Research on the Effect of Heat Tensioning on the Dynamic Stability of Circular Saw Blades with External Scrapers

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Abstract

Heat tensioning was proposed and proved to be effective for improving the dynamic stability of circular saw blades with ideal disk structure by a previous scholar. With the diversification of circular saw blade structure, circular saw blades with external scrapers are widely favored by the market because of their excellent resistance to sawing thermal stress. For circular saw blades with external scrapers, the effect of heat tensioning on the dynamic stability of the blades needs to be further studied. Therefore, the heat tensioning process of circular saw blades with external scrapers was built by the finite element method. The stress field and critical rotational speed of circular saw blades with a different structure after the heat tensioning process were calculated and analyzed. The relationships between circular saw blade structure, the dynamic stability of circular saw blades, and the heat tensioning process are clarified in this article. The results show that heat tensioning is not valid for all types of circular saw blades. For circular saw blades with external scrapers, the effect of heat tensioning on improving the critical rotation speed of the blades is gradually decreased with the number of external scrapers. When circular saw blades are heat tensioned, the average tangential stress of the outer edge of the blades and the critical rotation speed of the blades are higher.

Circular saw blades are the main cutting tools for cutting wood, metal, and other materials. Such blades have the characteristics of high processing efficiency and material saving. During the sawing process, circular saw blades will form a large temperature gradient, with high temperatures on the outer edge and low temperatures inside (Svoreň et al. 2022). Nasir et al. (2021) proposed a sensor fusion–based approach for indirect monitoring of the temperature of circular saw blades by acoustic emission sensors. Merhar (2021) studied the evolution law of the natural frequency of circular saw blades under cutting temperature load. In order to alleviate the adverse effects of cutting thermal stress, the optimum number and length of radial slots was proposed (Merhar and Dominika 2017). The temperature gradient will lead to the thermal stress field of circular saw blades, which is not conducive to the dynamic stability of the blades in the sawing process.

In order to mitigate the adverse effects of sawing heat, innovative work on sawtooth blades was carried out by scholars. Linear microtextures that parallel the sawtooth edge were fabricated on the surface of the blades by laser engraving. Lu et al. (2021) proved that this method can reduce the cutting temperature of circular saw blades. Li et al. (2017) proposed the use of sawtooth blades with a mic-zero-degree radial clearance angle, and it was proved to be effective for reducing the friction of the blades. An approach of deposition for uniform diamond films was proposed by Zhou et al. (2017) on circular saw blades made of cemented carbide using reflectors of brass sheets. Wilkowski et al. (2022) presented the effect of nitrogen ion implantation on

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tool wear and tool life during the sawing of wood-based materials.

In addition to the innovation of the sawtooth of circular saw blades, that of the circular saw blade body is also a focus in academic circles. A certain distribution of residual stress field should be generated inside the body of circular saw blades through the tensioning process. The tensioning process is beneficial to improve the dynamic stability of circular saw blades. Li et al. (2016) studied the residual stress distribution of a roll-tensioned circular saw blade by the finite element method. The generation and regulation mechanisms of the residual stress field of circular saw blades after multispot pressure tensioning were analyzed by Li and Zhang (2019a). The theoretical analysis model of the laser shock tensioning process was built by Li and Zhang (2018) based on laser shock wave theory. Laser energy, spot diameter, and impact zone distribution have a great effect on the residual stress field of circular saw blades. Li and Zhang (2019b) tried to use elastic thermal expansion to replicate the expansion effect of the plastic deformation zone. This approach was proved to be an effective way of obtaining the residual stress field of circular saw blades quickly. Droba et al. (2015) studied the critical rotational speed of several circular saw blades through a combination of theory and experiment. Ahmad and Stanley (2015a) studied the flutter instability speeds of guided splined disks and revealed the cause of this phenomenon through theoretical and experimental methods. The effect of circular saw rotation speed on power consumption and cutting accuracy was studied. Research results show that there is a significant increase in power consumption when cutting at super-critical and super-flutter speeds. The effect of rotation speed on sawing accuracy is complex and nonlinear (Nasir et al. 2020). The dynamic behavior of a guided splined circular saw was studied by the software MSC ADAMS and ANSYS, which can predict the critical speeds and flutter instability zones of a guided splined saw (Ahmad and Stanley 2015b).

Schajer and Kishimoto (1996) first put forward the principle of temporary tensioning, also called heat tensioning. The heat tensioning process is as follows. As shown in Figure 1, during the wood sawing process, an induction heater is placed on one side of the circular saw blade. As the blade rotates, the circular area on the surface of the blade is heated by the induction heater. The elastic thermal expansion of the circular area creates a tensioning effect on the outer edge of the blade. For blades with an ideal disk structure, this method is beneficial to improve the dynamic stability of the blade under working conditions. Previous

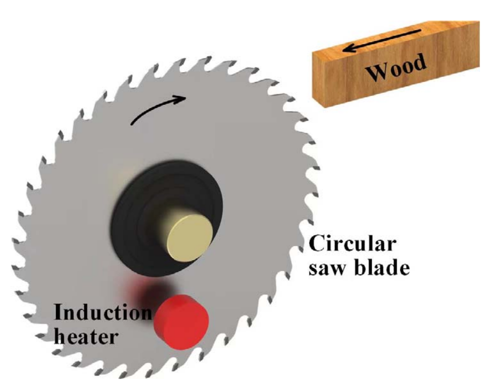

Figure 1.—Schematic diagram of heat tensioning process.

research results show that tangential tensile stress is generated at the outer edge of circular saw blades and that the critical rotational speed of the blades is increased during the temporary tensioning process. These are the reasons why the dynamic stability of circular saw blades is improved after temporary tensioning.

With the continuous development of circular saw blade manufacturing technology, the structure of circular saw blades has also changed. Due to their excellent resistance to sawing thermal stress, circular saw blades with external scrapers are widely favored by the market. Strictly speaking, this kind of circular saw blade is no longer an ideal disk structure (Li and An 2022). Therefore, for circular saw blades with external scrapers, there are some questions that need to be studied and answered. For circular saw blades with external scrapers, how does temporary tensioning affect the dynamic stability of the blade? During the temporary tensioning process, how do the stress field and critical rotational speed evolve?

