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DEFORMATION BEHAVIOR OF CIRCULAR SAW BLADES WITH DIFFERENT BODY STRUCTURES AFTER ROLL TENSIONING

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ABSTRACT

A roll tensioning process for circular saw blades with four typical body structures was built with the finite element method. After roll tensioning, the elastoplastic deformation behaviors of the four blades were simulated and tested and the effects of roll reduction displacement on flatness were analyzed. The abilities of the blades to withstand cutting temperature load after the roll tensioning process were compared. The theoretical results showed that each of the four circular saw blades with unique body structures had different process parameters in an appropriate tensioning state. Circular saw blades with different body structures showed variation in improvements of their ability to withstand cutting temperature load after an appropriate tensioning process.

KEYWORDS: Tensioning process, circular saw blade, residual stress, finite element method, deformation.

INTRODUCTION

When wood material is sawed, the body of a circular saw blade produces a temperature field, which cannot be mitigated by coolant. Instead, a roll 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 temperature field, as reported by Li et al. (2015a,b), Li and Zhang (2017). In tensioning technology studies, the saw blade body is assumed to be an ideal disc structure. Natural frequency and residual stress of circular saw blades are the main concerns of such research and are addressed with a combination of theory and experiment.

Kuratani and Oda (2010) tested the natural frequency of circular saw blades using a modal filter method to evaluate the tensioning effect. Natural frequencies of nodal circle Nc = 0 and nodal diameter Nd≥2 were clearly increased when a circular saw blade is roll tensioned.

Cristóvão et al. (2012) calculated the natural frequency of circular saw blades with the finite element method and discussed the effects of roll tensioning parameters on natural frequency. In addition to natural frequency, critical speed was also an important index of the saw blade body. Veselý et al. (2012) used a vibration displacement sensor to test the traveling wave frequency of a saw blade during rotation. They also calculated the critical speed of a saw blade by theoretical derivation, establishing a convenient and quick method for evaluating rotary characteristics of circular saw blades. Zhang et al. (2014) studied the evolution of natural frequency and residual stress of circular saw blades during a tangential rolling process based on the finite element method. They showed that the distribution of the plastic forming zone greatly affected tensioning. Finally, Gospodaric et al. (2015) proposed a method to reduce the vibration of saw blades during the cutting process, in which the current running through two electromagnets was controlled by a robust algorithm, considering the transverse deformation of saw blade. They found that transverse deformation caused vibration and failure of saw blade.

Szymani and Mote (1979) put forward a mechanical model for the roll tensioning process and calculated residual stress of the saw blade body, ultimately revealing the mechanism of residual stress on the saw blade body. Based on the work of Szymani and Mote (1979), Nicoletti et al. (1996) solved the mechanical model using the finite element method. Natural frequency and residual stress of circular saw blades were obtained. Considering the relationship between roll tensioning and circular saw blade, Heisel et al. (2014) established a simulation model for the roll tensioning process with finite element software, incorporating the saw blade material. The calculation results of residual stress were verified with the resistance strain measurement method. Based on Heisel et al. (2014), Merhar et al. (2017) analyzed the deformation and critical speed of roll tensioned circular saw blades using finite element software, showing the correctness and feasibility of using such software to simulate the roll tensioning process. In recent years, new tensioning technologies like laser shock tensioning have been studied as reported by Li and Zhang (2018a). For instance, Li and Zhang (2018b) built a theoretical analysis model of the laser shock tensioning process based on laser shock wave theory and numerical theory, ultimately demonstrating that the laser shock tensioning process was theoretically and experimentally feasible.

Some scholars have also studied the dynamic behavior ang thermodynamic behavior of circular saw blade in the process of sawing wood, as reported by Krilek et al. (2016), Svoreň et al. (2017), Kopeck et al. (2014), Buar and Merhar (2008), Sugihara and Sumiya (1955), Beljo-Lui and Goglia (2002), Kopecky and Rousek (2012). Starting in the mid 1990s, the body structure of circular saw blades changed such that they were mostly composed of a groove and scraper. Satoru et al. (1996) pointed out that a radial groove can separate low-order natural frequencies of the saw blade body. Stakhiev (2000) found that the radial groove shortened the unstable speed range of circular saw blades. However, the radial groove can also reduce the static transverse stiffness of the saw blade body. Merhar and Bucar (2017) found that the critical instability temperature of circular saw blades gradually increased with radial groove length and circumferential number.

