The Flattening and Stiffening Effect of Centrifugal Stress on Circular Saw Blades in Different States

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Abstract

Circular saw blades have many states, before and during the sawing process, depending on the different residual stresses and flatness of the circular saw blades. Based on the different states of circular saw blades, the effect of rotating centrifugal stress on the dynamic stability of circular saw blades is different, mainly reflected in flattening and stiffening effects. In this article, three representative states of circular saw blades were chosen and studied. The finite element method was chosen to simulate the deformation behavior of circular saw blades in the three states. The flattening and stiffening effects of centrifugal stress on circular saw blades in the three states were systematically studied. The axial stiffness of the outer edge of circular saw blades is increased with rotating speed. The rotating speed has a flattening effect on the circular saw blade, as a result of a centrifugal stress field. When the circular saw blade is in a different state, there are some differences in the flattening and stiffening effect of centrifugal stress.

The circular saw blade, an important production tool, is used to cut metal, stone, and wood. The sawing process is efficient and saves material. The dynamic stability of circular saw blades ensures the safety and reliability of the sawing process.

Factors that cause deformation during the sawing process include vibration, elastic deformation, and blade noise. Through theoretical and experimental methods, scholars strive to reveal the causes of instability and failure of circular saw blades and put forward methods to control the dynamic stability of circular saw blades. The influence of temperature difference between the rim and center of the saw blade on dynamic stability was analyzed (Merhar and Bučar 2017). For circular saw blades with a diameter 300 mm and thickness 2.18 mm, the optimum number of radial slots is six, and the optimum length of radial slots is 30 mm. Transverse deformation of the circular saw blade during sawing is an important performance of the dynamic stability of the circular saw blade. Based on motion control and image processing techniques, an automated system was developed by Chang et al. for testing the transverse deformation of the circular saw blade (Chang et al. 2013). The effects of vibration magnitude on system response in the sub- and super-critical speed regions were computed by Khorasany and Hutton. The effects of large displacement on critical speed behavior and forced response were investigated (Khorasany and Hutton 2012). Transverse deformation of the circular saw blade during sawing causes a ''washboard'' phenomenon. An analytical model of the circular saw blade was developed by Tian and Hutton for the purpose of understanding this phenomenon (Tian and Hutton 2001). The sound radiation from a rotating circular saw blade was studied (Maeder et al. 2019). The sound power was used as a global measure for acoustic performance. By comparing with other methods, the results of the model showed good agreement. Using a theoretical formula, an analytical tensioning model of thin inner-diameter saw blade with nonlinear large deformation was established (Pei et al. 2019). The transversal, radial, and circumferential displacements and in-plane stresses of the thin saw blade were solved analytically. A mathematical model of the inner-diameter slicing was presented (Pei and Zhang 2021). The developed mathematical model was meaningful and beneficial to understand the dynamic characteristics and wafer forming mechanism during the slicing process of the inner-diameter saw blade. The noise level of three structurally different circular saw blades was compared (Svoren et al. 2021).

When a circular saw blade is sawing, a temperature field is produced in the body of the circular saw blade, which cannot be mitigated by coolant. Instead, a tensioning process is used to generate a residual stress field for the saw blade body, which can counteract the thermal stress caused by the cutting

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temperature field. The roll tensioning process, the multi-spot pressure tensioning process, and the laser shock tensioning process have been studied by many scholars, using theoretical and experimental means (Cristovao et al. 2012; Li et al. 2015, 2016; Merhar et al. 2017; Li and Zhang 2018, 2019). Meanwhile, the circular saw blade has a high speed in the process of wood sawing. Initial shape, residual stress fields, cutting thermal stress, and rotating centrifugal stress are all factors affecting sawing stability of the circular saw blade.

The circular saw blade rotates at high speeds during the sawing process. Its speed can range from 3000 to 5000 r/min, or even higher. Owing to the action of rotating centrifugal force, a centrifugal stress field will be formed inside the circular saw blade, which is manifested as tangential tensile stress and radial tensile stress. Owing to the effect of the centrifugal stress field, the axial stiffness of the circular saw blade will be significantly improved, which is called a stiffening effect. The centrifugal stress field can also reduce the flatness of the circular saw blade, which is called a flattening effect. The above research results have been reported in the existing literature.

