	0.21	3.70

2.1 Experimental design

Two types of hole generation processes were investigated: hole drilling (piercing) and hole cutting as shown in Figure 2. Hole drilling was conducted on a CINCINNATI ARROW machine utilizing 6, 8 and 12 mm drill bits (D_b), with parameters established as follows: 6 mm (2,100 min^{-1} revolution and 0.23 mm/rev), 8 mm (1,600 min^{-1} revolution and 0.28 mm/rev), and 12 mm (1,000 min^{-1} revolution and 0.38 mm/rev) [14]. Circular hole cutting using pure waterjet (WJ) and AWJ processes was conducted on an SQ1313 Sunrise CNC waterjet cutting machine. The experimental parameters, including three levels of water pressure (P), traverse speed (V_t) and hole diameters (D_w) are summarized in Table 2. The designated D_w values were employed to generate the corresponding cutting paths (Figure 2).

Table 2
Process parameters for AWJ hole cutting

Parameters	Units	Level		
		1	2	3
Water pressure, P	MPa	150	250	350
Traverse speed, V_t	mm/s	30	40	50
Hole diameter, D_w	mm	6	8	12

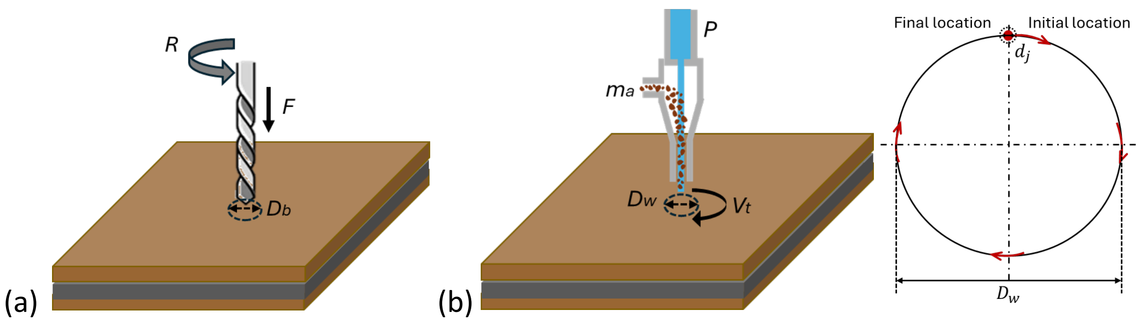


Fig. 2. Characteristics of (a) hole drilling and (b) hole cutting using AWJ

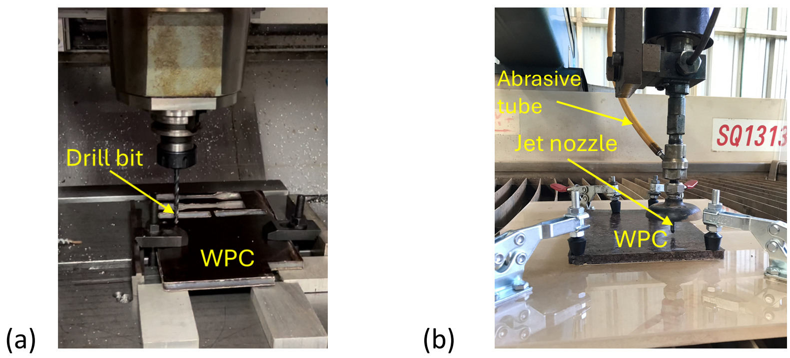
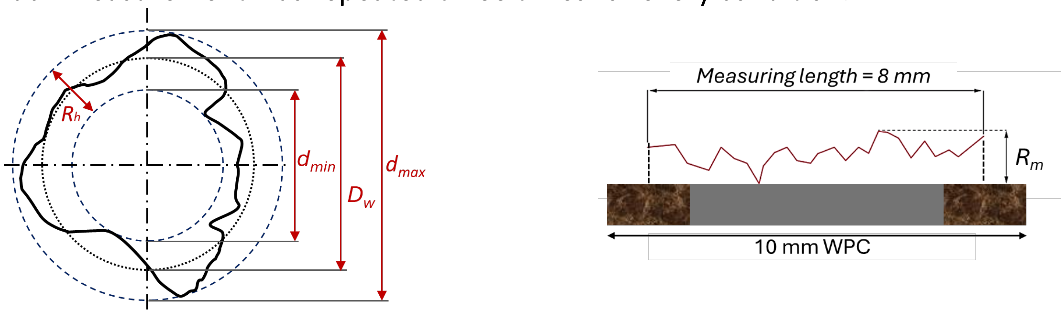


