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# Finite element analysis of fretting wear under variable coefficient of friction and different contact regimes

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## ABSTRACT

Fretting wear is a material damage in contact surfaces due to micro relative displacement between two bodies. It causes some unexpected results, such as loosening of fasteners or sticking in components supposed to move relative to each other. Since this micro motion of fretting wear is difficult to measure in experiments, finite element method (FEM) is widely used for investigating the evolution of contact variables and wear scars during fretting wear process. In most FEM simulations of fretting wear, coefficient of friction (CoF) is assumed to be constant in order to simplify the models. As measured in experiments, however, the evolution of CoF has a relation with the wear number of cycles, especially during the running-in stage. In this research, the effects of variable CoF are considered in both gross sliding and partial slip conditions of fretting wear. The wear scar and wear volume predicted by FEM models for constant and variable CoF cases are calculated. Results indicate that, in gross sliding condition, whether or not using a variable CoF has little effect on wear volume at the end of the steady state stage of fretting wear cycles. However, when considering partial slip or running-in stage of gross sliding conditions, FE models with variable CoF achieve predictions that are closer to experimental results.

## 1. Introduction

Fretting is a small movement between contact surfaces. Depending on different loading conditions, namely combinations of the normal load imposed in the contact bodies and the tangential displacement between them, it could result in two fretting conditions: partial slip and gross sliding. If the normal load is sufficiently high or the oscillatory displacement is small enough, points of the contact centre are in stick regime, while the remaining of the contact is in slip regime. This condition is called partial slip regime, since both sticking and slipping exist at the contact surface [1–10]. Decreasing the normal load or increasing the applied displacement amplitude, the sticking area reduces until it vanishes. In this case, the whole contact surfaces will slide with each other, which is known as gross sliding regime [11–14]. Fretting wear, defined as wear due to fretting in ASTM [15], occurs at both partial slip and gross sliding regimes. As material damage, fretting wear is still a challenge to engineers for design of engineering components that undergo vibration or oscillation, such as stem/cement of hip joint [16], blade/disk of dovetail joint in turbine [17], etc. This is because of the continuous change of the contact surfaces in component, which is difficult to measure during fretting wear experiments. Therefore, finite element method (FEM) is intensively used for predicting the process of fretting wear since it is suitable to solve problems like non-linearity of boundary conditions, changes in geometry and time integration effect, which all happen in fretting wear simulations. Finite element modelling of fretting problems has been reported in the literature by several authors [8,9,11,18–27].

Generally, two wear models are widely employed for FE wear simulations. The classical Archard model [28], which calculates wear volume based on the sliding distance, the normal load and the wear coefficient, is firstly integrated into FE model of fretting wear by McColl et al. [18] in 2004. Energy model is another wear model simulating fretting wear damage. This model is based on the experimental finding that wear volume is linearly related to the accumulated dissipated energy converting from frictional work, proposed by Fouvry in 1996 [7]. Later on, this energy model is implemented to simulate fretting wear surface evolution of Ti–6A1–4 V contact, which is the first time that energy model is combined with FE fretting wear simulation [19]. Using any of these two wear models, different aspects of fretting wear were modelled and studied including the plasticity behaviour of material [29], debris effects [13,20,30], the impacts of fretting wear on fretting fatigue [31–33] and coating performance under fretting

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wear process [22]. Comparing Archard model to Energy model, one can see that the main shortcoming of Archard model is that it does not directly consider the influence of CoF on the fretting wear process. In contrast, energy model is based on the conservation of energy, i.e. part of the frictional work is consumed by the wear process. The evolution of CoF during fretting wear is explicitly involved in the calculation of fretting wear volume, which makes it possible to investigate the effects of CoF on fretting wear by FEM. In addition, the wear process may consist of the material structure transformation, chemical and physical processes, and debris behaviour. Energy model is also convenient to explain different wear mechanisms and therefore, it is used in this paper to simulate the fretting wear process.

To balance efficiency and accuracy of FE calculations, FE model of fretting wear is usually simplified in some features. One of the common assumptions is that the coefficient of friction (CoF) is constant during the fretting wear process. CoF is a system-dependent parameter rather than an intrinsic property of a material or combination of materials. It is sensitive to the sliding distance and environmental effects such as contact pressure and surface quality [34]. Blau [35] grouped factors impacting the friction behaviour as: contact geometry, fluid properties and flow, lubricant chemistry, relative motion, applied forces, debris, temperature, stiffness and vibrations. For a given fretting couple, the continuous evolution of contact geometry induces the change of relative motion. Meanwhile, the debris trapped at the contact surface are also involved in fretting wear. These factors lead to the evolution of CoF during fretting wear process. This phenomenon has been observed for variety of fretting couples [18,36,37] in both partial slip and gross sliding conditions. Besides the time dependent evolution of CoF, it is also observed that CoF is function of displacement during one fretting wear cycle. However, this fact is usually present in fretting contact involving aluminium alloy, titanium alloy or nickel alloy [38–41] rather than the steel/steel for cylinder on flat contact. For instance, for the fretting loops shown in Fig. 1 (taken from [42]), in case of AISI 301 stainless steel/52100 steel contact, CoF (Tangential Force/applied normal load) was constant during one fretting wear cycle, but it was a function of the time. However, in the case of AISI 301 stainless steel/A356 aluminium, CoF is a function of the slip (displacement) amplitude during one cycle (maximum value occurs at each displacement amplitude), meanwhile, it was also a function of fretting wear cycles. For the material that we used in this work, it was found that the CoF kept constant during one cycle for the cylinder on flat contact between steel bodies or hard coatings [18].

