# Cutting Forces and Chip Morphology during Wood Plastic Composites Orthogonal Cutting

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The effect of chip thickness, rake angle, and edge radius on cutting forces and chip morphology in wood plastic composites (WPCs) orthogonal cutting was investigated. Three types of WPCs, Wood flour/polyethylene composite (WFPEC), wood flour/polypropylene composite (WFPPC), and wood flour/polyvinyl chloride composite (WFPVCC), that were tested exhibited different behavior with respect to the machinability aspects. The cutting forces of WFPVCC were the highest, followed by WFPPC and WFPEC. The most significant factor on the parallel cutting force of these three types of WPCs was the chip thickness, which explained more than 90%, contribution of total variation, while rake angle, edge radius, and the interactions between these factors had small contributions. The most significant factor on the normal cutting force of WPCs was also the chip thickness, which accounted for more than 60% of the total variation. The chips produced included long continuous chips, short continuous chips, flake chips, and granule chips when cutting these three types of WPCs.

*Keywords: Wood plastic composites; Cutting force; Chip morphology; Chip thickness; Rake angle; Edge radius*

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## INTRODUCTION

Wood plastic composites (WPCs) refer to any composites that contain wood flour or fiber and thermosets or thermoplastics (Klyosov 2007; Selke and Wichman 2004). The WPCs are promising, sustainable green materials that lend durability and strength without toxic chemicals. WPCs are considered more environmentally friendly and require less maintenance compared to the alternatives of solid wood treated with preservatives or solid wood. WPCs can be molded with or without visible wood grain details (Morton 2000; Smith and Wolcott 2005). These materials can also be used to replace a large range of solid wood or products mainly made from wood in building structures that are facing the problem of easy decay and sensitivity to water (Markarian 2005). WPCs are still new materials relative to the long history of natural lumber as a building material. The most widespread use of WPCs around the world is in outdoor deck floors, but they are also used for railings, fences, landscaping timbers, cladding and siding, park benches, molding and trim, window and door frames, and indoor furniture (Clemons 2002).

WPCs are produced by thoroughly mixing ground wood particles and heated thermoplastic resin. The most common method of production is to extrude the material into the desired shape, though injection molding is also used. WPCs may be produced from either virgin or recycled thermoplastics including polyethylene (PE), polypropylene

(PP), polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), polystyrene (PS), and so on (Matuana 2009). PE, PP, and PVC are the widely used thermoplastics for WPCs and currently they are very commonly applied in decking, building, furniture, automobiles, and infrastructure (Panthapulakkal *et al*. 2006). Depending on the wood particle geometry or size, wood can be used as a filler or reinforcement in plastic matrices to improve selected composite properties.

Wood/PE composites tend to be used primarily in building and structural components. Wood/PP composites are commonly used for automotive products. Wood/PVC composites are typically found in window and door manufacturing, as well as certain decking applications (Thomasnet 2013; Fabiyi and McDonald 2009).

With broadening applications for WPCs, including doors, windows, decking, building, automobiles, and infrastructure, more secondary manufacturing will be needed to process WPCs. For this reason, a better understanding of the properties of such composites with regard to cutting forces and chip morphology is necessary. Some research has shown that the cutting of WPCs causes greater wear to tools compared with solid wood, and solid wood has a rougher surface than WPCs (Buehlmann *et al.* 2009; Saloni *et al.* 2011).

Previous researchers have shown the knowledge acquired in machining solid wood is not suitable for WPCs because WPC is a relatively homogeneous wood-based composite material without grain compared with solid wood (Wechsler and Hiziroglu 2007). The thermoplastics used in the WPCs have a large influence on the machinability of WPCs. It is fundamental to ensure that the parameters selected are suitable for these materials. The knowledge of cutting mechanisms is vital from the standpoint of assessing machinability.

Cutting forces and chip morphology are two important issues in the machining of wood-based composites. Cutting forces have a direct influence on power consumption, tool wear, heat generation, and quality of the machined surface (Marchal *et al*. 2009; Wyeth *et al*. 2009). On the other hand, chip morphology is an important characteristic that affects the cutting forces, tool wear, and the quality of the machining (Soury *et al*. 2013). Machining parameters and types of composite materials essentially affect the types of chip being formed; *e.g*., sizes and shapes (Azmi 2013).

In order to achieve good machinability and to improve the product quality, it is desirable to learn how cutting conditions can affect cutting forces and chip morphology. However, the way in which the cutting conditions affect dependent variables may be different for each of these aspects, depending on the type of material being machined.

Orthogonal cutting, which is the basic method of the cutting process, is the machining situation in which the straight cutting edge is perpendicular to the direction of the relative motion of tool and work piece and where the surface generated is a plane parallel to the original work surface (Koch 1964). Most cutting problems associated with composite materials can be analyzed as the investigation of material orthogonal cutting (Caprino and Nele 1996; Barge *et al*. 2005). Thus, this method of orthogonal cutting was used in the analysis of WPCs cutting process.

As observed from the literature survey above, despite the importance of the WPCs in many industrial applications, very little is known about the machinability of these WPCs (Saloni *et al*. 2011).

The objective of this work was to investigate the effects of chip thickness, rake angle, and edge radius on parallel cutting force, normal cutting force, and chip morphology during orthogonal cutting of wood flour/PE composite (WFPEC), wood flour/PP composite (WFPPC), and wood flour/PVC composite (WFPVCC). Cutting forces were measured through orthogonal cutting of these WPCs, and photos of chip morphology were taken according to the experimental plan. The analysis of variance was applied to the experimental data in order to determine the effect of the process variables on the cutting forces, and then the chip morphology was also analyzed.

## EXPERIMENTAL

### Materials

Three types of WPCs, namely WFPEC, WFPPC, and WFPVCC, were used as the workpiece. The WPCs were supplied by Nanjing Jufeng Advanced Materials Company. These WPCs were made out of the dried and modified poplar (*Populus euramericana* cv.) wood flour sized from 80 to 100 mesh and recycled PE, PP, and PVC, which were also cleaned, dried, and granulated. The mass ratio of wood flour and each type of recycled polymer was 60:40. Flexural properties were determined according to ASTM D7032 in the three point bending mode at a cross head of 10 mm/min and with a span of 320 mm. The specimen size for flexural tests was 500 mm (*L*) ×30 mm (*W*) × 20 mm (*T*). Five specimens were tested in each run. All mechanical tests were performed at 25±2 °C. Table 1 summarizes the mechanical and physical properties of these WPCs materials tested. The samples were prepared in the dimensions of 160 mm (*L*) ×70 mm (*W*) ×70 mm (*T*) for cutting experiments.

