Determination of residual stresses and natural frequencies of roll-tensioned disc by a dynamic simulation of the rolling process

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Abstract. Roll tensioning is a common method for increasing locally the superficial strength of thin circular saws and in this way their dynamic stability. Through roll tensioning, residual stresses are induced into the disc material leading to a significant enhancement of its dynamic stiffness. In this paper, a FEM-methodology is proposed for determining the developed residual stresses in the discs after rolling and for investigating their effects on the circular saw natural frequencies. More specifically, a 3D-FEM model was developed for the dynamic simulation of the rolling process on circular saws, using the LS-DYNA software. This model enables the explicit determination of the developed residual stresses in the roll-tensioned discs. Furthermore, the natural frequencies of the pre-stressed circular saws were calculated by the ANSYS software. In these calculations, the already determined residual stresses were taken into consideration. Different distances of the roll-tensioned zone from the disc centre were taken into account for estimating their effect on the disc's natural frequencies. By the proposed methodology, optimum roll-tensioning conditions can be predicted for improving the dynamic behaviour of thin circular saws during cutting.

1. Introduction

Thin circular saws are often applied in wood industry at high cutting speed [1,2]. Due to the small thickness compared to their diameter, such tools are characterized by an insufficient dynamic behaviour. Depending upon the applied rotational speed, the circular saws are subjected to undesirable axial vibrations deteriorating the tribological conditions between the tool and the workpiece material, thus decreasing the tool life and the surface integrity. For enhancing the dynamic behaviour of thin circular saws, roll-tensioning procedures are usually applied on a certain circular area of such tools [3-5]. Through this method, because of the induced local plastic deformation of the tool material, residual stresses are developed in the disc material structure, changing its dynamic characteristics [3-7]. Hereupon, the residual stresses occurred in the circular saw after rolling are located in a limited radial width of a few millimetres [8]. These residual stresses affect the circular saw structure stiffness and thus, its natural frequencies [9].

Various methods have been developed for estimating the induced residual stresses after rolling in the circular saw material and their influence on disc's natural frequencies. In the literature [4,5], three-region theoretical models were proposed for approximating the circumferential and radial stresses in the relaxation stage. In these investigations, it was assumed that two external regions are stressed elastically and the intermediate one is permanently deformed, since the circular saw elastically springs back to a new equilibrium after the load removal [5]. In the literature [7], the induced residual stresses were evaluated with the aid of X-ray measurements inside and outside of rolling paths in both

