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Semi analytical fretting wear simulation including wear debris

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ABSTRACT

Many numerical models are proposed in the literature using finite element and finite discrete element methods to study fretting wear, barely including the effect of wear debris. These models being computationally expensive, simulating large number of fretting wear cycles is not practically feasible. A new methodology is proposed which needs only bulk material properties like friction/wear coefficients and uses semi-analytical methods to simulate fretting wear with entrapped debris. In this approach, debris are assumed to be attached to one of the surfaces during the fretting process. The results obtained from this approach were compared with fretting experiments. The proposed method permits to capture the wear depth and scar width, and results are very close to that observed in the experiments.

1. Introduction

Fretting wear is the material removal process occurring when two contacting bodies are in micro level relative motion and subjected to contact load. The wear rate during fretting depends on many parameters, from experiments conducted with cylinder and flats speciments, Warmuth et al. [16] concluded that the diameter at the interface and slip play a prominent role in fretting wear. Large diameter and low slip causes least wear, whereas a large slip causes significant material removal irrespective of the diameter. Li and Lu [17] studied the effect of displacement amplitude on fretting wear of Inconel alloy. They observed micro-cracks at the junction of adhesion and sliding zone. For large amplitudes, 'plow' effect was found at the edge of the wear scar. Apart from contact load and displacement, the nature of debris formed during the fretting wear process determines the wear modes. When debris particles formed during the fretting wear are entrapped at the contact zone, there will be significant effect in altering the wear mechanism and the resultant wear scar. Specially, contact profile and contact pressure changes based on the amount of debris present at the contact region. Everitt et al. [18] concluded from their work that formation of debris within the fretting interface generally indicates that fretting wear has reached the steady state. Also, that debris layer moves into the substrate by an oxidation process. Gas turbine combustor components such as hula seal, liner stops, crossfire tubes, collars, swirlers etc. are subjected to dry fretting wear at the contact interfaces and most of the time the contact is not opened frequently to release the debris. A numerical model which can include the effect of debris during fretting wear will be very useful to predict the wear profiles. Whereas faster ejection of debris occurs for fretting wear of valve-valve seat interface of internal combustor engines because valve opens to let out the combustion gases and allow fresh air into the cylinder. But, performing fretting wear experiments to replicate opening and closing of valves is time consuming and generally experiments are performed without opening the contact which leads to different wear profiles compared to the wear profiles observed in the field. To bridge this gap of wear profiles obtained from experiments to the real wear profiles observed in the field, numerical models capable of considering different level of debris ejection rates will be very useful.

Different types of fretting wear prediction methodologies without considering debris are found in the literature. Rodriguez-Tembleque et al. [19] applied 3D boundary elements to simulate 3D fretting wear problems. The methodology uses Lagrangian formulation to solve the contact problem and Archard wear law to compute wear. Fouvry et al. [20] performed 2D FEM wear simulation and showed that the wear profile evolves from an initial Hertzian, then elliptical and finally flat distribution. Tang et al. [21] proposed a multilayer node update method in FEM to simulate fretting wear involving large depth. The nodes interpolation method was provided for both 2D and 3D contact problems. Arnab el. al. [22] presented a damage mechanics stress based wear law to model fretting wear of Hertzian contact. They used FEM to obtain contact stresses and the wear coefficients obtained from their model was comparable to the values reported in the earlier literature. Lee et al. [23] formulated 2D contact model in terms of Cauchy integral equation to perform fretting wear analysis. They had

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Nomenclature

Surf1	3D geometry of first surface
Surf2	3D geometry of second surface
DebrLyr	Layer of debris particles
Ed	density of energy dissipated by friction during a fretting cycle (J/μm2)
f(Ed)	Wear law
μ	friction coefficient
p	the contact pressure (MPa)
w	the maximum number of time steps per cycle
Pk, k from 1 to w	the normal load history of each cycle (N)
sk, k from 1 to w	the corresponding local sliding amplitude (μm)
WP	wear partition coefficient between two bodies
WC	wear coefficient obtained from experiments
EDR	ejected debris ratio (from debris generated)
ΔN	the number of cycles to update the worn geometry
Nmax	the maximum number of cycles
ΔWearS1	wear on first surface in ΔN cycles
ΔWearS2	wear on second surface in ΔN cycles
E1	Young's modulus of first surface material
v1	Poisson's ratio of first surface material
E2	Young's modulus of second surface material
v2	Poisson's ratio of second surface material

numerically implemented the model by influence function method.