The flatness, tensioning stress field, and cutting thermal stress are all manifestations of the circular saw blade's state. Considering the different states of the circular saw blade, it is worth studying the different stiffening and flattening effects of the centrifugal stress field on the circular saw blade. The research results have guiding significance for the manufacturing process of the circular saw blade and usage maintenance of the circular saw blade.

Material and Methods

The circular saw blade was modeled by the finite element method, using ABAQUS software. The outer diameter, inner diameter, and thickness of the circular saw blade were 320, 120, and 1.2 mm. The sawtooth shape and hole and groove structure of the circular saw blade were not considered. The circular saw blade was made by 65Mn. The elastic modulus of the circular saw blade was 210 GPa. The Poisson ratio of the circular saw blade was 0.3. The density of the circular saw blade was 7.8 g/cm^3. The shell element was chosen for the circular saw blade. The total number of elements was 4800. The circular saw blade was meshed as shown in Figure 1.

The constraint conditions were as follows. The inner hole of the circular saw blade was fixed. The rotating centrifugal force was applied to the whole body of the saw blade. The value of the rotating centrifugal force was adjusted according to the rotation speed of the circular saw blade. The rotation speeds of the circular saw blade were 3000, 4000, and 5000 rpm.

In order to simulate the influence of the tensioning stress field caused by the tensioning process, the temperature load was applied to the whole body of the circular saw blade, which is linearly decreased from the center of the circular saw blade to the outer edge of the circular saw blade. The temperature difference between the outer edge and the inner edge of the circular saw blade was the key factor. The temperature of the outer edge of the circular saw blade can be set to 0°C or any other temperature. The temperature load was used to form a tensioning effect to the outer edge of the circular saw blade. It should be noted that the focus of this article was not the roll tensioning process or other tensioning methods, but the simplified circular saw blade with ideal disc structure. Therefore, we did not pay attention to the elastic–plastic deformation during the tension process. The goal was to make the circular saw blade produce a tensioning effect and form a simplified tensioning stress field quickly, which can help us quickly form a qualitative analysis.

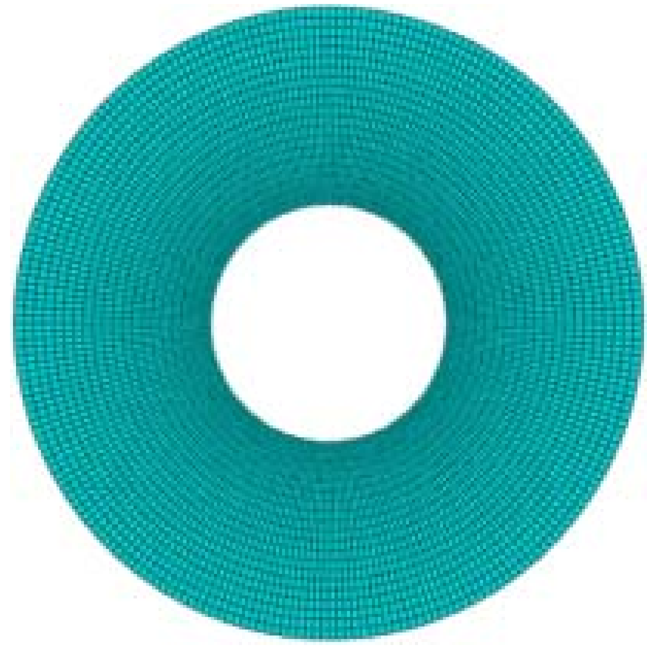

Figure 1.—Meshing of circular saw blade.

In order to simulate the influence of cutting thermal stress, the temperature load was applied to the whole body of the circular saw blade. The temperature load was used to form cutting thermal stress. It should be noted that the temperature increase process of the circular saw blade during the sawing was not the focus of this article. Therefore, a simplified cutting temperature was applied to the circular saw blade. The cutting temperature distribution model referred to Merhar (2021), which is linearly increased from the center of the circular saw blade to the outer edge of the circular saw blade. In the process of modeling, the cutting temperature load with a certain distribution pattern was applied to the circular saw blade.