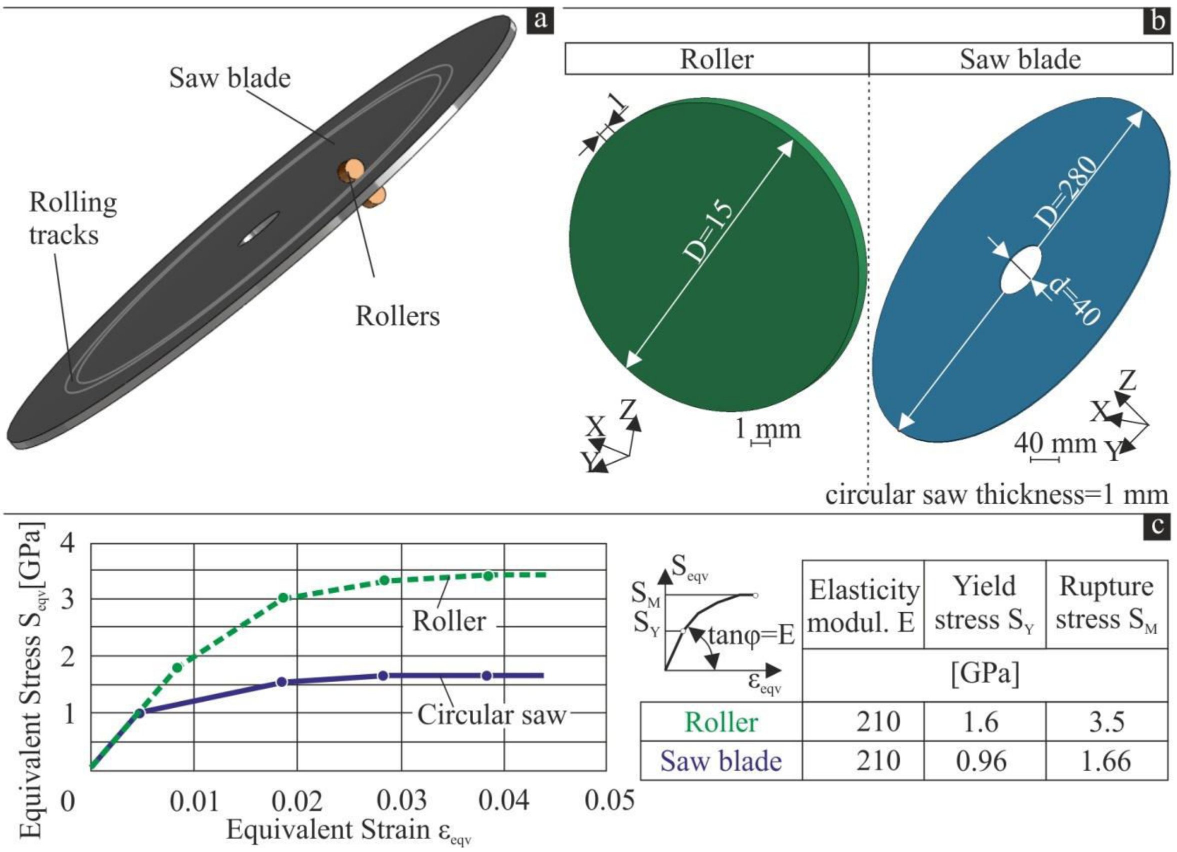

Figure 1. (a) A schematic presentation of the roll-tensioning process.
(b) The geometrical characteristics of the employed circular saw and the rollers.
(c) Mechanical properties of the employed materials.

tangential and radial directions. Moreover, a simulation model was developed for calculating the residual stresses induced by roll-tensioning [8]. The natural frequencies and the mode shapes of a circular saw with or without roll-tensioning were investigated employing modal analysis [5,6] and using appropriate experimental set-ups [4,10,11].

In this work, a methodology is introduced for an efficient assessment of the applied rolling conditions on the dynamic behaviour of circular saws. In this context, a dynamic simulation of the rolling process on a circular saw was developed for the explicit determination of the induced residual stresses using the LS-DYNA software [12]. Considering the determined residual stresses, a further FEM model was created for conducting eigenvalue analysis on the pre-stressed circular saw with the aid of the ANSYS software [13]. The FEM calculations were carried out at different distances of the roll-tensioned zone from the disc centre for revealing their effect on the disc's natural frequencies.

2. The dynamic FEM model developed for calculating the induced residual stresses in the circular saw material after rolling

2.1. The structure of the developed FEM model

A schematic presentation of the roll-tensioning process, in which the circular saw is locally deformed between the opposing rollers, is shown in figure 1a. The geometrical characteristics of the employed circular saw and the rollers in the developed FEM model for calculating the induced residual stress after rolling are illustrated in figure 1b. The roller width in the described investigations was intentionally selected to about 1 mm for calculating approximately the specific rolling force. For describing the circular saw and the rollers strength properties in the developed FEM model, materials with piecewise linear plasticity were used [14]. The stress-strain curves employed are illustrated in

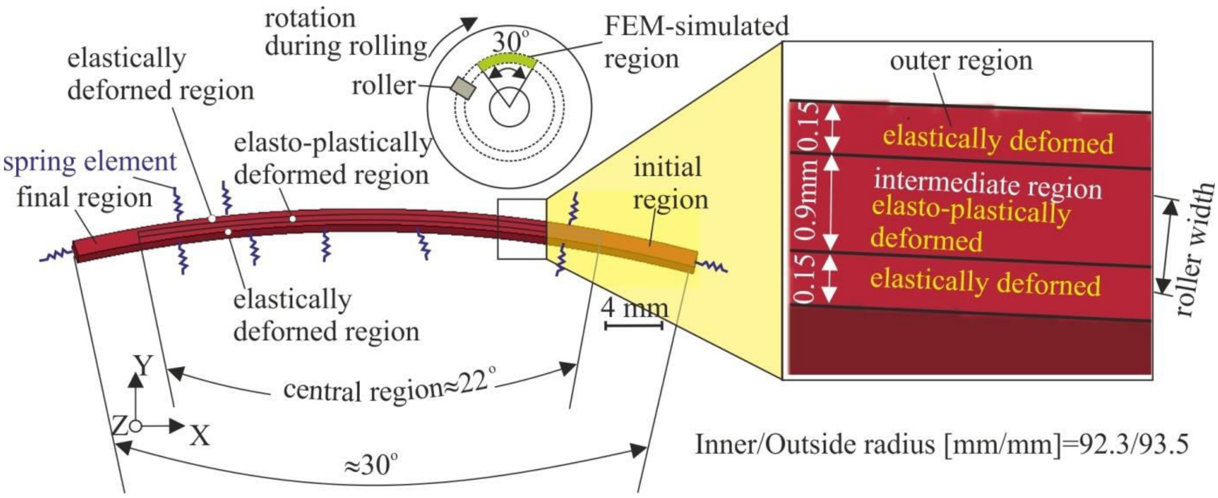

Figure 2. The applied geometry of circular saw in the developed FEM-model.

figure 1c. These curves were determined by evaluating nanoindentation results on the rollers and the disc using the procedures documented in [15]. These material properties are characteristic for a high carbon and a high-alloyed steel.

