

## **EFFECT OF AVERAGE CHIP THICKNESS AND CUTTING SPEED ON CUTTING FORCES AND SURFACE ROUGHNESS DURING PERIPHERAL UP MILLING OF WOOD FLOUR/POLYVINYL CHLORIDE COMPOSITE**

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### **ABSTRACT**

Wood flour/polyvinyl chloride composite (WFPVCC) is a kind of composite material that, over the years, is becoming more popular in constructions applications. In this work, cutting forces and machined surface roughness were studied during peripheral up milling of WFPVCC under different average chip thickness which was obtained by adjusting rotation speed and feed rate at both high and low speed cutting conditions. The results indicated that cutting forces components, parallel force ( $F_x$ ) and normal force ( $F_y$ ) greatly varied during the cutting process. Maximum  $F_x$ , maximum  $F_y$  and surface roughness increased with the increase of average chip thickness. Maximum  $F_x$  and maximum  $F_y$  at high speed cutting conditions were lower than that at low speed cutting conditions at a same average chip thickness. The machined surface roughness at high speed cutting conditions was better than that at low speed cutting conditions at a same average chip thickness. When meeting the requirement of certain surface roughness, higher cutting speed can allow higher chip thickness and then decrease the tool wear than lower speed cutting condition. Maximum negative  $F_y$  had great impact in machined surface roughness. Machined surface roughness increased with the increase of maximum negative  $F_y$ . Thus, high speed cutting conditions not only increase the machining productivity, but also decrease machined surface roughness during the peripheral up milling of WFPVCC.

**KEYWORDS:** Wood flour/polyvinyl chloride composite, peripheral milling, cutting forces, surface roughness, average chip thickness.

## INTRODUCTION

WFPVCC is a kind of composite material more and more popular used in the world, and gaining entry into the construction and building industries such as doors, windows, or facades because of its thermal stability, moisture resistance, and stiffness (Thomasnet 2013, Cheng et al. 2012, Fabiyi and McDonald 2010). Additionally, WFPVCC material is superior to high density polyethylene/wood composites and polypropylene/wood composites with respect to their higher modulus, creep resistance, weatherability, and flame retardance (Müller et al. 2011).

Although most shapes of WFPVCC products are formed at initial production, when applied in door, window, furniture, and other complicated profiled products, with broadening application of WFPVCC material, most secondary processing methods such as milling, planning, routing and sanding will inevitably be conducted (Saloni et al. 2011).

Peripheral milling, which is a process consisting of a rotary cutting motion and a linear feeding motion, is the most common machining operation, a material removal process, which can create a variety of features on a part by cutting away the unwanted material (Röbenack et al. 2013). In addition, high speed machining method is usually realized by milling method through Computer Numerical Control (CNC) machine. The CNC machine can provide high rotation speed and high feed rate. High speed machining typically refers to making light milling passes at high spindle speed and high feed rate to achieve a high material removal rate, resulting in shorter processing time and reduced production cost (Sütçü and Karagöz 2012, Lou et al. 1998). Nowadays, the processing of door and window is usually achieved by CNC machine (Zhang et al. 2008). So, the knowledge about the machinability is important during the peripheral up milling of WFPVCC through CNC machine.

Cutting forces and surface roughness are two important issues in the machining of wood-based composites, which reflect the machinability of material. Cutting forces have a direct influence on power consumption, tool wear, heat generation and quality of machined surface (Guo et al. 2014; Wyeth et al. 2009; Marchal et al. 2009). On the other hand, surface roughness is an important characteristic that describes the quality of the machining surface being, in most cases, a technical requirement for machined products. Additionally, the surface roughness also affects several attributes of machined parts like adhesion, friction, wear, water absorption, and heat transmission (Soury 2013, Kiliç et al. 2009, Cheng and Sun 2006). Some researches were performed to investigate the effect of cutting speed and feed rate on surface roughness in wood and wood based materials milling by CNC router (Budakçi et al. 2013, Sütçü 2013, Sogutlu 2010, Davim et al. 2009, Barčík et al. 2009, Costes and Larricq 2002). Another researches indicated that average chip thickness contributed more to increase parallel forces than other factors (Palmqvist 2003, Huang et al. 2003, Huang 1994). However, few researches were focusing the investigation on the effect of chip thickness and cutting speed on peripheral milling forces and machined surface roughness at the same time, and the relation between peripheral milling forces components and machined surface roughness.

