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Application of Abrasive Water Jet Cutting on Rubber Wood Plastic Composites

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ABSTRACT

Wood-plastic composites (WPCs) possess a diverse arrange of advantageous characteristics resulting from the combination of wood and plastic. These include a prolonged lifespan, cost-effectiveness, and environmental friendliness. However, the net shape can only be roughly achieved by the extrusion method used to make WPCs. WPCs require additional machining to comply with the dimensional accuracy and assembly conditions. As a result, more research into the cutting process of this composite is needed. In this work, abrasive water jet cutting was used to cut WPCs manufactured from rubber wood flour and polypropylene (PP). The emphasis was on two distinctive architectures of 1-layered and 3-layered WPCs with a thickness of 10 mm. The effects of cutting factors including water pressure, traverse speed, and abrasive mass flow rate were taken into account. The study employed a full factorial analysis to investigate the correlation between cutting parameters and cutting performance, including kerf characteristics and machined surface roughness. The abrasive and water pressure in the experiment had a significant effect in cutting both materials. In some cutting conditions, without an abrasive, non-through cutting happens, particular for the 3-layered WPC structures, that are particularly strong. An increase in water pressure decreased machining surface roughness and kerf width. The cutting parameters of 350 MPa water pressure, 30 mm/s traverse speed, and 6.67 g/s abrasive flow rate were suggested for both the 1-layered and 3-layered WPCs structures. This procedure was considered suitable for post-cutting without requiring for surface finishing.

1. Introduction

Wood plastic composites (WPCs) possess the potential for multiple uses and can be manufactured and utilized in a variety of ways. This composite material is employed as a substitute for wood through the combination of wood powder, wood sawdust, or wood fibers with plastic. The production of WPCs involves the implementation of molding methods [1]. The application of wood is expanding within the construction industry, including various uses such as wooden floors, battens, ceilings, roofing, as well as furniture items like tables, cabinets, and chairs [2]. The combination of

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wood and plastic has been found to enhance many mechanical properties, including fire resistance, strength, and absorption. When comparing wood with WPCs, it is evident that WPCs possess superior features that include resistance to sunlight and ultraviolet (UV) rays, recyclability, ease of maintenance, affordability, and a comparatively extended lifespan [3].

The shaping of WPCs, however, is constrained by the design of the mold, hence imposing constraints on the achievable shapes. Furthermore, the manufacturing of molds for the purpose of molding involves comparatively increased production expenses, producing it more suitable for situations involving high-volume production or the fabrication of workpieces characterized by simple shapes and uniform patterns. Modifying the WPC shape requires post-machining processes, such drilling, grinding, milling, or turning. The implementation of this strategy has the potential to enhance product diversity while concurrently simplifying the production process, so decreasing the requirement for the creation of a new mold and thus minimizing both manufacturing time and cost.

However, conventional machining would deteriorate WPCs due to heat generation and tool-to-workpiece contact, thereby damaging the surface and properties of the workpiece. This issue can be resolved by employing high-velocity waterjet (WJ) and abrasive waterjet (AWJ) cutting technologies, which generate no heat during the cutting process [4]. Due to the erosion mechanism used to remove material, the waterjet process can cut any substance with a smooth surface finish [5]. It is also adaptable to a variety of machining processes, including cutting, piercing, and trimming. From a review of the relevant literature, it was determined that the majority of the materials cut with high-pressure water cutting technology are engineering materials, such as metals, ceramics, glass, etc [6-10].

Several investigations have employed WJ and AWJ machining for composite materials, such as banana fibre reinforced polyester composites [11], graphite/glass/epoxy composites [12] and wood plastic composites [13]. Madara *et al.,* [14] investigated the modelling of surface roughness in AWJ cutting of a Kevlar 49 composite using an artificial neural network. The first model evaluated how surface roughness was affected by pressure and traverse speed, while the second model explored how surface roughness varied with standoff distance and mass flow rate. Hejjaji e*t al.,* [15] described the results of surface machining-induced damage characterization using AWJ milling on a carbon/epoxy composite. It was discovered that the erosion phenomenon caused by jet pressure contributed for the formation of craters. In addition, tests conducted with various surface textures and crater sizes indicate that the volume of the crater had a greater impact on tensile strength than surface roughness. The AWJ cutting had no effect on the properties of cut materials, especially for an isotropic material property, because of the special material removal mechanism that was in accordance with AWJ erosion process [13]. The machined surface quality of WPC cut by AWJ was caused from the distinct physical properties of the composite material's constituents, particularly wood and plastic [13,16]. The surface was irregularly damaged by the partial removal of wood particles from the plastic matrix, and little ragged clusters of wood fibres was also presented.

Macroscopic fractures caused disruptions on the surface of the workpiece in certain locations. These cracks were inherent to the material production process and do not have a substantial impact on the surface appearance after machining. The AWJ cutting may induce the generation of delamination that may affect the composites’ mechanical properties [14,17]. However, this frequently occurs in the case of an inappropriate cutting condition for anisotropic material properties, such as sandwich-structured or laminate-structured composites [17].

A review of the relevant literature indicates that AWJ machining technology can effectively cut composite materials. The AWJ traverse speed and water pressure were critical cutting parameters that significantly impacted the machining performance. However, knowledge regarding AWJ cutting on WPCs, specifically for different workpiece structures such as sandwich panels, remains limited.

