Forces and Heat Variation Laws of Pine Materials Processing and Microcosmic Characteristics of Surface Damage

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Pinus massoniana material was processed on a shaper in which a quartz three-component dynamometer and forward-looking infrared (FLIR) system were used to measure the cutting forces and cutting zone temperature, respectively. In addition, a high-speed camera and the FLIR systems were used to capture the chip formation process. Cutting forces and cutting zone temperature were measured under the cutting conditions of three different rake angles (25°, 40°, and 50°) and four different cutting depths (0.1 mm, 0.2 mm, 0.3 mm, and 0.5 mm), while feed speed was kept constant. Analysis of the experimental data and chip formation process showed that the cutting forces and cutting zone temperature of pine material were both decreased by increases of rake angle and increased by increases of cutting depth. Cutting forces were decreased under the cutting conditions of 0.3 mm cutting depth and rake angles of 40° and 50° due to the cleavage failure parallel to pine grain. The cutting temperature was not decreased under that cutting condition. The microcosmic characteristics of surface damage were mainly fiber burrs and fiber traces.

Keywords: Chip formation process; FLIR images; Pine materials; Force variation; Heat variation; Surface damage

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INTRODUCTION

Although the application of wood-based panels such as particleboard, fiberboard, and plywood is used widely in the woodwork manufacturing industry, solid wood still has an irreplaceable position (Gonçalves and Néri 2005; Qian 2010; Guo *et al.* 2017). With the improvement of Chinese awareness of environmental protection, people prefer environmentally friendly solid wood furniture, such as pine furniture. There are many useful features of pine material, such as vivid wood grain, warm wood color, soft touch, and durability (Liu 2007). In order to make full use of those features of pine material, the method of processing should be arranged properly, which includes common care milling, planing, routing, *etc*. The milling method is widely used in processing products in factories due to its high efficiency and precision (Guo *et al.* 2016a, 2017; Li *et al*. 2017). Most researchers have studied the application of milling in wood processing. However, orthogonal cutting is not often used in wood processing research. Orthogonal cutting is the most basic and simplest cutting method, which can reflect the common laws of various complicated cutting methods and cutting mechanisms (Budak *et al.* 1996). Therefore, this cutting method can be used to study the chip deformation, cutting force, and cutting heat during wood processing.

Merhar and Bučar (2012) studied the cutting force variability as a consequence of exchangeable cleavage fracture and compressive breakdown of wood tissue. Chips of varying length and thickness were modelled using the finite element method. Hernández *et al.* (2014) studied the effects of cutting parameters on cutting forces and surface quality of black spruce cants, showing that the lowest cutting forces and the best surface quality were obtained with 65° of rake angle. Cutting forces and surface quality were more affected by cutting depth than by cutting direction variations at 65° of rake angle. A few researchers have chosen orthogonal cutting to study the forces and heat variation laws during wood processing. Guo *et al.* (2014) studied the cutting forces during WPC (wood plastic composites) orthogonal cutting. The results showed that the most significant factor on the normal cutting force of WPCs was the chip thickness, which accounted for more than 60% of the total variation. Cáceres *et al.* (2018) studied the orthogonal cutting forces and surface quality of white spruce wood with and without the presence of knots at four rake angles. The results of that study showed that a rake angle of 40° produced weaker cutting forces and lower surface roughness. However, there are few articles on temperature changes during the wood orthogonal cutting process as well.

The studies show that rake angle, cutting depth, and chip formation have effects on cutting performance. However, these previous published articles analyzed the cutting force and heat mostly by test data, models, or wood theory. Few have analyzed the effect of chip formation on cutting forces and heat by observing the cutting process, which may explain, more effectively, the variation laws and failure mechanism. Wood processing is complicated because wood is an anisotropic and inhomogeneous material, and some wood pieces contain knots and silicates (Walker *et al.* 2006; Guo *et al.* 2017). Therefore, deconstructing the wood cutting process helps to observe every cutting action between tool and material and gain further understanding of the cutting mechanism.

In this study, the forces and heat variation laws in orthogonal cutting of pine parallel to grain and microcosmic characteristics of pine surface damage were investigated. A high-speed camera and FLIR (forward-looking infrared) systems were used to shoot the pine processing. The experiments were carried out on a shaper where cutting forces and cutting zone temperature were measured in processing.

