TECHNICAL NOTE: RESEARCH ON CUTTING FORCES AND CUTTING TEMPERATURE IN ORTHOGONAL CUTTING SOFTWOOD AND HARDWOOD PARALLEL TO GRAIN

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Abstract. Experimental results showed that the cutting force and cutting zone temperature of soft pine were lower than that of hard oak under the same cutting condition, and the influence degree of chip type on the cutting force of soft pine is lower than that of hard oak. Different chip formation shows little or no effect on cutting temperature in processing both soft pine and hard oak.

Keywords: Cutting forces, cutting temperature, orthogonal cutting, softwood, hardwood.

INTRODUCTION

In the past few years, wood-based panels such as particleboard, fiberboard, and plywood were rapidly developed and were applied to panel furniture (Gonçalves and Néri 2005; Qian 2010; Guo et al 2017a). However, too much adhesive used in the wood-based panels would give off harmful gas and reduce the quality of indoor air which would seriously harm human health (Pizzi 1994). With the increase of Chinese awareness of environmental protection and green life, people tend to choose environment-friendly solid wood furniture (Reiterer et al 2002). Solid wood can be divided into softwood and hardwood which have some pleasing features of vivid wood grain, warm wood color, soft

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touch, and durability (Fengel et al 2003). For example, Mongolian oak is widely used for the surface of csolid wood composite floors because of its vivid grain and high hardness. And *Pinus massoniana*, a kind of fast-growing wood in China, is also popular in the furniture industry.

Solid wood is anisotropic or inhomogeneous. Mongolian oak is a kind of hardwood which is ring-porous with large vessels in the earlywood and small vessels in the latewood. Oak also has lots of wood fibers and some even contain silicates. By contrast, *P. massoniana* have many tracheid as a kind of softwood which does not have wood fibers and vessels. These properties of solid wood make the processing of wood more complicated compared with metal cutting. So, different wood species may have different cutting properties because of their different wood properties and wood densities. To increase the utilization of wood and improve the machining surface quality, each tree species should choose the optimum processing parameters and the way of processing should be arranged properly as well (Li 2017). Basic cutting methods for wood processing are milling, planning, routing, and so on, and according to wood cutting theory, orthogonal cutting is the theoretical basis of studying wood cutting (Koch 1964). So through comparing the cutting performance of softwood and hardwood in orthogonal cutting, we may find the optimum cutting parameters of more wood species.

During wood processing, the primary standard for judging the processing quality is the machined surface and precision, which mainly depend on processing parameters and tool geometry (Guo et al 2018). Furthermore, chip formation changes with depth of cut and rake angle as well. Some tests reveal that different chip types may have some equivocal impacts on cutting force and cutting temperature (Guo et al 2017b). And, it is known that the cutting forces and cutting temperature are significant sources of information about experimental study. So, experiments also need reliable analysis on the impact of chip formation on cutting force and cutting temperature (Zhu et al 2017).

In this trial, the influence of rake angles and depths of cut on cutting force and cutting temperature in the orthogonal cutting of softwood and hardwood parallel to grain was investigated. The experiments were carried out on a shaper, and cutting force and cutting temperature of pine and oak were tested in process. This test also analyzed the difference of the chip formation process of pine and oak, by using a high-speed camera, and its impact on cutting force and cutting temperature.

MATERIALS AND METHODS

Test Materials and Tools

The fast-growing wood (*P. massoniana*) with an age of about 6-7 yr was chosen as the softwood and oak (*Quercus mongolica*) with an age of about 10-12 yr was chosen as the hardwood. These two species were the tested wood which were supplied by Shengxiang group Co., Ltd., Danyang, China. Experimental samples of softwood and hardwood were all cut into a size of 80 × 12 × 90 mm (radial × tangential × longitudinal) from normal sound wood and dried to a MC of 12.1% and 11.6%, respectively. The cutting was performed on the tangential surface and the cutting direction was longitudinal orientation. The moisture contents, and physical and mechanical properties of samples are shown in Table 1.

