Study on the Temperature Distribution and Natural Frequency of a Circular Saw Blade during Three Types of Wood Sawing Processes

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Abstract

The stability of a circular saw blade during the cutting process affects the knife life and the material utilization rate. In this article, continuous sawing experiments were carried out on medium-density fiberboard, *Pterocarpus soyauxii* board, and reconstituted bamboo lumber board. The temperature distribution of the saw blade surface was measured. The natural frequency of the saw blade under thermal stress was analyzed by the finite element method. The results show that the material density is positively correlated with the edge temperature of the saw blade. Greater temperature differences within the saw blade lead to worsening dynamic stability. When cutting the reconstituted bamboo lumber board, the saw blade will suddenly lose stability, and the surface temperature will rise rapidly, which greatly shortens the life of the saw blade.

Wood is an important renewable resource, which is widely used in musical instruments, furniture, and construction industries. As the main tool in wood processing, the dynamic stability of the circular saw blade directly determines the utilization rate of wood processing. A thinner thickness of the saw blade and a longer service life lead to a higher utilization rate of wood.

The cutting process will produce a large amount of heat, which enters the tool and makes the tool form a temperature gradient along the radius direction, which will reduce the dynamic stability of the tool and increase the transverse vibration of the saw blade during the cutting process. This reduces the utilization rate of the wood and the life of the saw blade. Different types of wood have different physical properties, which lead to variability in the heat generated during sawing. As such, the saw blade will show different stability profiles for different environmental conditions. It is thus necessary to analyze the temperature distribution and dynamic stability of the saw blade when cutting different kinds of wood.

Research by Darmawan et al. (2001) showed that increased cutting speed increases tool wear, but the use of coatings can reduce the amount of wear. Sheikh-Ahmad et al. (2003) analyzed the effect of machining parameters on the tool temperature distribution by measuring the tool temperature experimentally and feeding it into a numerical calculation model. Kusiak et al. (2005) analyzed the effects of coating and processing parameters on the average heat flux of a tool during wood cutting. Ratnasingam et al. (2010) tested the cutting force and tool temperature when cutting particleboard and solid wood, and the experimental results showed that the main cutting force and tool temperature change have similar rules, and there is a direct relationship between the two. Ishihara et al. (2010) used plate bending theory to calculate the natural frequency of a saw blade under thermal stress and tension stress. Pei et al. (2015) used infrared thermal imaging to analyze the change of tool temperature during the cutting of wood–plastic composites (WPC), showing that the cutting depth is the main factor affecting the tool temperature. Svorenõ et al. (2017) compared the operating temperature of saw blades with and without coating and found that the temperature gradient of the saw blades with the coating was smaller. Igaz et al. (2018) proposed a method for monitoring the tool temperature during

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Forest Prod. J. 74(3):213–219.
doi:10.13073/FPJ-D-24-00014

milling and analyzed the factors that were important. Mohammadpanah et al. (2019) monitored the online temperature of the saw blade and judged the working state of the saw blade based on the speed of the temperature change. Wei et al. (2018) analyzed the heat generated during cutting of WPC composites, and the experimental results showed that chip temperature was always higher than tool temperature. Fekiač et al. (2022) carried out an experiment of sawing plywood and extended the saw's service life by adjusting the temperature of the saw blade. Bonac et al. (2019) invented a temperature sensor device and a system for measuring temperature of a fast-moving surface. It can be used for measuring the temperature of a saw blade. A computer model of the dynamic behavior of a guided circular saw was built using a finite element model by Mohammadpanah and Lehmann (2019). That model can predict the critical temperature for a saw.

Previous research on tool temperature mainly focused on tool corrosion and wear, or tool temperature detection and control. These studies mainly focused on the milling cutter and turning tool, and when the diameter of the circular saw blade is large and the thickness is small. So, it is necessary to measure the temperature change when cutting the wood with a circular saw blade and then study its dynamic stability.

In this study, medium-density fiberboard (MDF), *Pterocarpus soyauxii* board (PSB), and reconstituted bamboo lumber board (RBLB) were selected for sawing experimentation, and the temperature of the saw blade was monitored in real time by infrared temperature sensor. The temperature field of the saw blade was input into the natural frequency calculation model established by the static/universal module of ABAQUS, and the temperature distribution and dynamic stability of the saw blade during cutting were analyzed. The results show that the saw blades are in different temperature states and have different dynamic stabilities when sawing different kinds of wood. Once the saw blade is unstable, the temperature of the saw blade surface will rise rapidly. This is because the axial displacement of the circular saw blade increases, leading to increased friction between the circular saw blade and the wood.