EXPERIMENTAL

Materials

Pine (*Pinus massoniana*) was used for the tested samples, which were supplied by Shengxiang Group Co., Ltd. (Danyang, China). Experimental samples were all cut into the size of 80 × 12 × 90 mm (Radial × Tangential × Longitudinal) from normal sound wood and dried to a moisture content (MC) of 12.1%. The cutting was done on the tangential surface, and the cutting direction was longitudinal orientation. The MOR (modulus of rupture), MOE (modulus of elasticity), and density of samples were about 62.1 MPa, 5089 MPa, and 446 kg/m^3, respectively.

Methods

The cutting tests were carried out on a shaper. Three cutting tools made of high-speed steel with different rake angles (25°, 40°, 50°) were used in this experiment. The tool geometry parameters include rake angle α, wedge angle β, and clearance angle γ. The mechanical properties of tools are shown in Table 1. The cutting depth h was assigned four different levels (0.1 mm, 0.2 mm, 0.3 mm, 0.5 mm), and feed speed v was kept constant as 13.6 m/min. In order to keep the cutting condition unchanged, each experiment was carried out with the cutting tool freshly ground. The tests were designed according to single factorial design and conducted in constant temperature conditions. In total, 12 groups of experiments were performed by the combinations of these cutting parameters, and they are given in Table 2. In order to reduce experimental error, each group of experiments was carried out for three times successfully. Thirty-six groups of experimental data were obtained after this experiment. Each group of experimental data includes average cutting forces (parallel tool force F_x and normal tool force F_y) and maximum cutting zone temperature.

Table 1. The Mechanical Properties of Tools

Tools Number	Structure Parameter			Mechanical Properties		
	Rake angle	Wedge angle	Clearance angle	Hardness (HRC)	Flexural strength (GPa)	Toughness (J/m³)
A	25°	50°	15°	65	4.9	36
B	40°	35°	15°			
C	50°	25°	15°			

Table 2. Machining Parameters Used in Experiments

Experience Number	Rake Angle γ (°)	Cutting Depth h (mm)
1	25	0.1
2	25	0.2
3	25	0.3
4	25	0.5
5	40	0.1
6	40	0.2
7	40	0.3
8	40	0.5
9	50	0.1
10	50	0.2
11	50	0.3
12	50	0.5

The diagram of the experimental system is shown in Fig. 1. In this experiment, the cutting force and cutting zone temperature were tested in orthogonal cutting of pine parallel to grain on the planer (B665 Shaper, Shenyang, China). The quartz three-component dynamometer (Kistler 9257B, Winterthur, Switzerland) with the sampling frequency of 1000 Hz was set on the workbench. Then the cutting tool was fixed on the dynamometer by a fixture. The pine samples were fixed on the tool carrier of the planer by a fixture. The relative motion between tool and samples was achieved through the feed movement of the tool carrier. In addition, the FLIR systems (ThermoVisionA20 Shanghai, China) were used to focus on the cutting zone for cutting temperature measurement, and its frame rate and resolution were 50 fps and 160×120 pixels, respectively. For observing the chip formation process, a high-speed camera (OLYMPUS *i-speed* 3, Tokyo, Japan) was used to focus on the cutting zone, and its frame rate and resolution were 5000 fps and 1280×1024 pixels, respectively.

