Tribology International 111 (2017) 159–166

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Space grease lubrication modeling: A discrete element approach

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ARTICLE INFO

Keywords:
Space greases
Discrete element
Fluid/particle
Lubrication

ABSTRACT

The tribological behavior of space grease is investigated with the Discrete Element Method. In the first step, the grease is described as a collection of particles of two kinds (oil and PTFE) in interaction. The development of the Grease Discrete Element Model (GDEM) used here, is based on rheometer-like characterizations. In the second step, the GDEM is subjected to tribometer-like conditions to investigate grease flow mechanisms and the role of the thickener (PTFE) in lubrication. The tribological behavior of grease seems to be controlled by the coupled influence of both granulometric (thickener particle sizes) and physico-chemical (interaction law) parameters. These results provide the starting point for identifying the parameters on which to act to reformulate greases.

1. Introduction

In the case of space applications, grease is commonly used as a fluid lubricant to minimize oil migration outside the contact and contamination mechanisms. Moreover, there are specific requirements due to the absence of gravity, very low ambient pressures and large temperature variations [1,2]. As the performances of lubricants clearly influence the mechanical reliability of space assemblies [3,4], the increasing complexity of spacecraft and satellites is directly linked to tribological problems. Thus, as has been understood for many years [5], it is vital to understand and control not only the rheological properties of space greases but also their tribological behavior.

Two approaches can be followed to design such dedicated greases. The first is to improve existing lubricants through iterative assessments on different laboratory tribometers that reproduce space tribological conditions and accelerate full life scale testing. The second approach is to develop significant grease tribological models that reproduce grease flows using the relevant parameters on which to act to control behavior and reformulate the grease.

Grease is composed of lubricating oil and a thickener. In addition to soaps [6], lubricating “additives” such as PTFE [7–12] are used as thickeners. Some experimental works [11,12] compared the relative lifetime, friction factor and degradation rates of PTFE greases, while others [7–10] investigated the role of PTFE during lubrication. In particular, under some circumstances, PTFE greases no longer behave as oils as the PTFE particles have been observed spread on friction surfaces, or the largest particles are accumulated at the contact entrance and prevent smaller particles and even oil from fulfilling their role of lubrication [9]. The direct tribological role of thickeners was also identified for non-space grease lubricated bearings, especially under low speed conditions [13–19]. This is of interest as most space mechanisms [1,2] move at low speeds. The solid-like lubrication films observed were much thicker that the predicted oil EHL (Elasto-Hydro-Lubrication) film thickness and had higher thickener content. In parallel to experimental investigations, an increasing number of complex rheological models have been proposed to describe the non-linear behavior of lubricating greases, ranging from empirical steady-state flow descriptions involving yield stress [20,21] to transient flow responses including viscoelastic and thixotropic effects [22–25], and EHL numerical analysis [26–28]. While these global models can describe grease behavior when thickeners play only an indirect role, experimental evidence has shown that classical continuous mechanics tools cannot describe the complexity of grease behavior, especially the direct tribological role of thickeners [7–10,13], due for the most part to the hypothesis of continuous mechanics used in the model which is not always satisfied in a real contact.

Thus alternative models must be used to overcome this difficulty. Nowadays, coupling continuous and discontinuous aspects is still a numerical challenge especially under contact conditions. Although several approaches allow simulating fluid/particle mixtures [29–31],

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http://dx.doi.org/10.1016/j.triboint.2017.03.002
Received 21 November 2016; Received in revised form 27 February 2017; Accepted 1 March 2017
Available online 01 March 2017

contact conditions are never taken into account, mainly due to the continuous description of the fluid.

The objective of the present work is to investigate the use of discontinuous mechanics to model tribological grease flows by using a Discrete Element approach. Such approaches are commonly used in tribology for dry lubrication problems [32,33] but can also be used to model full fluid flows [34] and continuous solid structures [35]. In the same vein, grease is therefore considered as a collection of two kinds of particle: one to represent oil and the other PTFE. In this initial attempt, the aim is not to provide a predictive tool but to propose a qualitative one to improve understanding of the complex discontinuous behavior of the grease under contact conditions. Section 2 presents the numerical framework used to represent the Grease Discrete Element Model (GDEM) and the associated parameter identification procedure based on rheometer-like simulations. Section 3 is dedicated to the investigation of GDEM behavior under tribological conditions, while the final section proposes conclusions and perspectives.

2. Development of the Grease Discrete Element Model (GDEM)

2.1. Numerical framework

Discrete Element Methods (DEM) are usually used to model the evolution of a large number of particles in interaction [36–38]. In the present case, they are used in a meshless approach and the particles are used to discretize the grease domain, as has already been done for solid continuous domains [35]. The main advantages of using DEM to model grease is to take into account both accurate contact conditions and grease separation (i.e. PTFE distribution changes within grease). The main difficulty resides in identifying the interaction laws between elements which should lead to obtaining an equivalent continuous behavior in agreement with experimental data [39].