The purpose of this study was to investigate the effect of average chip thickness on the peripheral up milling forces and machined surface roughness of WFPVCC material at both high and low speed cutting conditions. Also, study the relationship between peripheral milling forces components and machined surface roughness.

## MATERIAL AND METHODS

### Material

WFPVCC was used as the tested samples in these experiments which were supplied by Jufeng Company in China. The dimension of the tested WFPVCC samples was 50 ( $L$ )  $\times$  50 ( $W$ )  $\times$  10 mm ( $T$ ) which contained 40 % modified poplar (*Populus euramericana* cv.) wood flour, 50 % polyvinyl chloride, 5 % acrylic acid copolymer, 3 wt. % composite stabilizer and 2 wt. % polyethylene wax. The wood flour was screened through a sieve with mesh  $0.7 \times 2.1$  mm. The physical and mechanical properties of WFPVCC are described in Tab. 1.

Tab. 1: Physical and mechanical properties of WFPVCC.

Density ( $\text{kg.cm}^{-3}$ )	Flexural strength ( $\text{N.mm}^{-2}$ )	Tensile strength ( $\text{N.mm}^{-2}$ )	Impact strength ( $\text{kJ.m}^{-2}$ )	Elasticity modulus (GPa)
1.65	4.69	26.21	15.70	4.27

### Methods

The peripheral up milling tests for the WFPVCC were performed on CNC 5-axis machine (MIKRON, UCP 800 Duro). The milling tool with two straight teeth provided by Leitz Tooling Company was equipped onto the machine. Tungsten carbide, K10, was used as the materials of cutting edges. Rake angle, sharpness angle and clearance angle were respectively  $15^\circ$ ,  $50^\circ$  and  $25^\circ$ .

During milling, wood samples were fastened to a Kistler 9257B quartz three-component dynamometer, which was fixed to the feeding table of the CNC machine. A charge amplifier Kistler type 5019A equipped with a 180-kHz analog low-pass filter was used to amplify and condition input data. The cutting forces were measured according to  $F_x$ ,  $F_y$ , and  $F_z$  directions, which is illustrated in Fig. 1.  $F_x$  was defined as the cutting force component (parallel force) parallel to feed direction.  $F_y$  was defined as the cutting force component (normal force) perpendicular to feed direction.  $F_z$  was defined as the cutting force component (lateral force) which was parallel to axial direction. Each force was calculated as the force per unit width. Cutting forces were measured five times at each cutting condition and a mean value was reported.

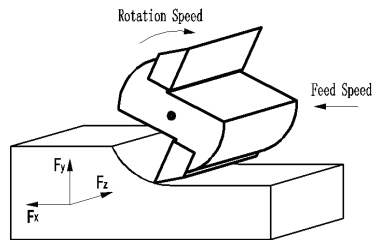


Fig.1:  $F_x$ ,  $F_y$  and  $F_z$  force components during up milling WFPVCC material.

The arithmetic mean deviation of the surface roughness, Ra, was reported to be the most important parameter for the evaluation of the machined surface quality by Sütçü and Karagöz 2013 and Hiziroğlu 1996. Thus, in this study, the dependent variable Ra was considered. The Ra was measured using a Mahr perthometer M2. The Ra parameter was measured on the cutting surface at five samples at the same cutting condition, and the average value was used in the analysis.

## Experimental design

The experimental design was designed primarily on the variable of the average chip thickness which ranged from 0.05 to 0.40 mm. Tab. 2 shows how the average chip thickness could be obtained in different ways where the cutting tool diameter ( $D$ ) was 16 mm, the number of teeth ( $z$ ) was 2 and the depth of cut ( $h$ ) was 2 mm. There are two groups of cutting conditions, i.e., high speed cutting condition and low speed cutting condition, which could reach the same average chip thickness in this experimental setup. The high speed cutting condition meant average chip thickness was attained by the combination of high rotation speed and high feed rate. The low speed cutting condition meant the average chip thickness was attained by the combination of low rotation speed and low feed speed. The aim of such experimental design was to investigate the effect of average chip thickness and cutting speed on cutting forces and machined surface roughness.

The average chip thickness calculating based on the Eq. given by Koch 1964:

$$a_{av} = \frac{U}{n \cdot z} \sqrt{\frac{h}{D}} \quad (\text{mm})$$

where:  $a_{av}$  - average chip thickness in mm,  
 $U$  - feed rate in mm.min<sup>-1</sup>,  
 $n$  - rotation speed in rpm,  
 $z$  - number of teeth on tool,  
 $h$  - cutting depth in mm,  
 $D$  - the tool's diameter in mm.