Fig. 3. Experimental setup of (a) hole drilling and (b) hole cutting using AWJ

For the AWJ cutting, 80-mesh garnet abrasive with flow rate (m_a) of 6.67 g/s was selected. The cutting control variables were fixed at a standoff distance of 2 mm, an orifice diameter of 0.33 mm and a nozzle diameter (dj) of 1.02 mm. A full factorial design yielded 54 experimental conditions, each repeated three times to obtain average values. The experimental set up of hole drilling and AWJ hole cutting are presented in Figure 3.

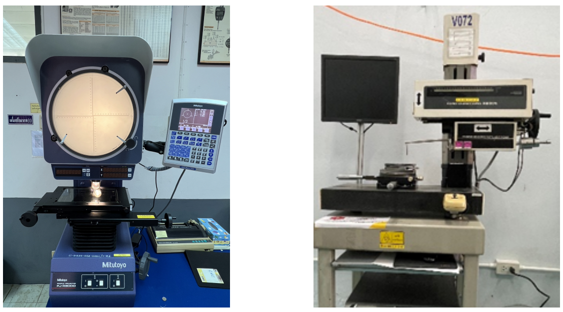
2.2 Hole characteristic measurement

This study evaluates the hole characteristics in terms of surface roughness, roundness, and material structure. The procedures for measuring roundness (R_h) and surface roughness (R_m) are shown in Figure 4. Roundness measurements followed the form tolerance criteria specified in ASME Y14.5 Dimensioning and Tolerancing Standard [15]. Roundness was determined by fitting two concentric circles, an inner circle (d_{min}) and an outer circle (d_{max}), such that all points on the measured circular profile were enclosed between them. The length (L) for roughness measurement was set at 8 mm with 0.0010 mm measure pitch. Hole roundness and surface roughness using PJ-A3000 profile projector and CONTOURECORD 2600E contour measurement tester, respectively, as illustrated in Figure 5. Each measurement was repeated three times for every condition.



(a) (b)

Fig. 4. Measurements of (a) hole roundness and (b) hole surface roughness



(a) (b)

Fig. 5. Measuring equipment: (a) PJ-A3000 profile projector and (b) CONTOURECORD 2600E contour measurement

