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A finite element thermomechanical study on the development of polygonal wear

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Abstract

Polygonal wear is a common type of damage on the railway wheel tread, which could induce wheel-rail impacts and further components failure. This study investigates the dynamic interactions between a polygonal wheel and a smooth rail with a finite element (FE) thermomechanical model. To analyze the influence of the thermal effect on wheel-rail contact pressure and wear depth, different material properties (i.e., elastic, thermal-elastic, elasto-plastic and thermo-elasto-plastic) are employed in the FE simulations. The results indicate that elasto-plastic material property should be considered in the polygonal wear study because the wear depth near the crest of the polygonal profile can be overestimated by using the elastic models. Thermal softening in the FE model may increase the contact pressure and the wear depth, which should also be involved to accurately predict the evolution of the worn profile along the wheel circumference. This study contributes to the prediction of polygonal wear development and provides some new insights into the mechanism of polygonal wear.

Keywords: polygonal wear; 3D-FE dynamic vehicle-track modeling; thermal effect; wheel-rail contact; contact pressure; wear development.

1 Introduction

Polygonal wear is typical damage that occurs on the wheels of locomotives, metros, and high-speed trains. Large vibrations caused by polygonal wear accelerate the degradation of train/track components and radiate high-level noises, which threatens the safety of railway operations and adversely affects the ride comfort of passengers.

The polygonal wheel must be timely maintained. The study on the development of the wheel polygonal wear and its influential factors contributes to the economic maintenance of railway wheels.

Numerous studies on the formation and growth of polygonal wear have been conducted by numerical modeling. The general approach is to couple train-track dynamics models with wear prediction models [1]. Train-track dynamics models can be categorized as the multibody dynamics (MBD) models and the finite element (FE) models.The MBD models handling contact with Hertzian theory or FASTISIM cannot deal with the material nonlinearities when impacts happen, and may thus not accurately calculate the polygonization-induced dynamic contact pressure and predict the development of wear. Although the FE models are able to provide accurate dynamic contact solutions [2], few of them have been combined with the wear model to calculate the development of polygonal wear. Besides, the friction heat, which influences the wear volume, is generally ignored in the existing models to study polygonal wear.

The friction heat may significantly influence the material properties and consequently the wear evolution [3]. The friction heat has been considered in some numerical studies on wheel-rail contact. Naeimi et al. [4] proposed a 3D dynamic thermal-mechanical FE wheel-rail contact model to deal with the temperature-dependent material properties. The temperature and stress field in the contact patch with a single wheel passage were obtained. Based on the research of Vo et al. [5], Lian et al. [6] proposed a FE model to calculate the temperature and the thermal-mechanical stress under multiple wheel loads. However, because the mechanical and thermal loads of the wheel were prescribed, the model failed to accurately calculate the real-time change of the temperature under complex wheel-rail interaction conditions.

This study simulates dynamic interactions between a polygonal wheel and a smooth rail using the thermal-mechanical FE method presented in [4]. The contact pressure and the wear depth on the polygonal wear tread are investigated. Simulations with different material models are conducted to investigate the influence of the thermal effect on the wheel-rail contact pressure distributions and consequent wear development.

2 Methods

2.1 The FE model

As shown in Figure 1, the thermal-mechanical FE model is established based on the parameters of V-Track, which is a 1/7 downscaled wheel-rail interaction test rig. The wheel, rail, and sleepers are modeled with 8-node solid elements. The fastenings and the ballast are modeled with spring-damper elements. The car body and bogie are simplified as lumped mass elements connected to the wheel axle with the spring-damper elements which represent the primary suspension. A contact pair is defined between the wheel and rail. To increase the computation efficiency, a partially refined mesh strategy is applied. The solution zones on the wheel and rail have the fine mesh with a size of 0.25 mm × 0.25 mm. The implicit-explicit procedure is followed to solve this FE model. In the implicit procedure, the static equilibrium of the wheel loading on the rail due to the gravity is reached. The deformation of the wheel and rail is then taken as an initial condition to the explicit procedure. Then, the wheel rolls along the rail in the explicit procedure with a speed of 3.6 m/s driven by a positive torque of 162.50 N·m under a full slip condition with the constrained lateral degree of freedom.