A 3D-FEM model describing the whole disc geometry using a fine discretizartion network for attaining a reasonable accuracy when simulating the rolling process on a circular saw leads to a long calculation time. In order to overcome this problem, only a certain region of the circular saw was employed in the conducted FEM simulation. More specifically, in the circumferential direction, a subtended angle of 30 degrees was used for describing the circular saw geometry, as shown in figure 2. Since only a circular arc was considered in the developed FEM model and not the whole disc, the regions included in the first and the last 4 degrees were not taken into consideration in the FEM calculations. The elements associated with these regions were elastically deformed due to the plastic deformation of neighbouring elements of the central region after rolling. Additionally, elastic spring elements were set as boundary conditions in the circumferential direction, possessing an elastic stiffness corresponding to the steel's elasticity modulus. A three regions model was built in the radial direction, as shown in figure 2. The width of these regions was appropriately selected depending upon the employed rolling conditions. The elements which are located in the intermediate region, are elasto-plastically deformed, whereas the related ones belonging to the outer regions only elastic. The rest circular saw material was substituted by elastic spring elements.

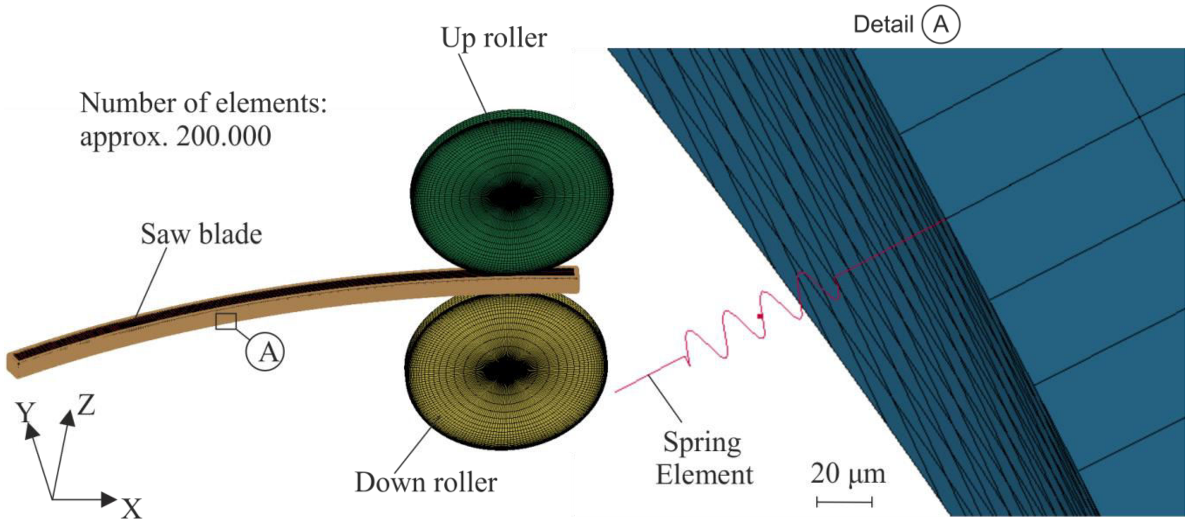

Figure 3. The developed FEM model and the corresponding discretisations of all model parts.