Materials and Methods

Materials

In this study, the saw blade used was 180 mm in diameter and 30 mm in central aperture, with 36 serrated teeth and 4 thermal expansion slots. The serrations were welded alternately left and right, with a front and back angle of 15°. The matrix thickness of the saw blade was 1.0 mm, and the width of the saw path was 1.3 mm. The sawing objects were MDF, PSB, and RBLB, all with a thickness of 30 mm. The material properties are shown in Table 1.

Table 1.—Material properties of the experimental materials.

Material	Density (kg/m^3)	Moisture content (%)
MDF	500	10
PSB	670	13
RBLB	800	12

Methods

Infrared thermometers are considered to be a reliable method for measuring cutting temperature, with reference to Emilios et al. (2022) and Heeley et al. (2018). Therefore, this study used infrared thermometers to measure the cutting heat generated during the cutting process by circular saw blades. The specific experimental design was as follows.

Sawing experiments were performed on a four-sided planer (Weinig P23EC; Fig. 1a). During the experiment, the speed of the saw blade was 6,000 rpm, the feed speed was 6,000 mm/min, and the diameter of the chuck was 60 mm. For on-line measurement of blade temperature during sawing, five infrared thermometers (Raytek MI3) were mounted on the metal frame so that the probes corresponded to the radii of the blade at 43, 56, 65, 80, and 85 mm, respectively (Fig. 1b). After the sensor probe was connected to the control box, the data were uploaded to the computer through serial communication (Fig. 1c). This study selected five sensors, distributed at different radius positions, in order to better obtain the temperature distribution in the radial direction of the circular saw blade. The sensor placement relative to the saw blade is shown in Figure 2.

To ensure testing accuracy, this study compared the test results from the infrared thermometer with those of a K-type thermocouple when the circular saw blade was heated and when heat was dissipated. The K-type thermocouple was fixed on the surface of the circular saw blades by adhesive bonding. Directly above the K-type thermocouple, the infrared thermometer was placed. The surface of the circular saw blade was bright, with an emissivity setting range of 0.25 to 0.4. When the emissivity of the sensor was set to 0.3, the temperature measured by the infrared thermometer had the best consistency with the temperature measured by the K-type thermocouple, as shown in Figure 3. The maximum difference between the temperature value measured by the infrared thermometer and the temperature value measured by the K-type thermocouple was 9°C, and the average temperature difference was 2.5°C.

In order to avoid decreased sharpness of the saw blades after prolonged cutting, new saw blades were replaced before sawing experiments on each material (Fig. 1e). The ambient temperature was 6°C to 8°C. The experimental system is shown in Figure 1.

Natural frequency calculation model for the saw blade

In the static/universal module of ABAQUS, a model for calculating the natural frequency of a rotating saw blade under a thermal load was developed in which the upper and lower surfaces of the saw blade chuck region were fixed. The modelling process referenced literature written by Yu et al. (2023) and Merhar and Dominika (2017). The S4R shell element was chosen for the saw blade model.

This study selected five sensors, distributed at different radius positions. This meant that five temperature values could be obtained in the radial direction. Normally, the temperature in the circumferential direction of a circular saw blade is considered to be uniformly distributed. Therefore, by using these five temperature values, a temperature distribution formula could be fit in the radial direction of the circular saw blade. Then, the temperature distribution formula of the saw blade during the cutting process was input into the simulation model, and the thermal stress distribution of the saw blade was obtained.

According to the rotational speed of the saw blade in the experiment, the centrifugal stress distribution of the saw blade was obtained by applying rotational force to the saw blade in the simulation model. The speed of the saw blade was 6,000 rpm, and the corresponding rotational angular velocity