The motivation of this work is improving FE fretting wear model by considering a time dependent CoF. In this study, fretting wear simulations of steel/steel with cylinder on flat contact configuration ranging from partial slip to gross sliding are conducted, and the wear scar and wear volume predicted for constant CoF and variable CoF cases are calculated. This paper is divided into 4 parts; after the introduction, the FE model used for simulations is described. Then, the comparison between the cases of constant CoF and variable CoF are presented taking into account the type of fretting regime, along with a discussion on other friction models. Finally, a conclusion is drawn.

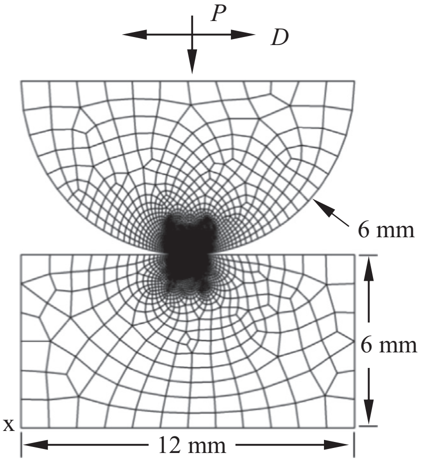


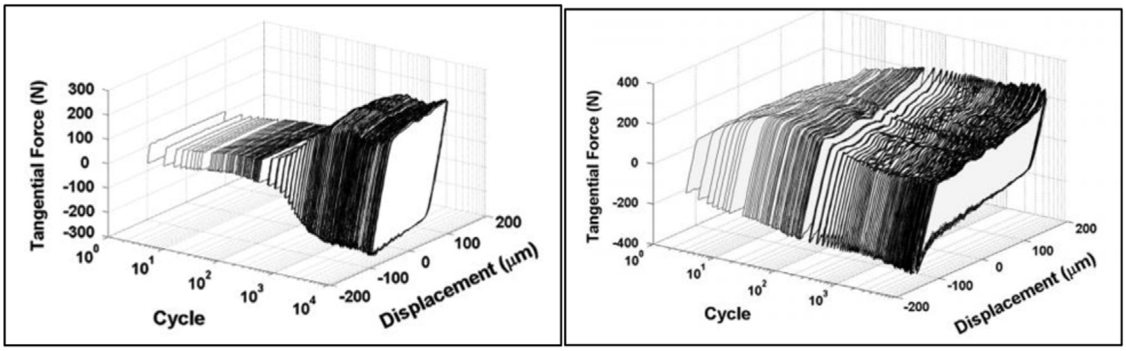
**Fig. 2.** Geometry and dimensions of basic model [18].

## 2. FE model

### 2.1. Geometry and configuration

The two-dimensional (2D) plane strain cylindrical/ flat contact model is generated for FE simulations by commercial FE software ABAQUS. Fig. 2 shows the geometry and dimensions of the FE model. These dimensions are the same as given in the literature [18], since the predicted wear scar could be validated using experimental results. The 4-node plane strain element (CPE4) is chosen for the meshes at contact zone, and the mesh size at that area for both pad and specimen is refined to 5 μm×10 μm.

The definition of contact at interfaces is of great importance in fretting wear analysis. Master-slave technique is used for contact discretization. The bottom surface of the cylinder is defined as master surface, while the top surface of specimen is defined as slave surface. By this setting, contact variables of the specimen could be easily extracted for wear calculations. The Coulomb's friction law with isotropic friction is defined as tangential behaviour. The hard contact is defined as the normal behaviour. The Lagrange multipliers is chosen as the constraint enforcement to solve the contact problem, instead of penalty method in order to achieve the exact relative slip in the contact surface. The finite sliding formulation is used for the contact tracking.



(a) (b)

**Fig. 1.** Fretting loops: (a) AISI 301 stainless steel/52100 steel and (b) AISI 301 stainless steel/A356 aluminium, $D$ =150 μm and $P$=255 N, taken from [42].