The cutting tests were carried out on a shaper. Three cutting tools made of high speed steel with different rake angles (25°, 40°, and 50°) were used in this experiment. Table 2 shows the structure parameter and mechanical properties of the tools. The cutting depth h was assigned four different levels (0.1 mm, 0.2 mm, 0.3 mm, and 0.5 mm), feed speed f was kept constant as 13.6 m/min. For keeping the cutting condition unchanged, each experiment was carried out with new resharpened tools. The tests were designed according to single factorial design and carried

Table 1. Physical and mechanical properties of pine.

Sample	Density (kg/m^3)	MC (%)	MOR (Mpa)	MOE (Mpa)
Pine	446	12.1	62.1	5089
Oak	723	11.6	108.9	10232

Table 2. The mechanical properties of tools.

Tools number	Structure parameter			Mechanical properties		
	Rake angle (°)	Wedge angle (°)	Clearance angle (°)	Rockwell hardness	Flexural strength (Gpa)	Toughness (J/m^3)
A	25	50	15	65	4.9	36
B	40	35	15	65	4.9	36
C	50	25	15	65	4.9	36

out in constant temperature conditions. Totally, 24 experiments that are given in Table 3 were performed by the combinations of cutting parameter.

Test Methods

To understand what happens during the processing wood, linear cutting was selected as the test method (Wyeth et al 2009). The diagram of the experimental system is shown in Fig 1. The cutting force and cutting temperature were tested in orthogonal cutting softwood and hardwood parallel to grain on the planer (B665 Shaper; Shenyang, China). To measure cutting forces, a quartz three-component dynamometer (Kistler 9257B; Winterthur, Switzerland) was fixed on the workbench of the shaper. An IR thermographic technique (ThermoVisionA20) was used for measuring cutting temperature in the cutting zone and a high-speed camera (OLYMPUS i-speed 3; Tokyo, Japan) was used for observing the formation of chips clearly.

As shown in Fig 2, the resultant force of frictional force F_f and normal force F_n is F. There are some relationships among them, see Eqs 1-3 (Ratnasingam et al 2009).

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

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

$$\mu = F_f / F_n = \tan\rho,$$

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

The resultant force F depends on factors such as depth of cut and rake angle. The rake angle is one of the most important cutting parameters which determines the tool/chip contact length. The normal force F_n is linked with rake angle and chip volume. The friction force F_f depends on normal force F_n and μ; so, the tool/chip contact length, rake angle, and chip volume affect F_f (Costes et al 2004).

The resultant force F could also be decomposed into parallel tool force F_x and normal tool force F_y. In this experiment, F_x and F_y could be tested directly.

Compared with the cutting force, cutting heat is complex and difficult to measure. In the cutting

Table 3. Machining parameters used in experiments.

Experience number (pine)	Rake angle γ (°)	Depth of cut h (mm)	Experience number (oak)
1	25	0.1	13
2		0.2	14
3		0.3	15
4		0.5	16
5	40	0.1	17
6		0.2	18
7		0.3	19
8		0.5	20
9	50	0.1	21
10		0.2	22
11		0.3	23
12		0.5	24

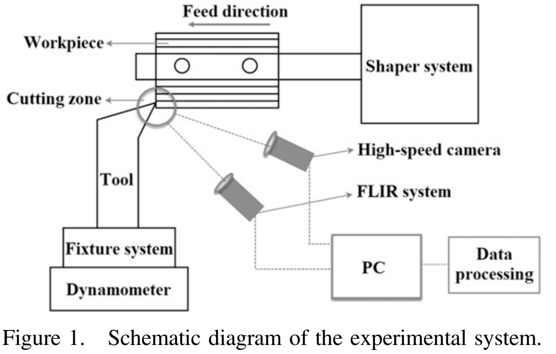

Figure 1. Schematic diagram of the experimental system.

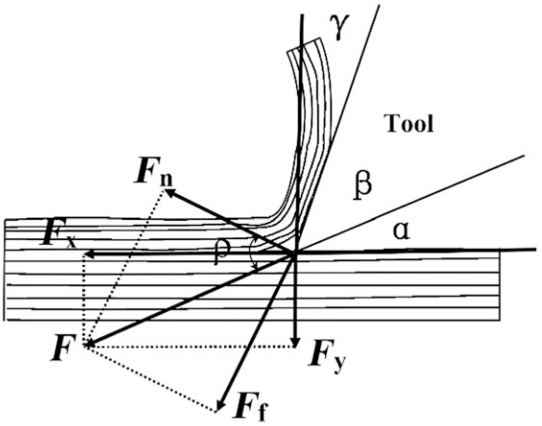

Figure 2. Cutting forces in orthogonal cutting parallel to the grain.