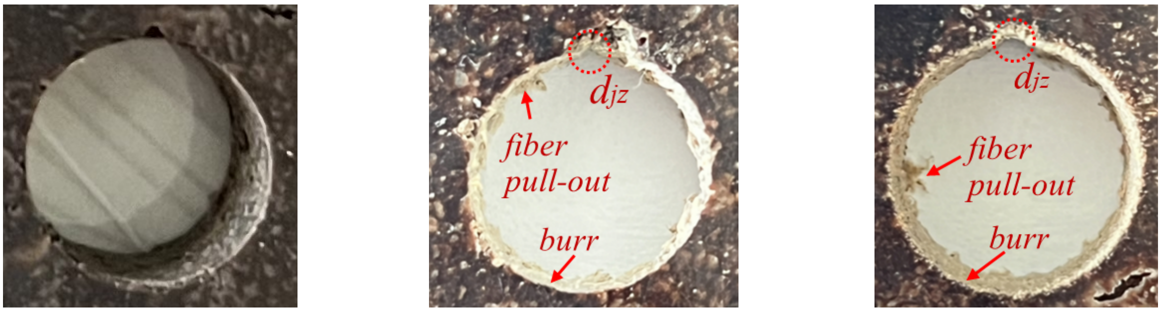
3. Results and Discussion

3.1 Hole characteristic

The hole characteristics created by drilling, WJ cutting, and AWJ cutting for single-layer and three-layer WPC are displayed in Figures 6 and 7, respectively. The drilled holes (Figure 6(a) and Figure 7(a)) demonstrate acceptable roundness with negligible burr development. In contrast, WJ and AWJ cutting result in edges that are not perfectly smooth, where burrs and chip can be observed around the perimeter. AWJ cutting, however, offers better hole roundness relative to WJ cutting, mainly due to the additional cutting energy granted by abrasive particles that increase the cutting force. In addition, the jet deviation zone is visible at the hole entrance. This is because the jet's initial shockwave impact causes a jet-induced damage zone at the point of entry [11]. Overcut at the jet deviation zone also arise from the exit position of the cutting path. This impact can be minimized by starting the cutting inside the hole, near the center, before the jet travels in a circular path and stops inside the hole after the cut is complete. The actual machined hole diameter (D_{aw}) exceeds the programmed diameter (D_w) by an amount roughly equivalent to the kerf width, that corresponds with the jet diameter. A compensation can be implemented by adjusting the programmed diameter to reduce the diameter deviation. The compensated programmed diameter is defined as follows:

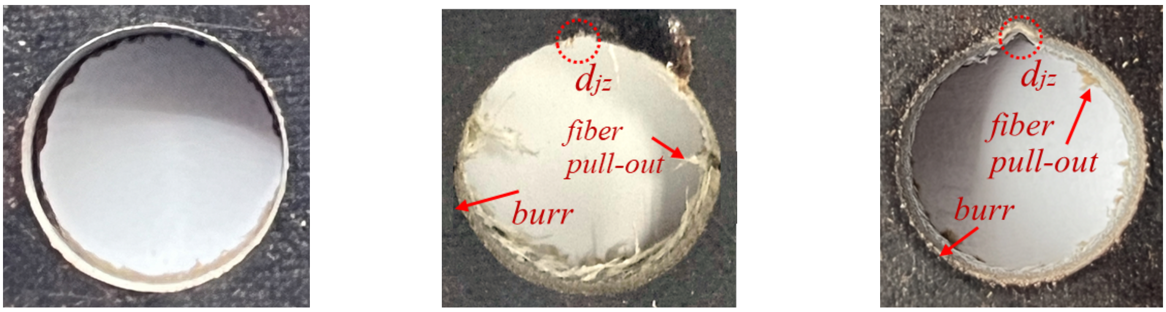
$$D_{aw} = D_w - d_f \quad (1)$$

where d_f is the deviation from the programmed hole diameter. This investigation found that the d_f values for WJ and AWJ cutting were 0.880 mm and 1.066 mm for 1-layer WPC, and 0.976 mm and 0.804 mm for 3-layer WPC, respectively, which approached but not exceeding the 1.02 mm nozzle diameter.



(a) (b) (c)

Fig. 6. Hole characteristics (12 mm) in single-layer WPCs: (a) drilled with a 12 mm drill bit, (b) WJ at P = 350 MPa and V_t = 30 mm/s, and (c) AWJ at m_a = 6.67 g/s, P = 350 MPa, and V_t = 30 mm/s.



(a) (b) (c)

Fig. 7. Hole characteristics (12 mm) in three-layer WPCs: (a) drilled with a 12 mm drill bit, (b) WJ at P = 350 MPa and V_t = 30 mm/s, and (c) AWJ at m_a = 6.67 g/s, P = 350 MPa, and V_t = 30 mm/s.

3.2 Roundness

Based on the experiment results giving in Table 3, all WJ and AWJ cutting condition can cut through 1-layer WPCs, but some conditions cannot achieve the through cut for 3-WPCs. This is due to higher hardness and tensile strength as shown in Table 1. With through cut condition, the AWJ cutting seem achieved better roundness than WJ cutting, particularly at high water pressure and low cutting speed.