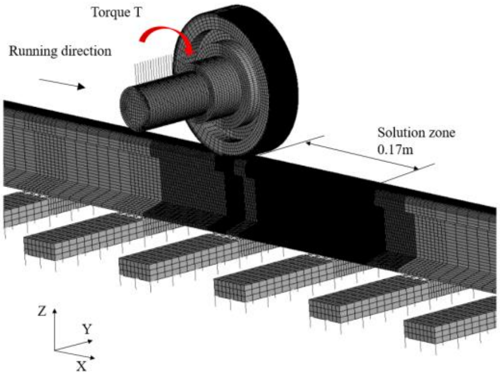

Figure 1: A 3D FE wheel-rail dynamic interaction model.

2.2 Polygonal wheel profile

The worn profile of the polygonal wheel model is assumed as a harmonic wave given in Equation (1).

$$R_p(\theta) = R + A \cdot \sin(N \cdot \theta) \qquad (0° \leq \theta \leq 360°) \tag{1}$$

where $R_p$is the modified wheel radius with polygonal wear; R is the radius of the wheel with a round profile; A is the amplitude of the polygonal wear with Nth order. R=65mm, A=0.029 mm, and N=68 are used in this study. θ is the corresponding angle in the polar coordinate, and can also indicate the angle that the wheel rolls over the rail, as shown schematically in Figure 2, which increases from 0 to about 90 degree in the simulations of this study.

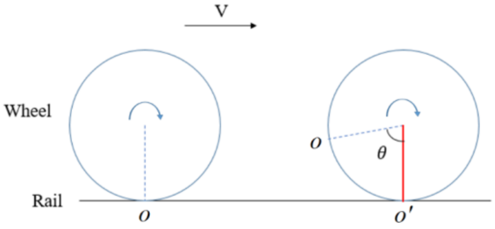

Figure 2: The angle that the wheel rolls over the rail.

2.3 The simulation cases

To evaluate the thermal effect on the polygonal wear, four different material models are used in the simulations, as listed in Table 1. The elastic-thermal (ET) material can conduct heat but it is always in the elastic state. The bilinear material type is applied to the FE model to calculate the contact solutions with elasto-plastic deformation in the model elasto-plastic (EP). Compared to the model EP, thermal softening can be considered in the model thermo-elasto-plastic with thermal softening (EPT). The temperature-dependent yield strength, Young’s modulus, and other parameters related to heat conduction applied in this study can be found in [4].

Model name	Material Type	Parameters	Value/units
E	Elastic material	Young’s modulus, *E*	210/Gpa
		Poisson’s ratio, *v*	0.3
ET	Elastic-thermal material	Young’s modulus, *E*	210/Gpa
		Poisson’s ratio, *v*	0.3
		Thermal parameters [4]	
EP	Elasto-plastic material	Young’s modulus, *E*	210/Gpa
		Poisson’s ratio, *v*	0.3
		Yield stress, σ_y	483/MPa
		Tangent modulus, G	21/Gpa
EPT	Thermo-elasto-plastic with thermal softening	Mechanical and thermal parameters in [4]	

Table 1: The material models used in the simulations.

3 Results

According to Archard’s wear model, the contact pressure is a critical input parameter for the calculation of wear depth. To investigate the thermal effect on the contact pressure and wear along the wheel profile, four cases with different material properties listed in Table 1 were simulated. The contact pressures calculated in 27 time steps within the solution zone are compared in Figure 3. The polygonal profile of the wheel is presented along the circumference which is indicated by the black solid curves. The lateral axis indicates the angle that the wheel rolls over the rail, i.e., θ shown in Figure 2. The dots (blue for the model E, pink for the model ET, green for the model EP, and red for the model EPT) indicate the calculated peak pressures of wheel-rail contact in each time step. It can be seen that the contact pressures calculated with the elastic models (E and ET) are mostly higher than those calculated with the elasto-plastic models (EP and EPT). Besides, the maximum contact pressures obtained with the elasto-plastic models (EP and EPT) are not at the crest of the polygonal profile, but a bit forward at the ‘downhill’ area. That is because the magnitude of the contact pressure is located in the leading part of the wheel-rail contact patch when plastic deformation occurs [7, 8]. There is no significant difference in the contact pressure between the two elastic models (E and ET), whereas the contact pressures of the model EPT are higher than those of the model EP at the crest of the polygonal profile and ‘downhill’ area, probably because the wheel-rail impact taking place there causes more significant thermal softening of the material. Wear depths of the four models are also calculated (not shown in this paper due to the words limit). The calculated wear depths vary periodically as the calculated contact pressure shown in Figure 3, and in each period, the maximum wear depths calculated with the elastic models (E and ET) are larger than those calculated with the elasto-plastic models (EP and EPT). Besides, the maximum wear depths of the elasto-plastic models move forward. It could be concluded that the thermal effect increases the peak wear depth and affects the wear position along the wheel tread by comparing the results of the models with friction heat (ET and EPT) with those of the other models (E and EP).