This article focuses on the above scientific and technological issues. The research results can provide key scientific data and theoretical support for circular saw blade application enterprises.

Materials and Methods

Main parameters of circular saw blades

Three types of circular saw blades were studied in this article, as shown in Figure 2. Circular saw blade 1 was an ideal disk structure. Circular saw blade 2 had two external scrapers on the outer edge of the blade. Circular saw blade 3 had four external scrapers on the outer edge of the blade.

For these three types of circular saw blades, outer edge diameter, collar diameter, and thickness were 355, 120, and 2 mm, respectively. They were made by 75Cr1. The density, modulus of elasticity, Poisson's ratio, and expansion coefficient of various types of steel are very similar. We have determined the values of these parameters by referring to some existing literature (e.g., Li and An 2022). Material parameters are shown in Table 1.

Finite element model of circular saw blade heating in the annular region

ABAQUS finite element software was chosen for simulation. Due to the thickness of the circular saw blade being much smaller than the diameter of the blade, the S4R shell element was chosen for the blade. The meshing of the three circular saw blades is shown in Figure 3. For circular saw blade 1, the number of S4R shell elements was 10,583. For circular saw blade 2, the number of S4R shell elements was 10,375. For circular saw blade 3, the number of S4R shell elements was 10,216. After evaluation of the mesh convergence checking function of ABAQUS, the meshing of the three blades was feasible.

For heat tensioning, the circular area of the circular saw blade is heated. The inner circle diameter of the annular heating area was 160 mm. The outer circle diameter of annular heating area was 240 mm. The uniform distribution of temperature along the circumference should be understandable because the circular saw blade rotates at a constant speed. The heat generated in the heating area will be transferred from the high-temperature area to the low-temperature area inside the blade during the heat tensioning process. At the same time, the blade undergoes convective

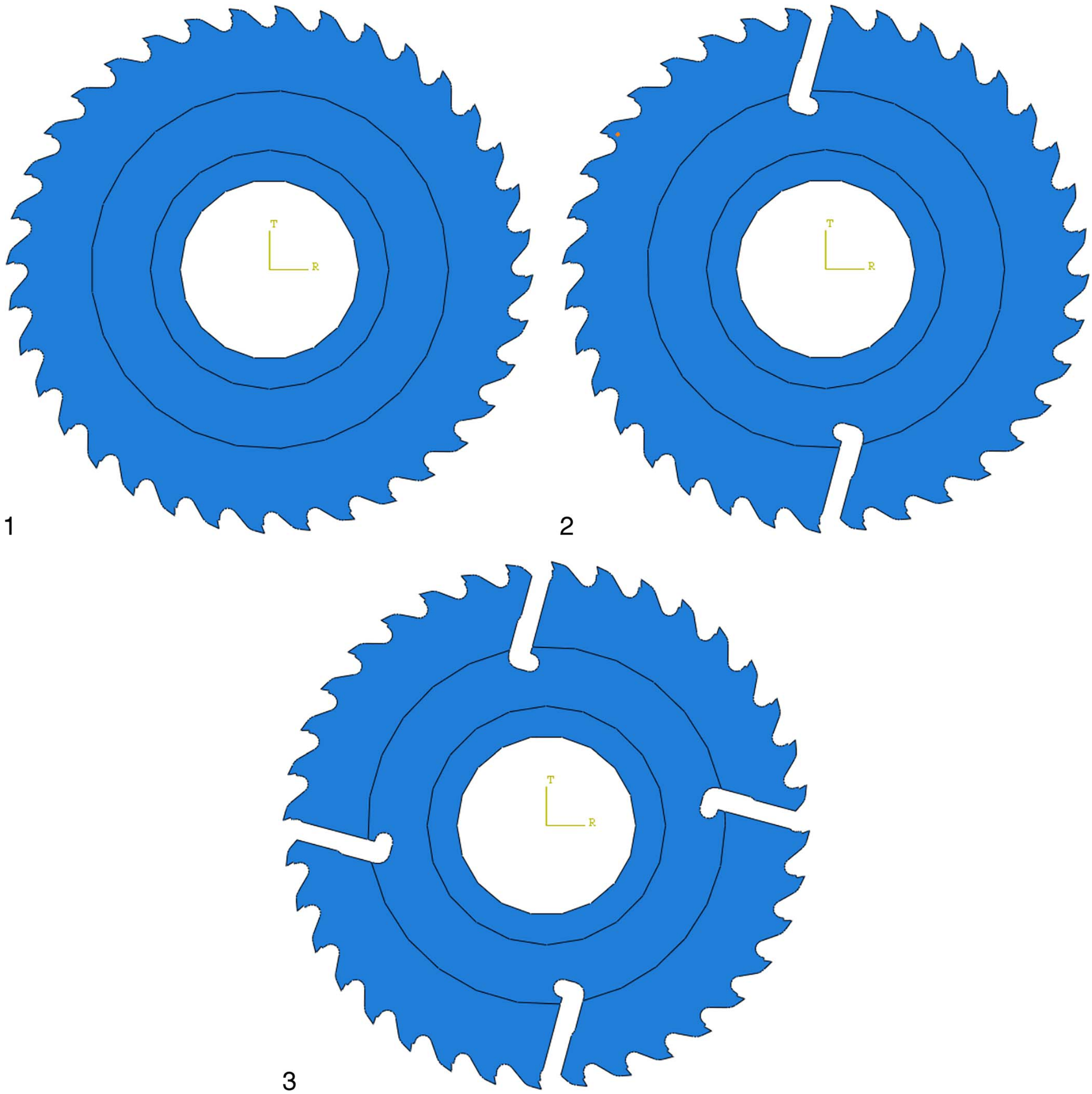

Figure 2.—Three types of circular saw blades: (1) circular saw blade 1 with ideal disk structure; (2) circular saw blade 2 with two external scrapers; (3) circular saw blade 3 with four external scrapers.

heat transfer with air. The higher the temperature of the blade, the greater the heat transfer between it and the air. Due to the small thermal inertia of the blade, the input heat source and heat dissipation will quickly reach an equilibrium state, keeping the temperature field of the blade stable.

Table 1.—Material parameters of saw blades.

Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Expansion coefficient (1/K)
7,850	210,000	0.3	0.00001

The temperature field of the blade after heat tensioning can be calculated by the heat transfer module of ABAQUS. In order to obtain the temperature field of the circular saw blade, some thermodynamic parameters need to be set. The thermal conductivity of the blade was set to 46 W/(m·°C) (Abou and Wuthrich 2012). The convective heat transfer coefficient between the blade and air was set to 22.35 W/(m^2·°C) (Hu et al. 2003). In the model, the collar area was assumed to be a constant reference temperature (0°C), and the influence of thermal radiation is ignored. The temperature difference in the radial direction of the blade is formed. The maximum temperature of the heating area was

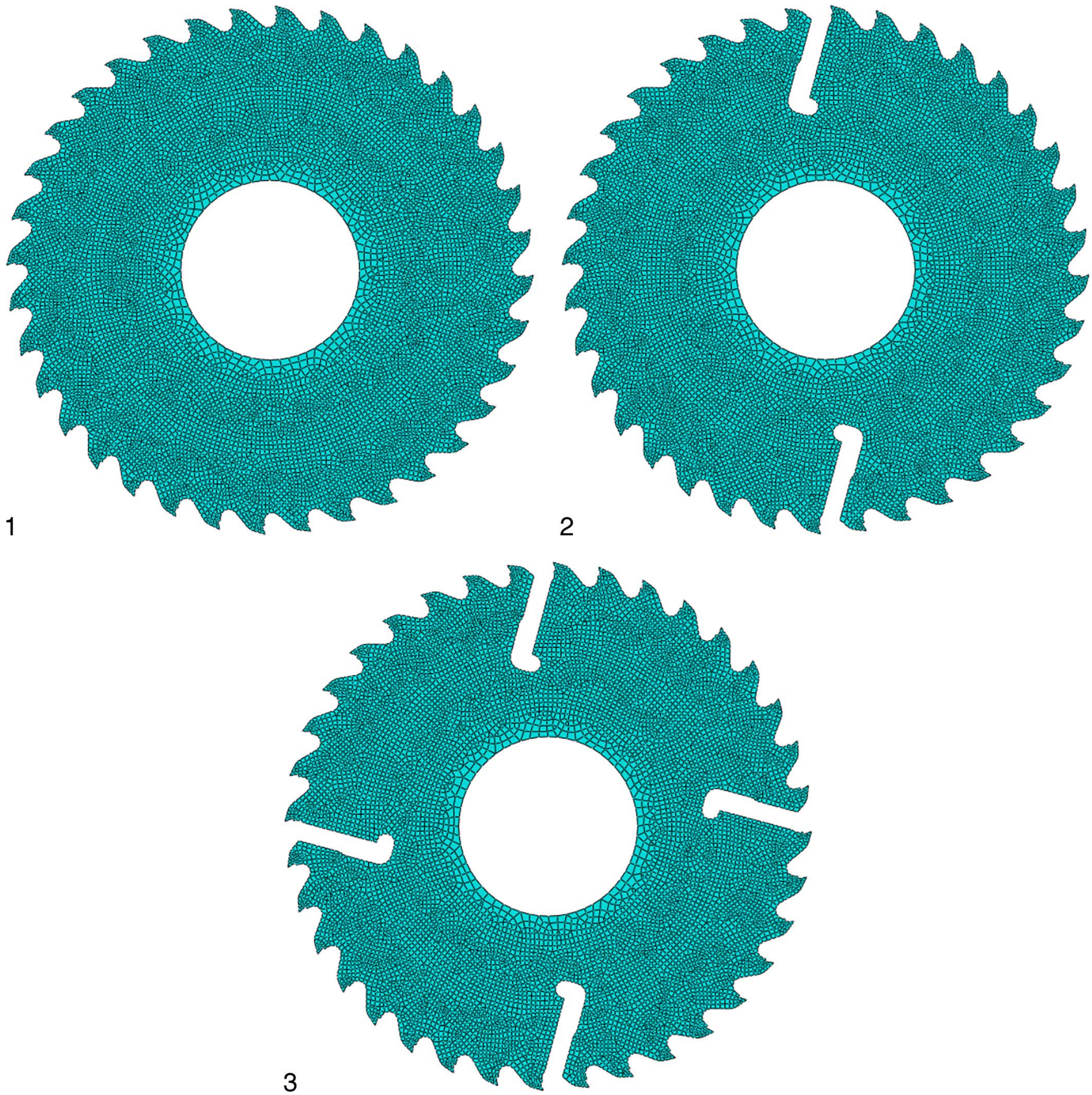

Figure 3.—Meshing of the three circular saw blades:(1) circular saw blade 1 and (2) circular saw blade 2; (3) circular saw blade 3.

set to 40°C, 80°C, 120°C, and 160°C, respectively. The temperature distributions in the radial direction of the blade corresponding to the four previously mentioned maximum temperature are shown in Figure 4.

Fixed constraint was applied to the position of circular saw blade collar. The simulation process included two analysis steps. Step 1 was the simulation of thermal expansion in the heating area and stress formation process. The static/general module of ABAQUS was used for calculating the stress field of the circular saw blade under temperature load. Step 2 was the calculation of vibration modes and natural frequencies of circular saw blades under temperature load. The frequency module of ABAQUS was used for calculating the natural frequency of the circular saw blade under temperature load.

