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Wheel-Rail Wear Modelling using Energy Dissipation Approach

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Abstract

This work is concerned with the thermomechanical numerical procedure to solve the wheel–rail contact problem and computes the distribution of surface flash temperatures, stresses as well as the wear evolution due to friction. The two-dimensional wheel-rail contact problem between a rigid wheel and an elasto-plastic rail lying on a rigid foundation is considered. The contact phenomenon includes Coulomb friction, frictional heat generation as well as the wear of the contacting surfaces. The displacement and stress of the rail in contact are governed by the coupled elasto-plastic and heat conductive equations. The wear depth function appears as an internal variable in the non-penetration condition updating the gap between the worn surfaces of the bodies. Moreover the dissipated energy due to friction is calculated to evaluate the loss of material and to determine the shape of the contacting surfaces during the wear evolution process. This contact problem is solved numerically using the finite element method as well as the operator splitting approach. In this approach first for a given temperature the displacements, stresses and wear depth are calculated using the semi-smooth Newton method. The plastic flow and friction inequality conditions are reformulated as equality conditions using the nonlinear complementarity functions. In the next step, for a given displacement and stress the temperature is updated using Cholesky method. The distribution of surface temperatures and stresses as well as the evolution of the shape of the contact surfaces and the wear depth are reported and discussed.

Keywords: elasto-plastic contact, frictional heat generation, wear, energy dissipation, FE model, generalized Newton method, wear distribution

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1 Introduction

Wear is a complex physical process characterized by the deformation and removal of material from a solid surface due to the mechanical action exerted by the another solid [1,2]. It frequently occurs as a progressive loss of material resulting from the frictional contact interaction of two loaded sliding surfaces. Many different physical and/or chemical factors may generate the occurrence of the wear phenomenon on contacting surfaces. In engineering practice four basic types of wear are considered: adhesive, abrasive, corrosive and surface-fatigue wear [1,2]. A comprehensive literature review of wear models and the predictive equations is presented in papers [1~6].

Archard phenomenological model [1] based on the theory of asperity contact is most frequently used to describe the sliding wear effects [1,2,6]. Many reports indicate [5,6,7,8] that an energy approach to evaluate the wear kinetics displays higher accuracy and stability than Archard model. In energy model the wear volume is proportional to the accumulated dissipated energy by the friction forces and the impact of frictional forces on the wear process through the friction coefficient is more precisely reflected. Using the energy wear coefficient [6] this model relates the wear debris volume and the accumulated dissipated energy. Experimental studies indicate that this approach provides rather consistent results in problems with unidirectional sliding [5]. In [6] the effect of the friction coefficient in the power dissipation in an elastic three-dimensional wheel/rail system is investigated through friction work modelling.

This paper deals with the simulation of the wear evolution in elasto-plastic rather than elastic wheel-rail contact problem including Coulomb friction [3] as well as the frictional heat flow [6,7]. Focusing on wear evolution in wheel-rail elasto-plastic contact problems extends the authors results from [9]. The wheel-rail contact problem is governed by the system of the mildly coupled time-dependent elasto-plastic and conductive equations. The elastic and plastic responses are approximated, respectively, by Hooke's law and by von Mises yield criterion with isotropic power law hardening. The wear phenomenon is modelled using the dissipative energy method where the volume of the worn material governed by the work of the friction force, both in global and local forms. The local form allows to introduce the wear depth function satisfying Archard model. The wear depth function directly enters into the contact non-penetration conditions enforcing the update of a gap between contacting surfaces.

2 Methods

The finite element method is used as a discretization method. In the simulation procedure, the elasto-plastic contact and thermal problems are solved sequentially in time. First at time t the elasto-plastic contact problem is solved, i.e., for a given temperature the normal contact traction and the wear depth are calculated. Next in the thermal analysis, the heat flux at time t+ Δt, where t is the time at which the solution to the elasto-plastic contact problem is known is approximated based on slip velocity and normal pressure and the temperature in the next time step t+ Δt satisfying the heat equation is calculated. If the Stop criterion is not satisfied the elasto-plastic contact problem at the time t+Δt is solved.

The associative plastic flow, non-penetration and friction conditions generate inequality type constraints. These conditions are reformulated in an equivalent set of nonlinear complementarity functions and transformed into the set of equality constraints [10]. The coupled nonlinear and non-differentiable system of the equilibrium equations including nonlinear constitutive material behaviour and heat flow as well as these equality constraints imposed on nonlinear complementarity functions is solved numerically using semi-smooth Newton method [10]. Since the material removal due to wear may lead to mesh distortion the worn volume calculated due to dissipated energy method is used to ensure the regularity of the mesh.