Table 3
Roundness results for 1-WPCs and 3-WPCs

WPC	Order	P (MPa)	V_t (mm/s)	WJ-Roundness (mm)			AWJ- Roundness (mm)		
				6	8	12	6	8	12
1-layer	1	150	30	0.854	0.809	0.349	0.862	0.496	0.626
	2		40	0.735	0.404	0.605	0.724	0.654	0.657
	3		50	0.411	0.607	0.965	0.502	0.641	0.647
	4	250	30	0.842	0.903	0.479	0.411	0.788	0.513
	5		40	0.806	0.412	0.401	0.566	0.919	0.582
	6		50	0.689	0.610	0.729	0.552	1.087	0.560
	7	350	30	0.711	0.521	0.527	0.239	0.488	0.351
	8		40	0.419	0.144	0.508	0.838	0.711	0.425
	9		50	0.614	0.497	0.467	1.055	0.949	0.454
3-layer	1	150	30	-	-	1.127	-	0.288	0.258
	2		40	-	-	-	0.491	0.676	0.710
	3		50	-	-	-	0.482	-	0.738
	4	250	30	-	0.996	1.102	0.680	0.599	0.653
	5		40	-	0.767	-	0.407	0.692	0.901
	6		50	-	-	-	-	-	-
	7	350	30	0.874	0.627	1.215	0.917	0.673	0.216
	8		40	0.504	-	-	0.179	0.445	0.349
	9		50	-	-	-	0.924	0.826	0.413