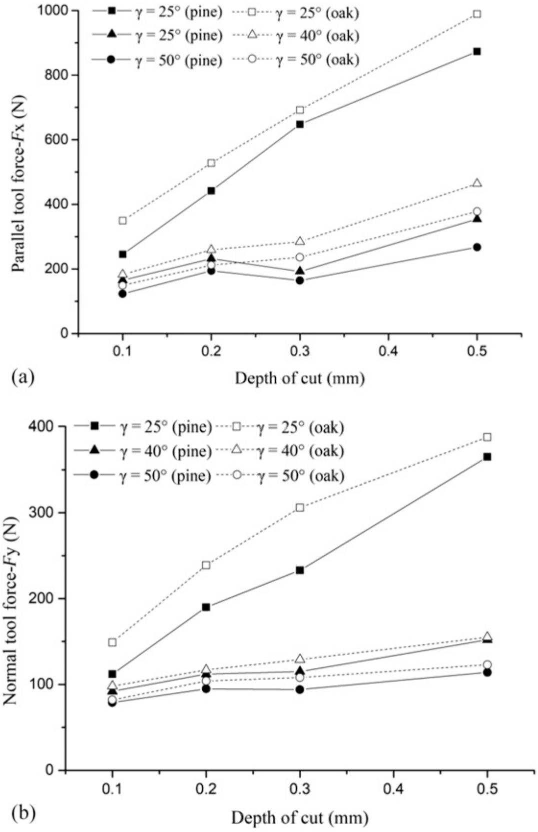

Figure 3. The parallel tool force F_x and normal tool force F_y at different cutting depths with different rake angles.

process, the tool shears the material to form chips and a new surface. So, the cutting zone temperature mainly depends on the condition of friction between the rake face and chip and between the clearance face and machined surface. The friction force F_f plays the lead role in raising the cutting temperature. Great friction force F_f will lead to a high temperature, which accelerates tool wear and reduces cutting life. Although the measurement of cutting heat is hard under these experimental conditions, it is still worthy of reference when comparing the differences in processing softwood and hardwood (Silva and Wallbank 1999; Wang et al 2004).

RESULTS AND DISCUSSION

Comparison of Cutting Force

As shown in Fig 3a and b, under the same rake angle and depth of cut, both parallel tool force F_x and normal tool force F_y of pine are larger than those of oak. Also, the cutting forces (F_x and F_y) of pine and oak are both decreased by the increase of rake angle. Besides, the cutting forces (F_x and F_y) with rake angles of 40° and 50° are much smaller than with a 25° rake angle. Generally, a large rake angle produces a larger shear angle, so, the tools with large rake angle could cut into the wood (whether it is pine and oak) easily. At this condition, the cutting forces decreased.

It also can be observed that cutting forces (F_x and F_y) of pine and oak are both increased by the increase of depth of cut, especially at a small rake angle. F_x of pine and oak at a small rake angle (25°) and large depth of cut (0.5 mm) can reach up to 784 N and 873 N, respectively, which also leaves a bad surface finish. By contrast, at the larger rake angles of 40° and 50°, the cutting forces (F_x and F_y) of samples of oak are constant with small changes when decreasing the cutting depth from 0.3 mm to 0.1 mm. This also matches the previous studies that the extent of the effect of cutting depth on cutting forces depended on the rake angle used.

The parallel tool force F_x of pine decreased a lot when the cutting depth increased from 0.2 mm to 0.3 mm with the rake angles of 40° and 50°.

