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Rough surface and damage mechanics wear modeling using the combined finite-discrete element method ☆

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ABSTRACT

In this investigation the combined finite discrete element method was used to analyze fretting wear of rough and smooth Hertzian contacts using the Archard wear equation and continuum damage mechanics. Surface roughness profiles were generated using the Voronoi tessellation procedure and scaled in order to analyze the effect of roughness on fretting wear. Using the Archard equation, wear loss increased with roughness in the partial slip regime. In contrast, in the gross slip regime roughness only played a role at the beginning of a test before all of the asperities had been removed. Using the damage mechanics, subsurface damage accumulation was found to be a linear function of cycles. In this approach, a long breaking-in period occurred before the first wear particles were detached from the surface; however, following initiation, wear loss was approximately a linear function of cycle number. The shape and evolution of fretting wear scars were in agreement with experimental results.

1. Introduction

Fretting occurs when two contacting surfaces experience small amplitude oscillatory motion. One characteristic of fretting wear is that more wear particles are retained in the contact than in rolling, unidirectional sliding or reciprocating sliding contacts. Detached wear particles play an important role in the fretting phenomenon [1] and wear in general [2] but are difficult to model. In this study a procedure for evaluating fretting wear of rough surfaces and particle detachment using the combined finite-discrete element method will be developed.

Initial numerical investigations of the third body effect used a wide variety of approaches such as quasi-hydrodynamic modeling [3] and kinetic modeling [4] however; two different approaches have become dominant: discrete elements and finite elements. In the finite element approach the third body is modeled as a mesh whose size can change based on the mass of wear particles. Ding et al. [5] presented the first finite element model of fretting wear. In their model the third body was modeled as a thin layer of elements with differing material properties which formed the top row of elements on the lower body. The third body properties were calibrated by matching the model's behavior with experimentally recorded fretting loops. The size of the "third body" finite elements fluctuated with the wear rate. In a more recent study Basseville et al. [6] also modeled the third body effect using ABAQUS. Instead of using a single set of finite elements attached to the primary mesh, they represented the third body mass as a number of rectangular domains composed of several finite elements. The third body meshes could grow based on wear and slide out of the contact. The third body was given the same material properties as the first bodies.

The second primary approach in modeling the third body effects is the discrete element method. The first and third bodies are composed of spherical particles where the elements comprising the first body are attached with springs. Fillot et al. [7] first presented this approach which can be used to observe the flow of third bodies between two surfaces and analyze particle detachment. The method was subsequently extended by Fillot et al. [8,9] to analyze third body flows in a small contact with and without periodic boundary conditions. Subsurface damage can also be modeled by allowing joints to fracture within the first body [10]. To allow the explicit introduction of material properties a finite element mesh can be used as a base for the discrete element simulation [11]. Two shortcomings of this approach are that it cannot analyze a large enough area to study an entire fretting contact nor can it model particle deformation. When modeling wear and subsurface failure joints are only broken when the stress exceeds a critical value; fatigue properties have not been introduced which would allow them to degrade gradually.

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The delamination theory of wear was first proposed by Suh [12,13]. It postulates that wear is caused by the initiation and growth of near surface cracks which is similar to a fatigue. One interesting aspect of this theory is that it is a "bottom-up" approach which sees the issue as the material breaking down allowing a particle to detach from the body rather than a "top-down" approach which looks at external factors removing material from the surface. Waterhouse and Taylor [14] have suggested that delamination wear causes the initial formation of wear particles in fretting wear and further, the third body develops transitioning the contact into abrasive wear. The delamination theory of wear leads to the conclusion that the wear rate per sliding distance in fretting depends on the material microstructure and surface topography [12]. The traditional Archard equation also supports viewing wear as a fatigue process. Its dimensionless wear coefficient can be thought of as the percentage of asperity contacts which result in particle detachment, a value which is typically less than 0.001 [15].

The damage mechanics approach has been successfully used to study the near surface phenomena of rolling contact fatigue. In rolling contact fatigue a subsurface crack initiates and then propagates toward the surface forming a spall. Damage mechanics provides a framework for modeling the progressive degradation of a material due to microscopic mechanisms such as the formation and growth of micro-cracks and voids. Both finite [16] and discrete element [17] models of rolling contact fatigue have been developed. In these models Voronoi tessellation is employed in order to discretize the domain and crack growth is assumed to be shear driven with crack propagating intergranularly along the weaker grain boundaries. The models captured both the initiation and propagation of fatigue cracks and have been used to generate Weibull slopes and crack spallation patterns in agreement with experimental results. The rolling contact fatigue phenomena is similar to the wear as described by delamination theory in which local voids nucleate and begin to propagate as cracks leading to material separation as spallation (rolling contact fatigue) or particle detachment (wear).