The material removal process due to wear is changing the geometry of the contacting surfaces. At finite element level it leads to the distortion of the mesh. These difficulties are avoided using two step procedure in the form of the wear box [5,8]. First the weighted wear depth and the deformation of the body are evaluated by solving the state system. If the wear depth is so large that finite element aspect ratio is not satisfied based on dissipated energy formula the amount on the worn material is evaluated and the balanced average wear depth value is calculated. The finite elements close to the contact surface are reevaluated and if necessary the worn material is redistributed among these elements.

3 Results

The stresses on the top surface of the rail for thermo-elasto-plastic material rail model are calculated and displayed. For the sake of comparison these stresses have been also calculated for elastic and elasto-plastic material rail models. The stresses for these material models differ in shape as well as in the magnitude due to the plasticity or thermal effects. The stresses are vanishing when there is no contact between the wheel and the rail. When the contact occurs the stress components are gradually built up. Having reached the maximum value, the stress components are decreased as the wheel moves away from the contact zone. The stress longitudinal attains the highest value for the elastic material model at the middle point of the contact zone. For elasto-plastic and thermo-elasto-plastic material models this stress attains lower values than for pure elastic model. On the other hand, the length of the contact zone for elastic-plastic material is higher than for elastic materials. The vertical stress attains the highest value for the thermo-elasto-plastic material. Moreover for these materials the residual stress can also be observed. The shear stress attains the highest value for the elastic material model however this value is significantly lower than peak values for the longitudinal or vertical stresses. The difference between the elastic and elasto-plastic contact stresses justifies the necessity to take material plastic behaviour into account. The dependence of von Mises stress on temperature is discussed. The fretting wear surface evolution for three different set of cycles where the displacement amplitude along the longitudinal axis is calculated. The plasticity effect results in increasing of the contact zone as well as the wear depth as the number of cycles is increasing. Moreover as the number of cycles is increasing due to temperature field the length of contact zone as well as the wear depth are also increasing.

4 Conclusions and Contributions

The thermo-elasto-plastic rolling contact problem with friction, heat flow and wear has been solved numerically using the semi-smooth Newton and Cholesky methods. The wear phenomenon is modelled using not only depth wear rate model but also the dissipation energy model. It allows to follow modification of contact surfaces location and evaluate the wear depth. The obtained numerical results indicate that the obtained contact patches are characterized by longer zones and lower stress intensity than in the elastic case. The dissipated energy method and contact interface shape update strategy are efficient and precise tools to evaluate the wear distribution. The impact of hardening parameters as well as temperature dependent material parameters and creepage on the wear evolution process requires further research. The wear evolution process where the location of contact zone may be also treated as the shape optimization problem. Therefore the choice of parameters ensuring the minimization of the worn material volume may be considered and formulated as the shape optimization problem where the dissipated energy is the criterion of optimization.

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References

[1] H.C. Meng, K.C. Ludema, “Wear models and predictive equations: their form and content”, Wear, 181-183, 443 – 457, 1995.

[2] K.L. Johnson, “Contact mechanics and the wear of metals”, Wear, 190, 162 – 170, 1995.

[3] M. Harmon and R. Lewis, “Review of top of rail friction modifier tribology”, Tribology: Materials, Surfaces and Interfaces, 10 (3), 150-162, 2016.

[4] J. Pomboa, J. Ambrosio, M. Pereira, et. al, Development of a wear prediction tool for steel railway wheels using three alternative wear functions Wear, 271(1), 238-245, 2011.

[5] S. Fouvry, P. Kapsa, H. Zahouani, L. Vincent, “Wear analysis in fretting of hard coatings through a dissipated energy concept”, Wear, 203/204, 393-403, 1997.

[6] G.I. Alarcon, N. Burgelman, J. M. Meza, A. Toro, Z. Li, “Power dissipation modeling in wheel/rail contact: Effect of friction coefficient and profile quality”, Wear, 366-367, 217-224, 2016.

[7] F. Braghin, R. Lewis, R.S. Dwyer-Joyce, S. Bruni, “A mathematical model to predict railway wheel profile evolution due to wear”, Wear, 261, 1253 – 1264, 2006.

[8] T. Doca, F.M. Andrade Pires, “Finite Element Modelling of Wear using the Dissipated Energy Method coupled with a Dual Mortar Contact Formulation”, Computers and Structures, 191, 62 -79, 2017.

[9] A. Myśliński and A. Chudzikiewicz, “Wear modelling in wheel-rail contact problems based on energy dissipation”, Tribology - Materials, Surfaces & Interfaces, 15, 138-149, 2021.

[10] C. Hager, B. I. Wohlmuth, “Nonlinear complementarity functions for plasticity problems with frictional contact”, Comput. Methods Appl. Mech. Engrg., 198, 3411-3427, 2009.