Calculation of critical rotation speed of circular saw blades under temperature load

The vibration of circular saw blades is the superposition of two waves traveling in opposite directions to each other. One is a forward-traveling wave, and the other is a backward-traveling wave. The frequency of these waves can be expressed as follows (Orlowski 2005, Orlowski et al. 2007):

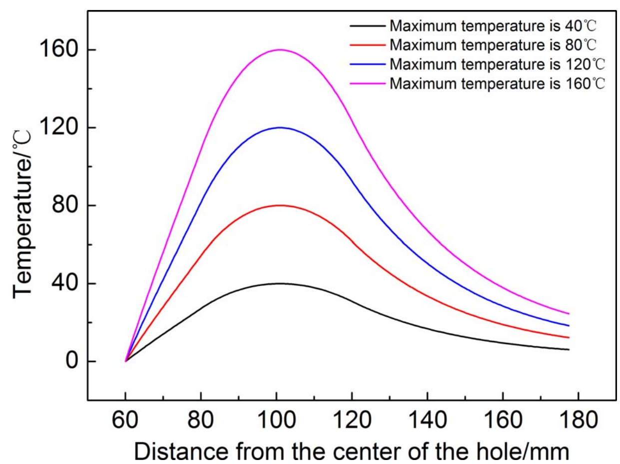

Figure 4.—Temperature distributions in the radial direction of the saw blade.

$$\text{Forward-traveling wave: } f_1 = f_{\mathrm{dyn}(n)} + \frac{k \cdot n}{60}[\mathrm{Hz}] \quad (1)$$

$$\text{Backward-traveling wave: } f_2 = f_{\mathrm{dyn}(n)} - \frac{k \cdot n}{60}[\mathrm{Hz}] \quad (2)$$

where $f_{\mathrm{dyn}}(n)$ = the frequency of the rotating circular saw blade in Hz, f_1 = the frequency of the forward-traveling wave in Hz, f_2 = the frequency of the backward-traveling wave in Hz, K = the number of nodal diameters, and N = the rotational speed in revolutions per minute (rpm).

When the rotational speed of circular saw blades is increased, the frequency of the backward-traveling wave at a certain rotational speed (besides the nodal diameters $k = 0$ and 1) becomes zero. This working speed is called ''critical rotational speed.'' This is a resonance point where even a small lateral force will cause a large lateral deflection of the blades.

From Equation 2, it is possible to derive the following equation:

$$n_k = \frac{60 \cdot f_{\mathrm{dyn}(n)}}{k}[\mathrm{rpm}] \quad (3)$$

where n_k = the critical rotational speed.

Because of centrifugal force, the natural frequency of rotating circular saw blades is increased parabolically with rotational speed. The relationship between the natural frequency of rotating circular saw blades and rotation speed is expressed in the following equation:

$$f^2_{\mathrm{dyn}(n)} = f^2_{\mathrm{stat}} + \lambda \cdot \left(\frac{n}{60}\right)^2 [\mathrm{Hz}] \quad (4)$$

where: f_{stat} = the natural frequency of the nonrotating circular saw blade in Hz and λ = the coefficient of centrifugal force. This critical rotational speed can be expressed by substituting Equation 4 with Equation 3:

$$n_k = \frac{60 \cdot f_{\mathrm{stat}}}{\sqrt{k^2 - \lambda}}[\mathrm{rpm}] \quad (5)$$

f_{stat} and λ can be calculated by the model in the previous section. This article used a combination of the finite element model and a theoretical formula calculation to calculate the critical rotational speed of circular saw blades. It has also been called first critical rotational speed in previous research (Svoren et al. 2015, Nasir et al. 2020).

Results and Discussion

The research method of this article is mainly simulation because studying the heat tensioning process through experimental methods poses a great challenge. For the temperature distribution in the heating area, the temperature difference in the radial direction was not considered in this article. Our focus is on the evolution of the dynamic characteristics of circular saw blades with different structures under the action of heat tensioning.

In addition, the temperature applied to circular saw blades during the heat tensioning process does not cause buckling deformation of the blades. Under the action of temperature load in this article, blades can still maintain a flat state.

Critical rotation speed of circular saw blades after heat tensioning

Critical rotation speed is an important index of circular saw blades. An increase in critical rotation speed enhances the dynamic stability of the blades.

The initial critical speed of circular saw blades with different structures varies as shown in Figure 5. This conclusion is consistent with previous findings (Droba et al. 2015). As shown in Figure 5, the critical rotation speed of circular saw blade 1 is increased from 6,053 rpm to 8,618 rpm when the temperature of the annular area is increased from 0°C to 160°C. The critical rotation speed of circular saw blade 2 is increased from 4,427 rpm to 5,211 rpm when the temperature of the annular area is increased from 0°C to 160°C. The critical rotation speed of circular saw blade 3 is basically maintained at 3,650 rpm when the temperature of the annular area is increased from 0°C to 160°C.

As shown in Figure 6, for circular saw blade 1, heat tensioning has the greatest effect on the critical rotation speed of the blade. For circular saw blade 2, the influence of heat tensioning on the critical rotation speed of the blade is obviously weakened. For circular saw blade 3, the influence of heat tensioning on critical rotation speed is almost nonexistent.

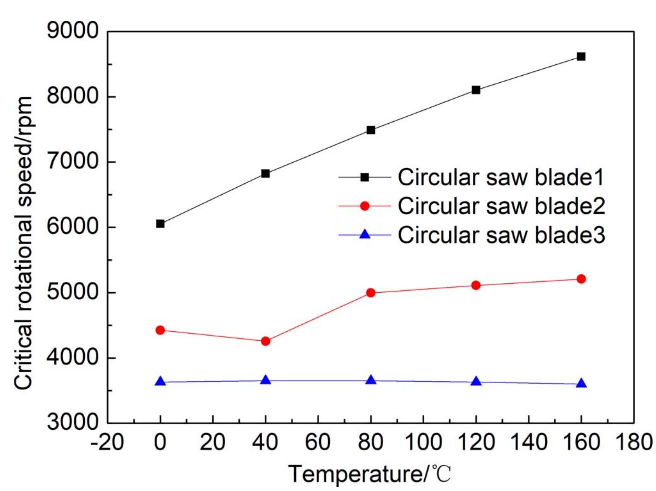

Figure 5.—Critical rotation speed with the temperature of the annular area.

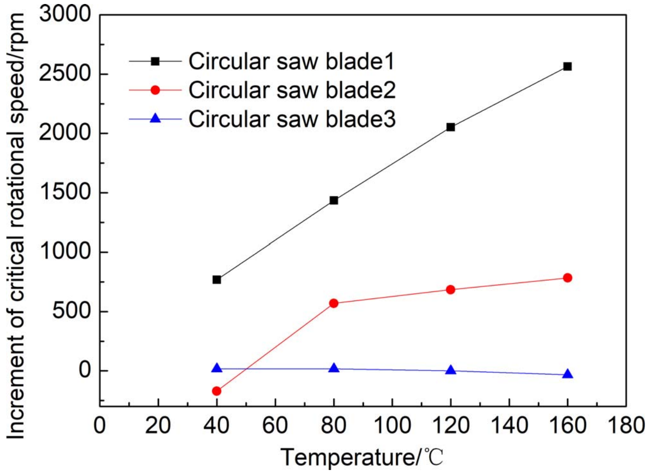

Figure 6.—Change of critical rotation speed with the temperature of the annular area.