The cutting tools used in the series of experiments were provided by Sandvik Hard Material Company. This kind of tool contains 10% cobalt, 89.5% tungsten carbide, and 0.5% other compounds. The cutting edge width was 3.9 mm and the clearance angle was constant at 15°.

**Table 1.** Mechanical and Physical Properties of Three Types of WPCs

| WPCs | Flexural strength[ab] (MPa) | Elasticity modulus[ab] (GPa) | Density[ab] ($g/cm^3$) |
|---|---|---|---|
| WFPEC | 20.32 (0.18) | 2.06 (0.05) | 1.14 (0.02) |
| WFPPC | 23.51 (0.51) | 2.17 (0.11) | 1.28 (0.05) |
| WFPVCC | 25.15 (0.39) | 2.25 (0.09) | 1.41 (0.03) |

[a] Each value is the mean of five measuring values of five samples.
[b] Number in the bracket is standard deviation based on five measuring values.

### Methods

*Cutting force measurement*

The cutting forces measurements were performed on special equipment that was utilized to carry out simulated orthogonal cuttings (Porankiewicz *et al*. 2011; Axelsson *et al*. 1993), as shown in Fig. 1. Three piezoelectric sensors were placed on the cutting tool. A rotating arm moved a workpiece past a cutting tool in a diameter circle. When the cutting tool cut the workpiece, the cutting forces were measured in the parallel ($F_P$), normal ($F_n$), and lateral ($F_l$) directions. Only the parallel ($F_p$) and the normal ($F_n$) cutting forces were recorded in this series cutting experiments. Data on cutting forces were computed using National Instruments LabVIEW with a sampling frequency of 25 kHz.

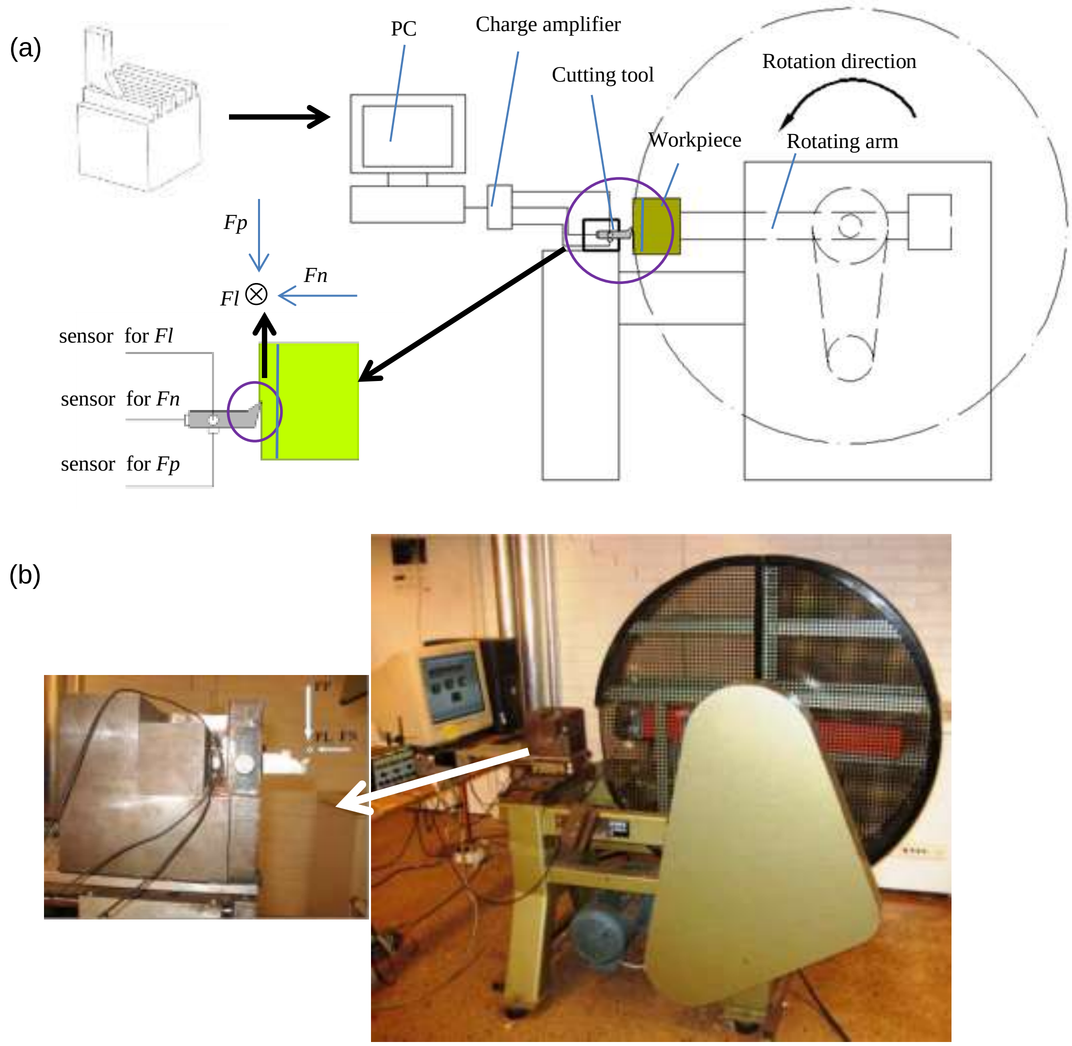


**Fig. 1.** Experimental setup: (a) Schematic diagram; (b) Picture

*Plan of the experiment*

Three parameters, namely chip thickness ($t$), rake angle ($\gamma$), and edge radius ($r$) were varied during the tests. Table 1 indicates the factors studied and the assignment of the corresponding levels; the term "level" refers to the values taken by the factors. A constant cutting speed ($v$=15 m/s) and a constant cutting width ($b$=3.6 mm) were adopted throughout the experimental program. All experiments were conducted at room temperature of 20±2 °C.

**Table 2.** Assignment of the Levels to the Factors

| Level | Chip thickness $t$ (mm) | Rake angle $\gamma$ (°) | Edge radius $r$ (μm) |
|---|---|---|---|
| 1 | 0.15 | 10 | 15 |
| 2 | 0.50 | 20 | 25 |
| 3 | 1.00 | 30 | 50 |

A full factorial experimental design was used with a total of five repetitions for each machining situation for cutting force. Main effects plots for cutting force were constructed. Analysis of variance (ANOVA) was performed using the software of Statistical Product and Service Solutions (SPSS version 19.0) with the objective of studying the influence of chip thickness, rake angle, and edge radius on the total variance of the results. Photos of chips produced in these experiments were taken and analyzed.