By contrast, the value of F_x of oak was constant with small changes under the same condition. F_y also has similar small changes. Figure 4a-d show the cutting process of pine and oak at different depths of cut with the same 40° rake angle. At the same 0.1-mm cutting depth, flow type chip with no cleavage failure was formed by shear, and both appeared in the cutting process of pine and oak. When the depth of cut changed from 0.2 mm to 0.3 mm, chips of pine were formed by a big split ahead of the cutting tool and then bending by the rake face. By contrast, because the fracture toughness and density of oak is higher than that of pine, chips of oak was formed by a small split and then bending by rake face into a circle. So, it can be concluded that the tool/chip contact frequency in processing oak is higher than that in processing pine which lead to the abovementioned different changes of cutting forces.

Comparison of Cutting Temperature

Take the cutting process of the 40° rake angle as an example. Figure 5 shows the thermal images of pine and oak of different depths of cut. The brighter areas represent the higher cutting temperature. So, thermal images show that most of the cutting heat was mainly distributed between the rake face and chip, and most of the heat generated in the cutting process is taken away by the chips.

As shown in Fig 6, the cutting zone temperature of pine and oak both increased as the cutting depth increased and both decreased as the rake angle increased. Besides, under the same cutting depth and rake angle, the cutting zone temperature of oak was always higher than that of pine. That is because a large cutting depth means a large chip volume and a small rake angle produces a small shear angle which

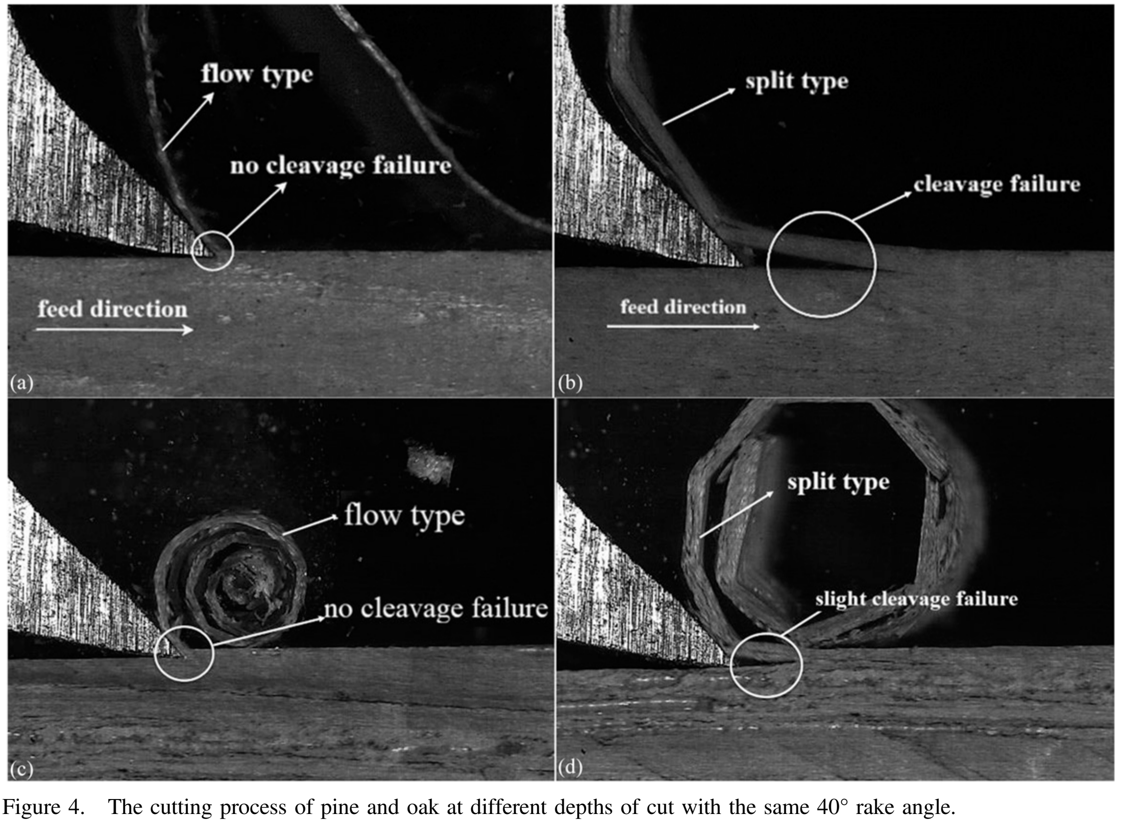

Figure 4. The cutting process of pine and oak at different depths of cut with the same 40° rake angle.