Therefore, the utilization of AWJ cutting on WPCs is the subject of this paper. Statistical analysis was used to evaluate the influence of water pressure, traverse speed, and abrasive flow rate on the machining performance of kerf width and surface roughness. The results of this research will allow for predictions of machining characteristics according to the conditions considered in this study.

2. Methodology
2.1 Wood Plastic Composites

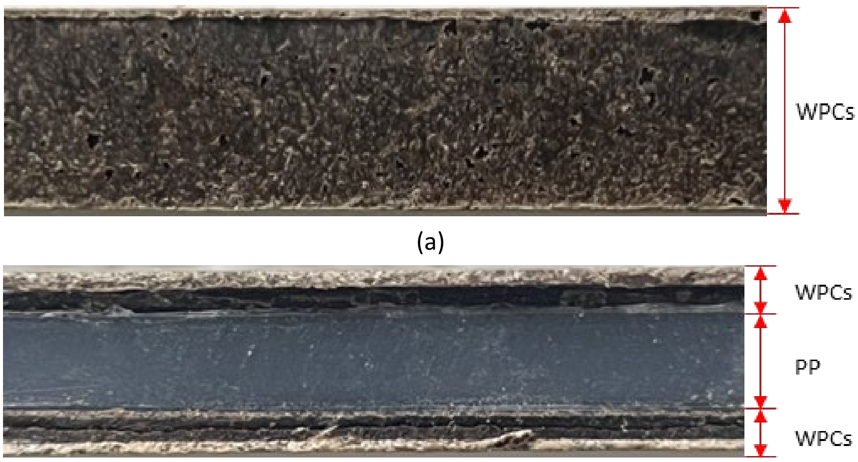
For the experiment, WPCs with dimensions of 160×260×10 mm were machined. Polypropylene (PP) matrix, rubber wood flour (RWF) size 80-120 µm. WPCs are composed of a polypropylene (PP) matrix, 80-120 µm rubber wood flour (RWF), UV stabilizer, Maleic anhydride-grafted polypropylene (MAPP), and paraffin. Table 1 shows the proportion of material components, while Table 2 details the properties of WPCs. The production of WPCs begins with the extrusion of material lines composed of combined materials into pellets. After that, sheets are created using compression molding. The materials were divided into two categories for the molding of WPCs: a 1-layer model with a thickness of 10 mm, as shown in Figure 1(a), and a 3-layers model comprised of WPCs-PP-WPCs with thicknesses of 2-6-2 mm, respectively, as shown in Figure 1(b). More information of developing and testing the WPCs was explained in the study of Srivabut *et al.,* [18].

Table 1
Composition of WPCs components [18]

Material	Weight	Type of chemicals				
		PP	RWF	UV stabilizer	MAPP	Paraffin
WPCs	(%)	50.3	44.5	3.9	0.2	1
PP		100				

Table 2
Material properties of WPCs [18]

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	2-6-2	79.24	24.26	0.21	3.70



(a)

(b)

Fig. 1. Side view of WPCs (a) 1-layer wood plastic composite (b) 3-layers wood plastic composite

2.2 Experimental Setup

Two different types of WPCs were fabricated using the SQ1313 Sunrise CNC waterjet cutting machine, which has a maximum pressure capability of 400 MPa. This investigation considers several machining factors, including water pressure, traverse speed and abrasive mass flow rate. The specific values for these parameters are obtained in Table 3. The control variables for AWJ cutting consisted of a 2 mm standoff distance, an orifice diameter of 0.33 mm, a jet nozzle diameter of 1.02 mm, and 80 mesh garnet abrasives, which are commonly used in industry. The abrasives have the following characteristics: 1.5% moisture content, 2.31 g/cm^3 bulk density, 3.805 g/cm^3 granules density, and a porosity of 39.29% [19].

Table 3
Parameters setup for WJ/AWJ cutting process

Parameters	Units	Setting range
Water pressure	MPa	150-250
Traverse speed	mm/s	30-50
Standoff distance	mm	2
Orifice of diameter	mm	0.33
Diameter of the water jet nozzle	mm	1.02
Abrasive mass flow rate	g/s	0-6.67
Abrasive grains garnet size	Mesh	80

2.3 Experimental Design

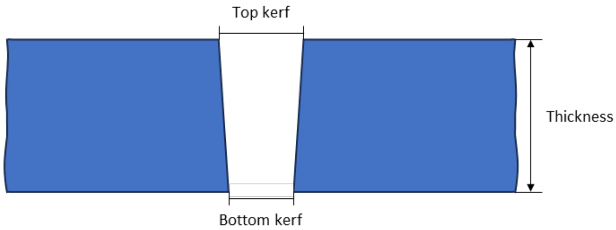
Table 4 presents the defined values for three distinct levels of water pressure (*P*) and traversal speed (V_t). The full factorial design approach was employed to determine the number of experiments, resulting in a total of nine cutting conditions. Additionally, these situations were evaluated both with and without abrasive, resulting in a total of 18 conditions. Each condition was repeated multiple times, resulting in a total of 54 cuts. The cut was made using a straight cut with a length of 20 mm. This investigation involved the implementation of a single cut.