## RESULTS AND DISCUSSION

### Analysis of Parallel Cutting Force

*Influence of chip thickness, rake angle, and edge radius on the parallel cutting force*

Table 3 shows the results for the parallel cutting force per unit width ($F_p$) for the full factorial experiment in three types of WPCs cutting. For each experiment, five measurements of cutting were taken, and the mean and standard deviation of these cutting force values was calculated as the final cutting force.

To systematically investigate the effect of chip thickness, rake angle, and edge radius on the parallel cutting force, main effects plots for parallel cutting force were constructed. In Figs. 2 to 4, the measured parallel cutting force are reported, respectively, against the rake angle $\gamma$, for different chip thickness $t$, and different edge radius $r$, during the cutting of WFPEC, WFPPC, and WFPVCC. Each data point was the mean value of five measurements; vertical bars denoted error bar.

As may be observed from Figs. 2 to 4, the trends of the parallel cutting force for these three types of WPCs were qualitatively similar to each other. In the main effects, chip thickness and rake angle were the most significant factor on the parallel cutting force for the cutting of each type of WPC evidently. As chip thickness increased, the parallel cutting force also increased. As the rake angle increased, the parallel cutting force decreased. However, there were small differences observed on the parallel cutting force owing to the variation of edge radius at the cutting conditions (rake angle of $10^{o}$, chip thickness of 0.15, 0.5, and 1 mm). But when cutting these composite materials at the conditions (rake angle of 30°, chip thickness of 0.15, 0.5, and 1 mm), the parallel cutting force increased with increase of edge radius. Further differences in parallel cutting force caused by edge radius were apparent when rake angle increased.

In addition, it can be also seen that the effect of rake angle on the parallel cutting force was becoming significant with the increase of chip thickness, because at constant edge radius, a decline of parallel force was apparent with an increase of chip thickness. And the effect of rake angle on the parallel cutting force was becoming insignificant with the increase of edge radius, because at constant chip thickness, a decline of parallel force was not apparent with the increase of edge radius.

However, from Figs. 2 to 4 the parallel cutting force of WFPVCC was the highest, followed by WFPPC and WFPEC, respectively, at the same cutting condition. This phenomenon was similar to the mechanical properties of these three types of WPCs shown in Table 1. These findings were probably reflective of the fact that these three types of polymers had different effects on the parallel cutting force, because they had different mechanical properties.

**Table 3.** Full Factorial Experimental Plan, Parallel Cutting Force, Normal Cutting Force

| Test No. | *t* (mm) | *γ* (°) | *r* (μm) | WFPEC [ab] | | WFPPC [ab] | | WFPVCC [ab] | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $F_P$ (N/mm) | $F_N$ (N/mm) | $F_P$ (N/mm) | $F_N$ (N/mm) | $F_P$ (N/mm) | $F_N$ (N/mm) |
| 1 | 0.15 | 10 | 15 | 20.43 (2.52) | 15.46 (1.56) | 21.42 (1.86) | 17.37 (1.56) | 24.14 (2.65) | 22.75 (2.06) |
| 2 | 0.15 | 10 | 25 | 22.00 (3.20) | 18.51 (1.42) | 22.92 (1.43) | 20.27 (2.43) | 24.86 (2.40) | 25.28 (2.72) |
| 3 | 0.15 | 10 | 50 | 23.09 (3.94) | 21.45 (1.61) | 24.36 (1.98) | 30.01 (2.04) | 25.18 (2.21) | 27.05 (2.54) |
| 4 | 0.15 | 20 | 15 | 18.86 (3.74) | 15.22 (1.94) | 17.45 (1.96) | 15.79 (2.96) | 21.46 (2.36) | 19.26 (1.08) |
| 5 | 0.15 | 20 | 25 | 20.71 (2.61) | 17.68 (1.64) | 20.10 (2.63) | 18.64 (2.94) | 23.64 (2.78) | 22.69 (1.56) |
| 6 | 0.15 | 20 | 50 | 22.24 (2.95) | 19.42 (1.87) | 23.08 (2.54) | 23.02 (2.09) | 25.12 (2.96) | 23.98 (2.31) |
| 7 | 0.15 | 30 | 15 | 15.36 (3.55) | 10.47 (1.60) | 14.04 (2.18) | 14.15 (2.54) | 20.46 (3.68) | 19.62 (1.51) |
| 8 | 0.15 | 30 | 25 | 19.42 (2.80) | 13.40 (2.06) | 17.58 (2.53) | 16.20 (2.52) | 21.73 (3.31) | 20.79 (1.76) |
| 9 | 0.15 | 30 | 50 | 21.36 (3.08) | 15.62 (1.55) | 21.83 (1.51) | 19.88 (3.44) | 23.50 (2.96) | 23.08 (1.08) |
| 10 | 0.5 | 10 | 15 | 37.38 (2.80) | 26.16 (2.28) | 42.84 (1.90) | 35.81 (2.93) | 48.34 (3.32) | 38.75 (2.08) |
| 11 | 0.5 | 10 | 25 | 38.89 (2.58) | 30.01 (1.72) | 43.59 (2.08) | 38.32 (2.58) | 48.72 (2.86) | 42.01 (1.48) |
| 12 | 0.5 | 10 | 50 | 41.12 (3.06) | 36.07 (2.38) | 44.43 (2.66) | 41.78 (1.59) | 49.39 (3.40) | 43.77 (2.48) |
| 13 | 0.5 | 20 | 15 | 34.36 (3.11) | 23.55 (1.18) | 34.92 (3.00) | 30.24 (3.24) | 44.27 (3.57) | 36.06 (2.35) |
| 14 | 0.5 | 20 | 25 | 36.56 (3.14) | 27.79 (2.61) | 40.21 (2.88) | 31.44 (3.48) | 48.41 (2.99) | 37.63 (1.93) |
| 15 | 0.5 | 20 | 50 | 38.64 (2.41) | 28.10 (1.69) | 43.39 (2.27) | 35.06 (3.74) | 49.24 (2.91) | 40.25 (2.95) |
| 16 | 0.5 | 30 | 15 | 30.45 (2.80) | 16.01 (1.77) | 30.91 (2.01) | 24.58 (3.93) | 41.30 (3.00) | 29.17 (2.50) |
| 17 | 0.5 | 30 | 25 | 33.43 (2.99) | 18.51 (1.71) | 35.17 (2.97) | 25.99 (3.12) | 46.13 (2.55) | 31.21 (2.33) |
| 18 | 0.5 | 30 | 50 | 37.10 (2.27) | 22.12 (1.93) | 40.92 (2.67) | 28.02 (1.24) | 47.58 (2.26) | 32.42 (1.09) |
| 19 | 1.0 | 10 | 15 | 64.99 (2.10) | 44.32 (1.68) | 65.94 (2.51) | 47.48 (1.55) | 66.65 (2.77) | 50.16 (2.20) |
| 20 | 1.0 | 10 | 25 | 66.31 (3.19) | 44.45 (1.77) | 66.46 (2.32) | 50.28 (2.74) | 67.17 (2.66) | 53.04 (2.54) |
| 21 | 1.0 | 10 | 50 | 66.69 (3.24) | 49.76 (1.76) | 67.26 (2.42) | 53.07 (2.97) | 67.55 (2.70) | 56.84 (1.99) |
| 22 | 1.0 | 20 | 15 | 59.30 (2.65) | 34.35 (2.16) | 60.76 (3.58) | 39.93 (3.44) | 63.05 (3.01) | 44.58 (1.52) |
| 23 | 1.0 | 20 | 25 | 61.29 (3.40) | 36.96 (1.66) | 62.87 (2.33) | 42.20 (2.59) | 65.95 (2.85) | 46.55 (1.87) |
| 24 | 1.0 | 20 | 50 | 66.07 (3.45) | 39.67 (2.35) | 65.45 (2.80) | 43.77 (2.45) | 68.02 (3.64) | 51.42 (1.24) |
| 25 | 1.0 | 30 | 15 | 51.75 (2.12) | 26.39 (2.43) | 46.96 (2.89) | 29.55 (2.86) | 54.60 (3.45) | 37.97 (2.99) |
| 26 | 1.0 | 30 | 25 | 55.85 (3.49) | 27.19 (2.93) | 56.11 (3.49) | 30.90 (2.67) | 60.97 (3.34) | 40.08 (1.32) |
| 27 | 1.0 | 30 | 50 | 58.24 (3.25) | 28.98 (2.02) | 58.53 (3.14) | 32.65 (1.08) | 62.73 (2.56) | 41.72 (1.79) |

