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Finite element analysis of stress singularity in partial slip and gross sliding regimes in fretting wear

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ABSTRACT

Fretting is a small oscillatory motion between two contact surfaces, which may cause wear or fatigue damage. Many parameters may affect fretting wear including normal load, applied displacement, material properties, surface roughness of the contact surfaces, frequency, etc. The design of engineering components subjected to fretting wear, such as couplings and splines, jointed structures, is still a challenge to engineers. This is because of the continuous change in the contact surfaces of component during fretting wear cycles. Therefore, a predictive technique that takes into account the wear progress during life cycle is desirable. Analytical solutions of wear problems are very difficult and limited to simple 2D configuration steady-state analysis. In contrast, numerical modelling techniques such as Finite Element Analysis (FEA) can be used for any type of structures in 3D configuration with many complicated details such as large deformation, material non-linearity, changes in geometry and time integration effect. In this article, we use FEA to find whether or not there exists a stress singularity at cylinder on flat contact according to different variables, such as applied displacement, coefficient of friction (COF) and fretting wear cycles. Based on a stress singularity signature method, it is found that stress singularity has close relation with fretting regime. There is no stress singularity neither in partial slip nor gross sliding after one-fourth of a fretting wear cycle for lower COF, but it exits for higher COF, in which condition the contact interface is almost stick. After 20,000 cycles, stress singularity exists in partial slip, while there is no stress singularity for gloss sliding condition, when COF is 0.8. Results reveal that more attention should be paid to the mesh size at contact interface, when the contact condition is under partial slip regime.

1. Introduction

The first report on fretting was by Eden et al. [1] in 1911. From then on, great developments have been achieved on not only theory of fretting and testing, but also numerical modelling of fretting damage. Fretting damage results from cyclic relative displacement between two contacting bodies. Depending on contact conditions, such as surface finish and COF, and loading conditions, such as normal force and applied displacement, fretting damage can be either fretting fatigue or fretting wear, or combination of both. The former generally results in failure, whereas the latter usually causes material removal and leads to a loss of fit, but meanwhile it may improve fatigue strength or life [2].

Both fretting fatigue life and wear rate are functions of applied displacement [3]. The risk for both wear and fatigue in the partial slip regime is increased with increasing the applied displacement. In the gross slip regime, although the wear rate continues to increase with increasing displacement, fretting fatigue life is improved significantly. A general explanation for this is that initial cracks are worn away in the gross slip situation because of fretting wear. Normal load applied on the contact surface is another important parameter of fretting, which influences fretting conditions directly. Moreover, an important distinction between fretting and reciprocating wear should be noticed. Wear debris can escape from the contact region easily in reciprocating condition, while in fretting wear process, the magnitude of applied normal force is sufficiently high and the amplitude of displacement is small enough to significantly restrict the flow of the debris to stay in contact surfaces [4].

Although fretting wear may happen in every contact surfaces suffered from cyclic load in partial slip and gross sliding regimes, researchers usually focus on stem/cement of hip joint, blade/disk of dovetail joint in turbine and contact between strands in steel wire ropes. The primary reason of failure in cemented total hip is aseptic loosening, which is further caused by generation of wear debris

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through wear of femoral components [5]. Authors of reference [6] successfully reproduced fretting wear at the stem/cement interface through in vitro wear simulation. They found that cement surface is severely damaged in contact with the fretting zones on the stem surface, with retention of cement debris in the micropores. Because of high cost of experiments, researchers choose numerical modelling method to investigate fretting wear.

With the rapid development of high performance computers and the methods for solving non-linear problems, FEA has been applied to simulate the process of fretting wear. Simulation of wear involves solution of a general contact problem, which is highly non-linear due to contact boundary conditions between interfaces [7].

Among the last 10 years of literature, there are two main methods to simulate fretting wear, namely Archard model and energy model. Reference [8] firstly presents an FE method to predict evolution of contact geometry, surface contact variables and sub-surface stresses both in partial slip and gross sliding conditions based on Archard model. The authors found that, for gross sliding, fretting wear is the predominant damage due to high wear rate, while for partial slip, fretting wear is less important. The risk of crack initiation is greater at the contact edges for small numbers of cycles and at the stick–slip boundaries for large numbers of cycles. Later, they compared the predicted results with experimental results and found an underestimation of wear volume. Furthermore, they studied methods to reduce simulation time, such as optimisation of mesh and optimisation of the increment in number of wear cycles [9]. Based on FEA tools, they revised the model to simulate the debris as a layer structure accumulated on the contact surfaces. These simulation tools incorporating the debris effects realised the redistribution of contact pressure and slip over the contact region to be estimated to finally predict debris effects on wear damage [10]. References [11,12] described an FEA tool that integrated wear modelling with fretting fatigue analysis to permit the prediction of the effect of fretting wear on fretting fatigue life. This method can predict the fretting wear-induced evolution of contact profile, contact stresses and a multi-axial fatigue damage parameter with cumulative damage effects, as a function of slip amplitude, for a laboratory fretting fatigue test arrangement. An elastic-plastic FEA method employed to investigate the evolution of the fretting variables in surface and subsurface was presented in reference [13]. Special attention was given to the evolution of plastic variables and effects of plasticity during fretting wear, using a kinematic hardening plasticity model to describe the cyclic plasticity behaviour.