Thus the grease domain is represented as a collection of contacting bi-dimensional rigid discs. Two kinds of particle are necessary. The first represents the viscous fluid (oil particles) while the other represents the thickener (PTFE particles) (cf. Fig. 1(a) and (b)). This discretization involves five interactions: “volume” interactions (oil/oil, PTFE/PTFE and oil/PTFE) and “surface” interactions (oil/boundary and PTFE/boundary) (cf. Fig. 2). For example, the oil/PTFE interaction should account for the chemical affinities between PTFE particles and oil while the oil/oil interaction should ensure that the whole set of oil particles matches the oil behavior at the macroscopic level (in homogenization).

In the first approach, the different interactions rely on a cohesive unilateral law already used to represent cohesive media [33] and based on two parameters: a cohesive attractive force denoted γ and a distance interaction denoted dw (cf. Fig. 3(b)). This contact law can be formulated as:

$$g \geq 0 (R_N + \gamma) \geq 0 g.\ (R_N + \gamma) = 0 \qquad (1)$$

where RN represents the normal part of the contact force and g the distance between two particles. Thus when two particles are separated of a distance greater than dw, no interaction force acts on them. When the separation distance is smaller than dw, the attraction force is activated, getting particles closer (cf. Fig. 3). Such a law confers to a given volume a viscous behavior. Moreover the unilateral relation between particles in contact allows to respect the incompressibility of the whole medium. At a given time step, for each particles, all interaction are identified (attraction and contact forces), allowing the motion of the set of particles.

2.2. Identification procedure

The development of the GDEM relies on two phases based on rheometer-like characterizations: first, the single oil and then the oil/PTFE mixture. Bi-dimensional shear cells with a dimension equal to 1.10^{E-6} m in both directions are used to determine the different parameters (Fig. 1(a) and (b)). Periodic conditions are used in the shear direction while rough surfaces are used as boundary conditions in the perpendicular shear direction to contain the domain and apply a shear velocity (lower boundary) equal to 1000/s. The distance between the two boundaries is maintained constant. For the present study, the comparisons are based on previous works [40,41] for which space oil (both mineral oils, such as Fomblin Z25 and synthetic oils, such as Penzanne 2001 A were used) and grease viscosities are measured (for the grease, a cone-plate rotational rheometer was used, cf. diagrams in Fig. 4(a)). For the grease considered, the viscosity of the oil is about 0.26 Pa.s, 1.4 Pa.s for the grease, for a shear rate of 1000/s at 20 °C. For the simulation, the dynamic viscosity, denoted η, is calculated as the ratio of the shear stress (Rx/Lx) to the shear velocity gradient (with Δ(Vx)/Δ(Ly)=Vx/Ly with a constant gradient, cf. Fig. 1 (Rx: shear reaction force in the X-direction at the lower boundary).

2.3. Oil characterization

To determine the ($\gamma_{o/o}$, $dw_{o/o}$) pair, we first used a model composed of only oil particles (cf. Fig. 1(a)). It is composed of 1100 elements. The average oil particle size is equal to 3.10^{E-8} m. It was considered that several oil molecules are necessary to model the oil flowing in film thickness, estimated to vary from a few to 400 nm in previous experimental work from EHL theory [9]. In this configuration, the oil/boundary interaction parameters (denoted γ_{ob} and dw_{ob}) are equal to those of the oil/oil interaction (denoted γ_{oo}, dw_{oo}). Several simulations were performed for different cohesion forces (γ_{oo}) while the cohesion distance dw_{oo} was kept constant, at 10% of the oil particle radius. The results are summarized in Fig. 5. It can be seen that the viscosity increases as the cohesion increases, then the final set of parameters (γ_{oo}, dw_{oo}) is determined as the cross section between the resulting curve and the experimental data.

2.4. Grease characterization

The introduction of PTFE leads to the use of two other sets of parameters, related to PTFE/PTFE interactions, denoted (γ_{PP}, dw_{PP})

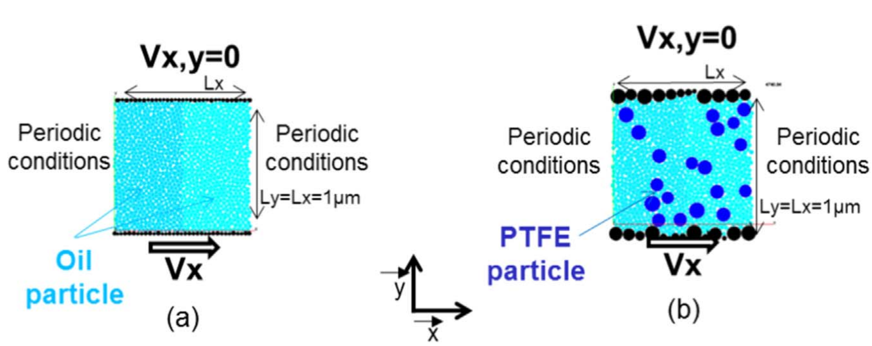

Fig. 1. The two DEM developed, (a) the Oil Discrete Element Model, (b) the Grease Discrete Element Model.