[a] The value is the mean of five measuring values of samples.
[b] Number in the bracket is standard deviation based on five measuring values.

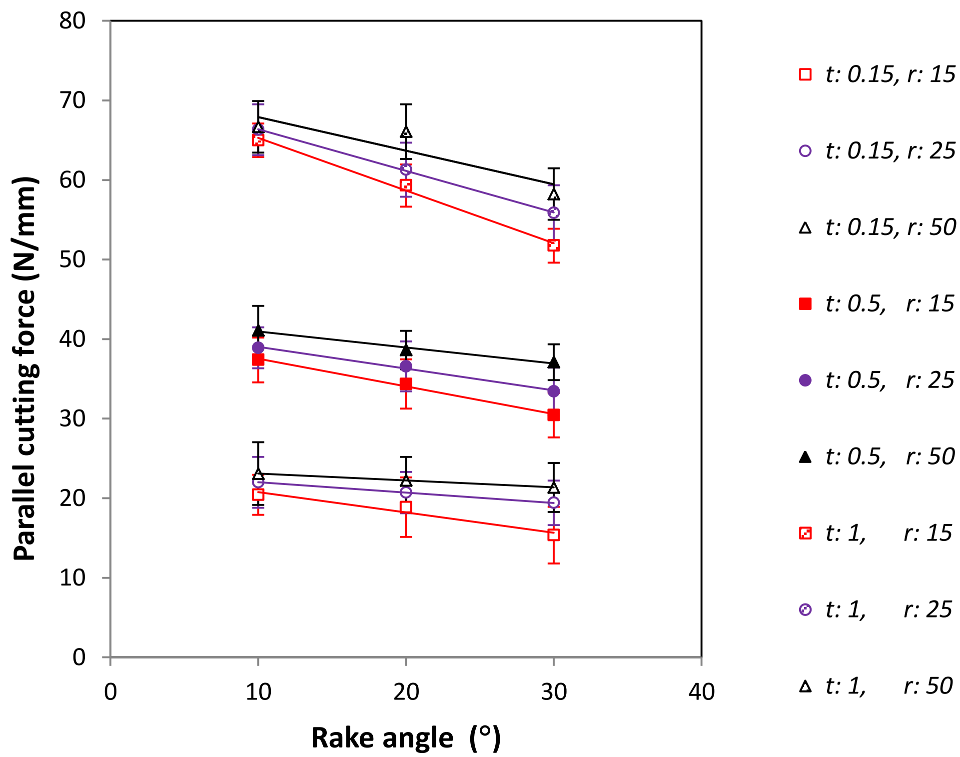


**Fig. 2.** Effect of parameters on parallel cutting force of WFPEC

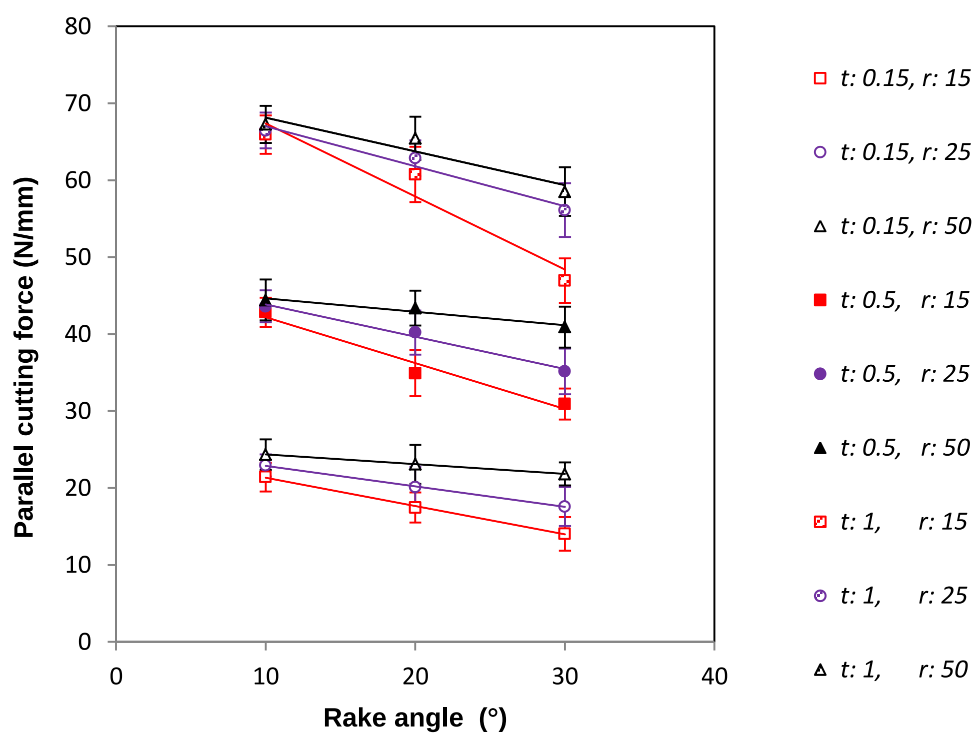


**Fig. 3.** Effect of parameters on parallel cutting force of WFPPC

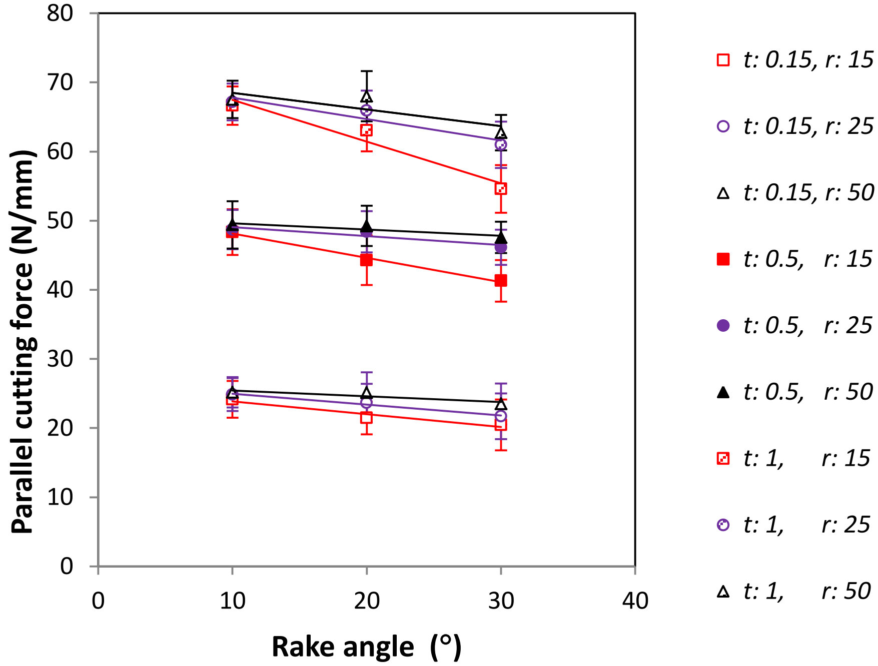


**Fig. 4.** Effect of parameters on parallel cutting force of WFPVCC

*ANOVA for parallel cutting force*

The analysis of variance was performed to find the statistical significance of the variables and their interactions on the parallel cutting force in cutting of these three types of WPCs for a level of significance of 5%.

**Table 4.** ANOVA for Parallel Cutting Force of WFPEC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| $t$ | 2 | 7596.84 | 7596.84 | 3798.42 | 6228.29 | 0.000 | 5.14 | 95.58* |
| $\gamma$ | 2 | 189.36 | 189.36 | 94.68 | 155.25 | 0.000 | 5.14 | 2.38* |
| $r$ | 2 | 96.40 | 96.40 | 48.20 | 79.03 | 0.000 | 5.14 | 1.21* |
| $t * \gamma$ | 4 | 47.85 | 47.85 | 11.96 | 19.61 | 0.000 | 4.53 | 0.60* |
| $t * r$ | 4 | 1.38 | 1.38 | 0.35 | 0.57 | 0.694 | 4.53 | 0.02 |
| $\gamma * r$ | 4 | 11.09 | 11.09 | 2.77 | 4.55 | 0.033 | 4.53 | 0.14* |
| Error | 8 | 4.88 | 4.88 | 0.61 | | | | |
| Total | 26 | 7947.80 | | | | | | |
| $R^2$= 99.9%; $R^2$(adj)= 99.8%. *Significant. | | | | | | | | |

As shown in Table 4, for the cutting of WFPEC, chip thickness, rake angle, edge radius, the interaction between chip thickness and rake angle, rake angle and edge radius had statistical significance on the parallel cutting force, according to the *p*-value of less than 0.05 and the *F*-value of greater than the $F_{0.05}$.