Simulation results show that the effect of heat tensioning varies with the structure of circular saw blades. The heat tensioning is not necessarily effective for all types of blades. To reveal the causes of the above phenomena, the stress field of blades after heat tensioning were analyzed as shown below.

Stress field of circular saw blade safter heat tensioning

Circular saw blade 1.—Circular saw blade 1 was tensioned at a temperature of 160°C; the stress field of circular saw blade 1 is shown in Figure 7. Both radial stress and tangential stress are nearly uniformly distributed along the circumference because circular saw blade 1 is an ideal disk structure. The tangential stress at the outer edge of circular saw blade 1 presents a state of tensile stress. This indicates that the outer edge of the blade is in tension. This state is conducive to the enhancement of dynamic stability of the blade. The blade obtains a beneficial stress field under the action of heat tensioning. Heat tensioning has the same effect as other tensioning methods, such as the roll tensioning process (Wang 2017).

The stress of nodes on the red path in circular saw blade 1, shown in Figure 7, was focused. When the heat temperature was changed from 40°C to 160°C, the stress distributions of the red path were analyzed, as shown in Figure 8. Heat tensioning is the same as other tensioning methods. Whether radial stress or tangential stress, the stress in the heating zone is in a compressive stress state. The tangential stress at the outer edge of circular saw blade 1 presents a state of tensile stress. Moreover, the value of tangential tensile stress increases with the increase of temperature.

Tangential stress on the outer edge of the circular saw blade can represent the tensioning effect of the blade. Many scholars have analyzed the tangential stress field formed on the outer edge of blades after the tensioning process. Tangential stress distributions along the circumference of circular saw blade 1 at different temperatures are shown in Figure 9. The outer edge of circular saw blade 1 is in tension, and the tension increases with temperature. This is why the critical rotation speed of circular saw blade 1 increases with the increase of temperature, as shown in Figures 5 and 6.

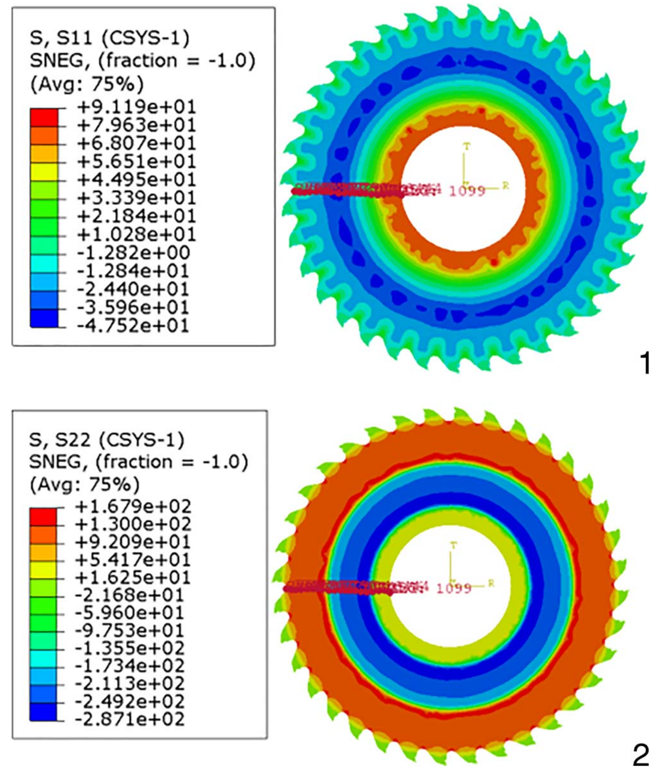

Figure 7.—Stress field of circular saw blade 1 after heat tensioning (160°C): (1) radial stress and (2) tangential stress.

To sum up, circular saw blade 1 has obtained a beneficial stress field after heat tensioning, which leads to an increase in the critical rotation speed of the blade, and finally the dynamic stability of circular saw blade 1 has been improved. For circular saw blades with ideal disk structure, previous research results show that the dynamic stability of blades is improved after the heat tensioning process (Mote et al. 1981). The results of this article are consistent with previous research conclusions.

Circular saw blade 2.—Circular saw blade 2 was tensioned at a temperature of 160°C; the stress field of circular saw blade 2 is shown in Figure 10. Both radial stress and tangential stress are not uniformly distributed along the circumference because circular saw blade 2 has two external scrapers on the outer edge of the blade. Both radial stress and tangential stress have an obvious change near the external scraper. The tangential stress on the outer edge of circular saw blade 2 shows two cycles of tensile stress and compressive stress because the blade has two external scrapers, and the tangential stress near the external scraper presents compressive stress.

The stress of nodes on the red path in circular saw blade 2, as shown in Figure 10, was focused. When the heat temperature was changed from 40°C to 160°C, the stress distributions of the red path were analyzed, as shown in Figure 11. Heat tensioning is the same as other tensioning methods. Whether radial stress or tangential stress, the stress in the heating zone is in a compressive stress state. The tangential stress at the outer edge of circular saw blade 2 presents a state of tensile stress. Moreover, the value of