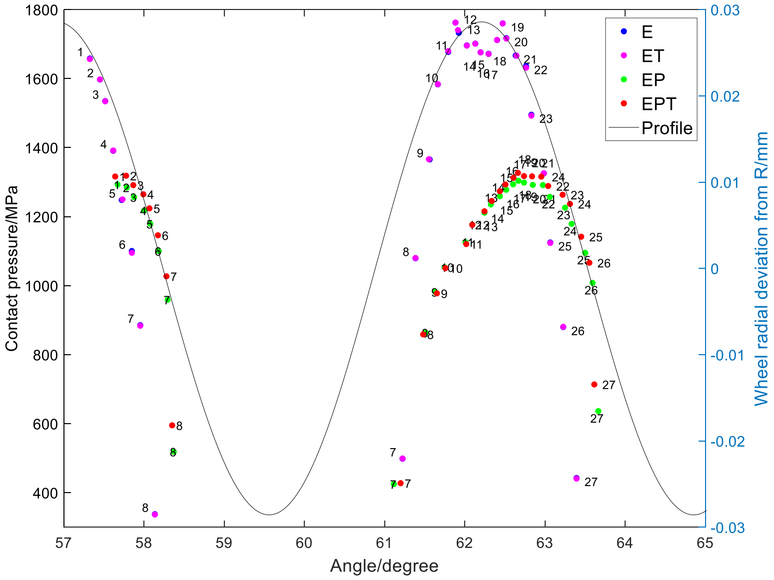

Figure 3: The contact pressure along the wheel profile.

4 Conclusions and Contributions

The influence of friction heat on the development of wheel polygonal wear is generally ignored in previous studies. This study simulates dynamic interactions between a polygonal wheel and a rail using the thermal-mechanical FE method. The contact pressure and the wear depth on the polygonal wear tread are investigated. Simulations with different materials are conducted to present the influence of the thermal effect on the wheel-rail contact pressure distributions along the polygonal wheel profile and consequent wear development. The following conclusions are drawn:

1) The contact pressures calculated with elastic models are mostly higher than those calculated with elasto-plastic models.

2) Because the magnitude of the contact pressure is located in the leading part of the wheel-rail contact patch when plastic deformation occurs, the maximum contact pressures calculated with the elasto-plastic models are not at the crest of the polygonal profile, but a bit forward at the ‘downhill’ area.

3) The contact pressures of the model EPT are higher than those of the model EP at the crest of the polygonal profile and ‘downhill’ area, probably because the wheel-rail impact taking place there causes more significant thermal softening of the material.

4) The maximum wear depths calculated with the elastic models are larger than those calculated with the elasto-plastic models.
5) The thermal effect increases the peak wear depth and affects the wear position along the wheel tread.
6) The friction heat should thus be considered when calculating the contact pressure and the wear depth along the polygonal profile especially when wheel-rail impacts may happen.

References

[1] J. C. O. Nielsen, A. Johansson, "Out-of-round railway wheels-a literature survey", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 214(2), 79-91, 2000.

[2] Z. Yang, X. Deng, Z. Li, "Numerical modeling of dynamic frictional rolling contact with an explicit finite element method", Tribology international, 129, 214-231, 2019.

[3] A. M. S. Asih, K. Ding, A. Kapoor, "Modelling rail wear transition and mechanism due to frictional heating", Wear, 284-285, 82-90, 2012.

[4] M. Naeimi, S. Li, Z. Li, et al., "Thermomechanical analysis of the wheel-rail contact using a coupled modelling procedure", Tribology International, 117, 250-260, 2018.

[5] K. Vo, A. K. Tieu, H. Zhu, et al., "The influence of high temperature due to high adhesion condition on rail damage", 330, 571-580, 2015.

[6] Q. Lian, G. Deng, A. K. Tieu, et al., “Thermo-mechanical coupled finite element analysis of rolling contact fatigue and wear properties of a rail steel under different slip ratios”, Tribology International, 141, 105943, 2020.

[7] Z. Yang, A. Boogaard, Z. Wei, et al., "Numerical study of wheel-rail impact contact solutions at an insulated rail joint", International Journal of Mechanical Sciences, 138, 310-322, 2018.

[8] X. Zhao, Z. Li, "A three-dimensional finite element solution of frictional wheel–rail rolling contact in elasto-plasticity", Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 229, 1, 86-100, 2015.