Chip thickness and rake angle contributed 95.58% and 2.38%, respectively, to the total variability of the results. Edge radius, interactions between chip thickness and rake angle, rake angle, and edge radius contributed less than 2% on the parallel cutting force. The interaction between chip thickness and edge radius was insignificant, the contribution being less than 1%.

**Table 5.** ANOVA for Parallel Cutting Force of WFPPC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| $t$ | 2 | 7513.25 | 7513.25 | 3756.63 | 2289.30 | 0.000 | 5.14 | 92.42* |
| $\gamma$ | 2 | 335.12 | 335.12 | 167.56 | 102.11 | 0.000 | 5.14 | 4.12* |
| $r$ | 2 | 162.63 | 162.63 | 81.31 | 49.55 | 0.000 | 5.14 | 2.00* |
| $t * \gamma$ | 4 | 55.90 | 55.90 | 13.98 | 8.52 | 0.006 | 4.53 | 0.69* |
| $t * r$ | 4 | 2.68 | 2.68 | 0.67 | 0.41 | 0.798 | 4.53 | 0.03 |
| $\gamma * r$ | 4 | 46.93 | 46.93 | 11.73 | 7.12 | 0.009 | 4.53 | 0.58* |
| Error | 8 | 13.13 | 13.13 | 1.64 | | | | |
| Total | 26 | 8129.64 | | | | | | |
| $R^2$=99.80%; $R^2$(adj)=99.50%; *Significant | | | | | | | | |

Table 5 shows the results of ANOVA analysis for the parallel cutting forces of WFPPC. As can be seen in Table 5, chip thickness, rake angle, edge radius, the interaction of chip thickness and rake angle, and the interaction of rake angle and edge radius had statistical significance on the parallel cutting force, since *p*-value of these factors was less than 0.05, and the *F*-value of these factors was greater than the $F_{0.05}$.

Chip thickness, rake angle, and edge radius contributed 92.42%, 4.12%, and 2.00%, respectively, to the total variability of the results. The interactions between chip thickness and rake angle, rake angle, and edge radius contributed less than 1% on the parallel cutting force. The remaining interaction between chip thickness and edge radius did not significantly influence the parallel cutting force, and also the contribution was less than 1%.