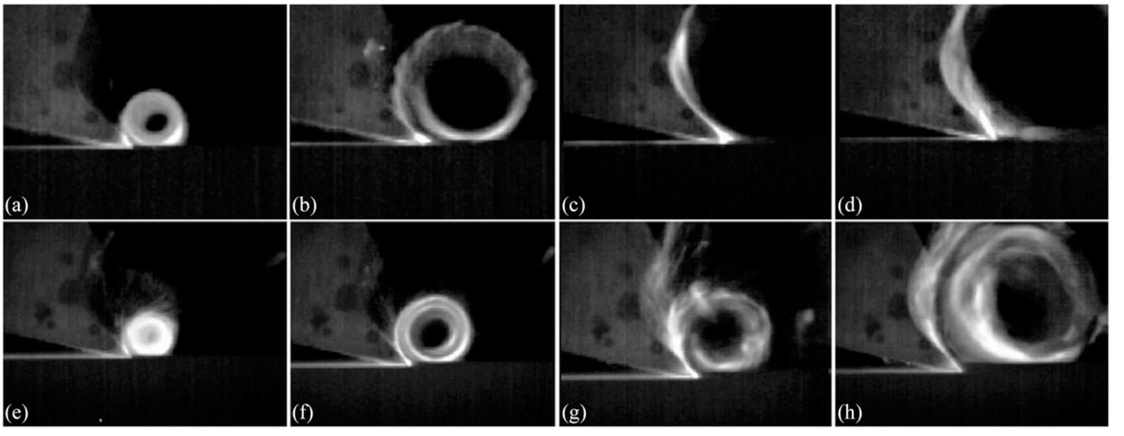

Figure 5. Thermal images with the 40° rake angle and different depths of cut.

needs more mechanical energy to overcome shear resistance and friction.

From the point of view of wood science, pine is a kind of softwood and oak is a kind of hardwood. Oak has lots of wood fibers and vessels, but soft pine does not. So, when processing hard oak, wood fibers may increase the friction forces between the tool and chips, and wood vessels may store the cutting heat constantly which may result in the higher cutting temperature. By contrast, there are no wood vessels in softwood that can store cutting heat. Because of the low density and specific gravity of soft pine, tools can also plunge into the wood and produced low cutting forces.

It is concluded when analyzing cutting force that the tool/chip contact frequency in processing oak is higher than that in processing pine. And that is also indicated by the fact that the tool/chip contact length in processing oak is greater than that of pine in unit time. So, the cutting temperature of oak was higher than that of pine. Compared with factors affecting the cutting force, different chip formation shows little or no effect on cutting temperature in processing pine and oak.

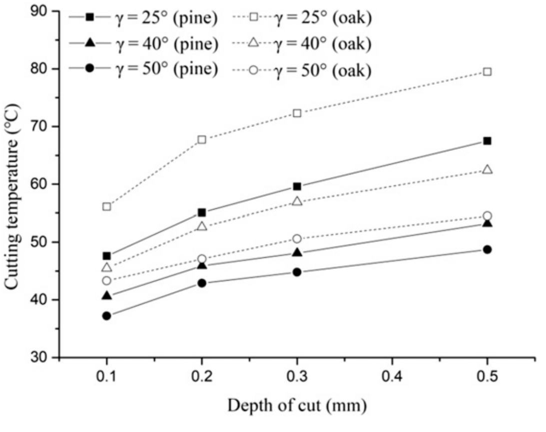

Figure 6. The cutting temperature with different rake angles and different depths of cut.

CONCLUSION

The following conclusion and observations in orthogonal cutting softwood and hardwood can be drawn from these investigations:

1. Under the same rake angle and depth of cut, the cutting forces (F_x, F_y) of hardwood are larger than those of softwood, and the cutting zone temperature of hardwood was always higher than that of softwood.
2. The cutting forces (F_x, F_y) and cutting temperature of softwood and hardwood both decreased as the rake angle increased and the depth of cut decreased.
3. Different chip formation shows little or no effect on cutting temperature in processing both softwood and hardwood, whereas the

influence degree of chip type on the cutting force of softwood is lower than that on hardwood.

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