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An elastic–plastic investigation of third body effects on fretting contact in partial slip

Arnab Ghosh, Weiyi Wang, Farshid Sadeghi*

Purdue University, School of Mechanical Engineering, West Lafayette, IN 47907, USA

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ABSTRACT

In this investigation, the third body effects in fretting contact is modeled using the commercially available ABAQUS finite element (FE) software. A two dimensional Hertzian line contact model is simulated in the presence of third bodies at the contact interface. The third bodies are modeled using simplified geometry like cylinders. Elastic–plastic material properties are used to model both the first bodies and third bodies. The FE model is used to investigate fretting phenomena under different displacement amplitudes and the influence of third body particles on contact stress and contact slip. In addition, the effects of different factors such as material properties of the third bodies and number of third body particles on fretting are investigated. Fretting loops obtained from the model show notable differences in shear stress distribution when compared to smooth Hertzian line contacts in the absence of third body particles. The results indicate that the third bodies deformed to platelet like structures as observed in experiments. The obtained results also indicate that contact stress decreases with the increase in the number of third bodies. As the number of third bodies in contact is increased, the contact shear force between the first bodies decreases while the contact slip increases. Due to this phenomenon, the dissipated energy is not affected and therefore does not influence fretting wear rate significantly. Although fretting wear rate is not directly influenced by the presence of third bodies, plastic deformation of the first body surfaces influences contact parameters which in turn impacts fretting wear.

1. Introduction

Fretting is a special wear process which occurs at the contact area between two bodies when they are subjected to minute oscillations and usually leads to wear and fatigue damage. This phenomenon exists in many machine components in industrial application, such as bearings, gears, couplings and joints. In the fretting procedure, there is an important phenomenon that needs attention – the amplitude of oscillation is smaller than the contact width, which results in entrapment of wear debris generated at the contact interface. The trapped debris or particles could be either detrimental or advantageous, depending on the volume of trapped particles, the material properties, as well as the friction conditions. The contact surfaces are separated by a layer of wear particles, which has a rheological property, and could accommodate the velocity differences (Iordanoff et al., 2002). Therefore the particles help reduce friction and alleviate wear. If the wear particles are hard and not present in optimized amount, it can aggravate wear.

The two rubbing bodies in sliding or fretting contact are called “first bodies”, while the wear debris or particles generated between them are called “third body”. This concept was introduced by Godet in the 1970s to connect the lubrication theory with dry contacts, but not until 1984 did he publish a paper about it (Godet, 1984). In fretting, the prevailed Coulomb’s friction law in sliding conditions does not match well with experimental results, therefore, many wear laws and equations have been proposed to describe the phenomenon. The existence of third body wear particles makes the job of integrating these laws quite difficult, because the entire problem of boundary conditions under those circumstances is not well known (Godet, 1984). The wear particles are generated in the contact due to several reasons such as micro-cutting. Mechanical failure of asperities in contact, cracks due to surface and subsurface fatigue, spalling and plastic deformation leading to formation of grooves and scratches (Zmitrowicz, 2005). Waterhouse and Taylor (1974) claimed that the first third body particles are detached from the first bodies due to delamination wear (Suh, 1973), which is the result of the initiation of sub-surface cracks which propagate parallel to the surface. After the third body particles are detached, they are either trapped inside the contact, compacting into a solid third body layer which separates the two contacting bodies or ejected outside the contact. In the early stages of fretting, when the wear particle mass is small, the

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* Corresponding author. Tel.: +17654945719; fax: +17654940539.
E-mail addresses: ghosh15@purdue.edu (A. Ghosh), wang2043@purdue.edu (W. Wang), sadeghi@purdue.edu, sadeghi@ecn.purdue.edu (F. Sadeghi).

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detrimental effect of the third body is more dominating than the beneficial effect. As wear occurs and the particles accumulate, it facilitates the formation of the compacted oxide particle layer, leading to a beneficial effect of the third body phenomenon (Iwabuchi, 1991). Experimental results have shown that a higher third body mass would lead to lower wear rate, implying that with a large amount of third body particles, the abrasive features of the wear debris is counterbalanced by the third body's beneficial effect (Iwabuchi, 1991). It should however be noted that the third body phenomena could also be influenced by factors such as particle properties (Iwabuchi, 1991), contact shape (Godet, 1984; Berthier et al., 1988; Lancaster, 1975), applied pressure (Godet, 1984; Berthier et al., 1988) and contact direction (Lancaster, 1975).

The concept of "tribology circuit" best explains the third body phenomenon (Berthier, 1990), which states that particles are generated, recirculated into the wear track, or ejected out of the contact. The continuous process of these three steps makes the third body behave like a flow, forming the source flow which increases the mass of third body and a wear flow which decreases the mass. When the flow rates equalize, a state of equilibrium is achieved, and a steady third body layer is formed (Fillot et al., 2007). The change of contact conditions could lead to a change in the particle generation and ejection rate and it will reach a new steady state, but a temporary disturbance won't change the original equilibrium.