Despite many previous studies, the relationships among circular saw blade body structure, roll tensioning process, elastoplastic deformation behavior, and tensioning effect have not been reported. If the size parameters and teeth number of circular saw blades are exactly the same, and only their body structures are different, it is not clear how to adjust the roll tensioning process. So far, there have been no relevant studies on the theoretical basis of tensioning process optimization for circular saw blades with different body structures. Therefore, this study aimed to qualitatively assess the relationship between circular saw blade structures like groove and scraper, the roll tensioning process, and tensioning effects of circular saw blades. For circular saw blades with different structures, the appropriate roll tensioning process parameter was simulated numerically and analyzed in this paper.

MATERIAL AND METHODS

A 3D elastoplastic model of the roll tensioning process was built using the finite element method, referring to previous research Heisel et al. (2014), Merhar et al. (2017). Residual stress field, deformation, and natural frequency of circular saw blades after the roll tensioning process were obtained with the finite element method, because the finite element method can analyze the deformation, displacement, stress and vibration mode of object.

Four circular saw blades with typical structures were chosen (Fig. 1): No. 1 with a radial groove structure, No. 2 with a radial groove structure and an internal scraper structure, No. 3 with an external scraper structure, and No. 4 with a radial groove structure, internal scraper structure, and external scraper structure. The outer diameter, center hole diameter, and thickness of the four circular saw blades were 355 mm, 30 mm, and 1.6 mm, respectively. The circular saw blades were made of 65 Mn steel, with elastic modulus 210 GPa, Poisson's ratio 0.3, and yield strength 780 MPa. The constitutive model of 65 Mn steel was set as ideal elastic-plastic.

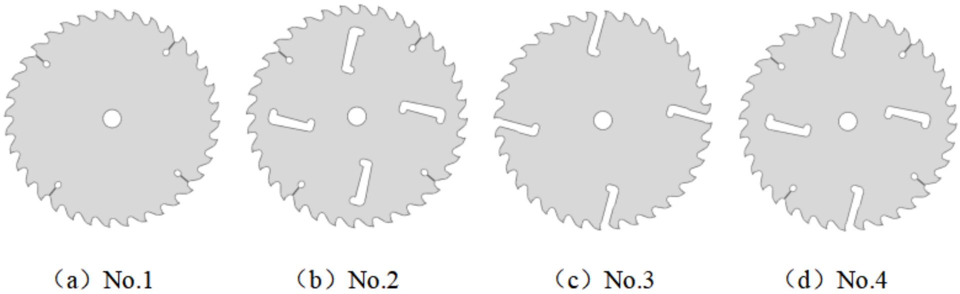


Fig. 1: Circular saw blades with four typical structures.

The 3D elastoplastic model of the roll tensioning process for circular saw blade No. 1 is shown in Fig. 2. The roll was set as an analytical rigid body. Reduction displacement of the roll was set to 0-0.1 mm. In this paper, the structure of circular saw blade is not an ideal disc structure. The suitable radius of the rolling ring for the circular saw blade in this paper has not been studied and is obviously different with the suitable rolling ring radius of the circular saw blade with ideal disc structure. Considering the influence of scraper structure and the actual production practice of circular saw blade manufacturing enterprises in China, the radius of the rolling ring was set to 105 mm. This paper not only reveals the deformation law of circular saw blade, but also provides corresponding guidance for enterprises.

The inner wall of the central hole of circular saw blade can rotate along the axial direction, and other degrees of freedom were constrained. The roll can move in the vertical direction and rotate along the central axis, and other degrees of freedom were constrained. Friction coefficient between roll and circular saw blade surface was set as 0.12. A 3D 8-node reduced integration element was chosen for the circular saw blade model. The elements in the rolling region were dense, as shown in Fig. 2.