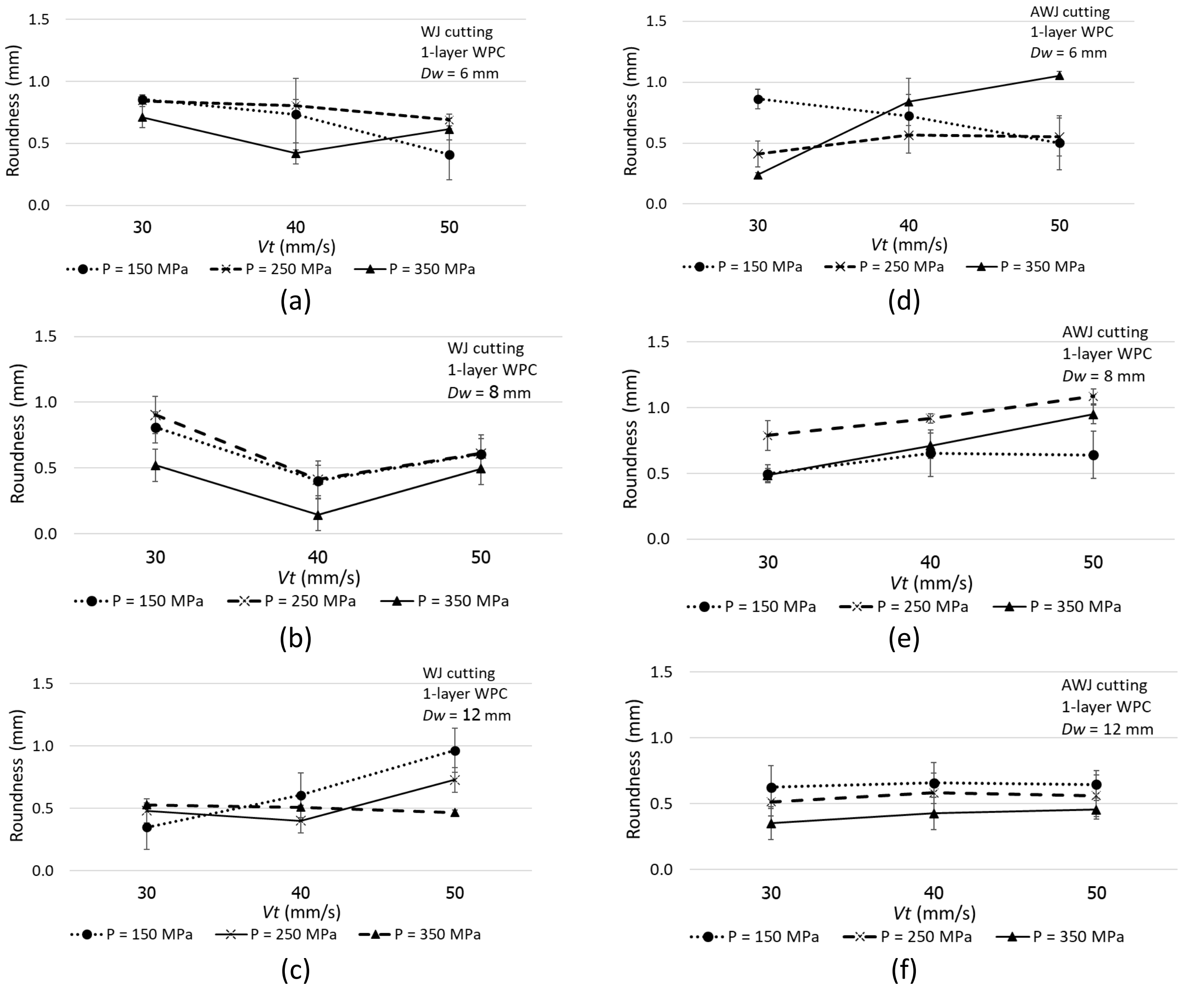


Fig. 8. Relationship between cutting parameters and roundness of single-layer WPCs.

The relationship between cutting parameters and roundness is shown in Figures 8 and 9 for 1-layer and 3-layer WPCs, respectively. Higher pressure and lower cutting speeds improved roundness, with AWJ cutting outperforming pure WJ cutting. Larger hole diameters reduced roundness variation, particularly at lower speeds, where 12 mm holes (Figure 8(f)) showed minimal sensitivity to cutting conditions. Greater roundness occurs in small holes due to increased jet swirl and instability along curved paths, suggesting that reducing traverse speed can improve roundness in small diameters [16]. The effect of traverse speed (V_t) on roundness in abrasive waterjet (AWJ) cutting of 3-layer WPCs at 350 MPa shows that roundness decreases at 40 mm/s for all diameters, with the lowest values at D_w = 6 mm. At 50 mm/s, roundness increases again for D_w = 6 and 8 mm, while the 12 mm holes remain relatively stable across all speeds.

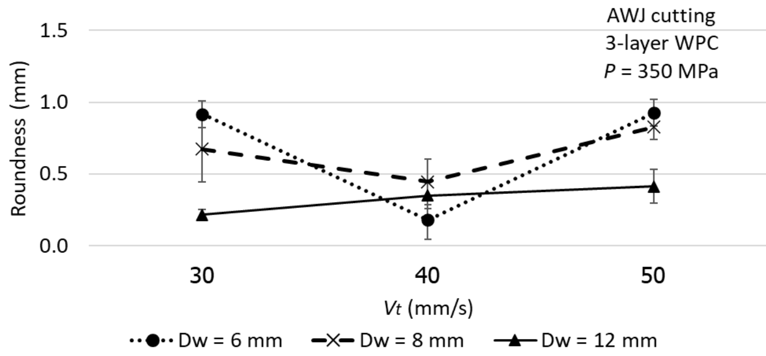


Fig. 9. Relationship between cutting parameters and roundness of three-layer WPC

3.3 Hole Surface roughness

Surface roughness was analyzed from the side (Figure 10), exhibiting both smooth and rough areas. In single-layer WPC, the rough area exhibited delamination and little fiber pull-out, whereas in three-layer WPC, matrix tear in the middle PP layer resulted in vertical stripes and grooves. These characteristics arise from the anisotropic response of fibers and matrix to cutting forces, with irregularities primarily caused by fiber pull-out, tearing, and delamination. Surface roughness increased with cutting depth because reduced jet energy caused insufficient penetration and unstable jet–workpiece interaction, consistent with prior studies [9].