After initial flatness, tensioning stress field, cutting thermal stress, centrifugal stress field, or other external factors are applied to the circular saw blade, the axial stiffness of the outer edge of the circular saw blade is calculated. A concentrated force was applied to the outer edge of the circular saw blade. The displacement of the force point can be calculated by the finite element method. The axial stiffness of the outer edge of the circular saw blade can be obtained by dividing the concentrated force by the displacement.

Results and Discussion

The flattening and stiffening effect of centrifugal stress on circular saw blades in different initial shapes

There is one situation where a circular saw blade has no residual stress field, but the initial state is uneven. For the dish shape example, place the circular saw blade on a flat surface, and the outer edge of the circular saw blade has a displacement above the central hole, as shown in Figure 2. For this situation, the flattening and stiffening effect of the centrifugal stress field

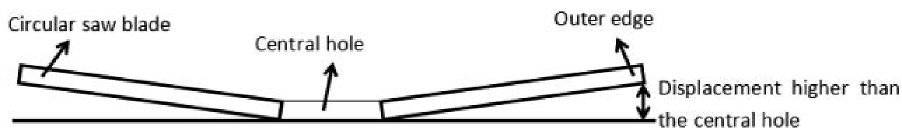

Figure 2.—Circular saw blade with initial dish shape.

on the circular saw blade has its particularity. The results and discussion are shown below. Four cases for circular saw blade were selected for analysis. For these four cases, the displacements of the outer edge of the circular saw blade above the central hole in the initial state were 0.4, 0.2, 0.15, and 0.1 mm respectively.

As shown in Figure 3, the centrifugal stress field can reduce the displacement of the outer edge of the circular saw blade above the central hole, which is called the flattening effect. The final displacement of the outer edge of the circular saw blade above the central hole is reduced with the rotation speed of the circular saw blade. This shows that the flattening effect is enhanced with rotation speed. The simulation also shows that the circular saw blade cannot be flattened completely when the rotation speed is changed in a limited range. For example, when the initial displacement of the outer edge of the circular saw blade above the central hole is 0.1 mm, at the rotation speed 5000 rpm, the final displacement of the outer edge of the circular saw blade above the central hole is 0.05 mm. This displacement occurs because the initial displacement of the outer edge of the circular saw blade above the central hole comes from the permanent deformation of the circular saw blade itself, not from the instability deformation caused by the imbalance of the stress field.

As shown in Figure 4, when a circular saw blade is rotating, a centrifugal stress field is formed in the circular saw blade. When the rotation speed is 5000 rpm, the maximum radial and tangential stresses can reach to 45 and 18 MPa. The radial centrifugal stress is decreased with the distance from the center of the circular saw blade. The tangential centrifugal stress is increased first and then decreased with the distance from the center of the circular saw blade. The initial shape of the circular saw blade has a certain effect on the value of centrifugal stress, because an additional stress field is generated during the flattening process of the circular saw blade.

Centrifugal stress shows radial tensile stress and tangential tensile stress. The axial stiffness of the outer edge of the circular saw blade is improved because of centrifugal stress. As shown in Figure 5, the axial stiffness of the outer edge of the circular saw blade is increased with rotation speed. This happens because the centrifugal stress is increased with rotation speed. Although the initial shape of the circular saw blade has a certain effect on the value of centrifugal stress, the effect has little influence on the axial stiffness of the outer edge of the circular saw blade. The axial stiffness of the outer edge of the circular saw blade is almost constant, with the initial displacement of the outer edge of the circular saw blade above the central hole.

The flattening and stiffening effect of centrifugal stress on the circular saw blade in different prestress fields

There is one situation where the initial shape of the circular saw blade is a plane and the circular saw blade has a negligible residual stress field. After roll tensioning or hammering processes, the prestress field is generated inside the circular saw blade, which can counteract the cutting thermal stress. When the value of the prestress field exceeds a certain limit, the circular saw blade will lose its stability and produce dish deformation. For this situation, the flattening and stiffening effect of the centrifugal stress field on the circular saw blade has its particularity. In this part, temperature distribution along the radius was applied to the circular saw blade. The temperature was decreased with the distance from the center of the circular saw blade.