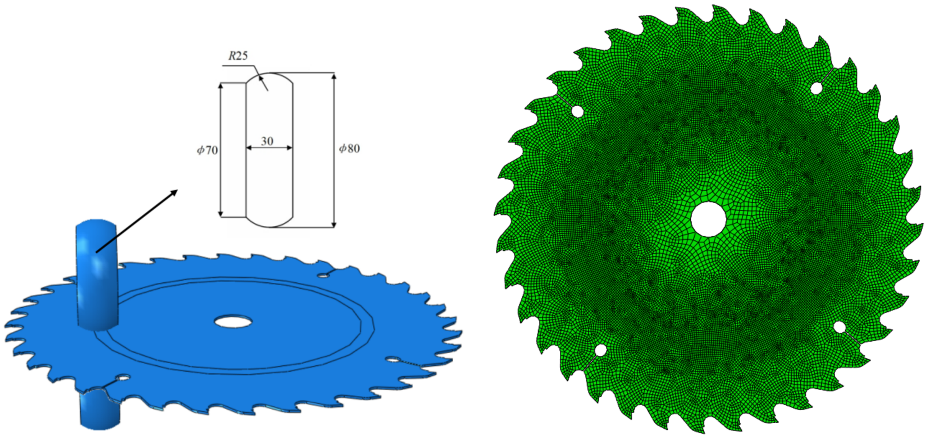


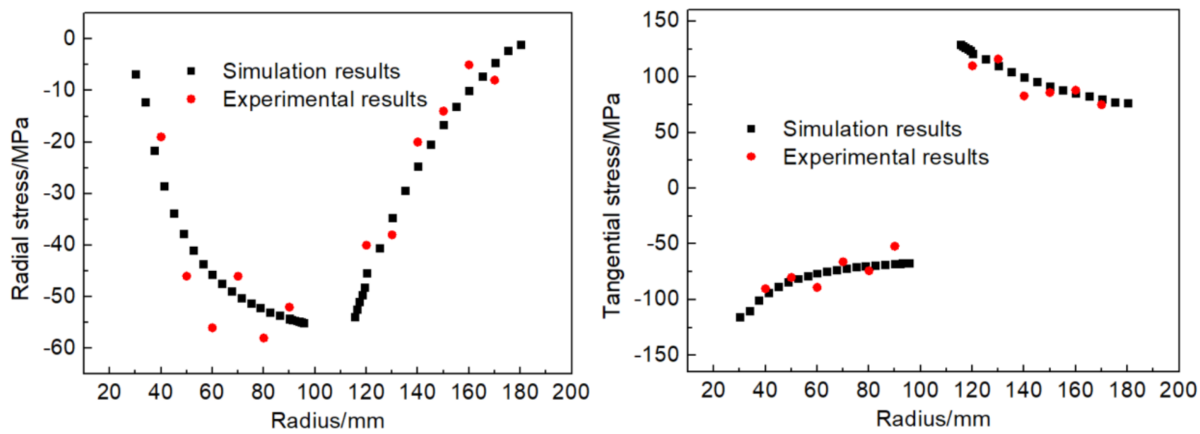
Fig. 2: 3D elastoplastic model for circular saw blade No. 1.

ABAQUS is generally accepted as a tool to simulate the elastic-plastic deformation process of metals. Li et al. (2016) demonstrated the feasibility of using ABAQUS to analyze the roll tensioning process of circular saw blades. Therefore the roll tensioning process of circular saw blades was built using the Dynamic/Explicit solution module of ABAQUS. The linear elastic unloading process of circular saw blades with an initial stress field calculated by the Dynamic/Explicit model was established with the Static/General solution module of ABAQUS. Residual stress field and deformation of circular saw blades after the roll tensioning process were obtained with this method.

For X-ray residual stress detection, the residual strain was obtained by measuring the displacement of the diffraction line, and then the residual stress is obtained by Hooke's law. The residual stress field outside the rolling region was tested using an X-350A type X-ray stress meter. The structure of circular saw blades used in the experiment is shown in Fig. 1a. Several test points were selected in the radial direction of circular saw blades. The radial and tangential stresses of the test points were obtained and recorded.

RESULTS AND DISCUSSION

Residual stress is produced in the body of saw blades after the roll tensioning. When the roll reduction displacement was 0.04 mm, the radial and tangential stress of the roll tensioned saw blade in Fig. 1a were tested. As shown in Fig. 3, the theoretical calculation results of radial and tangential stress obtained by the 3D model showed the same distribution trend as that tested by the X-ray stress meter. The simulation result of residual stress in the circular saw blade body calculated by ABAQUS were thus determined to be correct and feasible. The theoretical calculation results of radial and tangential stress obtained by the 3D model showed the same distribution trend as the previous research results (Heisel et al. 2014).