Each value of average chip thickness has numerous combinations of feed rate, rotation speed, number of teeth, cutting depth, and diameter of tool.

Tab. 2: The designed average chip thickness value can be reached by either by changing the feed rate at high rotation speed (left) or by changing the feed rate at low rotation speed (right).

Test Number	High speed cutting conditions		$a_{av}$ (mm)	Low speed cutting conditions		Test Number
	$n$ (r.min <sup>-1</sup> )	$U$ (mm.min <sup>-1</sup> )		$n$ (r.min <sup>-1</sup> )	$U$ (mm.min <sup>-1</sup> )	
1	18000	5090	0.05	3534	1000	9
2	16000	9050	0.10	2650	1500	10
3	14000	11880	0.15	2356	2000	11
4	12000	13580	0.20	2209	2500	12
5	10000	14150	0.25	2120	3000	13
6	8000	13580	0.30	2062	3500	14
7	6000	11880	0.35	2019	4000	15
8	4000	9050	0.40	1988	4500	16

## RESULTS AND DISCUSSION

### Cutting force components

Typical evolutions of parallel, normal, and lateral cutting forces during two adjacent cutting edges processing cycles at the cutting condition are shown in Fig. 2. For one cycle,  $F_x$  was always positive and increased as chip thickness increased. It is reported that the cutting edges could

generate force to push the test specimen forward with the feeding direction which was achieved by tool holder during peripheral up milling (Iskra and Hernández 2012).

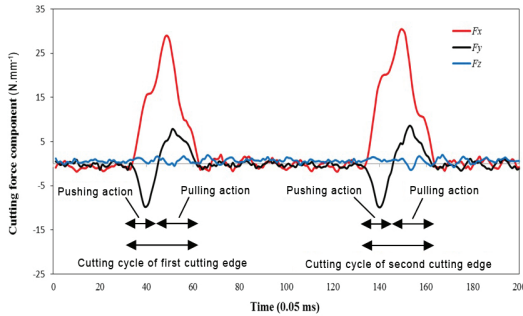


Fig. 2: Progression of parallel, normal, and lateral cutting forces during two cycles for two cutting edges ( $n=6000 \text{ r.min}^{-1}$ ,  $U=12000 \text{ mm.min}^{-1}$  and  $h=2 \text{ mm}$ ).

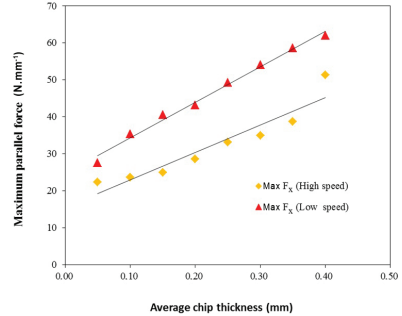


Fig. 3: Effect of average chip thickness on the maximum parallel force ( $\text{max } F_x$ ) at both high and low speed cutting conditions.

At the beginning of the cutting process,  $F_y$  was negative, which meant the cutting edge pushed the workpiece downward. As the cutting edge advanced in the cutting path, absolutely normal force  $F_y$  increased, reached a maximum negative value, then decreased to  $0 \text{ N.mm}^{-1}$ , turned positive and continue upward, pull the chip from the workpiece. When the normal force was negative, it revealed an important effect on machined surface roughness. Since the negative  $F_y$  reflects friction between clearance face and machined surface, the raised defects increase easily with increasing the friction.

The  $F_z$  was always close to  $0 \text{ N.mm}^{-1}$  because the milling tools with two straight cutting edges cannot cause axial force.

### Effect of average chip thickness on the maximum parallel force

Fig. 3 shows that the effect of average chip thickness on the maximum  $F_x$  at both high and low speed cutting conditions. It can be seen that the maximum  $F_x$  increased with the increase of the average chip thickness at both high and low speed cutting conditions under all tested range. This is because the cutting edge required more energy to remove the thicker chips away from the workpiece. In addition, it can also be seen that the maximum  $F_x$  during high cutting speed was lower than during low cutting speed at a same average chip thickness. This finding confirms that the cutting force decreases with the increase of cutting speed. The effect of cutting speed on the maximum  $F_x$  was becoming significant with an increase of average chip thickness.