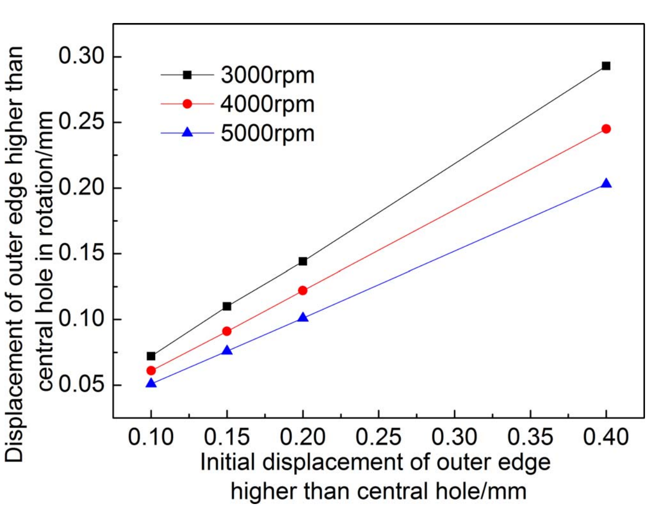

Figure 3.—Displacement of outer edge of circular saw blade above central hole in rotating state.

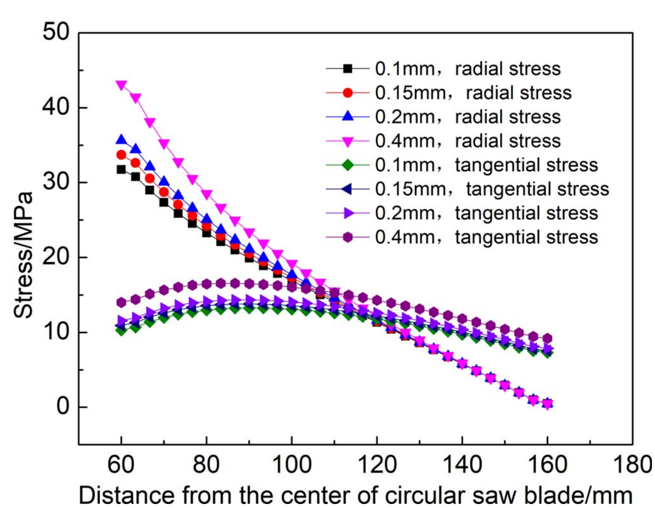

Figure 4.—Centrifugal stress field of circular saw blade in rotating state.

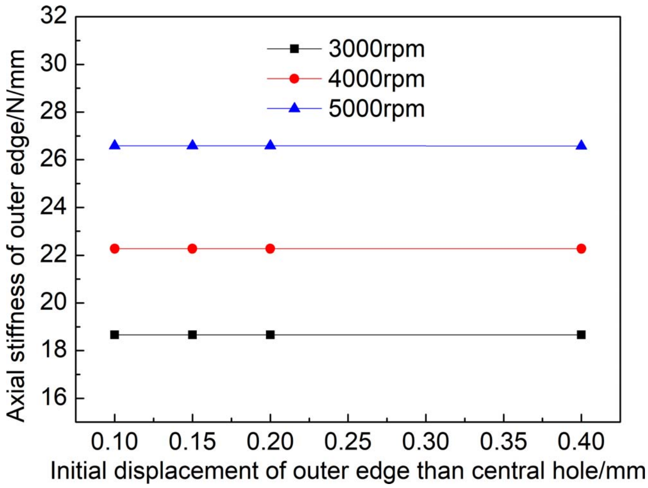

Figure 5.—Axial stiffness of outer edge of circular saw blade in rotating state.