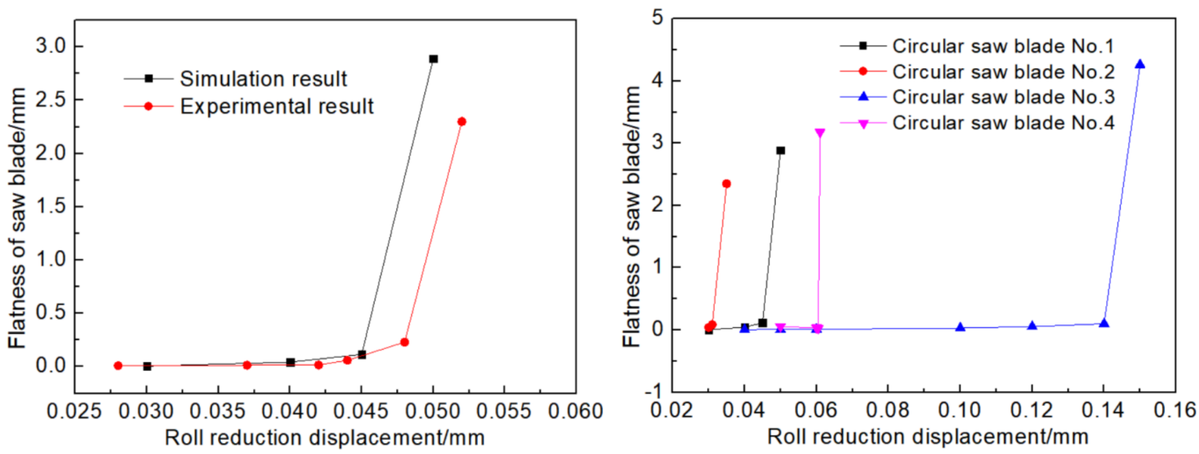


(a) *(b)*

Fig. 3: Contrast between the simulation and the measured results: a) radial stress distribution, b) tangential stress distribution.

The macroscopic deformation behavior of the circular saw blade body after the roll tensioning process, which determines blade flatness, has not been reported in previous studies Szymani and Mote (1979), Nicoletti et al. (1996), Heisel et al. (2014), Merhar et al. (2017), Li and Zhang (2017). Therefore, the flatness of the tensioned saw blade body was tested in order to verify the feasibility of the model in this paper. At present, no one has studied this problem.

The No. 1 circular saw blade was chosen for this experiment, and its flatness was tested using a dial indicator. The roll reduction displacement, also called the depth of annular rolling area, was tested using the pit depth meter. When the roll reduction displacement increases gradually, the circular saw blade can remain flat at the beginning (Fig. 4).