Introducing an energy concept to predict wear kinetics and geometrical changes of the wear scar is another method. The dissipated energy method can be dated back to 1960s. Reference [14] firstly proposed that friction power intensity (frictional energy dissipated per unit area) is related to wear when studying oil-lubricated Hertzian point and line contacts. Fouvry and co-workers [15,16] investigated fretting wear-based energy concept further. They explained the formation of Tribologically Transformed Structure (TTS) in fretting wear and demonstrated that there is a specific threshold dissipated energy before starting wear. In addition, they found an energy wear coefficient, which can relate the evolution of wear volume with the additional energy dissipated during fretting wear process. Later on, they demonstrated that energy concept is suitable for various materials (different steels and coatings) in both fretting and reciprocating conditions [17]. Then, based on energy concept, they developed FEA tools to simulate the process of fretting wear, while the maximum wear depth is underestimated because of ignoring the effect of debris [18]. Reference [19] presented an FEA method based on energy method to compare differences between different contact geometries under the same normal load, displacement and boundary conditions. This method was able to predict evolution of contact geometry, wear, salient surface and surface variables such as plasticity and fatigue damage parameters. Basseville et al. [20] proposed improved models, which introduced particles as wear debris in the contact surface to predict crack initiation in fretting fatigue.

Besides cylinder on flat or punch on flat 2D fretting wear models mentioned above, researchers have also simulated fretting wear in applications, which were usually 3D models. Authors of references [21,22] simulated fretting wear in steel wire ropes. They developed an FEA tool, which combines an FE wear model and a critical plane approach with Smith-Watson-Topper fatigue parameter for the prediction of fretting wear-induced cracks in thin steel wires. Reference [23] presented an FEA tool for fretting wear-fatigue prediction in a prosthetic hip implant.

When FEA of fretting contact is carried out, mesh size has significant influence on both of simulation results and computational time. Usually the denser mesh size, the more accurate results but less efficiency. Researchers always attempt to balance accuracy and efficiency when doing simulation. They often refine the mesh and compare with analytical method to get accurate results with higher efficiency. When there is no analytical solution available, such as stress distribution during fretting wear, the mesh could be refined to get converged results. However, if the results seem not converged with refined mesh, is it a good idea to keep refining the mesh? Especially refining the mesh of fretting wear model, in which case the meshes in the contact surface have to be swept in each increment of hundreds of thousands of cycles, will increase the computational cost by a large amount. In this situation, stress singularity analysis should be carried out because if stress singularity exists, refining mesh will be useless for obtaining converged results.

Stress singularity is known as a phenomenon that the stress becomes infinite, which occurs due to concentration loadings or discontinuity, such as geometric discontinuity or discontinuities in the material properties [24]. In fact, stress singularity is not existing in the real world, since no stress could be up to infinity. However, it could pretend as a specific value in FEM result. Therefore, it is important to recognise the presence of stress singularity in FEM results. Generally, in order to detect stress singularity there are two kinds of methods, namely asymptotic method and numerical method. Asymptotic method is an analytical method, which is focusing on special locations, such as the tip of a crack, the apex of a sharp notch or the corner of some slipping in complete contact. This method recognises that the stress distribution in its adjacent zone may be the same as all other features having the same local geometry [25]. This method has been employed in fretting fatigue to identify whether the threshold of stress intensity exists in order to find out whether fretting provides additional damage or not [26]. However, in the case of fretting wear, during which the contact surfaces are continuously changing, it is difficult to apply asymptotic method to identify stress singularity. Furthermore, as FEA is widely used in fretting wear, it will be very convenient in engineering application if the stress singularity could be detected by numerical simulations. Sinclair [27] presented an approach, named as stress singularity signature, which can be used to check whether or not there is a stress singularity based on numerical results. These numerical results usually are the peak stresses, of which the divergence will be calculated according to different mesh sizes. This method, which have been applied in the field of computational fluid dynamics [28] to confirm the local asymptotic identification of singularities induced by flow, will be employed in this article to identify stress singularity in FE model of fretting wear.

The motivation of the present work is to find out if there is stress singularity in the simulation of fretting wear. This article is concerned with the analysis of it using different applied displacements, COF's and fretting wear cycles for contact bodies in partial slip and gross sliding regimes using a cylinder on flat FEA model. The article is divided into