Table 4
Input variable factors

Parameters	Units	Level		
		1	2	3
Water pressure, P	MPa	150	250	350
Traverse speed, V_t	mm/s	30	40	50
Abrasive mass flow rate, $\dot{m}_a$	g/s	0	6.67	-

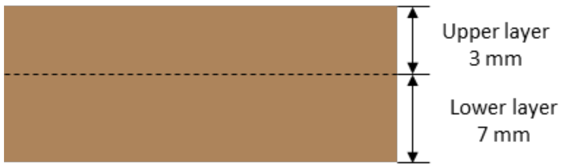
2.4 Measuring Machining Performance

For measuring machining performance, a Mitutoyo PJ-A3000 profile projector was used to measure the bottom kerf width values as depicted in Figure 2 (a) and (b). As illustrated in Figure 3(b), surface roughness (*Ra*) is measured by dividing the measurement area into layers in accordance with the WPCs model, with the upper layer serving as the measurement area of 3 mm of the top surface. As displayed in Figure 3(c), the measuring area for the 3-layers WPC will be divided into WPC 1, PP, and WPC 3 according to the various material layers. Using an Mitutoyo portable surface roughness tester SJ-210 as show in Figure 3(a), measure a length of 10 mm to calculate the average surface roughness value. The measurement procedure is repeated three times for each region.



(a) (b)

Fig. 2. Kerf width measurement (a) Mitutoyo PJ-A3000 profile projector and (b) kerf width characteristic



(a) (b)

(c)

Fig. 3. Surface roughness measurement (a) Mitutoyo portable surface roughness instrument, (b) surface roughness measurement for 1-layered WPC and (c) surface roughness measurement for 3-layered WPC

3. Results and Discussion

3.1 Effects of Cutting Parameters on 1-Layered and 3-Layered Wpcs

A comprehensive cut analysis (Table 5) revealed that both WJ and AWJ cutting can cut through a single layer of WPCs in a single pass under all 18 test conditions. However, the WJ process was incapable to create through cutting for 3-layered WPC. Figure 4(a) show kerf characteristics of a single layer WPC at the cutting condition of P = 250 MPa and V_t = 30 mm/s. For the AWJ process, non-through cuts of the 3-layers WPC occurred at the conditions of water pressure less than 350 MPa (Figure 4(b)). Nevertheless, the through cuts can be conducted at the maximum water pressure of 350 MPa, under all cutting speeds (Figure 4(c)).

Table 5
Experimental results of kerf geometry and quality surface roughness

No.	$\dot{m}_a$ (g/s)	P (MPa)	V_t (mm/s)	Kerf width (mm)		Surface roughness (μm)			
				1-layer	3-layers	Top	WPC 1	PP	WPC 3
1	0	150	30	0.724	-	10.861	-	-	-
2			40	0.873	-	8.300	-	-	-
3			50	0.818	-	8.613	-	-	-
4		250	30	0.762	-	7.644	-	-	-
5			40	0.671	-	9.315	-	-	-
6			50	0.775	-	8.013	-	-	-
7		350	30	0.750	-	7.569	-	-	-
8			40	0.754	-	6.901	-	-	-
9			50	0.769	-	8.075	-	-	-
10	6.67	150	30	0.906	-	12.575	-	-	-
11			40	0.939	-	12.803	-	-	-
12			50	0.946	-	12.797	-	-	-
13		250	30	0.752	-	12.126	-	-	-
14			40	0.789	-	11.943	-	-	-
15			50	0.804	-	12.140	-	-	-
16		350	30	0.580	0.476	13.079	7.572	14.541	17.563
17			40	0.676	0.533	12.720	7.297	15.565	16.535
18			50	0.653	0.577	13.134	7.650	16.388	18.528

As shown in Table 2, the hardness and tensile strength of three-layers WPCs are significantly greater than those of 1-layer WPC. The jet kinetic energy might not high enough to remove material. In addition, the sandwich structure of the three-layers WPC had distinct material properties for each layer, resulting in diverse removal kinetic energies and mechanisms. Following the direction of the cutting depth, the jet impact characteristics have to be adjusted for each layer, resulting in failure of the cutting edge to penetrate [12].

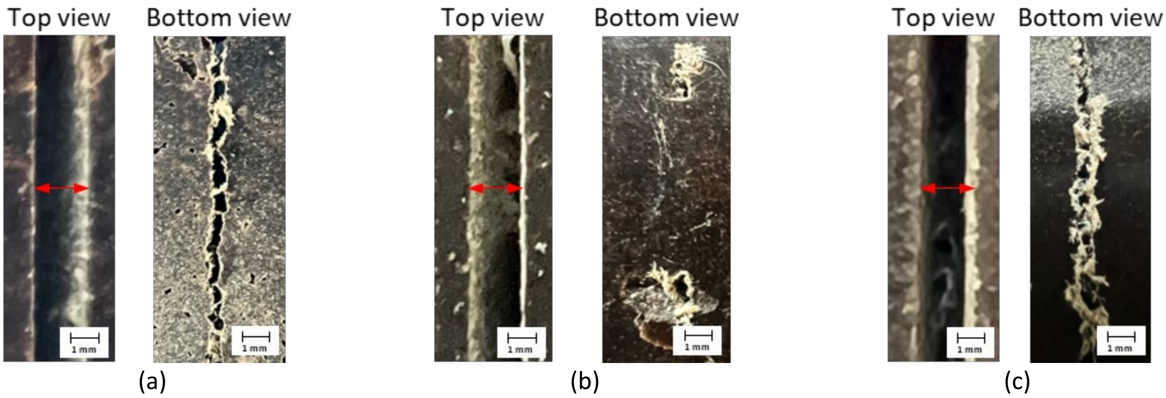


Fig. 4. Kerf characteristics of WPCs cut by AWJ (a) a through cut of 1-layer WPCs, (b) a non-through cut of 3-layered WPC and (c) a through cut of 3-layered WPC