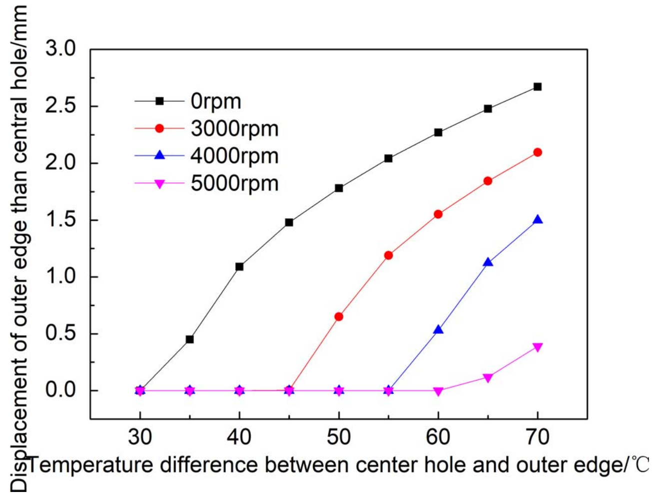

Figure 7.—The "dish" deformation of circular saw blade under temperature load.

The outer edge of the circular saw blade can form a tensioning effect by this temperature distribution. This modeling method can simulate the prestress field formed after the tensioning process of the circular saw blade. The rotation speeds of the circular saw blade were 3000, 4000, and 5000 rpm.

As shown in Figure 6, when the temperature of the inner hole of the circular saw blade is 60°C above the outer edge, the circular saw blade loses its stability and produces dish deformation. The displacement of the outer edge above the central hole reaches 2.271 mm. In application, people usually call this phenomenon ''movable core.'' Academically, scholars call this phenomenon buckling instability of the circular saw blade.

As shown in Figure 7, when the temperature of the inner hole of the circular saw blade is 35°C above the outer edge and the circular saw blade has no rotating centrifugal force, the displacement of the outer edge of the circular saw blade above the central hole reaches to 0.5 mm. When the temperature of the inner hole of the circular saw blade above the outer edge is less than 35°C, even if the circular saw blade does not have the effect of a centrifugal stress field, it can remain in an acceptable plane. When the rotation speed of the circular saw blade is 3000 rpm, as long as the temperature of the inner hole of the circular saw blade above the outer edge does not exceed 45°C, the circular saw blade can still be maintained in an acceptable plane state. When the rotation speed of the circular saw blade is 4000 rpm, as long as the temperature of the inner hole of the circular saw blade above the outer edge does not exceed 55°C, the circular saw blade can still be maintained in an acceptable plane state. When the rotation speed of the circular saw blade is 5000 rpm, as long as the temperature of the inner hole of the circular saw blade above the outer edge does not exceed 60°C, the circular saw blade can still be maintained in an acceptable plane state. There is a critical temperature difference for the circular saw blade at different speeds. Once the critical temperature difference is exceeded, the circular saw blade will produce large out-of-plane displacement. The critical temperature difference between the inner hole of the circular saw blade and the outer edge is increased with the rotation speed of the circular saw blade.

As shown in Figure 8, the axial stiffness of the outer edge of the circular saw blade is decreased with the temperature of the inner hole of the circular saw blade above the outer edge. The closer the circular saw blade is to the ''movable core'' state, the closer it is to the unstable state. Therefore, the axial stiffness of the outer edge of the circular saw blade is decreased.

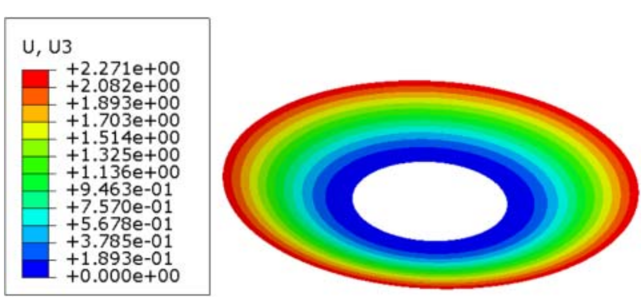

Figure 6.—The "dish" deformation of circular saw blade (Unit: mm).