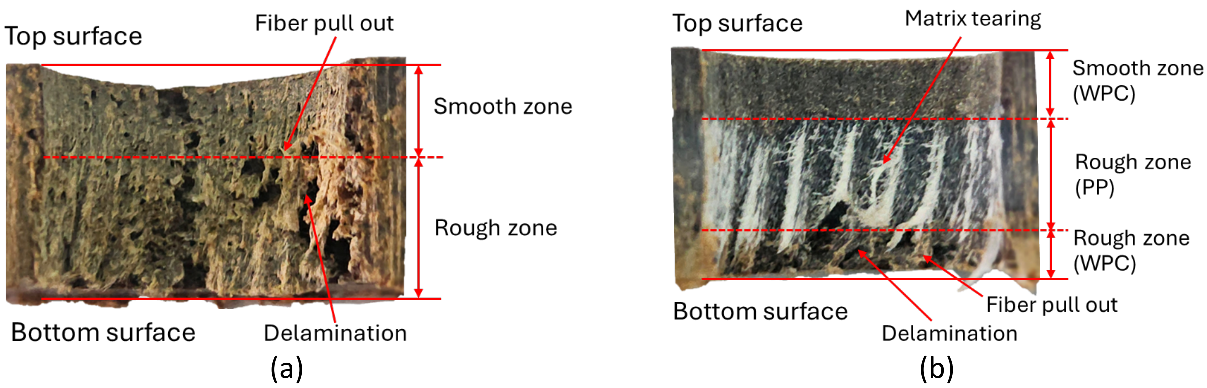


Fig. 10. Surface roughness: (a) sing-layer WPCs and (b) three-layer WPCs at P = 350 MPa, and V_t = 30 mm/s

Figure 11 illustrates the correlation between the cutting variables and the roughness of the hole surface. AWJ cutting yielded smoother surfaces than WJ cutting, with average roughness measurements of 0.448 mm and 0.265 mm, respectively, at a traverse speed of 30 mm/s and a pressure of 350 MPa. There was no discernible pattern of roughness variation with process parameters, which is accordance with Baykara [17]. There was little difference in surface roughness between traversal speed and hole diameter.

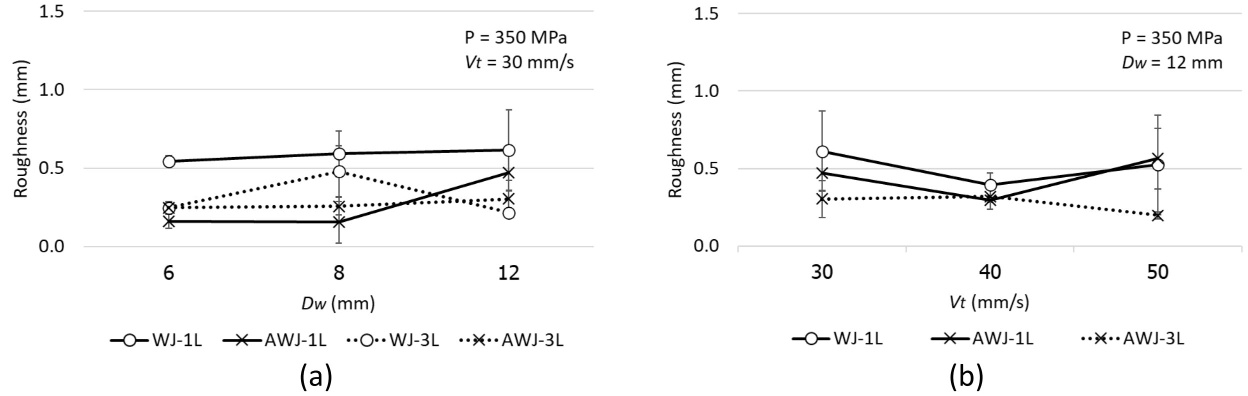


Fig. 10. Relationship between cutting parameters and roughness: (a) *different hole diameter* and (b) *different traverse speed*

3.4 Regression Analysis of Hole Roundness in AWJ Cutting

As discussed earlier, AWJ is capable of producing hole cuts in both single-layer and three-layer WPCs. However, in the case of three-layer WPCs, complete penetration could not be achieved under all cutting conditions. To address this, regression analysis was conducted to evaluate hole roundness under AWJ cutting parameters for single-layer WPCs at a 95% confidence level, as summarized in Table 4. The results show that the interactions of $P \times V_t$ and $P \times V_t \times D_w$ had p-values below 0.05, indicating a statistically significant influence on roundness. Nonetheless, the adjusted R^2 was initially inadequate, necessitating the elimination of some variables to improve model precision. The completed regression model, as illustrated in Eq. (2), obtained an adjusted R^2 of 77.43%, considered satisfactory for predicting the hole roundness of single-layer WPCs.