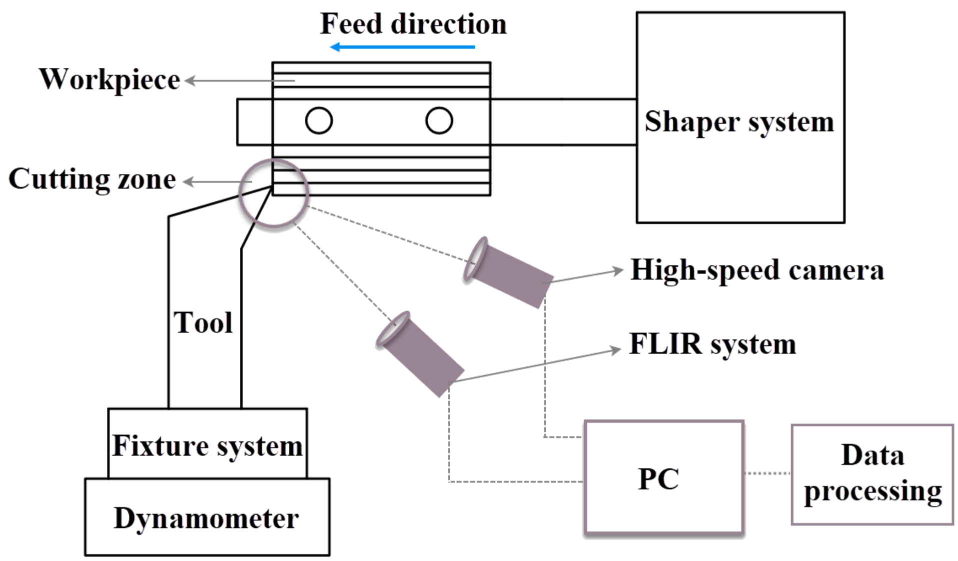

Fig. 1. Schematic diagram of experimental system

In orthogonal cutting parallel to pine grain, the cutting edge is perpendicular to feed direction, and the chip is assumed as a two-dimensional plane strain deformation without side spreading (Saglam *et al.* 2007). Hence, the cutting forces were tested only in the direction of feed direction and uncut chip thickness. As shown in Fig. 2, the resultant force of frictional force F_f and normal force F_n is F. The resultant force F depends on factors such as rake angle and cutting depth. Rake angle is one of the most important cutting parameters that determines the tool/chip contact area, and cutting depth plays a vital role in chip deformation (Guo *et al.* 2016b). Normal force F_n is linked with rake angle and chip volume. Friction force F_f depends on normal force F_n and μ, so tool/chip contact area, rake angle, and the chip volume affect F_f (McKenzie 1961; Costes *et al.* 2004). The resultant force F could also be decomposed into parallel tool force F_x and normal tool force F_y. F_x and F_y were tested by the dynamometer directly in this experiment. There are some relationships among them (see equations 1 through 3).

$$F = F_n\,(1+\tan^2\rho)^{1/2} \quad (1)$$

$$F_f = F_n \tan\rho \quad (2)$$

$$\mu = F_f/F_n = \tan\rho \quad (3)$$

where ρ is the angle between F and F_n, and μ is defined as the friction coefficient of rake face.

The cutting temperature depends on the condition of friction between rake face and chip, and between clearance face and machined surface (Wang *et al.* 2004). Therefore, the friction force F_f played the lead role in the rise of temperature in the cutting zone. Great friction force F_f will cause high temperatures, which accelerates tool wear and breakage (Guo *et al.* 2017). Temperature measurement zone was the same with the cutting zone of Fig. 1. Most of the heat generated in the cutting process was taken away by the chips from the cutting zone. Thus, chips and cutting tool were kept inside of the temperature measurement zone all the time which is a good indictor about the total heat generated.

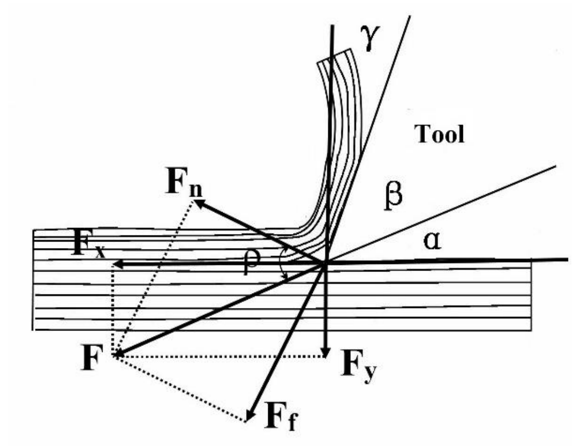

Fig. 2. Cutting forces in orthogonal cutting parallel to grain

RESULTS AND DISCUSSION

There is generally an optimum value of rake angle and cutting depth in pine processing. Deviating from the optimum value has a negative effect on cutting force and cutting temperature. This affects the cutting performance and accelerates the tool wear, which especially affects the processing quality of pine products. Excessive wear causes wider clearance face contacting with machined surface, which also leads to the increase in cutting forces and cutting temperature.