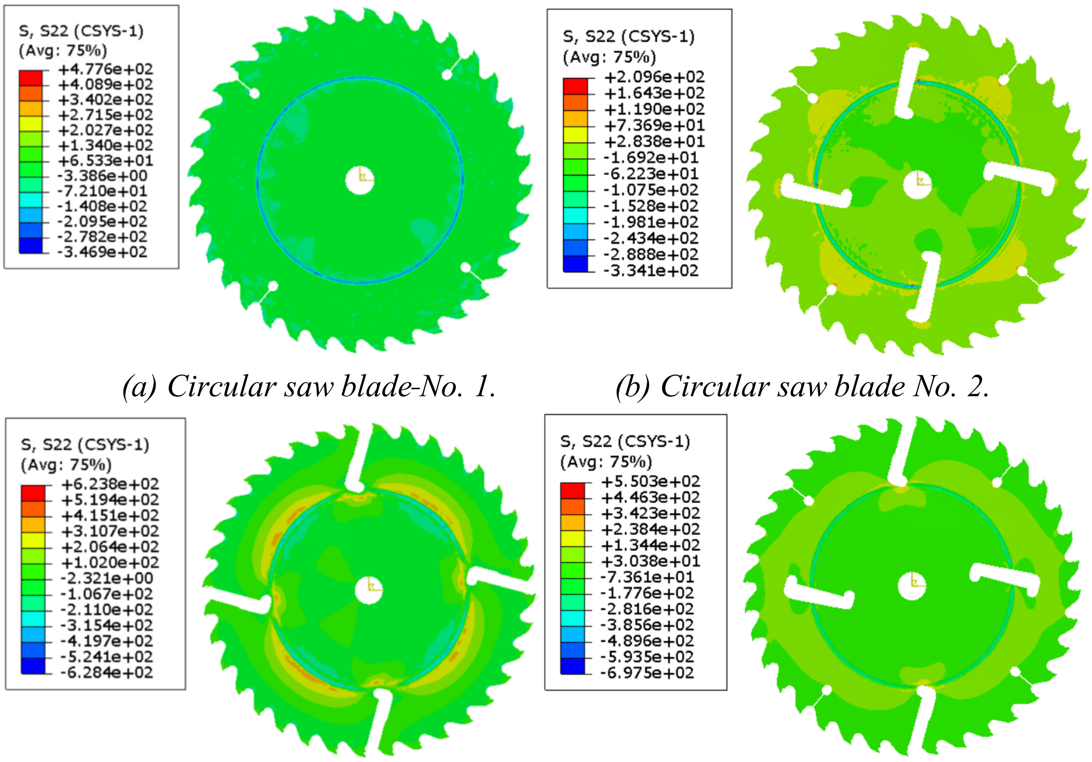
(a) *(b)*

Fig. 4: a) Effect of roll reduction displacement on flatness of circular saw blade No. 1, b) Effect of roll reduction displacement on flatness of the four circular saw blades.

When the roll reduction displacement exceeded a certain value, the flatness of the circular saw blade suddenly rose, and the blade buckled, producing a dish deformation and forcing the blade out of the plane state. Theoretical analysis and experimental tests both show this phenomenon, and the deformation laws of flatness with roll reduction displacement are similar in both. Therefore, the non-linear finite element model in this paper can predict the flatness of a circular saw blade after roll tensioning.

The residual stress field is produced in the saw blade body after the tensioning process. The value of residual stress is increased with roll reduction displacement. Due to the large value of residual compressive stress, circular saw blades buckle and cannot keep the plane state. For circular saw blade No. 1, when the roll reduction displacement is less than 0.045 mm, its flatness after the tensioning process is less than 10 μm. When roll reduction displacement is larger than 0.045 mm, circular saw blade No. 1 is in the state of buckling deformation (Fig. 4b).

As shown in Fig. 4b, when roll reduction displacement is 0.045 mm, 0.031 mm, 0.14 mm and 0.06 mm, flatness of circular saw blade No. 1, No. 2, No. 3 and No. 4 are less than 10 μm, they are appropriately tensioned. When roll reduction displacement is 0.045 mm, the maximum tangential stress in the rolling region of circular saw blade No. 1 is about -230 MPa (Fig. 5a).



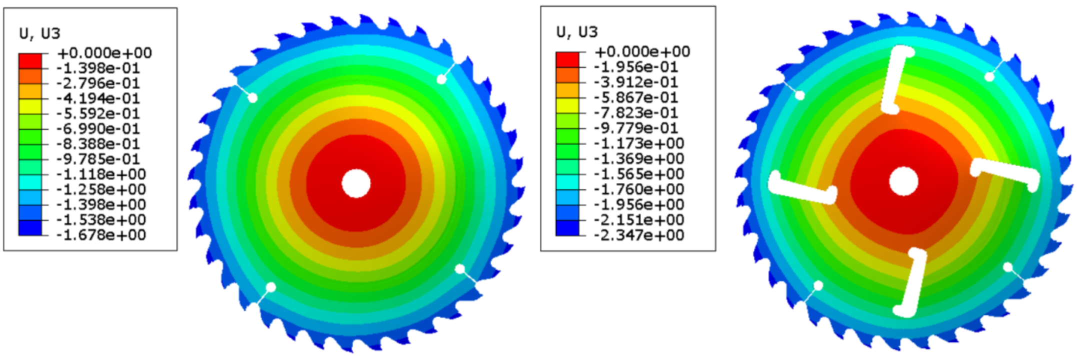
(a) Circular saw blade-No. 1. *(b) Circular saw blade No. 2.*