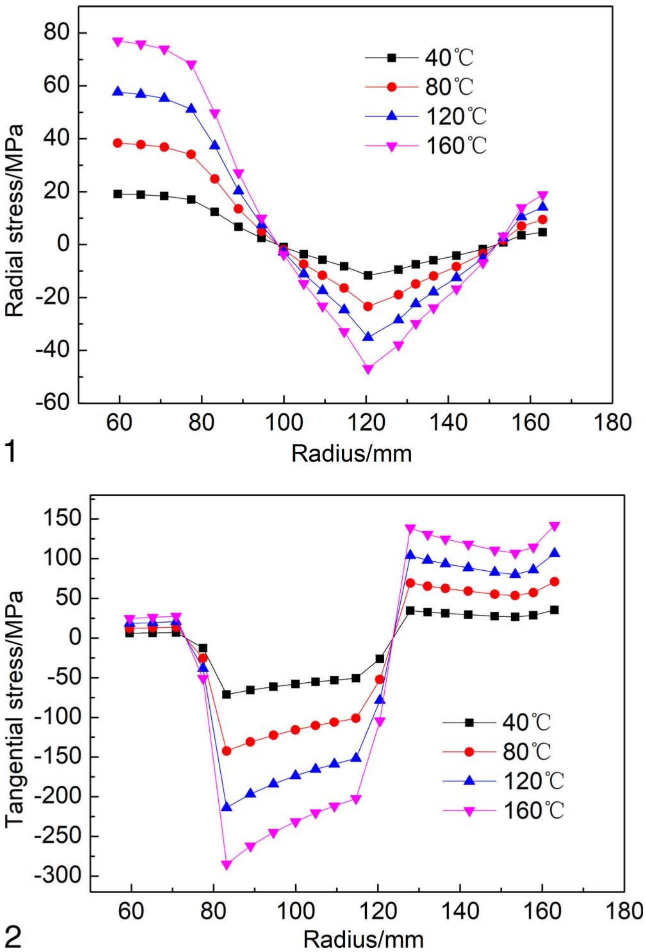

Figure 8.—Stress distributions of circular saw blade 1 at different temperatures: (1) radial stress and (2) tangential stress.

tangential tensile stress increases with the increase of temperature.

Tangential stress distributions along the circumference of circular saw blade 2 at different temperatures are shown in

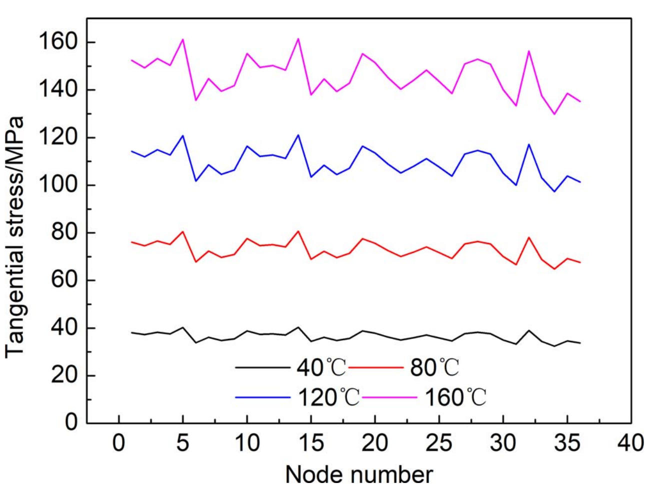

Figure 9.—Tangential stress distributions along the circumference of circular saw blade 1 at different temperatures (radius = 170 mm).

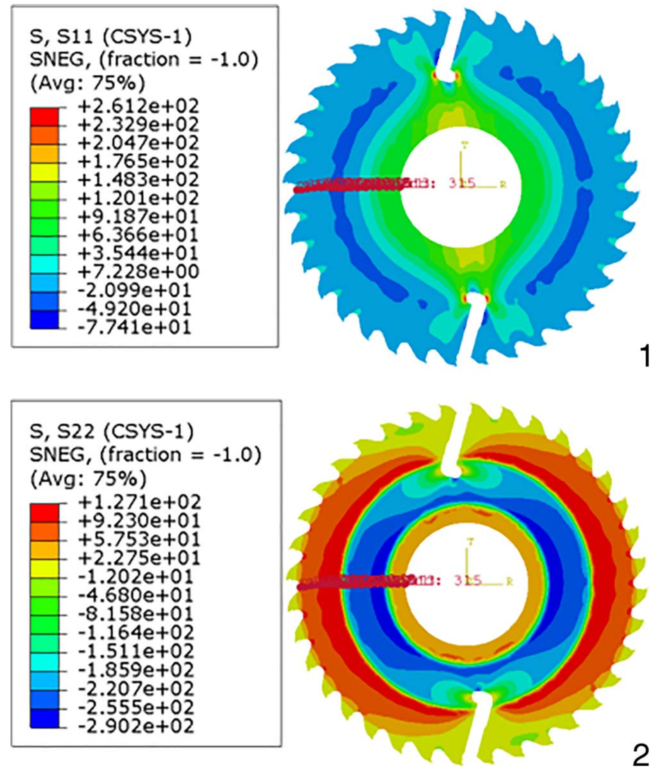

Figure 10.—Stress field of circular saw blade 2 after heat tensioning (160°C): (1) radial stress and (2) tangential stress.

Figure 12. Most areas of the outer edge of circular saw blade 2 are under tension. The tangential stress of these areas is tensile stress and increases with temperature. However, there are some areas of the outer edge of circular saw blade 2 in a relaxed state because of the two external scrapers. The tangential stress of these areas is compressive stress and also increases with temperature. On the whole, the outer edge of circular saw blade 2 is in a tension state, and the degree of tension increases with temperature. This is why the critical rotation speed of circular saw blade 2 increases with the increase of temperature, as shown in Figures 5 and 6.

To sum up, circular saw blade 2 has obtained a beneficial stress field after heat tensioning, which leads to an increase in the critical rotation speed of the blade, and finally the dynamic stability of circular saw blade 2 has been improved.

Circular saw blade 3.—Circular saw blade 3 was tensioned at a temperature of 160°C; the stress field of circular saw blade 3 is shown in Figure 13. Both radial stress and tangential stress are not uniformly distributed along the circumference because circular saw blade 3 has four external scrapers on the outer edge of the blade. Both radial stress and tangential stress have an obvious change near the external scraper. The tangential stress on the outer edge of circular saw blade 3 shows four cycles of tensile stress and compressive stress because the blade has four external scrapers, and the tangential stress near the external scraper presents compressive stress.