Forces Variation Laws of Pine Materials Processing

As shown in Fig. 3, the most remarkable results concluded were that the parallel tool force F_x and normal tool force F_y were decreased by increasing the rake angle, and the minimum value was both observed at 50° rake angle.

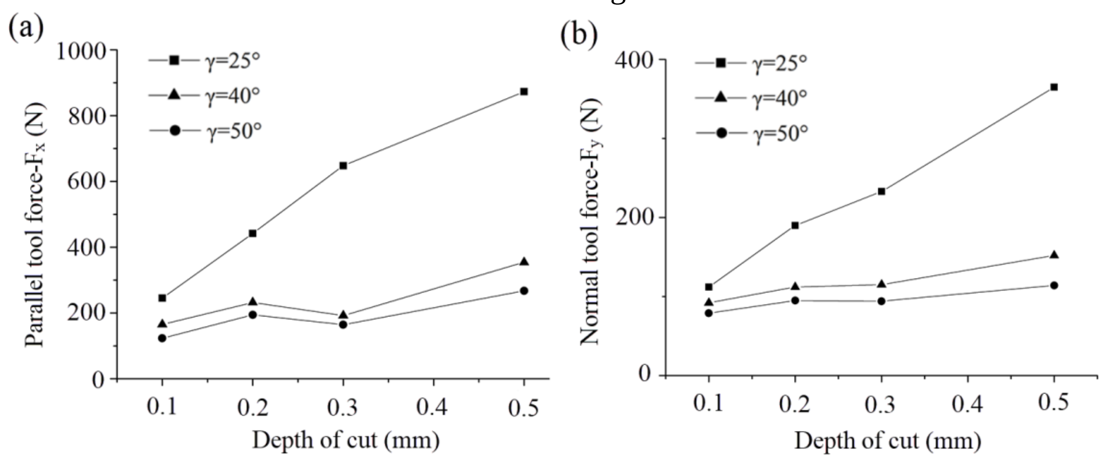

Fig. 3. The parallel tool force F_x (a) and normal tool force F_y (b) under the cutting condition of different cutting depth and different rake angle

When the rake angle increased from 25° to 40°, the cutting forces (F_x and F_y) were greatly reduced and the maximum drop of F_x and F_y were 519 N and 407 N, respectively, at the cutting depth of 0.5 mm. However, when the rake angle increased from 40° to 50°, the cutting forces (F_x and F_y) were just decreased a little and the maximum drop of F_x and

F_y were just 87 N and 7 N at the same cutting depth of 0.5 mm. This occurred because the large rake angles (40°, 50°) produced higher shear angles and small wedge angles. Tools can plunge into the pine fiber easily and reduce the local compression of the wood ahead of the cutting edge. In this way, the cutting resistance of tool edge could be reduced during the cutting process. Therefore, the cutting forces were decreased under this cutting condition.

The F_x and F_y values decreased by reducing the cutting depth, and the minimum value of both was observed at 0.1 mm depth of cut. When the cutting depth increased from 0.1 mm to 0.5 mm, the cutting forces (F_x and F_y) at the 25° rake angle were greatly increased, and the maximum value of F_x could reach as high as 873 N. However, the cutting forces (F_x and F_y) at the 40° and 50° rake angle increased slightly, and the maximum value of F_x and F_y at 40° and 50° rake angle was 354 N and 267 N, respectively. It is known that larger cutting depth means larger machining chip volume. Therefore, the cutting tool requires more mechanical energy in order to separate the chips from samples. Moreover, the cutting forces increased when the mechanical energy increased. Nevertheless, under the condition of 40° and 50° rake angles, the tool edge mainly cut off the wood fibres instead of squeezing the wood fibres, so the degree of chip deformation was smaller. Thus, there was a smaller cutting resistance of tools. The cutting forces of tools with 40° and 50° rake angles are much smaller than that of 25° rake angle.

