Numerical Simulation for Frictional Behaviors of PTFE Composite Sealing Ring

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Abstract. A Numerical method of frictional behaviors in the microscale is presented to meet the simulation demands of the tribological characteristics for composite sealing ring in the transmission of heavy-duty vehicle. The microscopic dynamic responses of sealing surfaces are visualized when loads are applied according to the actual working conditions. The frictional behaviors of the polytetrafluoroethylene (PTFE) composite sealing rings are analyzed within the simulation time. The properties and morphology of filler materials determine the frictional behaviors in the microscale. The microscopic frictional simulations indicate the effectiveness of the movable cellular automata method in the mixed lubrication of the sealing ring. It provides a reliable numerical experimentation for material selection of composite sealing ring.

Introduction

The sealing rings are assembled in a transmission device of a heavy vehicle and play the crucial functions in the reliability and durability. The sealing performance is an important evaluating indicator for general performance of a transmission device [1]. At the same time, seals are also the vulnerable and weak parts in the transmission device. In the actual application those sealing rings usually are seriously worn.

The emergence and application of new seal materials, especially the composite material, improve the sealing ability and increase the wide usage of original seals [2-4]. The sealing ring in transmission device of heavy vehicle adopts polytetrafluoroethylene (PTFE) matrix composites. At present, based on the continuous hypothesis, the researches on the friction and wear of the seals are mainly carried out by use of the contact model, numerical calculation or experiments [5-8]. Salant [9] discussed the contact problem of surface friction of the sealing system according to the corresponding elastic-plastic contact model. Frölich et al. [10] used a comprehensive approach for seals which took into consideration the interaction of temperature, friction and wear, and a macroscopic simulation model had been developed. Ilincic et al. [11] utilized the hybrid finite element method and boundary element method to calculate the contact pressure and the real area of contact for both normal and tangential loading between two rough surfaces. However, the heterogeneity and anisotropy characteristics of the composite material also bring about new challenges to the study of friction and wear issues.

We need to know about the sealing ring friction behaviors. Therefore, we build a numerical model of composite sealing rings by using a movable cellular automata (MCA) method so as to form a powerful calculation tool of friction simulation, which will reveal the mixed lubrication characteristics and wear properties of composite seals. In this way, the comprehensive and consistent friction and wear properties of sealing ring in the microscale can be obtained.

MCA Method

The investigation on frictional behavior of sealing ring in the microscale is carried out on the basis of modelling by the MCA method. This choice is determined by the features of the MCA method to simulate such complicated processes as: mass mixing, damage generation and accumulation and so on. The fundamentals of this method would be presented briefly and the algorithm to calculate the interaction forces is given.

In the local coordinate system of the pair *i-j*, stress tensor with specific normal σ_{ij} and shear τ_{ij} interaction forces are as follows:

$$F_n^{ij} = \sigma^{ij} s^{ij}, \quad F_t^{ij} = \tau^{ij} s^{ij}$$

where $F_n{}^{ij}$ is the normal potential force, and $F_t{}^{ij}$ is the tangential potential force. s_{ij} is the contact area between automaton *i* and *j*.

The interaction of two automata should be considered as an interaction of different bonded parts of a solid in the case of linked pair and as independent parts in the case of unlinked one. Elasto-plastic interaction of *i-j* pair is based on the deformation plasticity theory. In the framework of this approach, the following equations for local stresses are used:

$$\sigma_x = \varphi \varepsilon_x + (1 - \frac{\varphi}{K}) \sigma_e$$

$$\tau_{xy} = \frac{\varphi}{2} \gamma_{xy} \tag{1}$$

where $\sigma_x(\varepsilon_x)$ are diagonal components of stress (strain) tensor, and σ_e is the average stress, and $\tau_{xy}(\gamma_{xy})$ are off-diagonal shear (strain) components. φ and K are elastic constants of material of the automaton, and φ is defined by the following expression:

$$\varphi = \frac{2}{3} \frac{\mathrm{d}\sigma_{\mathrm{int}}(\varepsilon_{\mathrm{int}})}{\mathrm{d}\varepsilon_{\mathrm{int}}} \tag{2}$$

where σ_{int} is the equivalent stress intensity, that is

$$\sigma_{\mathrm{int}} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2} \tag{3}$$