The stress of the nodes on the red path in circular saw blade 3, as shown in Figure 13, was focused. When the heat temperature was changed from 40°C to 160°C, the stress distributions of the red path were analyzed, as shown in Figure 14. Heat tensioning is the same as other tensioning methods. Whether radial stress or tangential stress, the stress

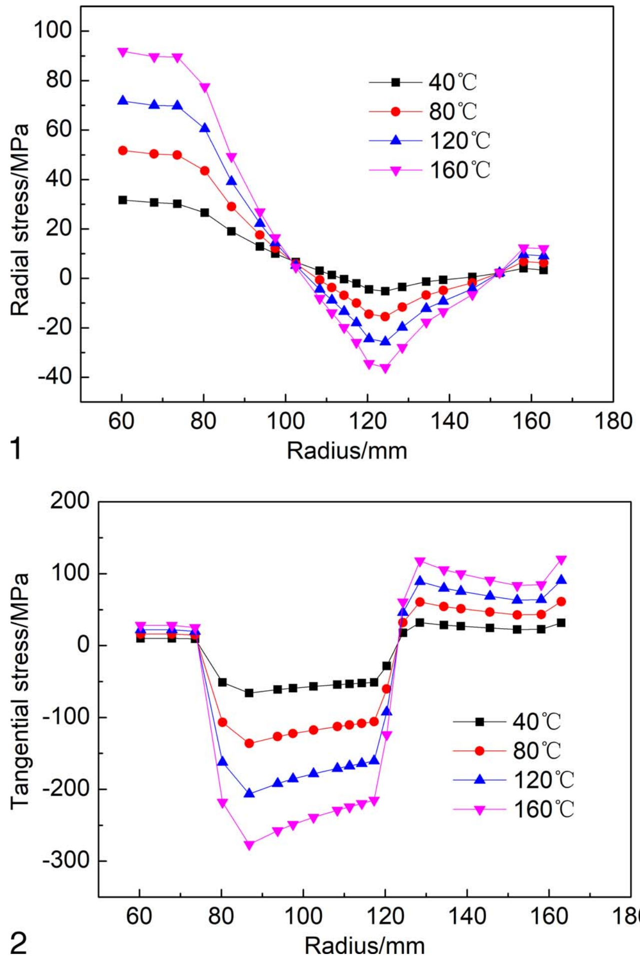

Figure 11.—Stress distributions of circular saw blade 2 at different temperatures: (1) radial stress and (2) tangential stress.

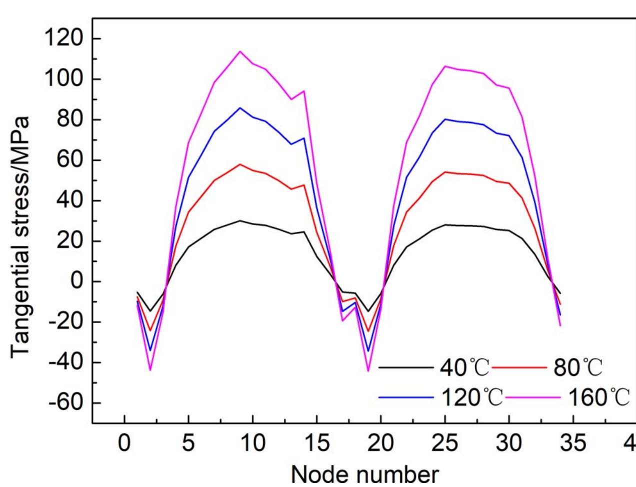

Figure 12.—Tangential stress distributions along the circumference of circular saw blade 2 in at different temperatures (radius = 170 mm).

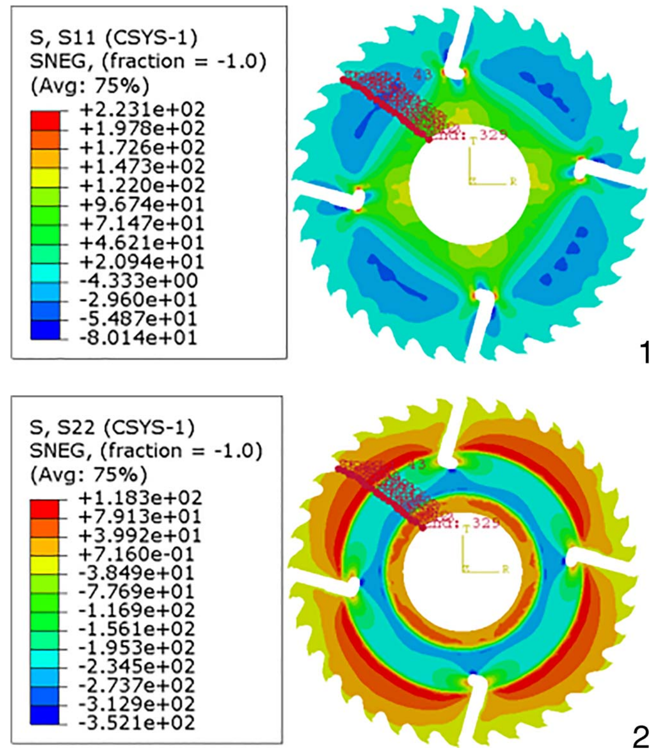

Figure 13.—Stress field of circular saw blade 3 after heat tensioning (160°C): (1) radial stress and (2) tangential stress.

in the heating zone is in a compressive stress state. The tangential stress at the outer edge of circular saw blade 3 presents a state of tensile stress. Moreover, the value of tangential tensile stress increases with the increase of temperature.

Tangential stress distributions along the circumference of circular saw blade 3 at different temperatures are shown in Figure 15. Half the areas of the outer edge of circular saw blade 3 are under tension. The tangential stress of these areas is tensile stress and increases with temperature. However, half the areas of the outer edge of circular saw blade 3 are in a relaxed state because of the four external scrapers. The tangential stress of these areas is compressive stress and also increases with temperature.

For circular saw blade 3, the tangential tensile stress and tangential compressive stress on the outer edge of the blade are almost offset regardless of the temperature of heat tensioning. This is why the critical rotation speed of circular saw blade 3 is almost constant, as shown in Figures 5 and 6.

To sum up, circular saw blade 3 could not obtain a beneficial stress field after heat tensioning. Heat tensioning could not increase the critical rotation speed of the blade because of the blade's special structure.