The parallel tool force F_x decreased slightly under the cutting condition of 0.3 mm cutting depth and 40° and 50° rake angles. Figure 4 shows the high-speed images of cutting process under the cutting depths of 0.1 mm, 0.2 mm, and 0.3 mm; and with a rake angle of 40°. Under the cutting depth of 0.1 mm, a flow type chip with no cleavage failure was formed, but under the 0.2 mm cutting depth, slight cleavage failure was formed. When the cutting depth was increased to 0.3 mm, the process periodically caused a split type of chip with big cleavage failure that originated at the tool edge and proceeded in the direction of the grain. This led to the reduction of chip deformation and tool/chip contact area in unit time. In this way, the mechanical energy would be decreased, and the cutting forces decreased as well. Compared with other wood materials, these cutting characteristics of pine wood can be applied to reduce the mechanical energy on the premise of ensuring good surface quality.

From the analysis of forces variation laws, 25° rake angle tools are difficult to use when processing pine materials. If the tool strength is guaranteed, tools with 40° to 50° rake angles can reduce the cutting forces and mechanical energy consumption.

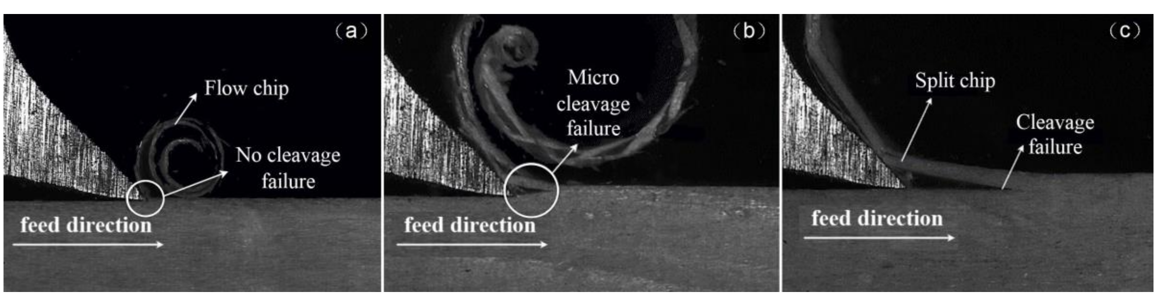

Fig. 4. The high-speed images of cutting processes under the cutting condition of different cutting depths and the same 40° rake angle: (a) 0.1 mm; (b) 0.2 mm; (c) 0.3 mm

Heat Variation Laws of Pine Materials Processing

The thermal images of pine material under the cutting conditions of 40° rake angle and 0.1 mm (a), 0.2 mm (b), 0.3 mm (c), and 0.5 mm (d) cutting depths are shown in Fig. 5. It was observed from the thermal images that cutting heat was generated principally in three areas: shear zone, rake face, and clearance face. Moreover, most of the cutting heat was generated between the rake face and chips.