$\varepsilon_{\mathrm{int}}$ is the equivalent strain intensity, that is

$$\varepsilon_{\mathrm{int}} = \frac{2}{3} \sqrt{\varepsilon_x^2 + \varepsilon_y^2 - \varepsilon_x \varepsilon_y + \frac{3}{4} \gamma_{xy}^2} \tag{4}$$

According to Equation (1), the normal stress σ_n^{ij} and tangential stress τ_n^{ij} for the interacting pair of automaton *i* and *j* at time step *n* are defined as follows:

$$\sigma_n^{ij} = \sigma_{n-1}^{ij} + \varphi_{n-1}^{i} \frac{\Delta\delta^{ij} + \Delta\delta^{ji}}{1 + \varphi_{n-1}^{i} / \varphi_{n-1}^{j}} \tag{5}$$

$$\tau_n^{ij} = \tau_{n-1}^{ij} + \frac{\varphi_{n-1}^{i}}{2} \Delta\gamma^{i(j)} \tag{6}$$

where

$$\Delta\delta^{ij} = \Delta\varepsilon^{i(j)} + \Delta\sigma_{av}^{ij} \left(\frac{1}{\varphi_{n-1}^{i}} - \frac{1}{K^i} \right)$$

$$\Delta\delta^{ji} = \Delta\varepsilon^{j(i)} + \Delta\sigma_{av}^{ji} \left(\frac{1}{\varphi_{n-1}^{j}} - \frac{1}{K^j} \right)$$

where Δ stands for the increment of a corresponding parameter per time step Δt. $\sigma_{av}^{ij}, \sigma_{av}^{ji}$ are the mean stress of the pair *i-j*.

In present study, the “fracture” criteria for linked–unlinked switch was defined as critical value of stress intensity in the interacting *i-j* pair: $\sigma_{\mathrm{int}}^{i(j)} \geq \sigma_b^i$ or $\sigma_{\mathrm{int}}^{j(i)} \geq \sigma_b^j$, where σ_b is the automaton material stress intensity.

Description of Numerical Method in Microscale

The local contact region simulated through the MCA method is represented in Figure 1.

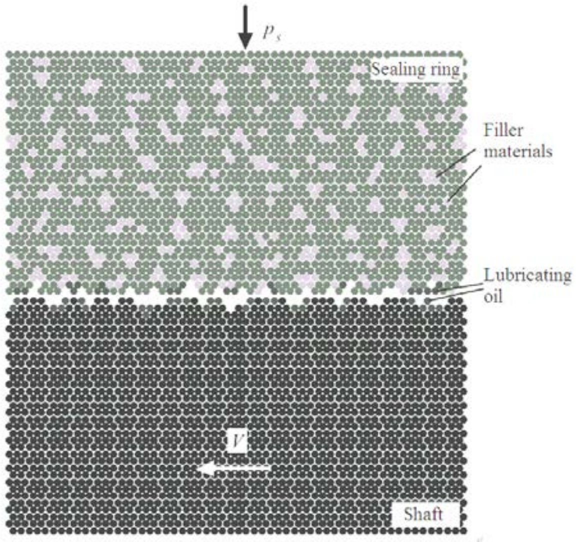


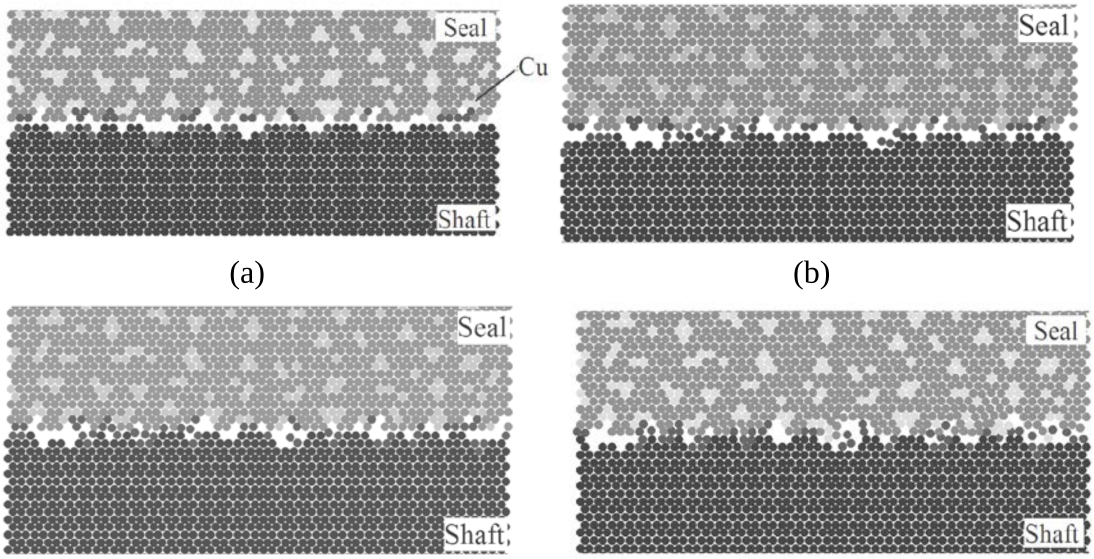
Fig. 1 The discrete model of sealing ring