**Table 6.** ANOVA for Parallel Cutting Force of WFPVCC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| $t$ | 2 | 7533.53 | 7533.53 | 3766.76 | 5239.87 | 0.000 | 5.14 | 97.01* |
| $\gamma$ | 2 | 108.40 | 108.40 | 54.20 | 75.40 | 0.000 | 5.14 | 1.40* |
| $r$ | 2 | 67.20 | 67.20 | 33.60 | 46.74 | 0.000 | 5.14 | 0.81* |
| $t * \gamma$ | 4 | 26.00 | 26.00 | 6.50 | 9.04 | 0.005 | 4.53 | 0.31* |
| $t * r$ | 4 | 4.60 | 4.60 | 1.15 | 1.60 | 0.265 | 4.53 | 0.06 |
| $\gamma * r$ | 4 | 20.21 | 20.21 | 5.05 | 7.03 | 0.010 | 4.53 | 0.24* |
| Error | 8 | 5.75 | 5.75 | 0.72 | | | | |
| Total | 26 | | | | | | | |
| $R^2$=99.9%; $R^2$(adj)=99.8%. *Significant. | | | | | | | | |

As the ANOVA Table 6 shows, for the cutting of WFPVCC, chip thickness, rake angle, edge radius, the interaction between chip thickness and rake angle, and the interaction between rake angle and edge radius had considerable effect on the parallel cutting force, because the *p*-value was less than 0.05, and the *F*-value of these factors was greater than the $F_{0.05}$.

However, chip thickness was the dominant contributor to the parallel cutting force, accounting for 97.01% of the total variability, while the rake angle accounts for 1.40%. Unlike the WFPEC and WFPPC, the contribution of edge radius to parallel cutting force of WFPVCC was less than 1%. The other factors provided contributions about less than 1% to the parallel cutting force. The interaction between chip thickness and edge radius was insignificant, the contribution being less than 1%.

From Tables 4 to 6, it can be seen that chip thickness was the dominant contributor to the parallel cutting force of these three composite materials, accounting for more than 90% of the total variability. Chip thickness had the highest impact on the parallel cutting force when cutting WFPVCC; this was followed by WFPEC and WFPPC. Also, Tables 4 to 6 indicate that the effect of edge radius was less significant than that of the rake angle for cutting of WPCs. However, the result was very different from data analysis of wood parallel cutting force, in which the edge radius had more significant impact on the parallel cutting force than rake angle (Cristóvão *et al*. 2012). These results might be because WPCs are relatively homogeneous polymer-based composite materials without grain compared with solid wood.

## Analysis of Normal Cutting Force

*Influence of chip thickness, rake angle, and edge radius on the normal cutting force*

Table 3 also shows the results for the normal cutting force per unit width ($F_n$) for the full factorial experiment. For each experiment, five measurements of cutting were taken and the average value and standard deviation of these normal cutting force values were calculated as the final normal cutting force.

To systematically investigate the effect of chip thickness, rake angle, and edge radius on the normal cutting force of these three types of composite materials, main effects plots for normal force were constructed. In Figs. 5 to 7, the measured normal cutting force per unit width are reported, respectively, against rake angle, $\gamma$, for different chip thickness, $t$, and different edge radius, $r$, during the cutting of WFPEC, WFPPC, and WFPVCC. Each data point was the mean value of five measurements; vertical bars denoted error bar.