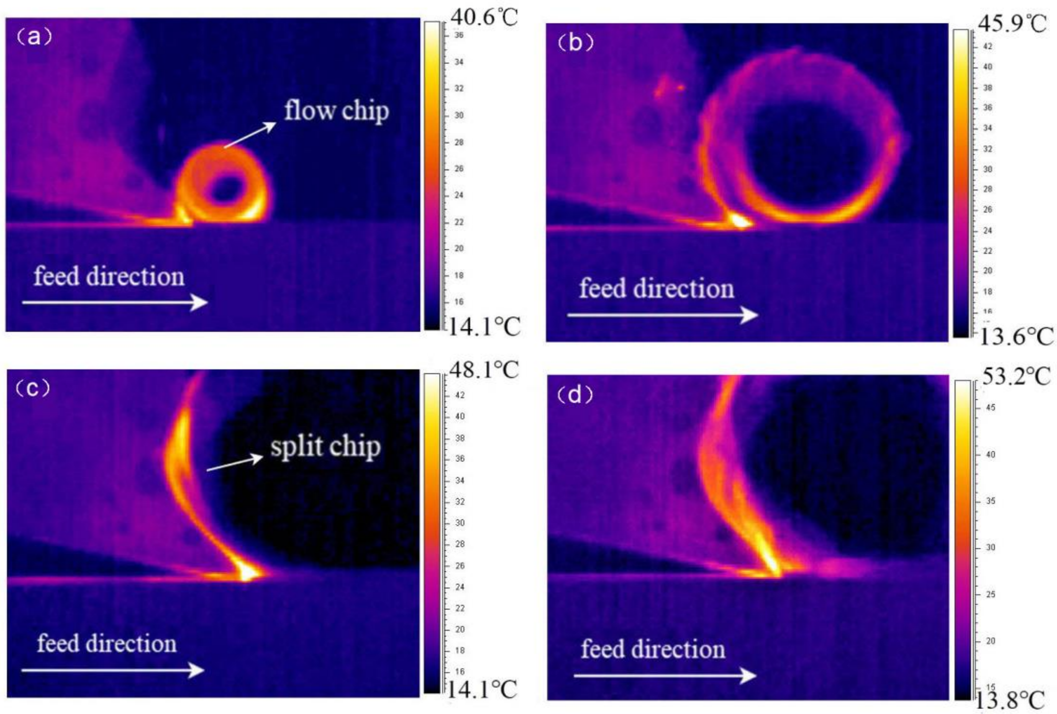

Fig. 5. Thermal images under the cutting condition of different cutting depths and the same 40° rake angle: (a) 0.1 mm; (b) 0.2 mm; (c) 0.3 mm; (d) 0.5 mm

As shown in Fig. 6, the cutting zone temperature was increased by increasing cutting depths. Whether the rake angles were 25°, 45° or 50°, the minimum value was observed at 0.1 mm depth of cut, and each increase in rate made little difference. When the cutting depth was decreased to 0.1 mm, the cutting zone temperature at 50° rake angle was decreased to 37.2 °C. However, the cutting zone temperature went up to 67.5 °C under the cutting condition of 0.5 mm cutting depth and 25° rake angle. This is in accordance with the cutting force variation. Since the main source of cutting heat was severe deformation of chips (which depended on rake angle and cutting depth) and frictional forces (which depend on cutting forces). On the one hand, large cutting depth produced large chip volume and led to the increase of tool/chip contact area, which caused serious deformation of pine. On the other hand, the great rate of mechanical energy from large cutting forces was converted into more cutting heat. Therefore, the cutting temperature was increased with the cutting depth increased.

The cutting zone temperature was decreased by increasing the rake angles. While the rake angle was increased from 25° to 50°, the cutting zone temperature was decreased and arrived at its minimum value at 50°. At the same cutting depth, the cutting temperature of 50° rake angle was about 3 °C lower than that of 40° rake angle. However, the cutting temperature of 40° rake angle was about 11 °C lower than that of 25° rake angle. In addition to the above reasons, a small factor is that large rake angles produced small wedge angles, and the sharp cutting edge could transfer the cutting heat into the air quickly.

It is also observed that the cutting zone temperature was not decreased when the cutting depth was increased from 0.2 mm to 0.3 mm. This is different from cutting force variation laws. As is well known, milling is a kind of intermittent cutting while orthogonal cutting is a kind of continuous cutting. Thus, the cutting heat converted from the mechanical energy accumulated constantly between chips and cutting tool as the time increased. The slight reduction in cutting forces had little effect on the total mechanical energy. Therefore, the cutting heat was little affected by the cleavage failure, and tools with 40° to 50° rake angle are effective in reducing the cutting zone temperature.

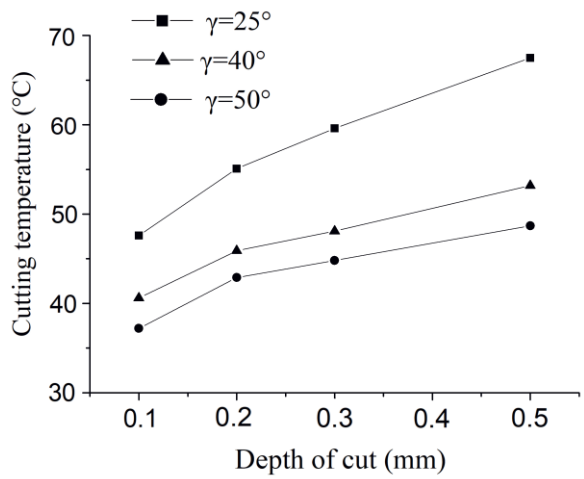

Fig. 6. The cutting zone temperature under the cutting condition of different rake angles and different cutting depths