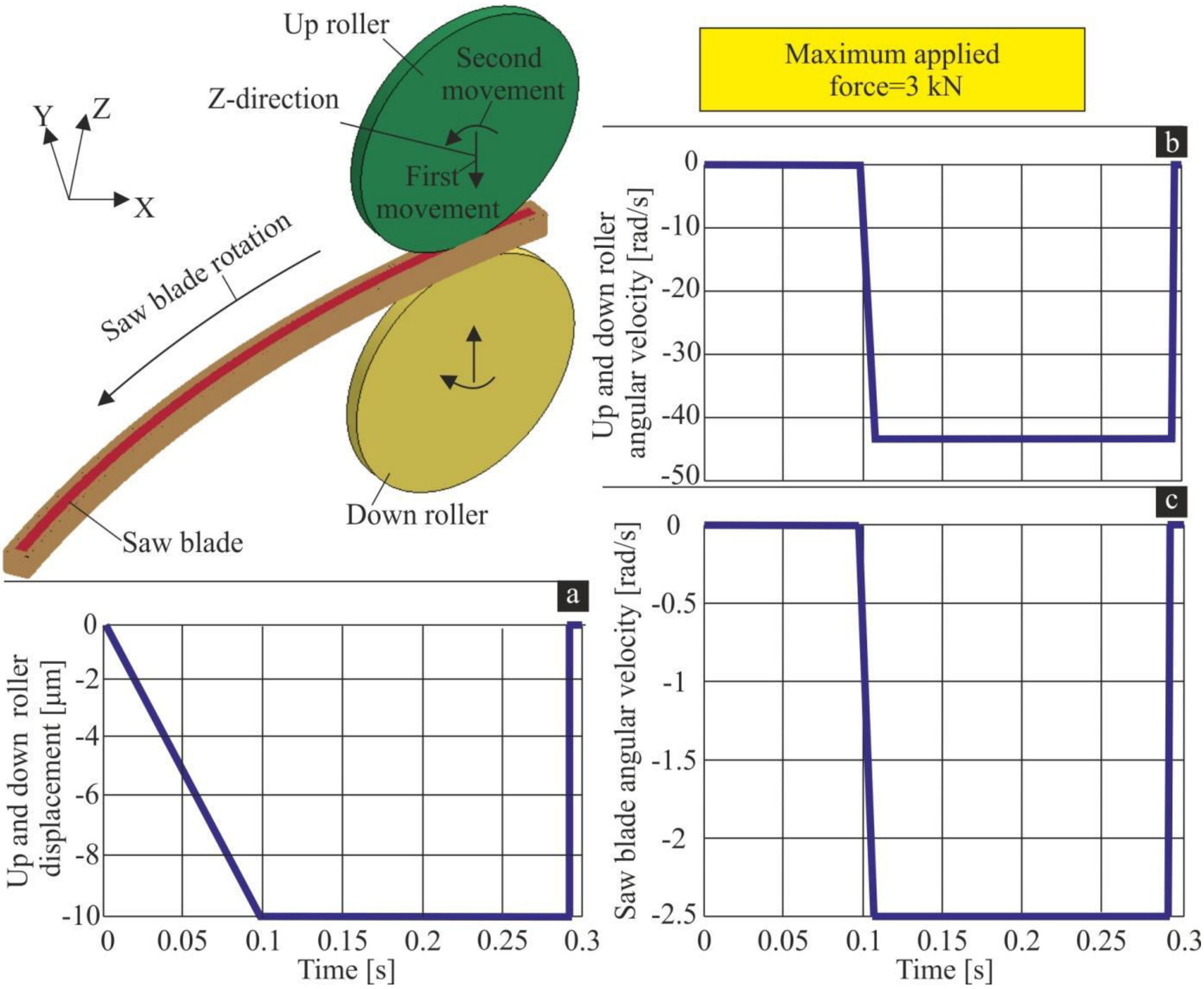

Figure 4. The employed kinematics of the circular saw and the rollers in the developed FEM model.

The developed FEM model and the corresponding discretisations of all model parts are shown in figure 3. Convergence studies were conducted to determine the optimum mesh density and obtain a mesh independent grid. Fully integrated solid elements were employed with poor aspect ratio for all parts, which is characterized as an efficient formulation [14]. A surface to surface contact was applied for describing the interface between the circular saw and the rollers in the developed FEM model [12,14]. This is a penalty-based contact with springs placed between all penetrating nodes and the contact surface [12]. A more coarsely meshed part is recommended to be identified as a master part in the LS-DYNA environment. Moreover, the rollers were coarsely meshed compared to the circular saw, since the goal of the conducted investigations was to determine the induced residual stresses in the disc's structure. Thus, the rollers were identified as the master parts, whilst the circular saw as the slave one. The density and the Poisson ratio of the employed parts are equal to 7.85×10^{-6}kg/mm and 0.3, respectively. The used static friction coefficient between the rollers and the circular was set equal to 0.15, corresponding to a lubricated rolling case [16,17].

The kinematics of the circular saw and the rollers used in the developed FEM model are presented in figure 4. The motions of the individual parts are introduced as a function of time and are linked to certain curves representing their time dependent values. The first movement is associated with the rollers' displacement up to a desired maximum depth, as shown in figure 4a. When the maximum indentation depth is achieved, then the rollers start rotating with a certain angular velocity (see figure 4b). At the same time, an angular velocity is applied at the circular saw for implementing the rolling process (see figure 4c). By employing the rolling conditions shown in figure 4, the maximum rolling force, calculated by the developed FEM model amounts to 300 daN.