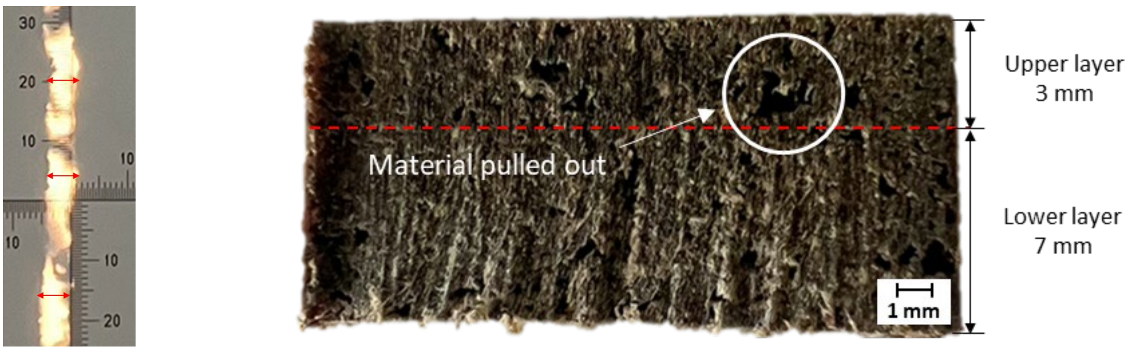
A statistical analysis using full factorial design was performed to determine the significant cutting factors influencing the quality of the machined WPCs, including kerf width and surface roughness at the confidence level of 95%. As shown in Table 6, the p-values for water pressure and traverse speed under AWJ conditions at 1-layer WPC kerf width were less than 0.05. Consequently, these parameters had a substantial impact on the kerf width. According to the surface roughness measurements, the p-value of water pressure under AWJ conditions was less than 0.05. This indicates that this parameter has a substantial impact on surface irregularity. These results are comparable to those of Sampath *et* *al.,* [20] and Murthy *et al.,*[21]. The data related to the average surface roughness of the 3-layered WPC has been separated according to the material type present in each individual layer during the analysis. During the assessment of surface roughness measurements, it was noted that the p-values for water pressure and traverse speed in the AWJ cutting circumstances were found to be less than 0.05 specifically on the third layer of WPC 3. This observation indicates that these characteristics have a notable impact on the level of surface roughness. In the following sections, the relationship between cutting parameters and machining performance for 1-layered and 3-layered WPCs were discussed.

Table 6
The result of factorial design

Model material	Process response	Method	P-value	
			Water pressure	Traverse speed
1-layer	Kerf width	WJ	0.258	0.545
		AWJ	0.000	0.004
	Surface roughness	WJ	0.053	0.693
		AWJ	0.001	0.622
3-layers	Kerf width	WJ	-	-
		AWJ	-	-
	Surface roughness	WJ	-	-
		AWJ of WPCs 1	0.092	0.545
		AWJ of PP	0.685	0.085
		AWJ of WPCs 3	0.000	0.000

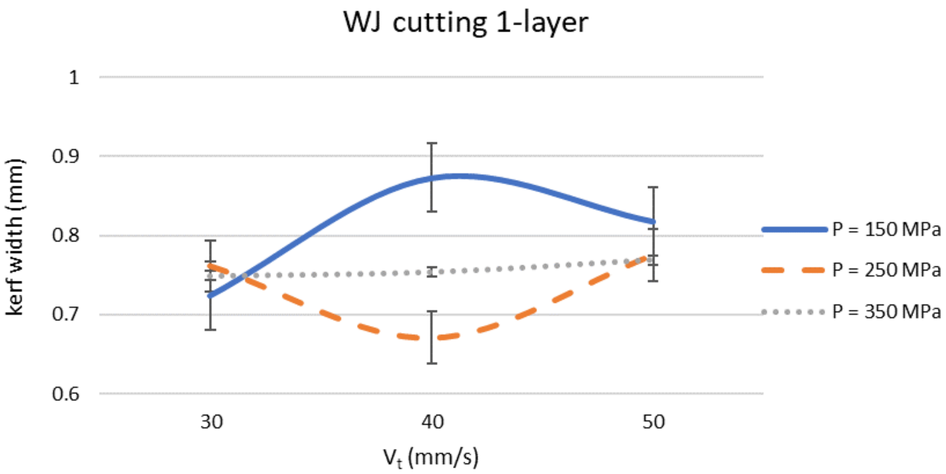
3.2 Relationship between Cutting Parameters and 1-Layered WPC Machining Performance

Figure 5 depicts the kerf width and surface roughness cut characteristics of a single layer WPC at the cutting condition of P = 350 MPa, V_t = 30 mm/s and $\dot{m}_a$ = 6.67 g/s. Both WJ and AWJ cutting were capable possible to cut through a single-layer WPC as show in Figure 5(a). It was observed from Figure 5(b) that cutting with AWJ affected the material, causing some material to pull out. This is the result of abrasive particles colliding with ductile materials [22]. Consequently, AWJ cutting results in a greater surface irregularity value than WJ cutting.