The damage mechanics approach has been applied to fretting and wear in several previous studies. Ireman et al. [18] derived a model with coupled fatigue and wear which were governed by damage mechanics and the Archard equation respectively. The model allowed wear loss to influence crack invitation which is important to accurately model fretting fatigue. In that study the approach was used to model a contact undergoing sliding wear. Zhang et al. [19] used damage mechanics to model plain fatigue of notched and un-notched specimens in three dimensions before applying to the model to the two dimensional plain strain fretting fatigue problem. In their study Zhang et al. [19] analyzed three different integration techniques for the damage mechanics equation: forward difference, central difference, and backward difference. They determined that the backward difference method was the optimal method because it was the only integration procedure to give conservative results.

Surface roughness is important for fretting wear but its effect on fretting wear has not been modeled using finite elements. Both experimental studies and numerical investigations have demonstrated that surface roughness plays a significant role on fretting wear. In a paper on the avoidance of fretting, Beard [20] suggests that shot peening and the associated increase in surface roughness should both reduce fretting wear and increase the fatigue life. Reducing surface roughness has been shown experimentally to lead to a higher coefficient of friction which is typically associated with high wear rates in gross slip [21]. Volchok et al. [22] found that laser texturing the surface of a specimen (increasing surface roughness) can extend its fatigue life due to the micropores' ability to collect wear particles from the contact. Srinivasan et al. [23] have found that laser shock peening had a similar beneficial effect on fretting fatigue life. Numerical fretting models have also been used to study surface roughness. Ciavaella et al. [24] computed the pressure and traction of sinusoidal rough fretting contacts. Kasarekar et al. modeled fretting wear [25] and fretting fatigue [26] of randomly rough surfaces. Kasarekar et al. found that increased surface roughness reduced the crack initiation life and increased the wear rate in partial slip. Eriten et al. [27] analyzed the energy dissipated by rough surfaces and determined that the energy dissipated by a contact (which is proportional to wear) increases with surface roughness.

In this study the combined finite discrete finite element method was used to investigate fretting wear of rough Hertzian contacts using the Archard wear equation and the damage mechanics approach. The damage mechanics modeling approach developed and described in this paper will allow fretting wear to be modeled using a stress based approach. This approach is stress based and thus does not need the Archard coefficient. This could lead to a wear modeling approach which does not require wear testing but only requires mechanical properties of materials (i.e. modulus of elasticity, yield strength, hardness, etc.). The input variables to the damage equation are subsurface stresses instead of contact parameters.

2. Numerical modeling

2.1. Generation of rough surfaces

This section describes how rough surfaces were generated in this study by using a Voronoi tessellation procedure. To create a Voronoi tessellation seeds points are distributed randomly throughout a domain and the region is subdivided into cells around each point [28].

Every location within each cell is closer to the central seed point than to any other in the domain. Random seeding of the domain ensures that each tessellation is unique. A sample Voronoi mesh is shown in Fig. 1. In this study the Voronoi cells were not used to represent metallic grains, but to generate a rough surface.

Each rough surface was created by removing all Voronoi cells above a defined line. The new top layer of nodes and edges became the upper surface of the new domain. The nodes were scaled in the horizontal and vertical direction in order to achieve the desired density of nodes and surface roughness. The region below the surface was meshed using Delaunay triangulation. A sample rough surface is shown in Fig. 2.

2.2. Implementation of damage mechanics

In order to model the effects of the third body during a fretting wear process, a particle detachment procedure must be based on

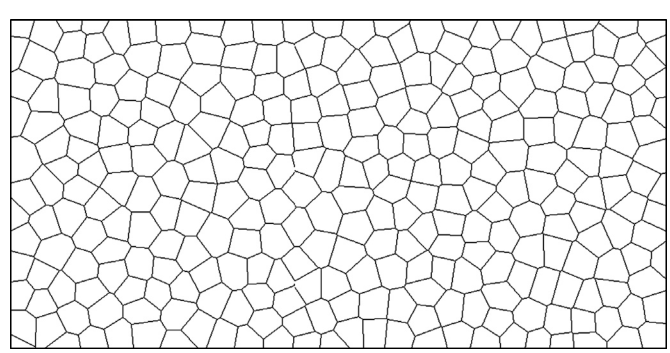

Fig. 1. A sample Voronoi mesh.