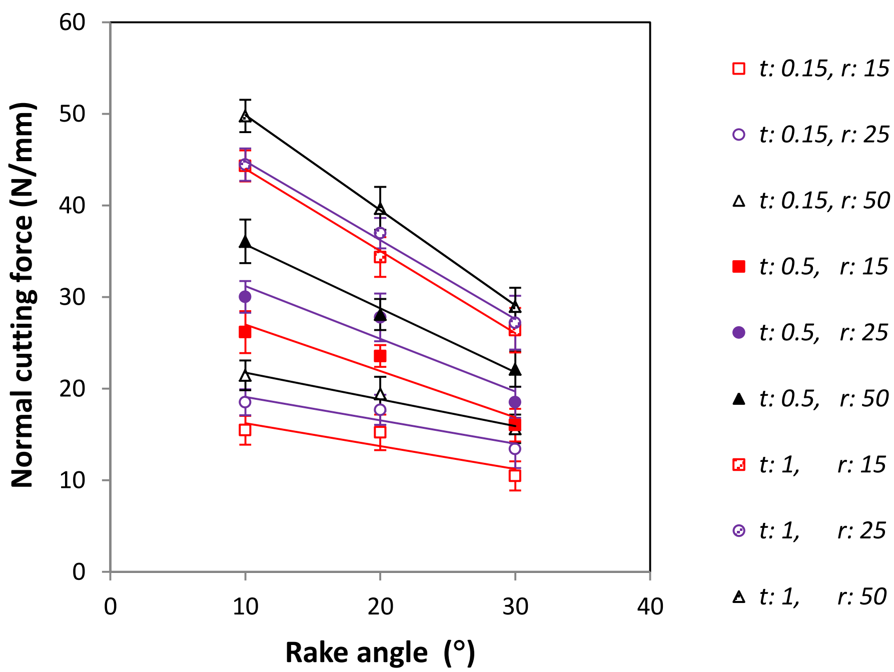


**Fig. 5.** Effect of parameters on parallel cutting force of WFPEC

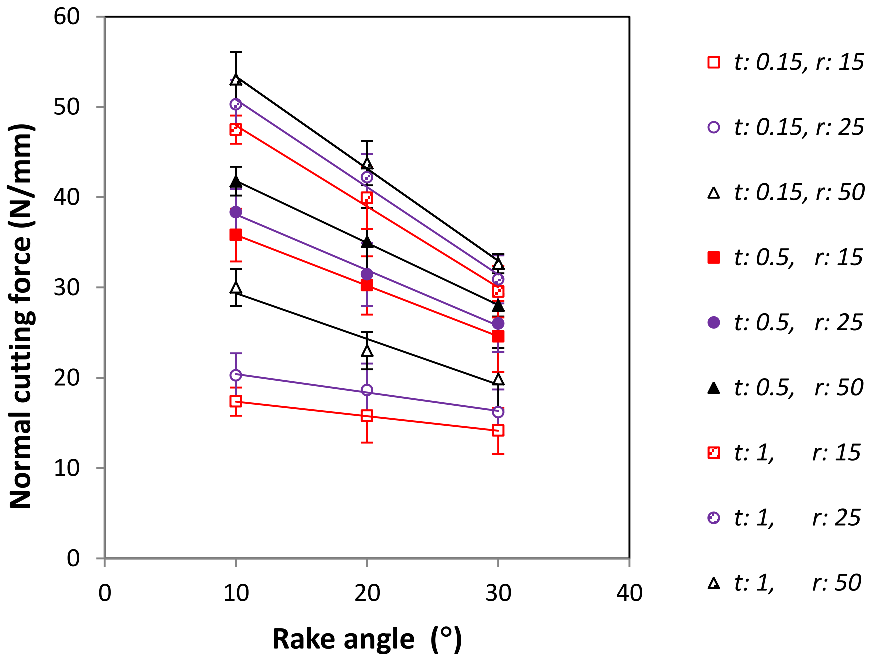


**Fig. 6.** Effect of parameters on parallel cutting force of WFPPC

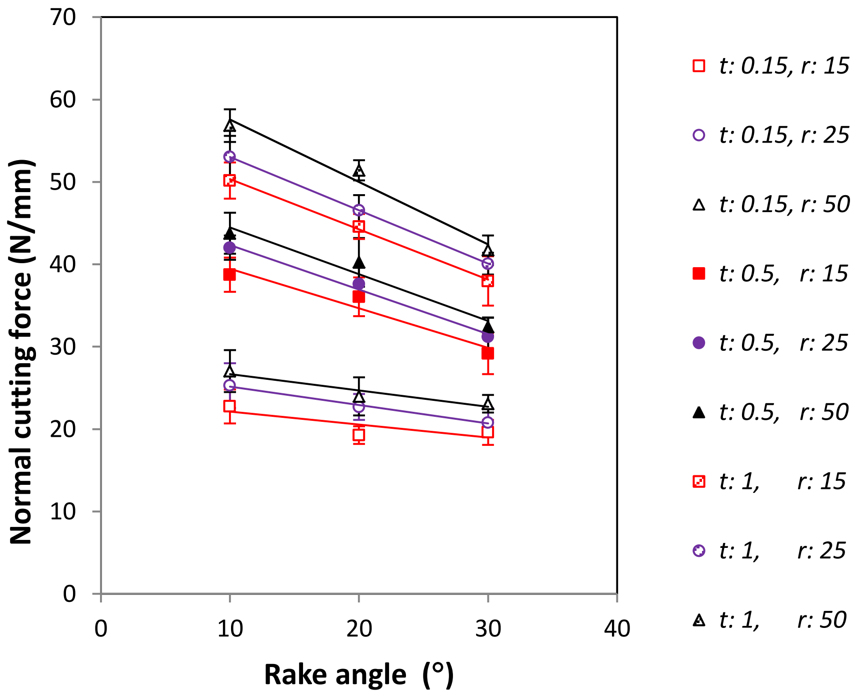


**Fig. 7.** Effect of parameters on parallel cutting force of WFPVCC

As may be observed from Figs. 5 to 7, the trends of the normal cutting force of these three types of WPCs were qualitatively similar to each other. In the main effects, chip thickness and edge radius had an increasing effect, while the rake angle had a negative effect. As chip thickness increased, the normal cutting force increased at constant rake angle and edge radius. As edge radius increased, the normal cutting force increased at constant rake angle and chip thickness. As the rake angle increased, the normal cutting force decreased at the condition of constant chip thickness and edge radius. In addition, it can be seen that the slope of the trend lines increased with the increase of chip thickness at constant edge radius from Figs. 5 to 7. This phenomenon indicated that the significance of rake angle was increasing with the increase of chip thickness. Also, it can be seen that the slope of trend lines at constant chip thickness was slightly increasing, which indicated that the significance of rake angle rose with the increase of edge radius.

Obviously, the normal cutting force of WFPVCC was the highest compared to the other two composite materials.

*ANOVA for normal cutting force*

Table 7 shows the results of ANOVA analysis for the normal cutting force of WFPEC. As can be seen in Table 7, chip thickness, rake angle, edge radius, and the interaction of chip thickness and rake angle had statistical significance on the normal cutting force, since *p*-value of these factors was less than 0.05, and the *F*-value of these factors was greater than the $F_{0.05}$.

Chip thickness, rake angle, and edge radius contributed 66.87%, 22.78%, and 4.73%, respectively, in the total variability of the results, while the interaction between thickness and rake angle accounted for 4.79% of the total variability.

The remaining interactions did not significantly influence the normal cutting force, and the contribution was less than 1%.

**Table 7.** Results of ANOVA for Normal Cutting Force of WFPEC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| *t* | 2 | 1907.62 | 1907.62 | 953.81 | 1072.46 | 0.000 | 5.14 | 66.87* |
| $\gamma$ | 2 | 649.75 | 649.75 | 324.88 | 365.29 | 0.000 | 5.14 | 22.78* |
| *r* | 2 | 135.03 | 135.03 | 67.52 | 75.92 | 0.000 | 5.14 | 4.73* |
| $t * \gamma$ | 4 | 136.70 | 136.70 | 34.18 | 38.43 | 0.000 | 4.53 | 4.79* |
| $t * r$ | 4 | 6.65 | 6.65 | 1.66 | 1.87 | 0.209 | 4.53 | 0.23 |
| $\gamma * r$ | 4 | 9.95 | 9.95 | 2.49 | 2.80 | 0.101 | 4.53 | 0.35 |
| Error | 8 | 7.12 | 7.12 | 0.89 | | | | |
| Total | 26 | 2852.82 | | | | | | |
| $R^2$=99.8%; $R^2$(adj)=99.2%. *Significant. | | | | | | | | |

Table 8 shows the results of ANOVA analysis for the normal cutting force of WFPPC.