Many authors have studied the role of debris on controlling friction and wear, through experiments and characterization of debris particles. Presence of oxide wear debris at the contact interface protects the surfaces when the dominant wear mechanism is adhesive and harms the surfaces when the dominant wear mechanism is abrasive. Colombie et al. [29] have studied the role of debris in fretting and concluded that the temperature raise during fretting wear is negligible and wear on first body is governed by the formation and maintenance of third body (debris) and abrasiveness of the third bodies. Cherif et al. [1] analyzed the alumina-zirconia materials generated during wear by abrasion. These wear debris contributed to redistribution of applied load on more contact points. They have observed that the debris decreases the surface porosity at low loads and in turn reduces the friction. At high loads, due to large plastic deformation and cracking, the surface becomes rough leading to increase in friction. Descartes and Berthier [28] have highlighted the experimental difficulties involved in studying the flow and rheology of third bodies and they have estimated these properties based on visualization tests. They have noticed that the material removed from one or two first bodies agglomerate to form particles and they accommodate the interfacial load and velocity.

Several numerical models have been proposed to include the effect of debris in the fretting wear simulation. Renouf et al. [24] proposed a unified discrete element approach that is suitable for modeling multi-physical behavior of third-body flows. The approach considers the mechanical, thermal and physicochemical properties of third bodies. Rice and Moslehy [25] modeled the unlubricated sliding contact interface comprising of asperities and debris through mechanical systems (lumped mass, spring and damper). The dynamic parameters like fluctuations in the friction and normal forces are obtained through the model. Wang et al. [26] established a stress-strain transmission mechanism to account for the third-body rheology in a three-body interface. An FEM-DEM coupling was developed and the multi-scale analyses of the three-body friction interface was performed. Lordanoff et al. [2] mentioned the practical difficulties of relating local stress and geometry on the physicochemical and thermomechanical properties of the bodies in dry contact. To simulate fretting wear at micro scale, online measurement of wear mechanism at sub-micron size needs to be recorded and a numerical model with fine discretization needs to be performed. This process involves difficulties during experimentation and measurements, and simulations become computationally very expensive. Fillot et al. [4] have constructed a discrete element wear model with third bodies and analyzed the influence of particle adhesion on wear. They have noticed formation of thicker third body layer as adhesion increases, but the flows of detached and ejected particles decrease which reduce the wear. Ding et al. [15] have performed fretting wear simulation with presence of debris using FE modeling. The debris layer was modeled using finite elements with the ability of large strain in the fretting direction to resemble the flow nature and smaller displacement in the normal direction compared to fretting direction. The simulation results show smaller scar width and greater wear depth when the debris is introduced. Basseville et al. [3] have studied the effect of third body trapped in the contact zone using finite element analysis. They used Dan Van's multiaxial fatigue model to predict crack initiation during the fretting test. The cylinder on plate finite element model developed by them takes about 8 s for one fretting cycle simulation. The model could capture the local overstress in the contact area due to presence of debris. Leonard et al. [5] developed a third body modeling in fretting using the combined finite-discrete element method. Here the third body is analyzed as discrete elements while the first bodies are modeled using finite elements. The simulations could demonstrate non-linear velocity gradient through the height of the third body by increasing the size of particles which in turn adhere to each other. With the increase in number of particles, the area of the slip zone carrying load got increased. Jin et al. [8] studied the effect of temperature rise during fretting and found that the presence of oxide debris layer increases both the average temperature rise and peak temperature rise in the contact if the thermal conductivity of debris layer is lower than base material. Yue and Wahab [7] have built a finite element fretting wear model including the debris layer (of thickness 5 μm, 10 μm and 20 μm) and observed that the effect of Young's modulus of the debris layer on the contact pressure is not significant. Ding et al. [15] have extensively studied the wear progression with debris and proposed a finite element based approach to include a layer of debris in wear simulation. They have also identified the stages of wear progression to start the release of debris and reach a stable release rate. It is to be noted that all the previous models recalled above are based on assumption of plane strain (i.e. 2D).

As discussed above wear debris formed during the process of fretting have a significant role on the wear profile. The available literature shows the requirement of simplified approach of modeling fretting wear in presence of debris. An attempt has been made here to simulate fretting wear including the effect of debris, and validate the

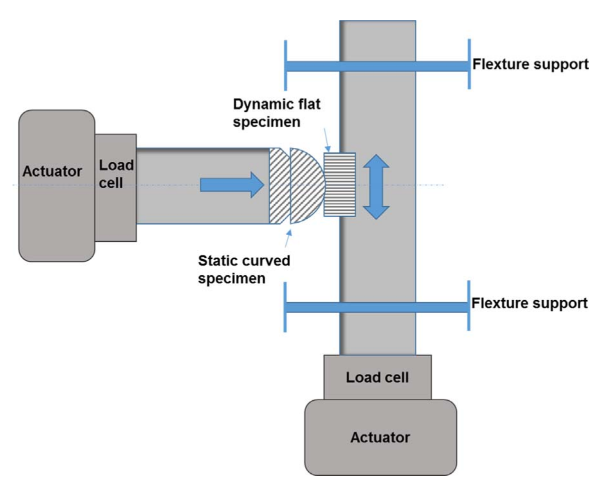

Fig. 1. Experimental test setup for fretting wear.