The seal material characteristics and particle sizes of the filler materials are considered in the model to select each automaton size. In this study, the diameter of an automaton is 5μm. The cross-sectional area during simulation is of the order of 0.3×0.3 mm^2.

In the model, the particles correspond to interacting automata of finite size which are linked to each other. Only one very small contact is regarded in two dimensions and a micron-sized cross-section is defined as both sides of the sealing interface, i.e. the sealing ring and shaft. On the sealing ring's side, we assume a primary contact site and provide the Cu particles used in the sealing ring as reinforcing elements. The material of the shaft was alloy steel. The lubricating oil as sealed fluid is selected as a kind of cellular automata.

Results and Discussion

Figures 2 show the visual simulation results of sliding contact for PTFE seal in the microscale. In order to compare with the simulation results easily, Figure 2(a) show the initial structure of automata positions of simulated contact region for four seals pairs at 0 μs. According to the simulation results, a friction layer forms in the contact region for PTFE seal materials, as indicated in Figures 2(b)-(d). This friction layer is a mixture of loose worn particles and lubricating oil in the form of unlinked automata. This layer exhibits a process of deformation, fracture, and intensive mass mixing, which doesn't propagate to the bulk of the seal and shaft. Generating the layer has the liquidity, and leads to the reduction of effective resistance to the relative motion of the mating pair, which has the dual effect of fluid lubrication and solid lubrication. With the mixing of material from the seal and shaft, this layer is termed a mechanically mixed layer (MML), a concept mentioned by several researchers in their studies on dry friction [12]. Steady state means that the thickness of the MML no longer changes during further sliding. This formation of MML could be regarded as the formation of a third body caused by the friction process. The MML remains spatially localized close to the surfaces of the interacting bodies.



(a) (b)

(c) (d)

Fig. 2 Simulation results of sliding contact of sealing ring

The analysis of seal surface automata shows that seal surface layers have the differ structures in comparison with the initial structures of automata positions in Figures 2(b)-(d). The damaged regions near the free surfaces can be described as plastically deformed. The cellular automata of lubricating oil are dispersed in the MML. Some cellular automata detach from the bulk of the seal and then form the flaky structure. The obtained data prove that local pressure in contact patches could significantly exceed the nominal one and is sufficient for the plastic deformation of the surface layers. In particular, some detached PTFE cellular automata adhere to the steel cellular automata, which indicates signs of adhesive wear. We also find that some copper automata are worn from the matrix material. From the perspective of Cu particle sizes in PTFE matrix material, large copper particles are earlier to detach from the bulk of the seal during the sliding contact and formed the worn particles in the MML. Small copper particles are also earlier to be worn from the seal, while medium copper particles rarely detach from the bulk of the seal according to the simulations.

Conclusion

In this study, a two-dimensional sliding contact of two rough surfaces of seal pair by using MCA method is presented. With the MCA method, we can accurately know the friction characteristics in micro scale and grasp the operation state of sealing ring comprehensively. The results from this study indicate that it is useful to apply this MCA method for solving other tribological problems.

Through the microscopic friction state simulation, we can clearly understand local friction and wear condition. The formation of a MML of loose worn particles is important for understanding the frictional behavior of sealing ring. This MML is caused by the elastic and plastic deformation, shearing and fracture of the bulk materials in the friction zone, which is favorable from the aspect of anti-wear.

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