There are typically two approaches to model the third body effect based on its different mechanical characteristics, the continuum and the discrete approach. The continuum models concerns more about the third body's rheological properties, it regards the third bodies as continuum and isotropic and solves the problem from a more macroscopic point of view. Solid mechanics and fluid mechanics are used in the models depending on whether the third body behavior is more close to the rheology of a solid or a liquid (Iordanoff et al., 2002), Hou et al. (1997) and Heshmat (1995) have developed corresponding models. Heshmat (1995) Iordanoff et al. (2002) also investigated the parameters like geometry of particles and pressure that determine whether the third body should be treated as solid or fluid (Heshmat and Brewe, 1994, Iordanoff and Berthier, 1999, Heshmat, 1993). However, in reality, the solid third body is discontinuous, heterogeneous and anisotropic, thus the continuum mechanics equations are not enough to depict and solve the problem (Iordanoff et al., 2002). As a consequence, granular model based on Discrete Element Method (DEM) have been used. These models usually assume Couette flows with periodic boundary conditions and to achieve efficient computational effort, explicit methods are often employed (Iordanoff et al. 2002). DEM was developed by Cundall and Strack (1979) in 1979, and first applied to the solid third body problem by Elrod and Brewe (1992) in 1991. Their model related microscopic properties (particle shapes, size and first body roughness) and macroscopic properties (velocity accommodation, slipping and friction coefficient) (Iordanoff et al., 2002). Eich-Soellner and Führer (1998) and Jean (1999) induced contact dynamics to describe jumps in speeds and the force thresholds in the discrete element model. Iordanoff et al. (2002) developed one of the first 2D discrete element models to study the third body flow. They were interested in the influence of the particle size and the inter-particle forces on the macroscopic responses of the contact and extended the model to 3 dimensions [Iordanoff et al., 2005]. Fillot et al. (2004) induced wear to the discrete element model by making one of the first bodies degradable, allowing the particles to be detached from a granular material. They showed the influence of the contact constraints and particle adhesion on the thickness of the degradation layer and the particles ejection rate (Fillot et al., 2004; 2007)

As an extension of DEM, a finite element model (FEM) was developed in this investigation and applied to the simulation of third body effect. Using FEM, the bodies can be modeled deformable instead of rigid as in DEM. There are two integration techniques in FEM, namely implicit and explicit. The implicit technique is suitable for a slowly evolving static process such as structural dynamics and contact mechanics. On the other hand, an explicit technique can only reach a conditional stable state which requires a very small time step and deals with processes with rapid changes like wave propagation and impact engineering. Thus the explicit method is more suitable for granular flow problems like the third body flow (Kabir et al., 2008). Kabir et al. (2008) used the explicit FEM to simulate a dense flow of discrete grains in a 2D shear cell with sliding and wall roughness factor for unity. They compared the FEM with DEM and suggested that FEM is more advantageous as compared to DEM. FEM provides better evaluations of complex contact conditions, allows deformation of elements and depends mainly on material properties instead of numerical fitting parameters. Cao et al. (2011) coupled continuous and discontinuous descriptions by making the lower body deformable, while keeping the upper first body and the third body rigid. They employed a set of hybrid elements in the contact by attaching discrete rigid elements to the surface of the first body which was meshed with finite elements. They compared this approach to DEM in performance of velocity and stress profile and underlined the influence of first body rigidity on third body rheology, as well as the fact that the interaction law has a strong effect on it. Linck et al. (2003) used FEM to simulate contact of two first bodies with smooth surface subjected to a constant coefficient of friction and showed the effect of local behaviors like stick, slip and separation of contact surfaces by evaluating the normal and tangential stresses in the contact region. They suggested that simulation results could not be correlated to experiments due to several contact mechanisms involving detachment of particles. Ding et al. (2007) modeled the third body as a thin layer structure with an anisotropic elastic–plastic material different from the first bodies. The thickness of the third body layer was calculated by considering the trapping and escaping of wear particles. The simulation results indicated that the introduction of the third body layer caused a narrower but deeper wear scar on the surface. Basseville et al. (2011) modeled the third body as rectangular finite element meshes and studied its effect on the stress field and wear. Their simulation showed that the debris were ejected in gross slip, while remain trapped in partial slip due to the stick-slip mechanism. Leonard et al. (2014) applied the finite-discrete element method (FDEM) to model the effect of the third body on fretting. The third body is analyzed as discrete elements, while the first bodies are modeled using finite elements. This approach builds a link between the large scale models which treat the mass of wear debris as a small number of bodies and small scale models which focuses on a control volume. The material properties of the third body particles have also been investigated recently by Everitt et al. (2009) by conducting nano-indentation measurements on the debris and substrate layer. Ding et al. (2009) also implemented an oxidation equation to investigate the evolution of elastic–plastic response of the third body layer.

In this investigation, the effect of third body phenomenon of a 2 dimensional Hertzian contact was simulated using the finite element method (FEM). Both the first body and the third body are modeled using finite elements with elastic–plastic material properties. Due to the complex nature of the problem, certain assumptions are made to simplify the problem. The main focus of this study is to determine the changes in contact parameters as fretting wear initiates and third body particles are trapped inside the contact. During the simulation, the particles are plastically deformed and a platelet type shape is obtained. The effect of third body particles on contact pressure and shear stress in partial slip regime is investigated in detail. In addition, influence of particle number on contact parameters is also analyzed. Fretting loops in presence of multiple third body particles are also obtained. The analysis shows that the third body particles affect contact parameters which can result in alleviating fretting wear at the contact of two first bodies.