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Third body modeling in fretting using the combined finite-discrete element method

Benjamin D. Leonard [a], Arnab Ghosh [a], Farshid Sadeghi [a,*], Sachin Shinde [b], Marc Mittelbach [c]

[a] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907-1288, United States
[b] Siemens Energy Inc., Orlando, FL 32826, United States
[c] Siemens AG, Muelheim, Germany

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ABSTRACT

A new approach was developed for modeling the effect of the third body on fretting. This was accomplished using the combined finite-discrete element method (FDEM) in which the third body is analyzed as discrete elements while the first bodies are modeled using finite elements. This approach provides a link between large scale models which treat the mass of wear debris as a single or small number of bodies and small scale models which only study a control volume. The FDEM was used to analyze the behavior of third body particles between flat sliding surfaces. When the third body mass is composed of unconnected particles, it behaves as a Newtonian fluid, but this behavior ceases when the particles are connected into platelets. The FDEM was also used to study the behavior of third body particles inside a Hertzian line contact. As the number of particles and platelet size increase the load carried by the worn slip zone grows larger in relationship to the unworn stick zone.

1. Introduction

Fretting occurs when two contacting bodies are subject to small amplitude oscillatory motion which leads to both wear and fatigue damage. This phenomenon is common in machine components such as bearings, gears, couplings, dovetail joints, and wire ropes. An important characteristic of fretting is that motion is smaller than the contact width, allowing wear particles to remain trapped inside the contact. The wear debris generated in the contact can be either a beneficial or detrimental depending on its material properties. A third body layer of compacted oxide can accommodate the difference in velocity, reduce friction, and separate the opposing surfaces. On the other hand, hard particles can cause abrasive wear.

In a sliding or fretting contact the two contacting surfaces are referred to as "first bodies" while the wear particles which develops between them is referred to as the "third body." Godet presented this concept during the 1970s in order to link lubrication theory with dry contacts, but he did not write about it until 1984 (Iordanoff et al., 2002). In continuum mechanics solutions the third body is sometimes modeled as an incompressible fluid (Dragon-Louiset, 2001). Third body wear debris play an important role in fretting and have been cited as one of the reasons why synthesizing the hundreds of wear laws found in published literature describing the phenomena is so difficult (Meng and Ludema, 1995). There is debate over the mechanism by which the first wear particles are formed. It is most often attributed to adhesion (Colombie et al., 1984; Samuels et al., 1980), but Waterhouse and Taylor (Waterhouse and Taylor, 1974) ascribed the formation of the first detached particles to delamination wear (Suh, 1973, 1977) which is caused by the initiation and growth of near surface cracks. As more wear particles are created the abrasive action of debris becomes the leading cause of particle detachment. Once loose wear debris are oxidized and ground down into micron size particles (Iwabuchi, 1991), some of the loose particles will be ejected from the contact while others are compacted into a solid third body layer. Generally, over time sufficient wear debris become trapped in the contact to separate the two primary surfaces. Lower wear rates have been linked experimentally with higher third body mass implying that wear particles' abrasive qualities are more than canceled out by their beneficial features (Colombie et al., 1984). However, the third body phenomena is thought to depend heavily on wear particle properties (Berthier et al., 1988), contact shape (Colombie et al., 1984), and contact orientation (Lancaster, 1975).

The third body concept is best illustrated by the tribological circuit (Berthier, 1990). Wear flows from the two first bodies into the third body (particle generation) and then some portion of the third body is ejected from the contact (particle ejection). A stable equilibrium is reached when the particle ejection rate is equal to the particle generation rate. If the contact conditions change leading to a different particle ejection or generation rate, the contact will move to a new equilibrium. However, if the disturbance is

* Corresponding author.
E-mail address: sadeghi@ecn.purdue.edu (F. Sadeghi).

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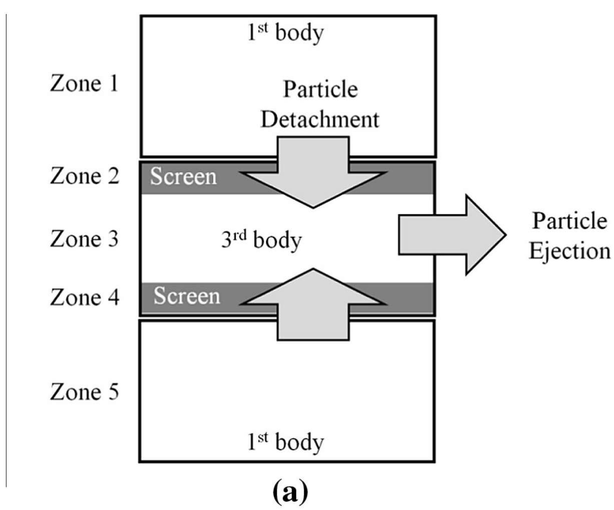
temporary, the contact Fig. 1(a) illustrates the zones, bodies, and flow channels making up a third body wear system while Fig. 1(b) shows competition of third body flow rates.