### Effect of average chip thickness on the maximum normal negative and positive forces

The evolution of the maximum negative  $F_y$  and the maximum positive  $F_y$  in one chip processing cycle with the increase of average chip thickness at both high and low speed cutting conditions were shown in Fig. 4. It can be seen that the maximum negative  $F_y$  increased with the increase of average chip thickness during high and low speed cutting conditions. Also, the maximum positive  $F_y$  increased with the increase of the average chip thickness during high and low speed cutting conditions under all tested range. This is because the cutting edge required more energy to remove the thicker chips away from the workpiece.

In addition, it can also be seen that the maximum negative  $F_y$  at high speed cutting condition was smaller than that during relatively low cutting speed at the same average chip thickness, and the maximum positive  $F_y$  at high speed cutting condition was also smaller than that during relatively low cutting speed at the same average chip thickness. This finding, also confirms that the normal cutting force also decreases with the increase of cutting speed.

Interestingly, the effect of the cutting speed on maximum negative  $F_y$  was becoming less important with the increase of average chip thickness, on the other hand, the effect of the cutting speed on maximum positive  $F_y$  was becoming significant with the increase of average chip thickness.

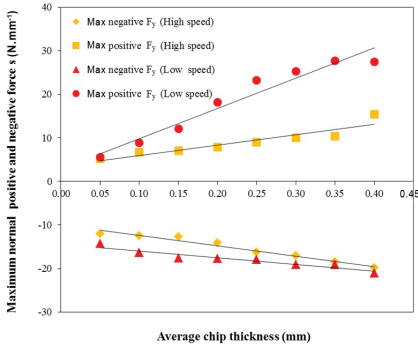


Fig. 4: Effect of average chip thickness on the maximum positive and negative normal forces (max positive  $F_y$  and max negative  $F_y$ ) at both high and low speed cutting conditions.

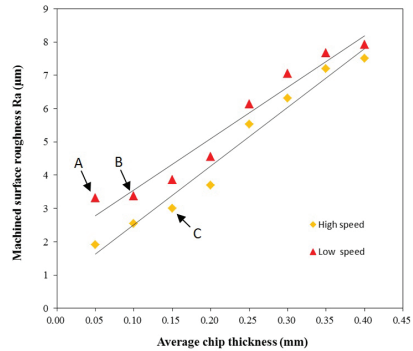


Fig. 5: Effect of average chip thickness on machined surface roughness at both high and low speed cutting conditions.

### Effect of average chip thickness on machined surface roughness

Fig. 5 shows the effect of average chip thickness on machined surface roughness at both high and low cutting speed conditions. It can be seen that machined surface roughness increased with the increase of average chip thickness. In addition, the machined surface roughness at low speed cutting condition was higher than that at high speed cutting condition. And, the effect of the cutting speed on the machined surface roughness was becoming insignificant with the increase of average chip thickness.

It can be concluded that decreasing average chip thickness resulted in small surface roughness (good surface quality), however it increases the specific cutting work, which can cause more tool wear (Cristóvão et al. 2012, Grönlund 2004). From Fig. 5, it can be noted that it can produce lower surface roughness at the point C (average chip thickness of 0.15 mm, at high speed cutting condition) than at the point A and B (smaller average chip thickness of 0.10 and 0.05 mm, and low speed cutting condition). From tool wear perspective, machining with 0.15 mm produce less tool wear than machining with 0.10 and 0.05 mm. Thus, for meeting the requirement of certain surface roughness, the higher cutting speed can allow high chip thickness, and then decrease the tool wear than lower speed cutting condition.

On the other hand, Tab. 2 illustrates that the small average chip thickness can be reached through high speed cutting condition (increasing rotation speed at high feed rate) or low speed cutting condition (decreasing feed rate at low rotation speed). However, it is evident that the high speed cutting condition can not only increase the machining productivity, but also improve the surface quality. Therefore, high speed cutting condition is a better method to be used for

improving the machinability of WFPVCC.

### Effect of maximum normal negative forces on machined surface roughness

Previous researches have shown that normal negative force is considered critical for defects left on the newly created surface (River and Miniutti 1975; Stewart 1980; Stewart and Crist 1982). This force component is responsible for the amount of transverse compression that occurs when the cutting edge attacks the workpiece. Excessive compression may produce material crushing at the surface and subsurface as indicated. As the Fig. 1 shows, the negative  $F_y$  primarily occurs in the first stage of the cutting cycle. So, the effect of the maximum negative  $F_y$  on the machined surface roughness is significant. Fig. 6 shows that effect of maximum normal negative force on machined surface roughness at both high and low speed cutting conditions. It can be seen that machined surface roughness increased with the increase of maximum normal negative force at both high and low speed cutting conditions.