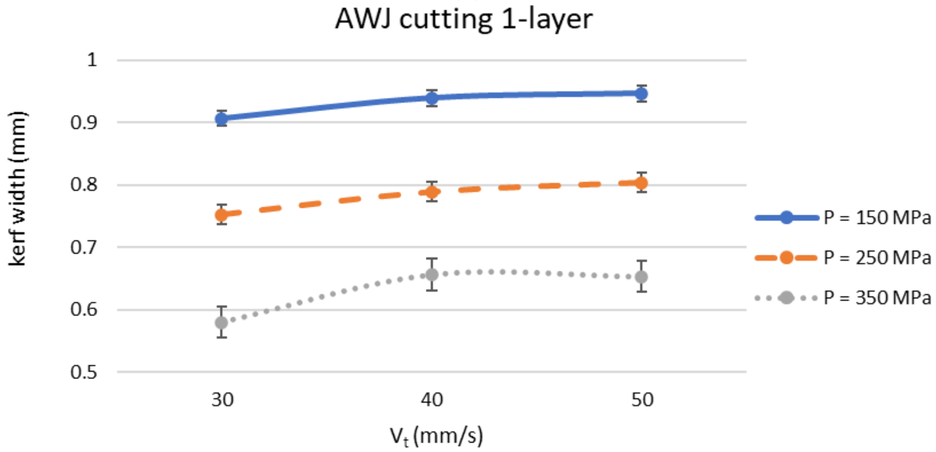


(a) (b)
Fig. 5. The cut characteristics of 1- layer WPC: (a) kerf width and (b) surface roughness

Figure 6 depicts the relationship between cutting parameters and the machining performance of 1-layered WPC. From Figure 6(a), the kerf width without an abrasive was limited as 0.671 mm with water pressure of 250 MPa and traverse speed of 40 mm/s. Figure 6(b) demonstrates that the kerf width decreased with an increase in the water pressure and abrasive mass flow, but increased with and a decrease in traverse speed. Due to the increased velocity of the abrasive waterjet, fewer abrasive particles contact the target, resulting in a smaller cut slot and kerf width [20]. Nevertheless, the kerf width was mostly determined by the jet nozzle's size [23], suggesting that, based on the nozzle utilized in this investigation, the kerf width should not be much greater than 1.02 mm. The results of kerf width were small compared to that of traditional cutting tools such a saw blade.



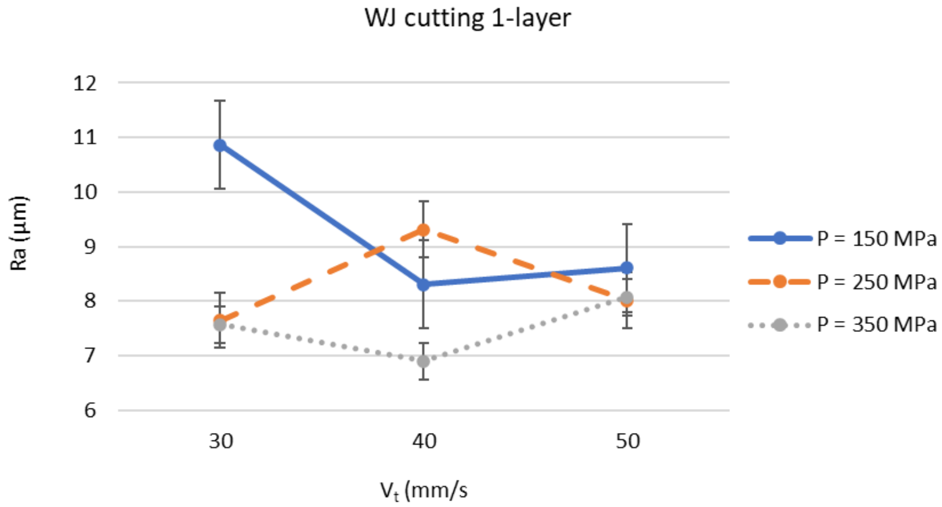
(a)