Table 4
Regression Analysis of hole roundness in AWJ cutting of single-Layer WPCs

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	9	0.68855	0.076505	2.84	0.031*
P	1	0.11215	0.112149	4.16	0.057
V_t	1	0.01891	0.018911	0.70	0.414
D_w	1	0.06463	0.064628	2.40	0.140
$P*P$	1	0.00752	0.007522	0.28	0.604
V_t*V_t	1	0.01606	0.016063	0.60	0.451
$P*V_t$	1	0.21829	0.218293	8.09	0.011*
$P*D_w$	1	0.08853	0.088534	3.28	0.088
V_t*D_w	1	0.08425	0.084253	3.12	0.095
$P*V_t*D_w$	1	0.12635	0.126354	4.68	0.045*
Error	17	0.45852	0.026972		
Total	26	1.14706			
R-sq (adj)	38.86%				

Note: * Parameters have a significant effect at the 0.05 significance level.

$$R_h = -2.275 + 0.012P + 0.040V_t + 0.179\, D_w - 1.500 \times 10^{-5}P^2 - 4.400 \times 10^{-4}\, PV_t - 0.003\, V_tD \quad (2)$$

Single-layer WPCs were circularly cut with a 12 mm hole diameter for assessing the accuracy of the regression models. The anticipated and actual results were then compared. The difference between the predicted and actual values averaged 3.19%, which is within 5%. This shows that the regression equations are acceptable for predicting hole roundness. An investigation of optimal cutting parameters was performed to decrease hole roundness. The findings suggested an abrasive flow rate of 6.67 g/s, a water pressure of 350 MPa, and a cutting speed of 30 mm/s, resulting in a roundness of 0.351 mm and a desirability rate of 84.8%.

3.5 Performance Comparison of AWJ Cutting and Drill Bit

A comparison of AWJ cutting and drilling, as shown in Figures 6 and 7 along with Table 5, indicated that drilling yields greater roundness values compared to AWJ. This phenomenon occurs because the drill bit specifies a set hole diameter, and material removal operates through direct contact between the sharp cutting edges and the WPC, generating uniform force throughout all cutting depths. In contrast, AWJ utilizes an erosion mechanism in which the workpiece surface is impacted by waterjet and abrasive particles. In the case of plastic properties of WPCs, this procedure may distort the adjacent material, and the roundness typically increases with cutting depth due to the decreased effective cutting force throughout the layers [18]. The decrease in cutting speed is recommended to improve penetration and achieve better roundness in deeper layers.

Table 5
Comparison of Hole Roundness Between AWJ Cutting and Drill Bit

WPC	Diameter (mm)	Roundness (mm)	
		AWJ (P = 350 MPa and V_t = 30 mm/s)	Drill bit
Single-layer	6	0.239	0.041
	8	0.488	0.025
	12	0.351	0.035
Three-layer	6	1.040	0.052
	8	0.982	0.075
	12	0.216	0.050

Considering operating time, AWJ cutting is also more efficient. On average, AWJ requires approximately 9 s. per hole, whereas drilling takes around 12 s. per hole. Furthermore, drilling requires additional time to change drill bits when different hole sizes are needed, whereas AWJ cutting can continue operation without interruptions for tool changes. Thus, AWJ cutting offers a combination of hole quality and operational efficiency compared to drilling.

4. Conclusions

This research examined the machinability of creating holes in WPCs utilizing AWJ cutting and compared results with conventional drilling processes. A full factorial experimental design was implemented, including various cutting factors such as water pressure, traverse speed, abrasive mass flow rate, and hole diameter. The effect on hole characteristics, roundness, and surface quality was examined. The results indicated that AWJ cutting achieved better hole roundness than WJ, aided by the cutting energy of abrasive particles, though burrs and chips were observed around the hole circumference. The relationship between water pressure and traverse speed significantly influenced roundness; particularly, higher pressure coupled with lower traverse speed reduced both roundness and surface roughness. An abrasive flow rate of 6.67 g/s, a water pressure of 350 MPa, and a traverse speed of 30 mm/s were determined to be the optimal cutting conditions. A regression model developed to estimate roundness, with validation demonstrating an average difference of approximately 3.19% between predicted and actual values. Although AWJ cutting provided slightly higher roundness values than traditional drilling, it was more beneficial for variable hole sizes and continuous production as it provided shorter processing times and eliminated tool change pauses. The findings indicate that AWJ is a feasible and efficient alternative for drilling in hole creation within WPCs, capable of achieving comparable cut quality while delivering operational advantages that facilitate its wide implementation in composite machining.

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