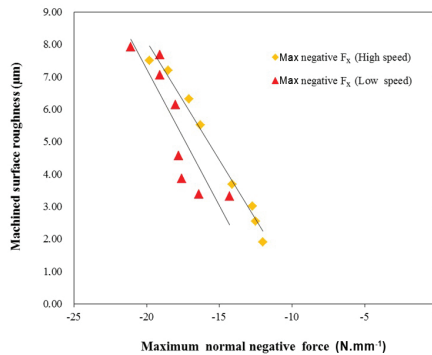


Fig. 6: Effect of maximum normal negative force on machined surface roughness at both high and low speed cutting conditions.

## CONCLUSIONS

The cutting forces and machined surface quality are two key parameters for reflecting machinability of WFPVCC. This study was aimed at determining the effect of average chip thickness and cutting speed on the peripheral up milling force components and machined surface roughness at both high and low speed cutting conditions. From the results and discussion above, some significant conclusions can be drawn:

1. Maximum  $F_x$ , maximum negative  $F_y$ , and maximum positive  $F_y$  during high cutting speed were lower than during low cutting speed at a same average chip thickness.
2. Machined surface roughness increased with increase of average chip thickness at both high and low speed cutting condition, and machined surface roughness at low speed cutting condition was higher than that at high speed cutting condition.
3. When meeting the requirement of certain surface roughness, higher cutting speed can allow higher chip thickness and then decrease the tool wear than lower speed cutting condition.
4. Maximum negative  $F_y$  had great impact in machined surface roughness, and the machined surface roughness increased with the increase of maximum negative  $F_y$ .
5. Thus, a high cutting speed conditions not only increase the machining productivity, but also decrease machined surface roughness during the peripheral up milling of WFPVCC.

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## REFERENCES

1. Barčík, S., Pivolusková, E., Kminiak, R., Wieloch, G., 2009: The influence of cutting speed and feed speed on surface quality at plane milling of poplar wood. *Wood Research* 54(2): 109-116.
2. Budakçı, M., İlçe, A.C., Gürleyen, T., Utar, M., 2013: Determination of the surface roughness of heat-treated wood materials planed by the cutters of a horizontal milling machine. *BioResources* 8(3): 3189-3199.
3. Cheng, E., Sun, X., 2006: Effects of wood-surface roughness, adhesive viscosity and processing pressure on adhesion strength of protein adhesive. *Journal of Adhesion Science and Technology* 20(9): 997-1017.
4. Cheng, R.X., Li, Z., Li, Y., 2012: Study on bonding properties of PVC-based WPC bonded with acrylic adhesive. *Journal of Adhesion Science and Technology* 26(24): 2729-2735.
5. Costes, J.P., Larricq, P., 2002: Towards high cutting speed in wood milling. *Annals of Forest Science* 59(8): 857-865.
6. Cristóvão, L., Broman, O., Grönlund, A., Ekevad, M., Siteo, R., 2012: Main cutting force models for two species of tropical wood. *Wood Material Science and Engineering* 7(3): 143-149.
7. Davim, J.P., Clemente, V.C., Silva, S., 2009: Surface roughness aspects in milling MDF (Medium Density Fibreboard). *International Journal Advanced Technology* 40(1-2): 49-55.
8. Fabiyi, J.S., McDonald, A.G., 2010: Physical morphology and quantitative characterization of chemical changes of weathered PVC/pine composites. *Journal of Polymer and the Environment* 18(1): 57-64.
9. Grönlund, A., 2004: Wood machining. (Träbearbetning). Träteknik-Institutet för Träteknisk Forskning, Växjö, Stockholm, Sweden, 475 pp (in Swedish).
10. Guo, X., Ekevad, M., Marklund, B., Li, R., Cao, P., Grönlund, A., 2014: Cutting forces and chip morphology during wood plastic composites orthogonal cutting. *BioResources* 9(2): 2090-2106.
11. Hiziroglu, S., 1996: Surface roughness analysis of wood composites: A stylus method. *Forest Product Journal* 46(7-8): 67-72.
12. Huang Y.S., 1994: Cutting force components in orthogonal cutting parallel to the grain (90-0). I. Effect of rake angles. *Mokuzai Gakkaishi* 40(10): 1134-1140.
13. Huang, Y.S., Chen, S.S., Hwang, G.S., Tang, J.L., 2003: Peripheral milling properties of compressed wood manufactured from planted China-fir. *European Journal of Wood and Wood Products* 61(3) : 201-205.
14. Iskra, P., Hernández, R.E., 2012: Analysis of cutting forces in straight-knife peripheral cutting of wood. *Wood and Fiber Science* 44(2): 134-144.