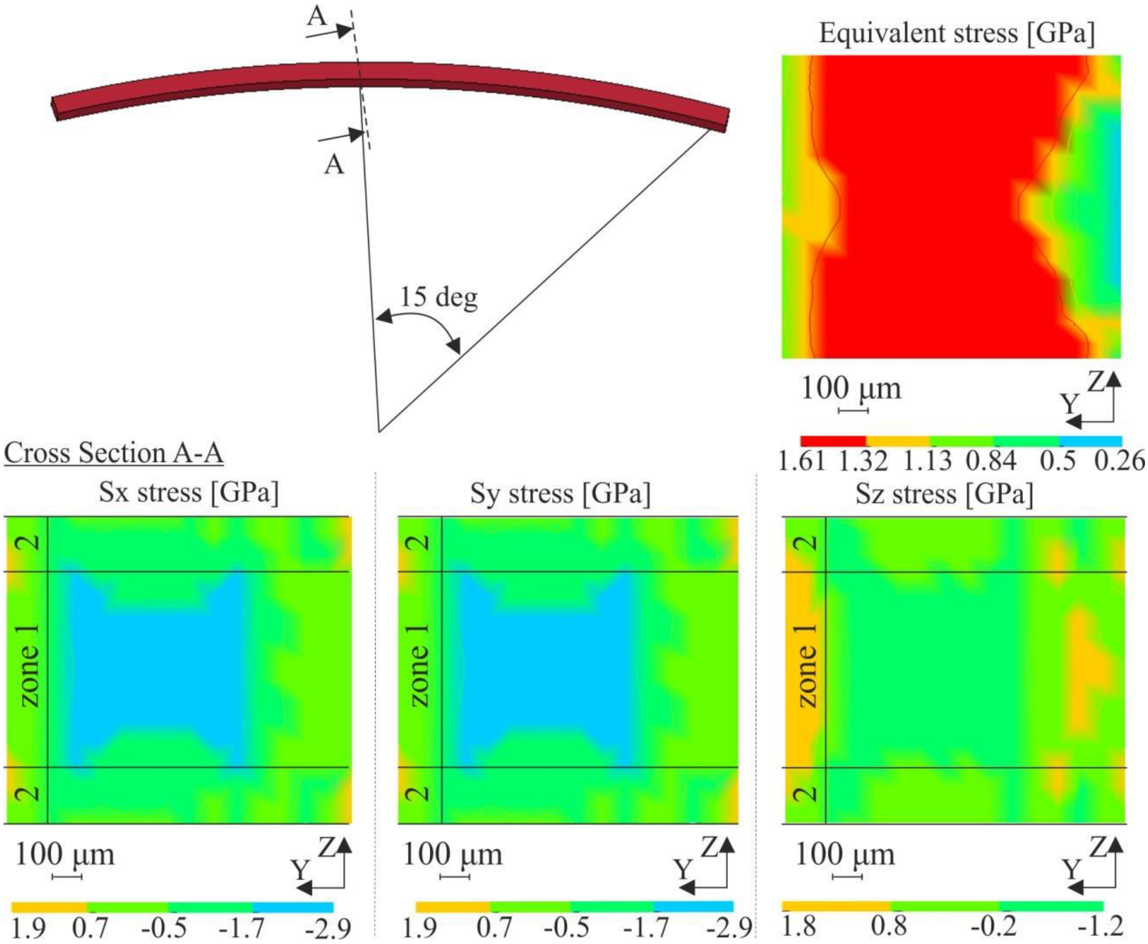

Figure 5. Residual stress distributions in the circular saw material in x, y and z directions after roll-tensioning.

2.2. The determination of the disc's residual stress using the developed FEM model

Calculations were conducted by the developed FEM model for the explicit determination of the residual stress distributions in the circular saw material in x, y and z directions after rolling. The equilibrium differential equations are integrated for incremental solution time steps of few milliseconds. Each solution step is based on the results of the previous one (explicit method) [12]. Figure 5 shows characteristic stress fields developed at a cross section of the circular saw in the middle of its length. The equivalent stress field is also illustrated. Highly compressive stresses are induced in the central region remaining in all directions after the relaxation. As a consequence, tensile stresses are developed in the outer regions.

This is visible in figure 6, where the stress distributions along the roll-tensioned zone (radial direction) are exhibited. These results correspond to the middle of the disc's thickness which is associated with the most loaded region after rolling and they cover a zone of approximately 60% (zone 1) of the overall circular saw thickness (see figure 5). The related stress distributions along the roll-tensioned zone were also calculated in the zone 2 within the circular saw thickness (see figure 5). The residual compressive stresses are nullified at a distance of approximately 450 μm from the roll-tensioned zone's centre. At a larger distance, tensile stresses are developed in all directions. The width of the roll-tensioned zone in the radial direction was appropriately selected in order to nullify all the residual stresses. The curves describing the course of the residual stresses were approximated by discrete values as shown in figure 6. These values were taken into consideration in a further FEM model for capturing the effect of the residual stresses on the disc's natural frequencies.