(c) Circular saw blade No. 3. *(d) Circular saw blade No. 4.*

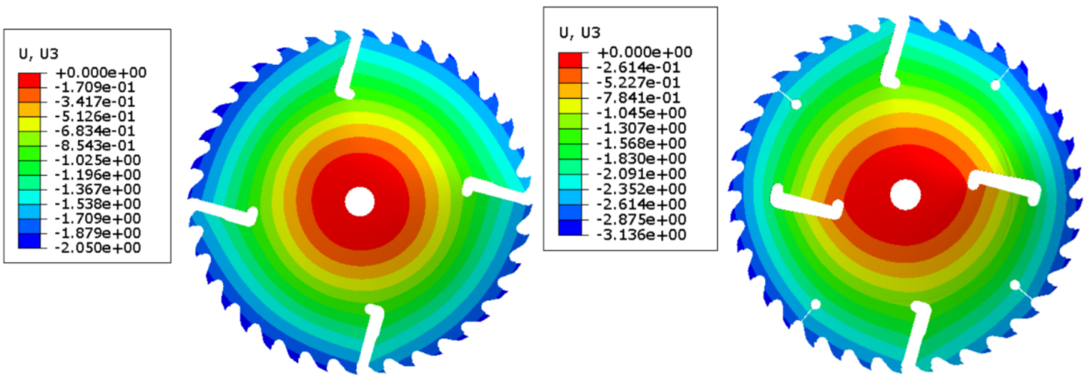
Fig. 5: Tangential stress field of the four appropriately tensioned circular saw blades.

For circular saw blade No. 2, when roll reduction displacement is less than 0.031 mm, the maximum tangential stress in the rolling region is about -200 MPa (Fig. 5b). For circular saw blade No. 3, when roll reduction displacement is less than 0.14 mm, the maximum tangential stress in the rolling region of circular saw blade No. 3 is about -350 MPa (Fig. 5c). For circular saw blade No. 4, when the roll reduction displacement is less than 0.06 mm, the maximum tangential stress in the rolling region of circular saw blade No. 4 is about -280 MPa (Fig. 5d).

As shown in Fig. 6, for the four types of circular saw blades, once their roll reduction displacement exceeded a certain value, they experienced dish deformation. Regardless of the structure of circular saw blades, over tensioning will lead to large displacement at the outer edge of the blade. Structures on the outer edge of circular saw blades like radial grooves and external scrapers can improve the plane holding capacity of the saw blade body. The larger the outer edge opening of a circular saw blade, the stronger its plane holding capacity. For circular saw blades with stronger plane holding capacity, roll reduction displacement can be increased appropriately. On the contrary, the structures inside a circular saw blade body, like internal scrapers, reduce the plane holding capacity. The larger the hole of circular saw blades, the weaker the plane holding capacity of the saw blade body. Li and Zhang (2017) described the above problem. However, no systematic quantitative analysis was carried out. The structure of circular saw blade was also not considered. Satoru et al. (1996), Stakhiev (2000), Merhar and Bucar (2017) expounded the influence of circular saw blade structure on its natural frequency and critical speed. However, they did not consider the relationship between circular saw blade structure, flatness and tensioning process.



(a) Circular saw blade No. 1. *(b) Circular saw blade No. 2.*



(c) Circular saw blade No. 3. *(d) Circular saw blade No. 4.*

Fig. 6: Dish deformation of the four circular saw blades.

As shown in Fig. 4b, for circular saw blades No. 1, 2, 3, and 4, when the roll reduction displacement is 0.045, 0.031, 0.14, 0.06 mm, respectively, their flatness aspects are acceptable and the roll tensioning process parameters for the four saw blades are appropriate. Under the above four working conditions, the four circular saw blades have similar flatness. When circular saw blades are used to cut wood, the circular saw blade body bears a temperature load and a centrifugal force load. The rotation speed of circular saw blades in this paper was 3000 r·min^{-1}. When a circular saw blade is used to cut wood, the temperature decreases gradually from the outer edge of the circular saw blade inward. In this paper, the environment temperature for circular saw blade operation is set to 10°C. The temperature decreases gradually to the environment temperature from the outer edge of the circular saw blade inward. The temperature distribution model was simplified as shown in Fig. 7.