Through the above analysis, the tension state of the outer edge of circular saw blades can reflect the tensioning effect. Therefore, the average tangential stresses of the outer edge of the three blades at different temperatures were calculated, as shown in Figure 16. For circular saw blade 1, the average tangential stress of the outer edge is increased with temperature (see Fig. 5). The critical rotation speed of circular saw blade 1 is also increased with temperature. For circular saw blade 2, the average tangential stress of the outer edge is increased with temperature, but the increase is

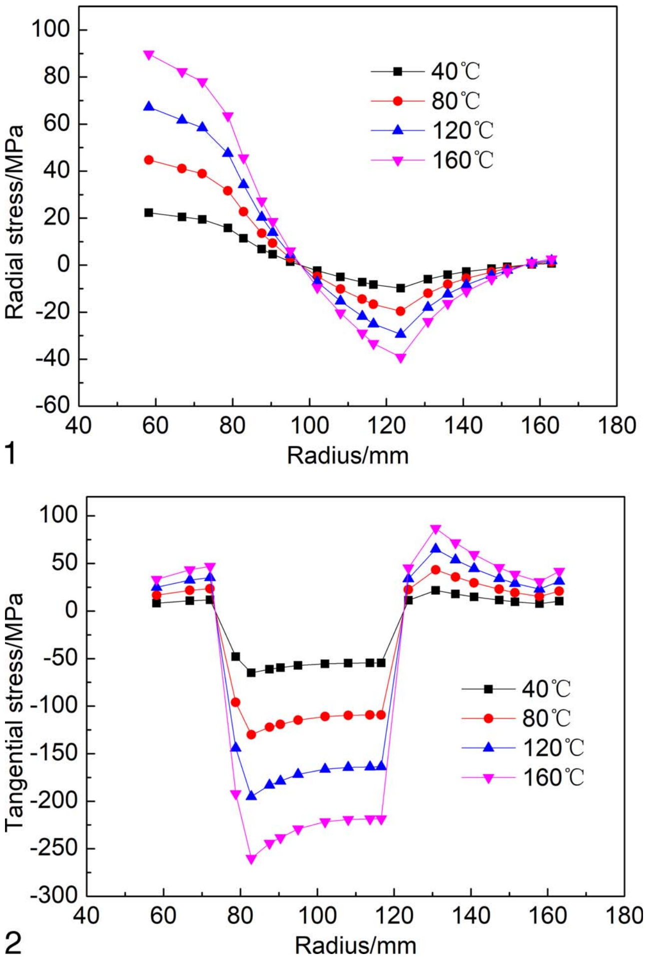

Figure 14.—Stress distributions of circular saw blade 3 at different temperatures: (1) radial stress and (2) tangential stress.

less than circular saw blade 1 (see Fig. 5). The critical rotation speed of circular saw blade 2 is also increased with temperature, and the increase is also less than that of circular saw blade 1. For circular saw blade 3, the average

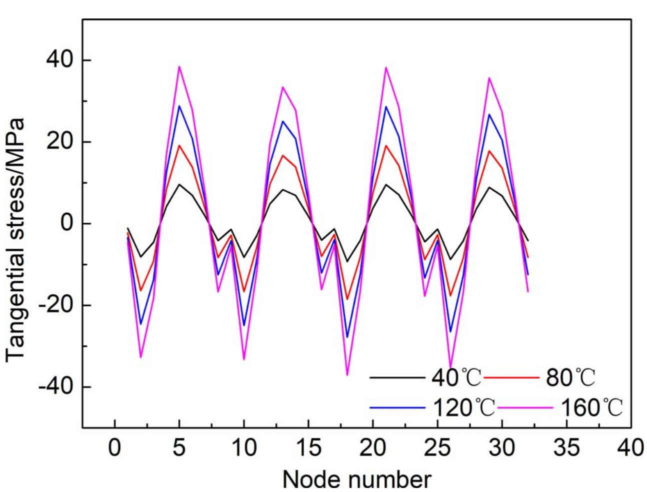

Figure 15.—Tangential stress distributions along the circumference of circular saw blade 3 at different temperatures (radius = 170 mm).

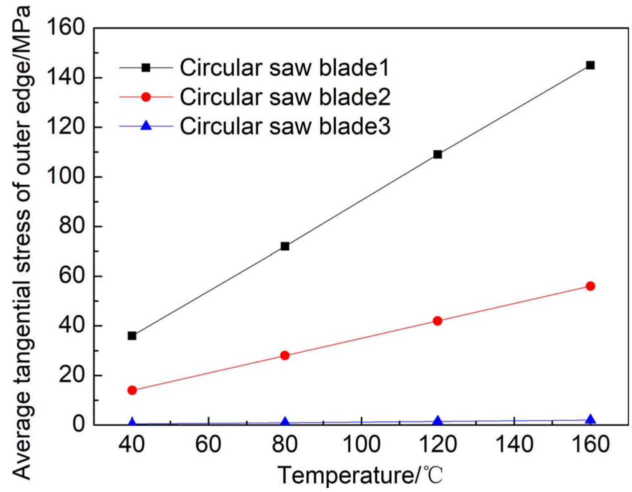

Figure 16.—Average tangential stress at the outer edge of circular saw blade.

tangential stress of the outer edge is almost constant with temperature (see Fig. 5). The critical rotation speed of circular saw blade 3 is also almost constant with temperature.

To sum up, the average tangential stress of the outer edge of circular saw blades is strongly related to critical rotation speed. The higher the average tangential stress of the outer edge of the blade after heat tensioning, the higher the critical rotation speed of the blade and the better the dynamic stability.

Conclusions

1. The finite element model of the heat tensioning process of three types circular saw blades was built by ABAQUS. The stress field and critical rotation speed of blades after heat tensioning were obtained. The effects of the heat tensioning process on dynamic stability of blades were analyzed.
2. Heat tensioning is not valid for all types of circular saw blades. For blades with ideal disk structure, the effect of heat tensioning on improving the critical rotation speed of the blade is obvious. For blades with external scrapers, the effect of heat tensioning on improving the critical rotation speed of the blade gradually decreased with the number of external scrapers.
3. When circular saw blades are heat tensioned, the average tangential stress of the outer edge of the blade is strongly related to the critical rotation speed. The higher the average tangential stress of the outer edge of the blade, the higher the critical rotation speed.
4. The research method of this article is mainly simulation. Our focus is on the evolution of the dynamic characteristics of circular saw blades with different structures under the action of heat tensioning. Conducting systematic experimental research will be our future focus of work.

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