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Influence of the wear partition factor on wear evolution modelling of sliding surfaces

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A B S T R A C T

Wear of engineering components is crucial to assess their performance during all their service life. Numerical wear models are a promising tool, cheaper and quicker than experimental tests, both to investigate wear effects and to compare design solutions. However, frequently, numerical models assume that only one body gets worn or both elements undergo the same volume loss.

This study proposes a generalization of the Archard wear law, introducing the concept of wear partition factor α to take into account different wear behaviours of the rubbing elements of a coupling. The proposed approach is applied to the case of a cylinder sliding over a plane with different stroke amplitudes s_t. A numerical wear model has been developed in Abaqus®, exploiting the UMESHMOTION routine. Implementation procedures are described and discussed along with the model convergence. Twenty combinations of α and s_t were simulated covering the cases both of unilateral/bilateral wear and fretting/sliding wear. Results provide important indications on the evolution of wear volumes, wear profiles and contact variables with travelled distance, revealing the remarkable role of α.

The present study aims to improve both understanding and modelling of sliding wear evolution thus clarifying some critical issues slightly discussed by the literature.

1. Introduction

Wear is a damaging process that affects both biological and engineering systems, from human to gear teeth, from bearings to artificial joints and so on. Indeed, wear occurs anytime two surfaces are in contact and in relative motion. Thus, two crucial issues arise about the reliability and performance of rubbing couplings: to predict the damage of the components during their service life and to establish when they need to be replaced. In-silico wear simulations can greatly help to achieve these aims and this explains the large number of wear models available in the literature, from the simplest to the most advanced ones.

First of all, when developing a predictive wear model, it is worth observing that wear can affect only one of the contact surfaces or both of them, depending on their wear resistance. The different response can be influenced not only by the surfaces intrinsic properties (e.g. hardness and roughness) but also by the loading, kinematic and lubrication conditions. Typically, when one of the mating surfaces has a wear resistance much higher than the other one, the wear model is simplified as only one body wears out (unilateral wear). Otherwise, both surfaces get worn and need to be modelled (bilateral wear). Generally, when surfaces with identical or similar material properties are coupled, the wear is bilateral, otherwise is unilateral, as in the case of plastic coupled with steel, where typically only the former gets worn.

Another key issue in wear modelling is the definition of a wear law, able to describe the relationship among volume loss, material properties and testing/working conditions. According to the literature, the most widespread wear law was proposed by Archard and states that the volume loss is proportional to the product of the normal contact force L_N and the sliding distance d, via a dimensional wear coefficient k, i.e.

$$V = k\ L_N\, d \tag{1}$$

Generally, Eq. (1) is applied to the entire coupling, meaning that V represents the total volume loss of the two elements, and k a kind of total wear coefficient. The use of a single value of k is quite common in the wear modelling literature, and entails that the bodies jn contact wear out the same volume or that only one of them lose material, which unfortunately is not a general case. Moreover, the adaptation of Eq. (1) to estimate separately the volume loss by each contact surface is rarely employed. In particular, as far as the wear modelling of general pin-on-flat sliding/fretting configurations is concerned, a review of the literature reveals that different wear resistances, i.e. different wear coefficients, of the articulating surfaces have been considered only

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in a few studies, e.g. [1–5], and, to the best of our knowledge, the concept has been faced only marginally. Indeed, such studies are generally focused on the discussion of new wear models and computational strategies rather than on the effect of such a difference in wear resistances. The only work that has recently deepened this matter [1] has compared the wear evolution of a pin-on-plate coupling for different values of the so-called "wear mode index", a parameter defined as a function of the wear coefficients of the contact pair, the sliding distance per cycle and the pin radius. The main limitation of such study is that the wear coefficients are considered as independent one from the other, i.e. not related to the total k. Moreover the tribological role of the wear mode index, hence also of the wear resistance, is not widely discussed; rather, it seems a tool for presenting results.

From an experimental point of view, in order to define separate Archard equations for the two bodies in contact, also separate measurements of their volume losses are required. However, frequently, the wear loss is assumed to be equally distributed between the contact surfaces (single k value) even when experimental wear tests point out a significant difference between the wear volumes of the elements [6–8].

Thus, the present paper moves from a theoretical generalization of the Archard law (Eq. (1)), which is based on the introduction of a wear partition factor α. Such a factor describes how the volume loss of the entire contact pair is distributed between the two elements. Then, the novel approach is applied in a predictive wear model.