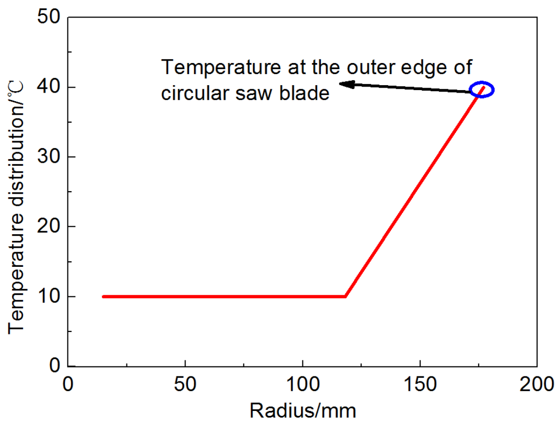
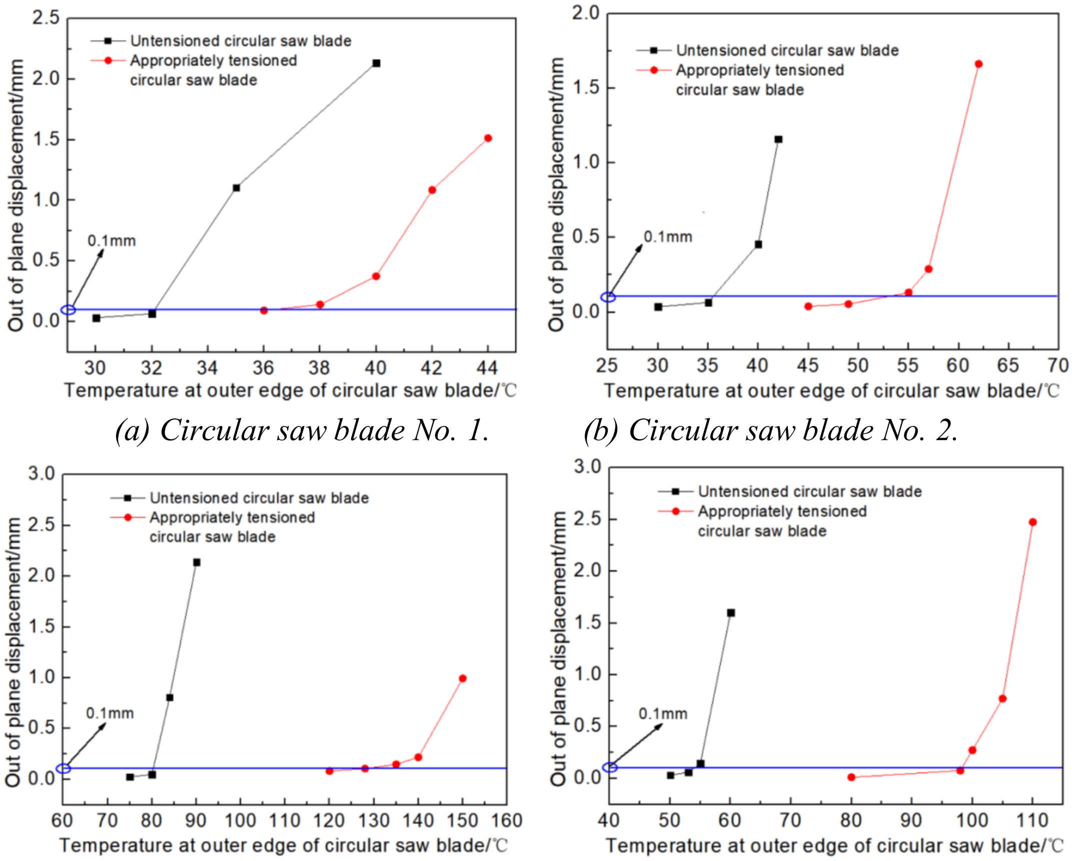


Fig. 7: Simplified temperature distribution model for a circular saw blade.