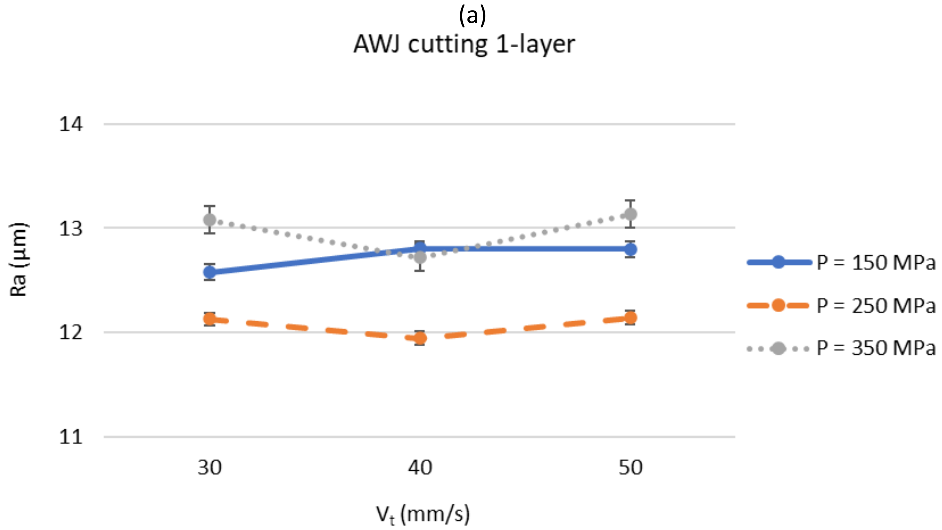
(b)

Fig. 6. Relationship between cutting parameters and kerf width of 1-layered WPCs (a) WJ cutting and (b) AWJ cutting

From Figure 7(a), the surface roughness (*Ra*) under the WJ cutting gave the lowest value of 6.901 µm at 350 MPa water pressure and 40 mm/s traverse speed. On the hand under the AWJ cutting (Figure 7(b)), the lowest *Ra* of 11.943 µm occurred at the cutting condition of water pressure 250 MPa and 40 mm/s traverse speed. Machined surface was more noticeable with AWJ cutting than with WJ cutting (Figure 5(b)). The *Ra* values under AWJ cutting was higher than WJ cutting because the effect of abrasive particles removing material by scratching process, leading to rough surface (Figure 5(b)) [22]. For the evaluation of the machined surface quality of WPC utilizing AWJ technology, Mitalova *et al.,* [20] applied the standard of cut surface SN 214001:2010. The evaluation of roughness quality was divided into five zones ranging from rough to smooth: Q1 (*Ra* = 50 µm), Q2 (*Ra* = 25 µm), Q3 (*Ra* = 12.5 µm), Q4 (*Ra* = 6.3 µm), and Q5 (*Ra* = 3.2 µm). Thus, most machined roughness results in this investigation (as shown in Figure 7) were at the Q3 level. This is consistent with the results of Mitalova *et al.,* [16], that examined AWJ cutting on WPC using this set of parameters: traverse speed of 5.73 –7.58 mm/s, water pressure of 150–300 MPa.



(a)



(b)

Fig. 7. Relationship between cutting parameters and surface roughness of 1-layer WPCs (a) WJ cutting and (b) AWJ cutting

3.3 Relationship between cutting parameters and 3-layers WPCs machining performance.

Figure 8 depicts the kerf width and surface roughness cut characteristics of the 3-layered WPC at the cutting condition of P = 350 MPa, V_t = 30 mm/s and $\dot{m}_a$ = 6.67 g/s. It can be observed that only AWJ cutting is capable to create a through cut for 3-layers WPCs at only the water pressure of 350 MPa that the kerf width can be measured for both top and bottom surface (shown in Table 5) as show in Figure 8(a). Figure 8(b) indicates that smooth surface roughness was noticed at the top layer of WPC 1, while the large irregular roughness was found at the middle layer of PP and the bottom layer of WPC 3. This was caused by the scratching of abrasive particulates on the plastic target material [16]. As depicted in Figure 8(c), some particulates were also imbedded in the material.