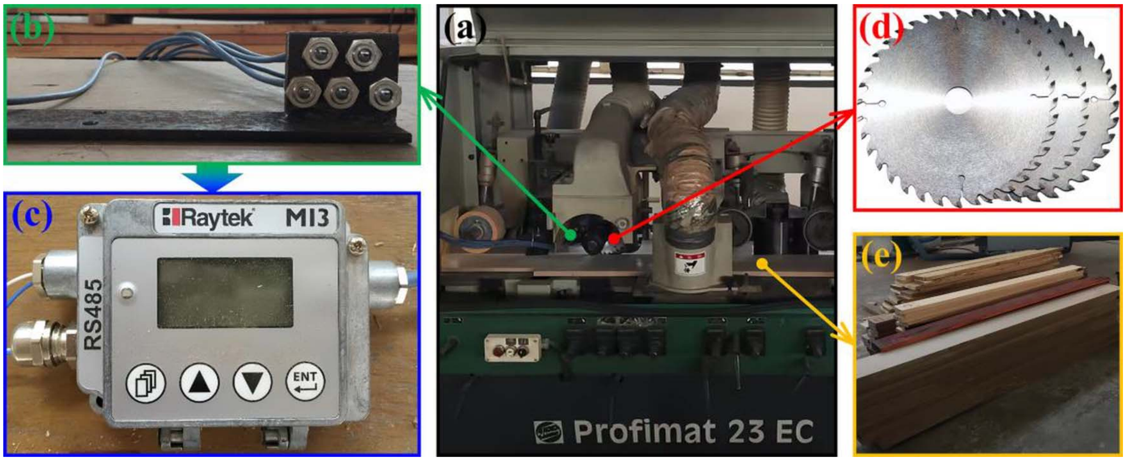


Figure 1.—Experimental system for the measurement of the saw blade temperature: (a) sawing system; (b) infrared thermometer probes; (c) infrared thermometer control box; (d) saw blade; and (e) experimental material.

was 628 rad/s. The rotational angular velocity of 628 rad/s was input into the simulation model.

A linear perturbation analysis of the saw blade under the combined action of centrifugal stress and thermal stress was carried out to obtain the natural frequency of the saw blade during cutting. The cutting temperature during the circular saw blade cutting process changes in real time. It is extremely difficult to obtain the natural frequency of a circular saw blade under a cutting thermal load through experimental methods. Obtaining the natural frequency of circular saw blades under a thermal load through simulation is currently the mainstream method. This method has been proven to be feasible and can be referenced in the literature written by Merhar and Dominika (2017), Yu et al. (2023), Merhar (2021), and Li et al. (2016).

Results and Discussion

Temperature distribution of the circular saw blade during cutting

The three types of wood selected in this study are representative of the wood types used in industries for wooden furniture, wooden doors, and artificial board. Whether it is a manufacturing enterprise or a user of circular saw blades, the cutting heat of circular saw blades during the cutting process is the focus of attention.

As shown in Figure 4, for the three types of wood selected in this study, the temperature of each position within the circular saw blade will rapidly increase when the sawing starts. Next, the saw enters a stable sawing state, and the temperature of different positions within the same cutting blade tends to stabilize. For MDF, the maximum temperature at the outer edge of the circular saw blade can reach 33°C under stable sawing conditions. For PSB, the maximum temperature at the outer edge of the circular saw blade can reach 54°C under stable sawing conditions. For RBLB, the maximum temperature at the outer edge of the circular saw blade can reach 70°C under stable sawing conditions. In a stable sawing state, a stable temperature field will form on the surface of the circular saw blade, and the accumulated heat and dissipated heat will reach a balance.

During the process of sawing RBLB, the wood cut by the circular saw blade experienced a burning phenomenon in a short period of time. This is due to the high density of RBLB. As shown in Figure 5, when the circular saw blade sawed for 32 minutes, the surface temperature of the circular saw blade suddenly increased. The maximum temperature on the surface of the circular saw blade reached around 280°C, accompanied by a harsh noise during the onset of burning. Before the occurrence of burning, the temperature field on the surface of the circular saw blade remained relatively stable. Regardless of the

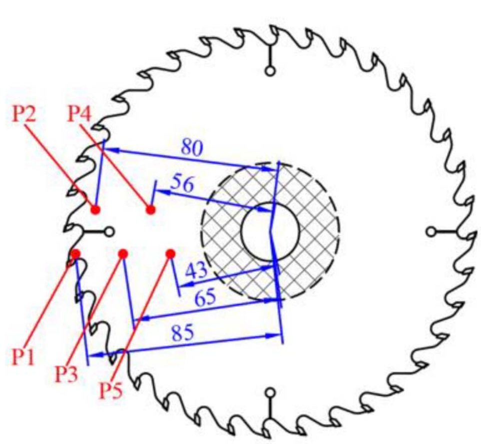


Figure 2.—Experimental system for the measurement of the saw blade temperature.