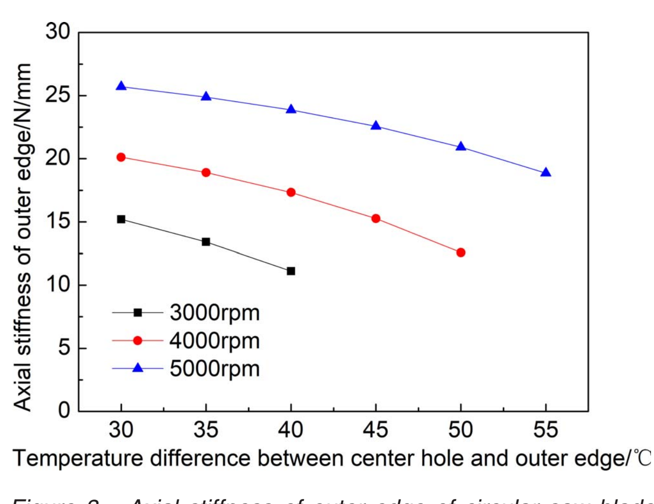

Figure 8.—Axial stiffness of outer edge of circular saw blade under temperature load.

The flattening and stiffening effect of centrifugal stress on the circular saw blade in different cutting temperature distributions

During the sawing process, heat is generated in the outer edge of the circular saw blade, resulting in temperature increase. In the process of temperature conduction to the interior of the circular saw blade, the temperature distribution along the radius direction is formed. The temperature is decreased from the outer edge to the central hole. The cutting temperature will cause cutting thermal stress of the circular saw blade. In this part, temperature distribution along the radius was applied to the circular saw blade. The temperature was increased with the distance from the center of the circular saw blade. This modeling method can simulate cutting the thermal stress field and thermal deformation of the circular saw blade. The rotation speeds of the circular saw blade were 3000, 4000, and 5000 rpm. Periodic vibration excitation of the circular saw blade in the sawing process has an effect on the stress field in the sawing area of the circular saw blade. It will excite the vibration of the circular saw blade, but it does not affect the flattening effect of the centrifugal stress on the circular saw blade. Therefore, it should be noted that the periodic vibration excitation of the circular saw blade in the sawing process was not introduced into analysis.

As shown in Figure 9, when the temperature of the outer edge of the circular saw blade above the inner hole reaches to 60°C, the outer edge of the circular saw blade produces obvious wavy deformation, and the maximum out-of-plane displacement is 1.852 mm. When the temperature of the outer edge of the circular saw blade above the inner hole is increased, tangential compressive stress is formed in the outer edge of the circular saw blade. When the tangential compressive stress in the outer edge of the circular saw blade exceeds a certain value, the circular saw blade will buckle, and wavy deformation is produced. At this time, if the circular saw blade is in the sawing state, it will burn quickly, resulting in tool damage.

As shown in Figure 10, when the temperature of the outer edge of the circular saw blade is 30°C above the inner hole and the circular saw blade has no rotating centrifugal force, the maximum out-of-plane displacement at the outer edge reaches 0.25 mm. When the temperature of the outer edge of the circular saw blade above the inner hole is less than 30°C, even if the circular saw blade does not have the effect of the centrifugal stress field, it can basically remain in an acceptable plane. When the rotation speed of the circular saw blade is 3000 rpm, as long as the temperature of the outer edge of the circular saw blade above the inner hole does not exceed 40°C, the circular saw blade can still be maintained in an acceptable plane state. When the rotation speed of the circular saw blade is 4000 rpm, as long as the temperature of the outer edge of the circular saw blade above the inner hole does not exceed 50°C, the circular saw blade can still be maintained in an acceptable plane state. When the rotation speed of the circular saw blade is 5000 rpm, as long as the temperature of the outer edge of the circular saw blade above the inner hole does not exceed 55°C, the circular saw blade can still be maintained in an acceptable plane state. There is a critical temperature difference for circular saw blades at different speeds. Once the critical temperature difference is exceeded, the circular saw blade will produce large out-of-plane displacement. The critical temperature difference between the inner hole of the circular saw blade and the outer edge is increased with the rotation speed of the circular saw blade.