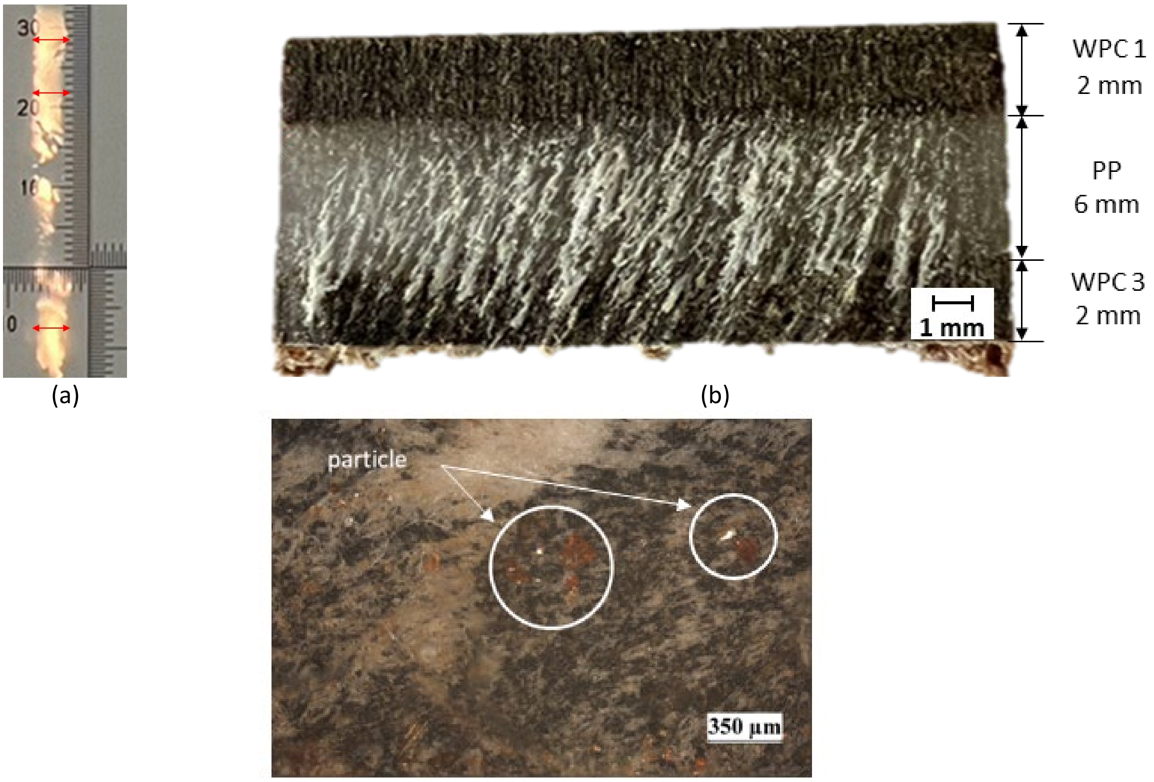


Fig. 8. The cut characteristics of 3- layered WPC (a) kerf width, (b) surface roughness and (c) embedment of a particle inside a material

As mentioned previously, the 3-layered WPC can only be cut using the AWJ process at the maximum water pressure of 350 MPa at all cutting speeds. As shown in Figure 9, the analysis of the relationship between cutting parameters and the 3-layered WPC machining performance was limited to this condition. At 350 MPa water pressure, 30 mm/s traverse speed, and 6.67 g/s abrasive mass flow rate, it can be observed that the kerf width measured 0.476 mm. With an increase in traverse speed, the period of material removal decreases, thereby diminishing the material removal rate [23].

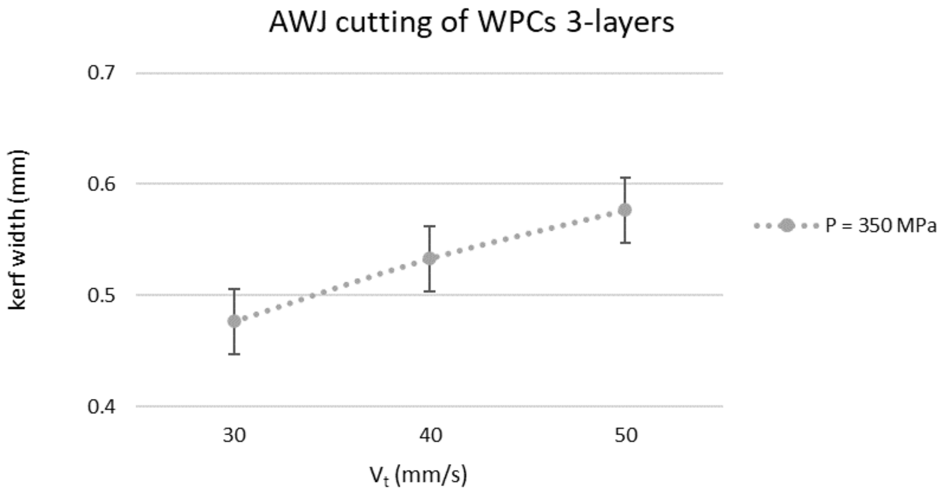


Fig. 9. The result of kerf width with AWJ cutting on WPCs 3-layers

In order to gain more extensive understanding, the analysis of surface roughness for each layer of the 3-layered WPC was also considered. At a water pressure of 250 MPa and a traverse speed of

40 mm/s, the top layer (or WPC 1) has a low surface roughness value of 6.912 µm as shown in Figure 10(a). The middle layer of the PP exhibits a reduced surface roughness value of 14.541 µm at a water pressure of 350 MPa and a traverse speed of 30 mm/s, as depicted in Figure 10(b). As water pressure increases, surface roughness decreased, but it increased as traverse speed diminishes.