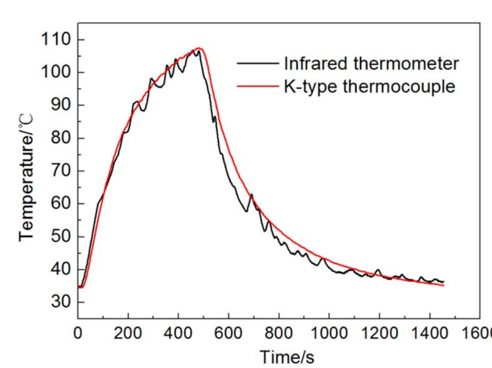


Figure 3.—Comparison between the temperature measured by the infrared thermometer and the temperature measured by the K-type thermocouple.

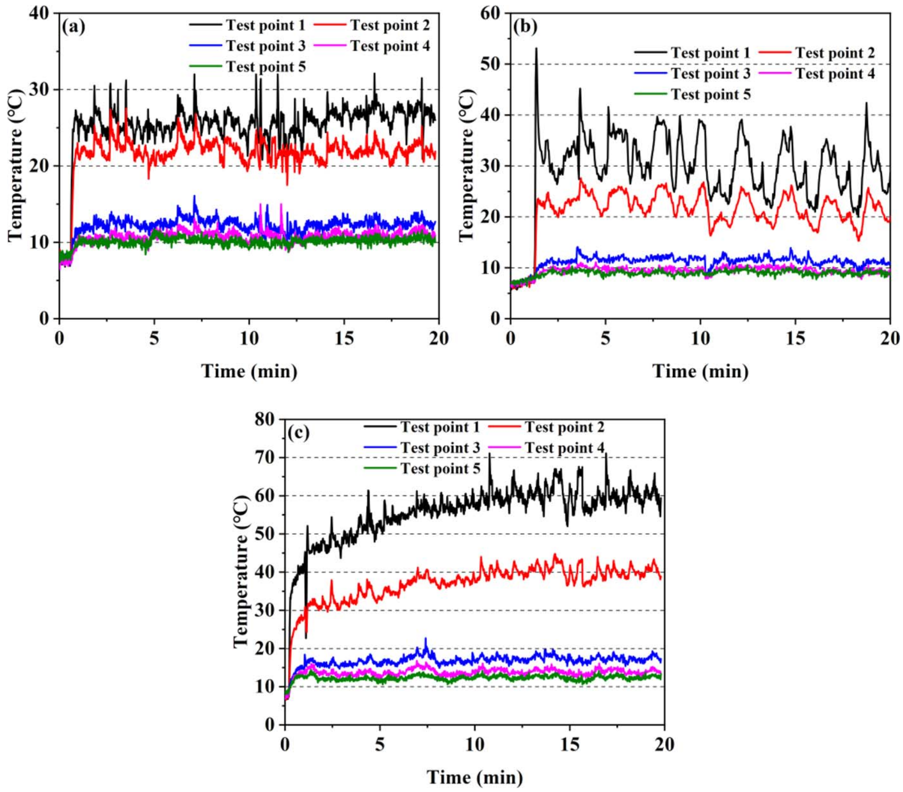


Figure 4.—Temperature distribution of circular saw blade surface during sawing with different materials: (a) medium-density fiberboard (MDF) sawing; (b) Pterocarpus soyauxii *board (PSB) sawing; and (c) reconstituted bamboo lumber board (RBLB) sawing.*

wood material, in a stable sawing state, a stable temperature field will form on the surface of the circular saw blade.

As shown in Figure 6, during the cutting process of the circular saw blade, the outer edge temperature was the highest. However, closer to the collar, the surface temperature of the circular saw blade gradually decreased to the ambient temperature. The outer edge temperature of the circular saw blade was the highest for RBLB because RBLB has a high density. The outer edge temperature of the circular saw blade was the second highest for PSB, and the outer edge temperature of the circular saw blade was the third highest for MDF. For the wood material, the density of the material largely determines its strength.

The temperature distribution formed during the cutting process of circular saw blades has been studied by many scholars, like Merhar and Dominika (2017), Yu et al. (2023), and Merhar (2021). The temperature of the circular saw blade in the circumferential direction can be considered to be uniformly distributed, and there is a consensus on this point among everyone. Therefore, the temperature distribution (T) of the circular saw blade is only related to the radius (R).