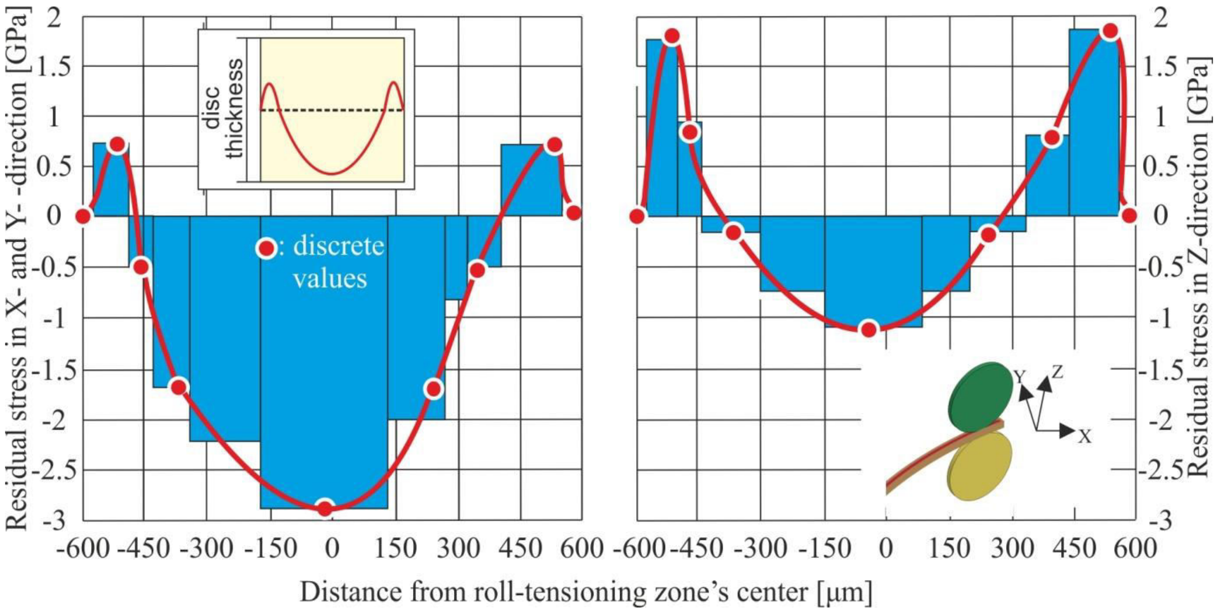

Figure 6. Residual stress distributions in the circular saw material along the roll-tensioned zone.

3. Effect of the disc's residual stresses after roll-tensioning on its natural frequencies

For investigating the effect of the induced residual stresses in the circular saw structure after rolling on its natural frequencies, eigenvalue analyses were conducted using the ANSYS software [13]. The 3D-FEM model developed for performing a pre-stressed eigenvalue analysis is illustrated in figure 7. The saw teeth do not appear in the developed FEM model, since their effect on the natural frequencies of a circular saw is negligible [5]. The geometrical characteristics of the circular saw were introduced in figure 1. The application of the disc circular fixture is simulated by fixing the nodes of the FEM model located up to a radius of 60 mm from the disc centre corresponding to the circular fixture radius. The distance of the roll-tensioned zone from the disc's centre is a variable and changeable parameter. The procedure for conducting a pre-stressed eigenvalue analysis consists of two steps. Initially, a static solution is performed considering the induced residual stresses due to the rolling process at the individual directions. The developed stresses in the disc material under loading start progressively to increase. If the developed stresses exceed its yield stress, then the remaining plastic deformation during the material relaxation induces residual stresses and strains. Thus, if the disc is reloaded, the plastically deformed material behaves as possessing yield strength greater than the pristine one (see figure 8). In a further step, eigen-frequencies analysis is carried out on the already pre-stressed circular saw. Related calculations were conducted on a stress free circular saw. In the case of a pre-stressed disc, the resulting stresses and strains in the roll-tensioned zone are integrated in the calculations made.

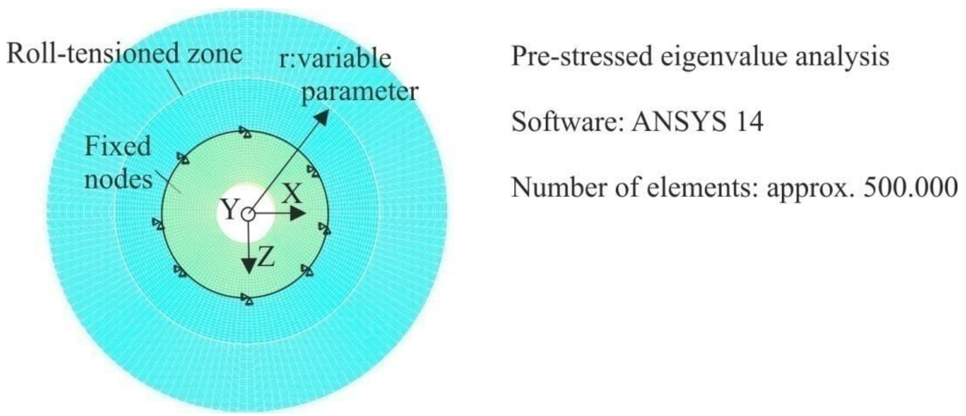

Figure 7. The employed FEM-model for conducting eigenvalue analysis.