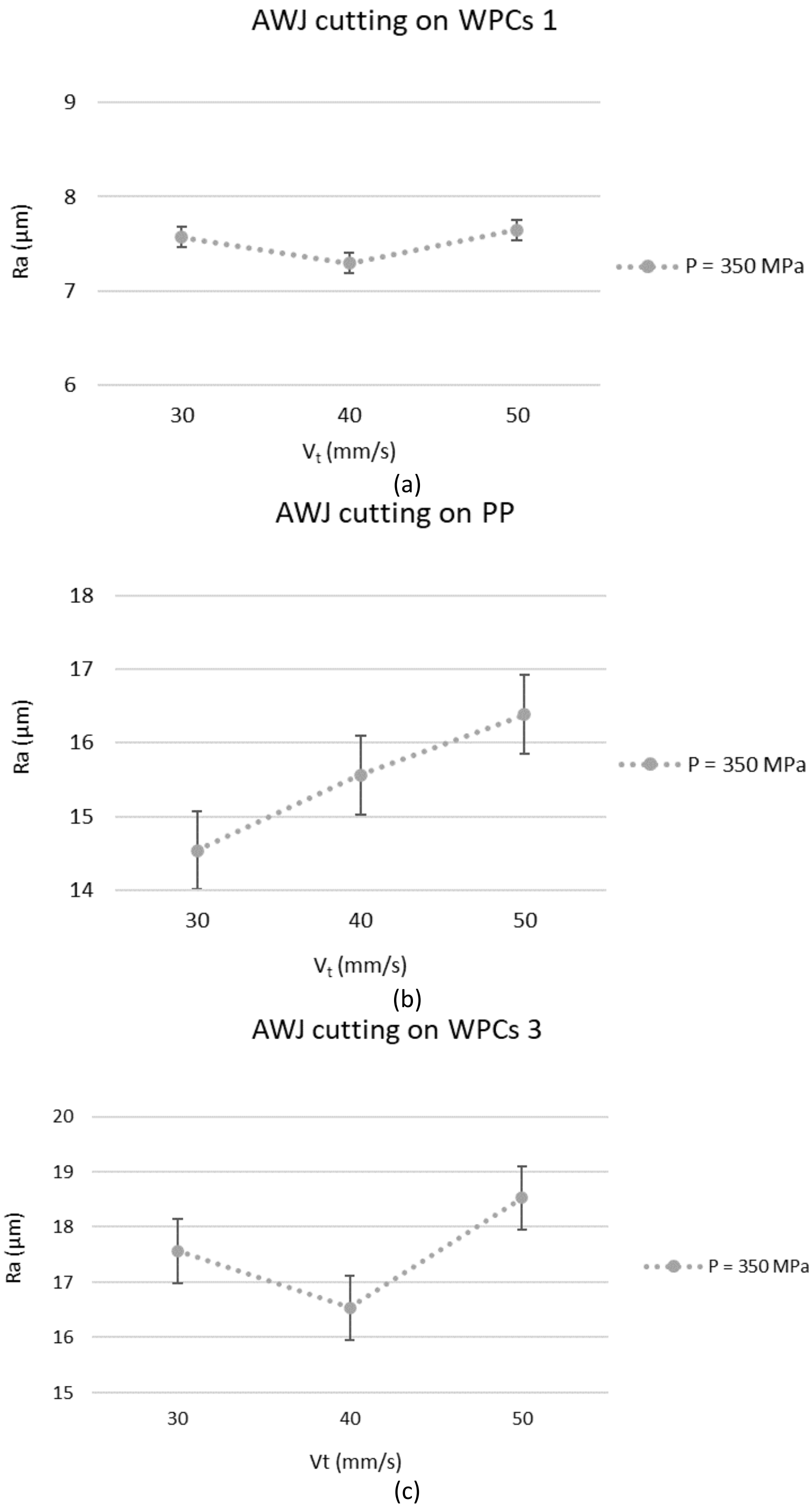


Fig. 10. The result of surface roughness with AWJ cutting on WPCs model 3-layers (a) on WPC 1 (b) on PP (c) on WPC 3

As shown in Figure 10(c), the bottom layer (or WPC 3) at 250 MPa water pressure and 40 mm/s traverse speed generated a lower value of 16.241 µm. Due to the decrease in kinetic energy of the jet as the cutting depth increases, the jet becomes unstable and produces an irregular surface, causing the *Ra* at the top layer was greater than the *Ra* at the bottom layer. The surface roughness of the heterogeneous WPC (i.e., 3-layered WPC) exhibited greater roughness compared to the homogeneous WPC (i.e., 1-layered WPC). The machined surface roughness results were in accordance with the Q2 level specified in the SN 214001:2010 standard [16]. It can be concluded from the experiment that an abrasive mass flow rate of 6.67 g/s, 350 MPa water pressure, and 30 mm/s traverse speed are optimal for attaining the desired kerf width. For both layers, a water pressure of 250 MPa and a traverse speed of 40 mm/s are suggested for attaining the desired surface roughness. For overall cutting quality, a mass flow rate of 6.67 g/s, water pressure of 350 MPa, and a traverse speed of 30 mm/s were recommended.

4. Conclusions

In conclusion, the AWJ cutting technique is appropriate for composite materials; however, the optimal parameters vary depending on the material properties. Therefore, the effect of AWJ cutting parameters on the machining performance of 1-layered and 3-layered WPCs was examined in this study. The variables investigated were water pressure, traverse speed, and abrasive mass flow rate. The study employed an intensive factorial analysis to investigate the correlation between cutting parameters and cutting performance, including the characteristics of the cut and the surface roughness of the machined material. The experiment revealed that both the abrasive and water pressure significantly impacted the cutting process of both WPC structures. When cutting certain materials-especially 3-layered WPC-the lack of an abrasive might lead to non-through cutting. Specific removal kinetic energies are needed for each of the three layers of WPCs because of their sandwich construction, which results in varying material characteristics. This results in a decrease in the energy of the jet cutting process, leading to uneven surface roughness on the workpiece and incomplete cutting. The machined surface of a three-layer WPC is rougher than that of a single WPC. This phenomenon occurs because of the impact between abrasive particles and plastic, particularly in the intermediate layer of PP. The suggested cutting parameters for the 1-layered and 3-layered WPC structures in the comprehensive cutting condition are: water pressure of 350 MPa; traverse speed of 30 mm/s; and abrasive flow rate of 6.67 g/s. This method is considered suitable for post-cutting applications without requiring surface polishing.

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