For MDF, the temperature field on the surface of the circular saw blade in a stable cutting state was calculated as follows.

$$T = 0.0127 \times R^2 - 1.253 \times R + 40.733 \qquad (1)$$

For PSB, the temperature field on the surface of the circular saw blade in a stable cutting state was calculated as follows.

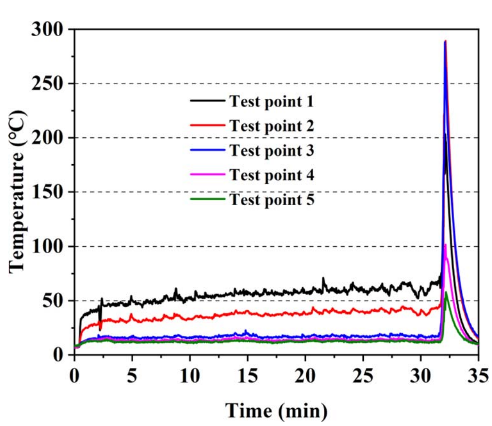


Figure 5.—Temperature field evolution of circular saw blade during complete sawing process.

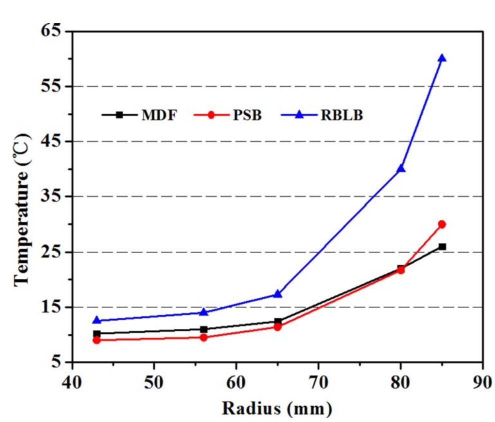
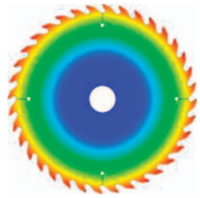
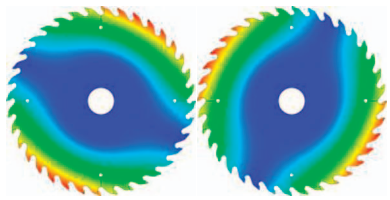
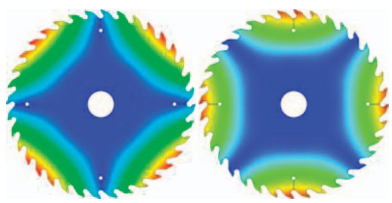
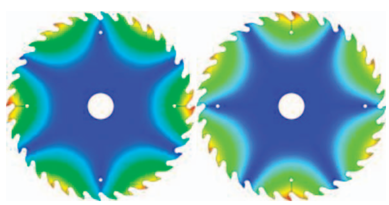
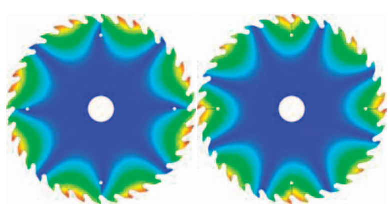


Figure 6.—Temperature distribution in radial direction of circular saw blade during sawing process.

Table 2.—Natural frequencies of circular saw blades in different states.

Vibration mode	Mode shape	Natural frequency (Hz)				
		Original	Idling	MDF	PSB	RBLB
$Nc = 0$		236	267	287	286	307
$Nd = 0$						
$Nc = 0$		237	271	281	280	291
$Nd = 1$		237	271	281	280	291
$Nc = 0$		268	306	290	290	269
$Nd = 2$		276	314	294	293	272
$Nc = 0$		394	429	386	385	328
$Nd = 3$		394	429	386	385	328
$Nc = 0$		588	618	566	564	498
$Nd = 4$		610	641	583	582	508

$$T = 0.0182 \times R^2 - 1.8678 \times R + 56.019 \quad (2)$$

For RBLB, the temperature field on the surface of the circular saw blade in a stable cutting state was calculated as follows.

$$T = 0.0016 \times R^3 - 0.261 \times R^2 + 14.214 \times R - 243.15 \quad (3)$$

Next, the temperature distribution formula of the saw blade in the cutting process was input into the simulation model, and the thermal stress distribution of the saw blade was obtained.