As shown in Figure 11, the axial stiffness of the outer edge of the circular saw blade is decreased with the temperature difference between the outer edge of the circular saw blade and the inner edge. The closer the circular saw blade is to the wavy deformation state, the

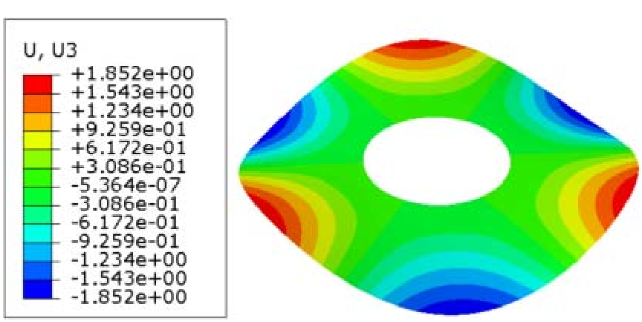

Figure 9.—Circular saw blade with wavy deformation (Unit: mm).

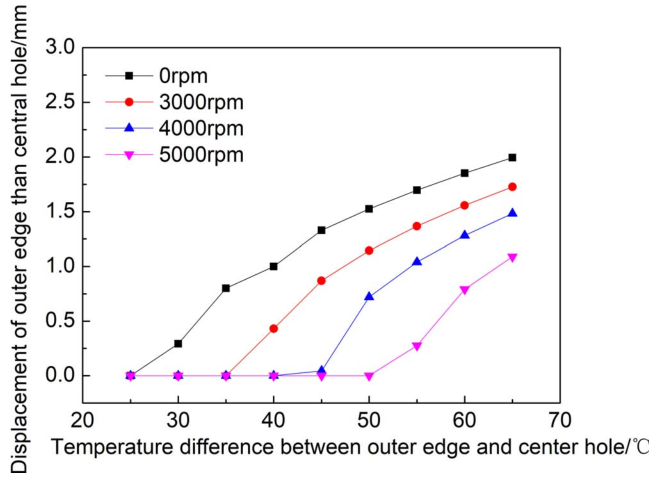

Figure 10.—The "wavy" deformation of circular saw blade under cutting temperature load.

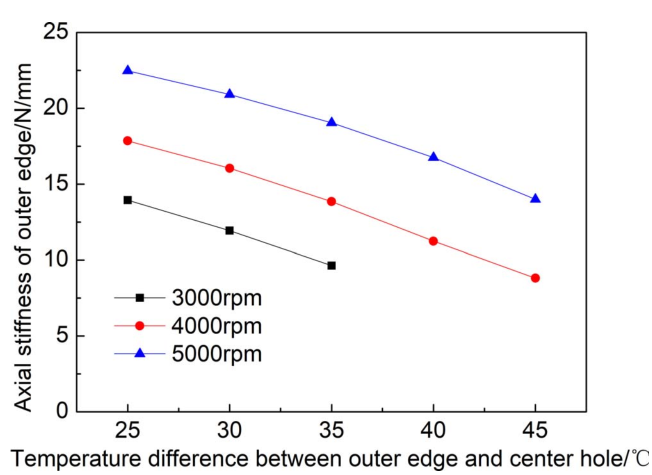

Figure 11.—Axial stiffness of outer edge of circular saw blade under cutting temperature load.

closer it is to the unstable state. Therefore, the axial stiffness of the outer edge of the circular saw blade is bound to show a downward trend.

Conclusion

(1) The rotating speed can generate centrifugal stress field in the circular saw blade, including radial and tangential tensile stresses. The axial stiffness of the outer edge of the circular saw blade is increased with rotating speed.

(2) Regardless of the initial state of the circular saw blade, the rotating speed has a flattening effect on the circular saw blade, due to the existence of centrifugal stress fields.

(3) The circular saw blade with the dish shape itself cannot be flattened completely when the speed changes from 3000 to 5000 rpm. The circular saw blade with dish shape caused by the residual stress or cutting temperature cannot be flattened completely when the speed changes from 3000 to 5000 rpm and the dish deformation is within a certain range.

Acknowledgments

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