Microcosmic Characteristics of Surface Damage

The surface quality under the cutting conditions of the same 0.1 mm cutting depth and rake angles 25° (a) and 50° (b) is shown in Fig. 7. It was obvious that the surface quality under the 50° rake angle achieved the higher quality compared to the 25° rake angle. This was related to the different processes of chip formation. Figure 7 also shows the corresponding SEM (scanning electron microscopy) images of surface quality. The chips that formed under the 25° rake angle were squeezed by the rake face. This led to compression of the chips, so pine fibers of machined surface were squeezed instead of being cut off by the cutting tool, which left many long burrs on the surface. In contrast, pine chips formed under the 50° rake angle were not compressed, which left a smooth surface. Therefore, the surface quality with compressive pine chips was worse than that with flow chips. In addition, the cutting force of the 25° rake angle was much greater than that of the 50° rake angle, which led to unstable processing. Thus, the surface quality decreased greatly under a small rake angle.

By comparing Fig. 7(b) and 7(c), it became clear that SEM picture (c) still had many short burrs and microcosmic fiber traces under cutting conditions of 50° rake angles. This indicated that cutting depth has an important influence on the processing quality of pine wood. This is because pine material is a soft wood material, and the fiber is elastic and hard to cut off. Thus, pine fibres were not always cut at the edge but were bent before the cutting edge and removed by attrition, especially at a large cutting depth. As shown in

Fig. 7(d), tracheid cleavage fracture occurred due to the tool attrition and chip formation of split type, and it left a worse surface finish.

In summary, if cutting force, cutting heat, and surface quality all were considered together, the optimum rake angle and cutting depth could be assumed as 40° to 50° and 0.1 mm, respectively.

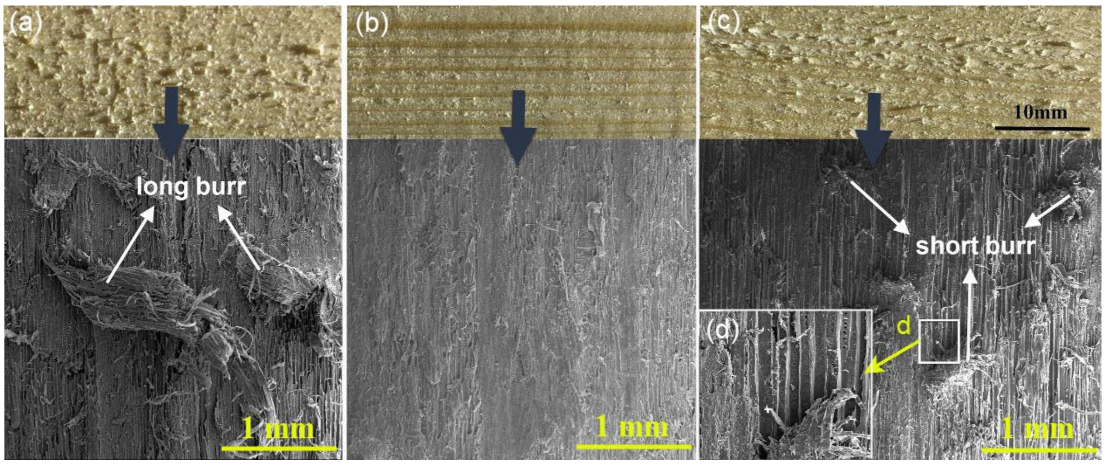

Fig. 7. SEM images of machined surface under the cutting condition of different cutting depth and different rake angle: (a) 25°, 0.1 mm; (b) 50° 0.1 mm; (c) 50°, 0.3 mm

CONCLUSIONS

1. In orthogonal cutting of pine material parallel to grain, both cutting forces (F_x and F_y) were increased by the increase of cutting depth and decreased by the increase of rake angle. A split type of chip with cleavage failure originating at the tool edge and proceeding in the direction of the grain could reduce the cutting forces a little.
2. The cutting zone temperature was also increased by the increase of cutting depth and decreased by the increase of rake angle. However, the cutting heat was little affected by the cleavage failure.
3. The surface quality was improved by the decrease of cutting depth and the increase of rake angle. The microcosmic characteristics of surface damage were mainly fiber burrs and fiber traces.
4. If the tool strength is ensured, and the cutting forces, cutting heat, and surface quality are considered together, the optimum rake angle and cutting depth can be assumed as 40° to 50° and 0.1 mm, respectively, when processing pine wood.

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