15. Kiliç, M., Burdurlu, E., Aslan, S., Altun, S., Tümerdem, O., 2009: The effect of surface roughness on tensile strength of the medium density fiberboard (MDF) overlaid with polyvinyl chloride (PVC). *Materials and Design* 30(10): 4580-4583.
16. Koch, P., 1964: *Wood machining processes*. Ronald Press, New York.
17. Lou, M.S., Chen, J.C., Li, C.M., 1998: Surface roughness prediction technique for CNC end-milling. *Journal of Industrial Technology* 15(1): 1-6.
18. Marchal, R., Mothe, F., Denaud, L., Thibaut, B. and Bleron, L., 2009: Cutting forces in wood machining-Basics and applications in industrial processes. *Holzforschung* 63(2): 157-167.
19. Müller, M., Radovanovic, I., Grüneberg, T., Militz, H., Krause, A., 2011: Influence of various wood modifications on the properties of polyvinyl chloride/wood flour composites. *Journal of Applied Polymer Science* 125(1): 308-312.
20. Palmqvist J., 2003: Parallel and normal cutting forces in peripheral milling of wood. *European Journal of Wood and Wood Products* 61(6) : 409-415.
21. River, B.H., Miniutti, V.P., 1975: Surface damage before gluing weak joints. *Wood Wood Prod.* 80(7): 35-36, 38.
22. Röbenack, K., Ahmed, D., Eckhardt, S., Gottlöber, C., 2013: Peripheral milling of wooden materials without cutter-marks. A mechatronic approach. *WSEAS Transactions on Applied and Theoretical Mechanics* 8(2): 170-179.
23. Saloni, D., Buehlmann, U., Lemaster, R.L., 2011: Tool wear when cutting wood fiber-plastic composite materials. *Forest Products Journal* 61(2): 149-154.
24. Sogutlu, C., 2010: The effect of the feeding direction and feeding speed of planing on the surface roughness of oriental beech and scotch pine woods. *Wood Research* 55(4): 67-78.
25. Soury, E., Behraves, A.H. Jam, N.J., Haghtalab, A., 2013: An experimental investigation on surface quality and water absorption of extruded wood-plastic composite. *Journal of Thermoplastic Composite Materials* 26(5): 680-698.
26. Stewart, H.A., 1980: Some surfacing defects and problems related to wood moisture content. *Wood and Fiber Science* 12(3): 175-182.
27. Stewart, H.A., Crist, J.B., 1982: SEM examination of subsurface damage of wood after abrasive and knife planing. *Wood Science* 14(3):106-109.
28. Sütçü, A., 2013: Investigation of parameters affecting surface roughness in CNC routing operation on wooden EGP. *BioResources* 8(1): 795-805.
29. Sütçü, A., Karagöz, Ü., 2012: Effect of machining parameters on surface quality after face milling of MDF. *Wood Research* 57(2): 231-240.
30. Sütçü, A., Karagöz, Ü., 2013: The influence of process parameters on the surface roughness in aesthetic machining of wooden edge-glued panels (EGPs). *BioResources* 8(4): 5435-5448.
31. Thomasnet, 2013: Wood plastic composite. <http://www.thomasnet.com/articles/plastics-rubber/composite-wood-plastic>.
32. Wyeth, D., Goli, G., Atkins, A., 2009: Fracture toughness, chip types and the mechanics of cutting wood. *Holzforschung* 63(2): 168-180.
33. Zhang, H., Ai, C., Zhao, F., Ze, X., 2008: The CNC development of the sawing and milling machining center for plastic door and window PVC profile based on fanuco. In: *Proceedings of the 7<sup>th</sup> World Congress on Intelligent Control and Automation (WCICA)*, 25-27 June, Chongqing, China. Pp 56-9361.

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