It is worth mentioning that the thermal stress and deformation of circular saw blade under temperature load are determined by the internal and external temperature difference, when the temperature distribution of circular saw blade is fixed. Compared with an untensioned circular saw blade, a tensioned circular saw blade can resist higher temperatures at its outer edge while maintaining an acceptable flatness. When temperature at the outer edge of a circular saw blade is increased, out of plane displacement changes slightly at first and then increases suddenly. For circular saw blade No. 1, when out of plane displacement does not exceed 0.1 mm, temperature at the outer edge of an appropriately tensioned circular saw blade (roll reduction displacement is 0.045 mm) is about 36°C, and temperature at the outer edge of an untensioned circular saw blade is about 32°C (Fig. 8a). For circular saw blade No. 2, when out of plane displacement does not exceed 0.1 mm, temperature at the outer edge of an appropriately tensioned circular saw blade (roll reduction displacement is 0.031 mm) is about 55°C, and temperature at the outer edge of an untensioned circular saw blade is about 35°C (Fig. 8b). For circular saw blade No. 3, when out of plane displacement does not exceed 0.1 mm, temperature at the outer edge of appropriately tensioned circular saw blade (roll reduction displacement is 0.14 mm) is about 130°C, and temperature at the outer edge of an untensioned circular saw blade is about 80°C (Fig. 8c). For circular saw blade No. 4, when out of plane displacement does not exceed 0.1 mm, temperature at the outer edge of appropriately tensioned circular saw blade (roll reduction displacement is 0.06 mm) is about 98°C, and temperature at the outer edge of an untensioned circular saw blade is about 55°C (Fig. 8d). Fig. 8 also shows that for circular saw blades with different structures, even if they have the same size parameters, the temperature load they can bear is also different when they are untensioned. When they are roll tensioned appropriately, the improvement of their abilities to withstand temperature load is also different.



(a) Circular saw blade No. 1. *(b) Circular saw blade No. 2.*

(c) Circular saw blade No. 3. *(d) Circular saw blade No. 4.*

Fig. 8: Ability to withstand temperature load of appropriately tensioned circular saw blades.

The four circular saw blades were all roll tensioned with roll reduction displacement of 0.07 mm. Circular saw blades No. 1, 2, and 4 are over tensioned when the roll reduction displacement is 0.07 mm. When out of plane displacement does not exceed 0.1 mm, temperature at the outer edge of a circular saw blade is called critical temperature load. As shown in Fig. 9, for circular saw blades No. 1, 2 and 4, the critical temperature load is greatly increased by over tensioning, compared with no tensioning and an appropriately tensioned state. Circular saw blade No. 3 has not yet reached an appropriately tensioned state. Therefore, the critical temperature load for roll reduction displacement of 0.07 mm is less than that for its appropriately tensioned state.

Fig. 9 shows that circular saw blades with different structures have different abilities to resist cutting temperature when they are not tensioned. When they are appropriately tensioned, their ability improvements to resist cutting temperature are also different (Figs. 8 and 9). When they are tensioned by the same roll reduction displacement, their improvements in ability to resist cutting temperature are also different, because their tensioning states are different.

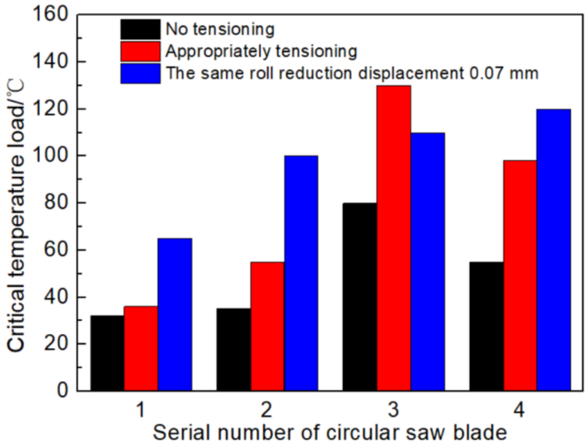


Fig. 9: Ability to withstand temperature load of circular saw blade.

CONCLUSIONS

(1) The macroscopic deformations of four types of circular saw blades after undergoing a roll tensioning process were studied using the finite element method. Simulation results show that the four types of circular saw blades all produce dish deformation when they are over tensioned. *(2)* Roll reduction displacement occurs with the roll tensioning process, resulting in a sudden, large out of plane displacement in circular saw blades, making the blades buckle. For the four types of circular saw blades, the roll reduction displacements that cause buckling deformation are different, due to their different structures. *(3)* For the four types of circular saw blades with different structures, the temperature loads they can withstand when they are tensioned appropriately are different. For circular saw blades, the larger roll reduction displacement that causes buckling deformation, the higher temperature load the blade can withstand.

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