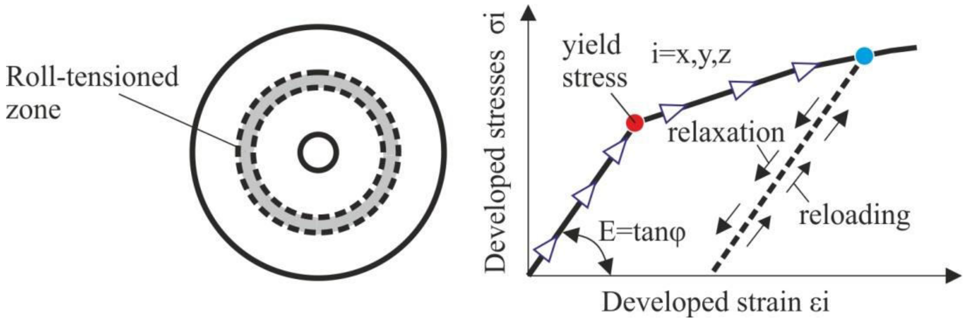

Figure 8. Mechanical behaviour of roll-tensioned zone during reloading.

Figure 9 shows characteristic results after obtaining a static solution in the pre-stressed model at certain distance from the disc's centre. The residual stresses induced in the disc's structure after rolling (see figure 5) were considered as input data in the developed FEM model for conducting static analysis. In order to introduce these stresses into the FEM model, the discrete values shown in figure 6 were taken into account along the pre-tensioned zone with respect to the position of each element within the circular saw thickness (see figure 5). These stresses were introduced into the FEM model taking into consideration the local coordinate system of its element within the pre-tensioned zone. Compressive residual stresses are developed x and z directions. As a consequence, tensile stresses are induced in a perpendicular y direction for equilibrium reasons.

The first six natural frequencies of the roll-tensioned circular saw were calculated at various distance of the treated region from the disc's centre through the FEM-supported eigenvalue analysis (see figure 10). The same diagram exhibits the related natural frequencies of an untreated disc. The larger the distance for conducting rolling on a circular saw from the disc centre, the higher the natural frequencies are. The first three natural frequencies decrease roughly to the magnitude of those ones