Natural frequency of the circular saw blade during cutting

By applying the surface temperature field of the circular saw blade obtained from the experiment to the simulation model, we obtained the natural frequency of the circular saw blade under the combined action of temperature and centrifugal force. Through our research, the thermodynamic mechanisms that occur during the working process of circular saw blades can be better understood. The research approach of this article refers to many previous studies, like Li et al. (2016), Merhar (2021), and Merhar and Dominika (2017). The simulation model for calculating the natural frequency of circular saw blades has been proven to be feasible by Yu et al. (2023).

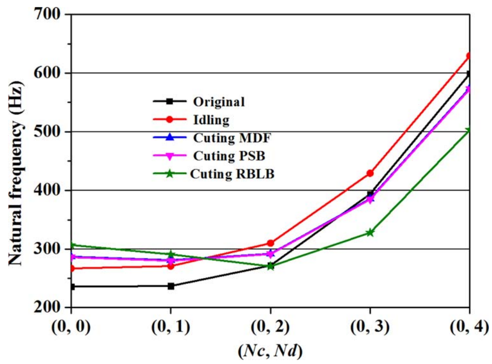


Figure 7.—Natural frequency of saw blade changes in the working state compared with the original state.

The dynamic characteristics of the structure can be characterized by modal modes and natural frequencies. The vibration mode of the circular saw blade is characterized by a node circle (Nc) and a node diameter (Nd). In the sawing process, the common vibration modes are $Nc = 0$ and $Nd = 0$ to 4. The natural frequencies of the circular saw blades in different states are shown in Table 2.

As shown in Figure 7, when the circular saw blade is idle, the centrifugal stress will effectively increase the natural frequency of each order of the saw blade, which improves the dynamic stability of the saw blade. When the circular saw blade cuts the wood material, the surface of the circular saw blade will form a temperature gradient in the radial direction, which leads to the formation of a tangential compressive stress on the outer edge of the circular saw blade. Therefore, compared with an idle saw blade, the natural frequency of mode shape ($Nd = 2$ to 4) all decreases, while the natural frequency of mode shape ($Nd = 0$ to 1) all increases. This phenomenon indicates that the dynamic stability of the circular saw blade decreases in the sawing state. During the experiment, the temperature of the outer edge of the circular saw blade was the highest, and the instability of the circular saw blade also appeared. Therefore, from the point of view of natural frequency, we can observe that under the sawing process of RBLB, the natural frequency of mode shape ($Nd = 2$ to 4) all decreases the most, and the natural frequency of mode shape ($Nd = 0$ to 1) all increases the most.

Conclusions

This study conducted continuous sawing experiments on three types of wood material. The stable temperature field formed on the surface of the circular saw blade during the sawing process was tested by an infrared temperature sensor. The stable temperature field was imported into a finite element model, and the natural frequencies of the circular saw blades during the sawing process were calculated. The following research conclusions were obtained through the experimental and theoretical data analysis.

(1) During the process of sawing wood, the circular saw blade will gradually enter a stable sawing state. In the stable sawing state, a stable temperature field will form on the surface of the circular saw blade. The outer edge temperature of the circular saw blade is the highest, and the temperature gradually approaches ambient temperature toward the collar. Through our research, wood processing enterprises can also better understand the thermodynamic mechanisms that occur during the working process of circular saw blades.

(2) Due to the differences in density properties between different wood materials, the stable temperature fields of the circular saw blade while sawing different wood material are different. This is mainly reflected in the temperature value of the outer edge of the circular saw blade. This study selected three representative types of wood materials, which can provide reference for wood processing enterprises. This article provides data support on how to optimize the use of circular saw blades for wood materials with similar properties.

(3) When the circular saw blade enters an unstable state, the surface temperature of the circular saw blade will suddenly increase. Before the circular saw blade becomes unstable, there is no abnormal temperature on the surface of the circular saw blade. It is crucial to monitor and control the temperature of the circular saw blade during the sawing process.

(4) Due to the different stable temperature fields of the circular saw blade while sawing different wood materials, the natural frequency of the circular saw blades will vary to varying degrees. A higher temperature at the outer edge of the circular saw blade will lead to worsening dynamic instability. The natural frequency of the circular saw blade under a thermal load can indirectly reflect the stability of the circular saw blade.

Acknowledgment

We gratefully acknowledge the financial support of the National Natural Science Foundation of China (no. 32171710).

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