**Table 8.** Results of ANOVA for Normal Force of WFPPC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| *t* | 2 | 1929.31 | 1929.31 | 964.65 | 132.83 | 0.000 | 5.14 | 64.72* |
| $\gamma$ | 2 | 484.76 | 484.76 | 242.38 | 33.78 | 0.000 | 5.14 | 16.26* |
| *r* | 2 | 131.04 | 131.04 | 65.52 | 9.02 | 0.009 | 5.14 | 4.40* |
| $t * \gamma$ | 4 | 314.65 | 314.65 | 78.66 | 10.83 | 0.003 | 4.53 | 10.56* |
| $t * r$ | 4 | 29.44 | 29.44 | 7.36 | 1.01 | 0.455 | 4.53 | 0.99 |
| $\gamma * r$ | 4 | 33.56 | 33.56 | 8.39 | 1.16 | 0.398 | 4.53 | 1.13 |
| Error | 8 | 58.10 | 58.10 | 7.26 | | | | |
| Total | 26 | 2980.86 | | | | | | |
| $R^2$=98.1%; $R^2$(adj)=93.7%; *Significant | | | | | | | | |

As can be seen in Table 8, chip thickness, rake angle, edge radius, and the interaction of chip thickness and rake angle had statistical significance on the normal cutting force, since *p*-value of these factors was less than 0.05, and the *F*-value of these factors was greater than the $F_{0.05}$. Chip thickness, rake angle, and edge radius contributed 64.72%, 16.26%, and 4.40%, respectively, to the total variability of the results, while the interaction between chip thickness and rake angle accounted for 10.56% of the total variability. The remaining interactions did not significantly influence the normal cutting force, and the contribution was less than 2%.

Table 9 shows the results of ANOVA analysis for the normal cutting force of WFPVCC. As can be seen in Table 9, chip thickness, rake angle, edge radius, and the interaction of chip thickness and rake angle had statistical significance on the normal cutting force, since *p*-value of these factors was less than 0.05, and the *F*-value of these factors was greater than the $F_{0.05}$.

Chip thickness, rake angle, and edge radius contributed 82.11%, 12.03%, and 3.05%, respectively, to the total variability of the results, while the interaction between thickness and rake angle accounted for 2.50% of the total variability.

The remaining interactions did not significantly influence the normal cutting force, and the contribution was less than 1%.

From Tables 7 to 9 it is evident that chip thickness was the dominant contributor to the normal cutting force of these three materials, accounting for more than 60% of the total variability. Chip thickness had the highest impact on the normal cutting force when cutting WFPVCC, followed by WFPPC and WFPEC.

**Table 9.** Results of ANOVA for Normal Cutting Force of WFPVCC

| Source | DOF | Seq SS | Adj SS | Adj MS | *F*-test | *p* | $F_{0.05}$ | Contribution(%) |
|---|---|---|---|---|---|---|---|---|
| *t* | 2 | 2660.12 | 2660.12 | 1330.06 | 3427.01 | 0.000 | 5.14 | 82.11* |
| $\gamma$ | 2 | 389.75 | 389.75 | 194.88 | 502.12 | 0.000 | 5.14 | 12.03* |
| *r* | 2 | 98.94 | 98.94 | 49.47 | 127.46 | 0.000 | 5.14 | 3.05* |
| $t * \gamma$ | 4 | 80.97 | 80.97 | 20.24 | 52.16 | 0.000 | 4.53 | 2.50* |
| $t * r$ | 4 | 3.46 | 3.46 | 0.865 | 2.23 | 0.155 | 4.53 | 0.11 |
| $\gamma * r$ | 4 | 3.53 | 3.53 | 0.882 | 2.27 | 0.150 | 4.53 | 0.11 |
| Error | 8 | 3.11 | 3.11 | 0.388 | | | | |
| Total | 26 | 3239.88 | | | | | | |
| $R^2$=99.9%; $R^2$(adj)=99.7%. *Significant. | | | | | | | | |

## Chip Morphology

Cutting forces of composite materials are significantly influenced by chips produced when cutting (Davim *et al*. 2009; Su *et al*. 2003). In the present work, the resulting chip form was strongly influenced by the work materials and cutting conditions, especially chip thickness. The physical appearance of the chips produced when cutting these three types of WPCs at thickness of 0.15 and 1 mm, respectively, at rake angle of 10 and 30°, respectively, at edge radius of 15 μm, is shown in Fig. 8. Long continuous chips (Fig. 8 (a, b, and c)), short continuous chips (Fig. 8 (d, e, f , g, and h)), flake chips (Fig. 8 (i)), and granule chips (Fig. 8(j)) were obtained within the tested range when cutting these composite materials.

From Fig. 8, it can be seen that it was very easy to produce the long continuous type of chip when cutting WFPEC and WFPPC at chip thickness of 0.15 mm, whatever edge radius was at tested range. This fact may be related to ductile behavior of WFPEC and WFPP, which would cause the softening and sliding of the work material on the rake face of the tool. It also represented that ductile properties of materials can lead to the lowest cutting force. This fact coincided with the results of cutting forces above.

But short continuous chips were produced at chip thickness of 1 mm when cutting WFPEC and WFPPC. This finding indicated that chip thickness had a significant impact on chip form similar to the trend of the cutting force. The effect may be a result of a transition in the cutting mode from ductile to brittle cutting with the increase of chip thickness in WPCs cutting.

However, short continuous chips were obtained at chip thickness of 0.15 mm when cutting WFPVCC compared with the other two materials. This reason may be related to brittle behavior of WFPVC.  Further, flake chips were produced when cutting WFPVCC at chip thickness of 1 mm, at rake angle of 30°, and chips tended to be granule at rake angle of 10°. With the increase of chip thickness, or the decrease of rake angle, the chips produced were getting shorter or smaller. So it can be thought that chip thickness and rake angle had significant impact on the chip form when cutting WFPVCC.


**Fig. 8 (a, b, f, g).** Chip morphology during cutting of WFPEC (a,f), WFPPC (b, c, g and h) and WFPVCC (d, e, i and j) at *t*=0.15 and 1 mm, at *v*=15 m/s


**Fig. 8 (c-e & h-j).** Chip morphology during cutting of WFPEC (a,f), WFPPC (b, c, g and h) and WFPVCC (d, e, i and j) at *t*=0.15 and 1 mm, at *v*=15 m/s

## CONCLUSIONS

1. Three types of wood-polymer composites (WPCs) exhibited different behavior with respect to the machinability aspects. The cutting forces of wood flour/ polyvinyl chloride composite (WFPVCC) were the highest, followed by wood flour/polyethylene composite (WFPEC) and wood flour/polypropylene composite (WFPPC).
2. Statistical results indicated that the parallel cutting force was most significantly influenced by chip thickness, which explained more than 90% of the contribution to total variation, while rake angle, edge radius, and the interactions among these factors had less contribution.
3. Statistical results indicated that the normal cutting force was significantly influenced by chip thickness and rake angle which accounted for more than 60% and 10% of total variation, respectively, for WPCs cutting. The edge radius and the interactions between these factors had a smaller effect on the normal cutting force.
4. WFPEC and WFPPC tended to be long or short continuous chip when cutting at tested range, while WFPVCC tended to be from short continuous chip to flake and granule chip when chip thickness increased or rake angle decreased.

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