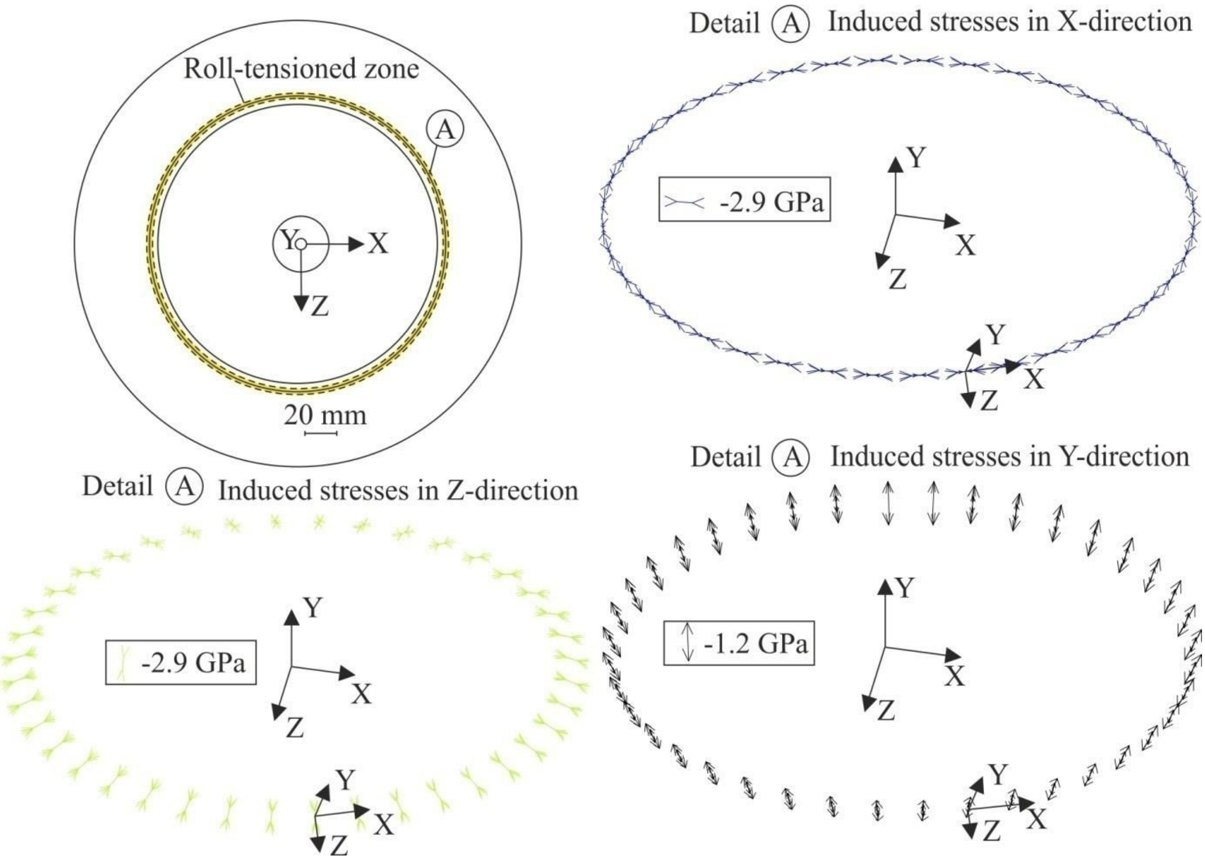

Figure 9. Characteristic results after a static solution at the pre-stressed eigenvalue analysis.

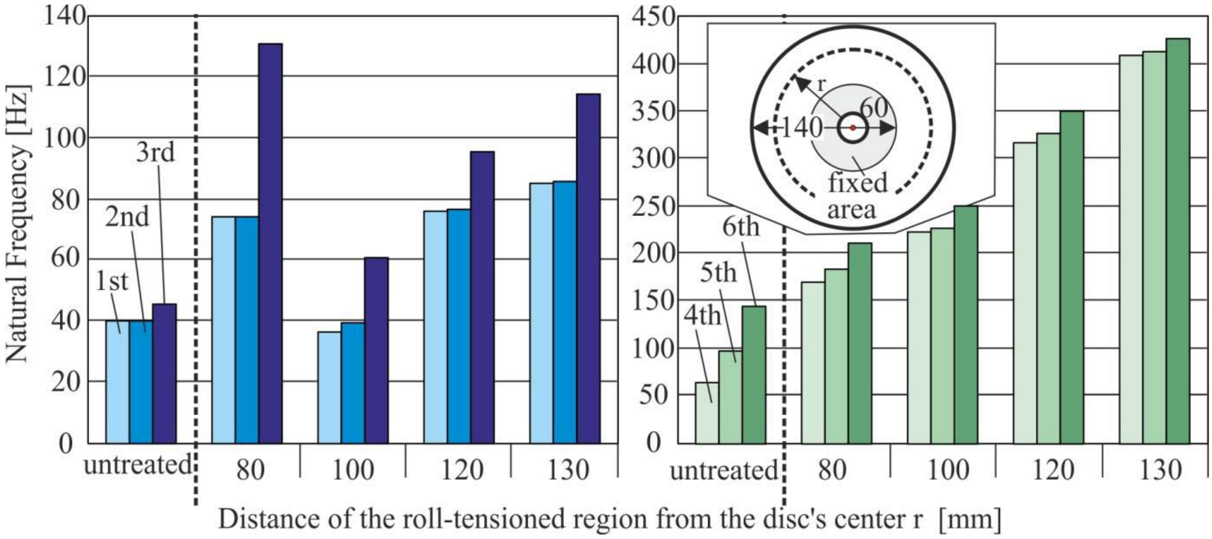

Figure 10. Natural frequencies of the circular saw after the conduct of roll-tensioning at various distances from the disc centre.

of the untreated circular saw when the rolling process is conducted on the middle of the rotation disc i.e. up to a distance of approximately 100 mm from the disc centre. This effect has been mentioned in various publications [5,6,9].

4. Conclusions

This paper proposes a methodology for predicting appropriate roll-tensioned conditions of circular saws, which can improve their dynamic behaviour. More specifically, a 3D-FEM model was developed for the dynamic simulation of the rolling process on circular saws, enabling the explicit calculation of the induced residual stresses. Furthermore, eigenvalue analysis on the pre-stressed circular saws was conducted by the ANSYS software taking into consideration the residual stresses already determined. Through the methodology developed, optimum rolling conditions can be predicted, thus minimizing the experimentation cost.

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