The aim of this work is to numerically investigate the wear evolution of sliding surfaces with different wear resistances. A Finite Element (FE) wear model of a sliding cylinder-on-plate configuration has been developed in a parametric form with respect to the wear partition factor α and the stroke length, s_t. Such a simple geometry has been chosen to facilitate the generalization of the present approach to more complex applications. Twenty combinations of α and s_t have been simulated, covering the cases of both unilateral and bilateral wear, also with different wear resistances, and both sliding and fretting wear, depending on the stroke length. The sensitivity of the wear evolution to α and s_t has been investigated by comparing the wear profiles and contact pressure distributions, given the total travelled distance. Hopefully, this study allows to achieve an improved understanding and modelling of the wear evolution thus clarifying some critical issues slightly discussed by the literature.

The organization of the manuscript is as follows. Section 2 introduces the Archard wear law in its more common form and its implementation in Abaqus® according to two basic procedures. Then the case study on which the paper is focused is described. In Section 4, the concept of the wear partition factor, through the generalization of the Archard law, is introduced. Secondly, the FE wear model and the simulation cases are described. Third, the specific features of the wear model implementation adopted for the selected case study are reported. Finally, Section 5 is organized in several subsections describing: i) the numerical convergence of the model, assessed on the basis of the sensitivity analysis to both mesh and simulation parameters; ii) the main results for a reference simulated case; iii) the effect of α and s_t on the wear evolution; iv) the comparison with literature studies.

2. Background

2.1. Archard wear law

As discussed in Section 1, the Archard wear law commonly adopted in wear modelling employing a single wear coefficient. This assumption corresponds to two special cases: only one surface wears out or both surfaces wear of the same amount, i.e. have the same wear resistance. However, the implementation into a FE code of the Archard wear law requires further steps as the form in Eq. (1) refers to a translational relative motion between the coupling elements, under constant load. In general, we need to simulate a more complex configuration, characterized by a time-varying load, a not uniform contact pressure and a generic three-dimensional kinematics. In such a case, it is convenient to re-write Eq. (1) in local form, introducing the wear depth or linear wear at a point P of each contact surface as

$$h(P) = k \int_{\gamma_P} p(P,s)\ ds \tag{2}$$

where s is the arc length along the travelled path γ_P at a given time instant t (i.e. $s(t)$), and $p(P,s)$ is the local instantaneous contact pressure in P at s. Thus the volume loss is obtained as

$$V = k \int_A \int_{\gamma_P} p(P,s)\ ds\, dA \tag{3}$$

Equations (1)–(3) hold both for unilateral and bilateral wear, and, additionally can be used both for the whole coupling and for each one of the bodies in contact. That can generate a misunderstanding in defining the correct value of k to be used. In particular, when both surfaces wear of the same amount, if k holds for the couple, $k/2$ should be applied for the single bodies.

In order to model a more general wear problem with contact surfaces characterized by different wear resistances, a generalization of Eqs. (1)–(3) is needed and will be presented in Section 4.1.

2.2. FE wear model in Abaqus: basic procedures

In this section the basic procedures for simulating wear evolution in Abaqus are described. Although some concepts have already been described in the literature, we prefer to present them in this section using our own approach that will be consistent and useful also for the original part (Section 4.3).

Abaqus FE code is considered because it is one of the most widespread codes for numerical wear simulations [2,9–12], but some basic steps can be found in other codes as well.

The implementation in Abaqus of a wear model is based on the interaction among the standard FE solver, the FORTRAN user subroutine UMESHMOTION (UMM) and the adaptive mesh smoothing (AMS) available in Abaqus. Indeed, wear simulation is an incremental process, which consists in the repetition of three fundamental steps (included in one single Abaqus STEP), which constitute an FE wear cycle: i) solution of the contact problem to evaluate the contact pressure and the sliding distance, executed by the standard FE solver; ii) wear computation executed by the UMM and iii) wear implementation and mesh smoothing, executed by the UMM+ AMS.

Different strategies can be adopted to reduce the computational cost of a wear model, mainly depending on the type of loading history, as described in the following paragraphs.

2.2.1. Generic loading history

Let us consider a generic loading history, as shown in Fig. 1. For modelling wear evolution, such history is typically discretized in n uniform increments (corresponding also to Abaqus INCREMENTs) and, for each increment i ($i=1 \dots n$), an FE wear cycle is performed, repeating the three steps listed above. Thus, n geometry updates are performed for describing the wear process. It can be observed that at each increment i the contact variables, i.e. the contact pressure p_i^κ and sliding distance s_i^κ at each every contact node κ, are passed into the UMM to compute the incremental wear