One approach to modeling the third body uses the discrete element method which was developed by Cundall and Strack (1979). A review of discrete element investigations of the third body by Berthier and Descartes (Berthier and Descartes, 2002) shows that DE models are generally used to analyze the third body in a condition of Couette flow between flat surfaces with periodic boundary conditions and use explicit integration methods. Discrete element modeling of the third body began in the early 1990s (Elrod and Brewe, 1991). Iordanoff et al. (2002) created one of the first two-dimensional dynamic discrete element models of third body particle flow. This approach was later extended to three dimensions (Iordanoff et al., 2005). Fillot et al. (2004) implemented wear into the discrete element model used to study two flat parallel surfaces. One body was made degradable and composed of linked discrete elements while the other remained a rigid surface. Fillot et al. (2004) showed that the steady state thickness of the third body depends on both applied loading and material properties. Fillot et al. (2007) extended the wear model to three dimensions and found that adhesion between particles controlled the particles ejection rate and thickness of the third body layer. Iordanoff et al. (2008) modeled subsurface damage from polishing by breaking the joints connecting the discrete elements comprising the degradable first body. Abrasive particles were modeled as degradable assemblies of spheres; the edges of these groups of elements caused fractures within the first body. Kabir et al. (2008) made an explicit finite element model along the lines of earlier discrete element studies. Each granular particle was represented as a finite element mesh with 81 elements. Third body flow was modeled in a shear cell between parallel surfaces where the effect of material properties and gap height on the velocity and solid fraction was studied. The explicit finite element and discrete element approaches were compared and the former was found to give a slightly lower velocity throughout the gap and a lower solid fraction at the boundaries. Cao et al. (2011) coupled the finite element and discrete element approaches by attaching a row of circular discrete elements to the surface of a finite element mesh for contact calculations. They modeled third body discrete element flow between flat parallel surfaces in a manner similar to previous studies but studied the stress within one of the first bodies using finite elements.

The finite element approach has also being applied to the third body phenomenon. Linck et al. (2003) modeled the third body as a finite element mesh rubbing against a rigid surface and found that under most conditions there is a combination of stick and slip in the contact. They demonstrated that the regions of stick and slip move as waves along the surface. The authors postulated that the slip waves which had not been detected experimentally help explain the mechanism of particle detachment and heat generation. Ding et al. (2007) modeled third body wear of a Hertzian line contact using finite element method. The third body was modeled as a thin upper layer of elements on the first body which had different materials properties from the substrate. The height of the third body layer varied based on the wear rate. The mechanical properties of the third body were determined by adjusting them to match experimentally measured fretting loops. The presence of a third body resulted in a narrower and slightly deeper wear scar. Basseville et al. (2011) modeled the third body as a series of rectangular finite element meshes placed between the contacting surfaces. Third body finite element domains with dimensions of 5 μm by 1 μm were placed in the contact covering the surface at the beginning of the simulation. Wear loss of the first body was reflected by a growth in the height of the third body domains and particle ejection was modeled by the rectangular finite element meshes sliding out from between the two first bodies.

In this study the effect of the third body on fretting wear of a Hertzian contact was modeled using the combined finite-discrete element method. The first body was modeled using the finite element approach while the third body was modeled as discrete elements. The effect of wear particles on the pressure and frictional shear stress in a Hertzian fretting contact is demonstrated.



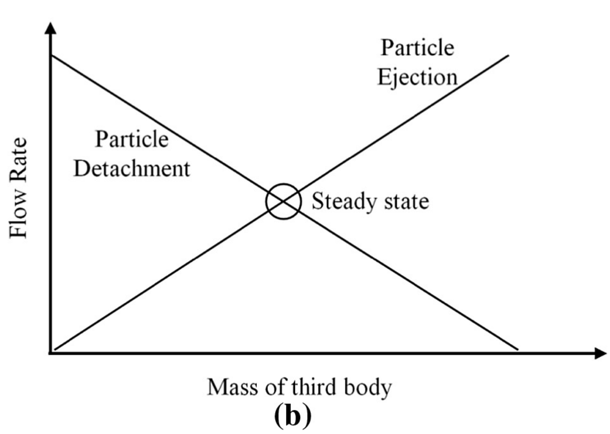


Fig. 1. The third body can be understood by considering the (a) zones and directions of flows within a contact and the (b) competition between particle ejection and detachment.

2. Combined finite discrete element model of the third body

The previously developed (Leonard et al., 2011, 2012) combined finite discrete element model (FDEM) was extended to investigate the effect of the third body in fretting wear. In the FDEM the contact interaction between bodies is solved using the discrete element method, however, the deformation of individual bodies was calculated using the finite element approach. The first bodies are modeled using finite elements while the third body particles are simulated by discrete elements. A review of the FDEM model is provided in the next section.

2.1. Finite element model

The stress within deformable bodies is calculated using the explicit finite element method. The dynamic relaxation method (Underwood, 1983) is used to solve each element's stiffness matrix