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Nanomechanical testing of third bodies

Richard R. Chromik*, Yinyin Zhang

Materials Engineering, McGill University, Montreal, QC, Canada

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A B S T R A C T

During wear, materials undergo chemical and mechanical changes that lead to the formation of what are known as 'third bodies'. Tribologists have long understood that third bodies have significant influence on the friction and wear performance of materials. However, the inhomogeneous nature of third bodies and how they form at the 'buried interface' of a sliding tribological contact has long made it difficult to fully characterize and study them. Recently, there have been significant advancements in nanomechanical testing such that researchers have begun to use these techniques to, for the first time, determine mechanical properties of third bodies. Coupling these measurements with high resolution electron microscopy and surface chemical analysis has finally given tribologists the ability to obtain the necessary data to understand and model third bodies and their connections to friction and wear. This review will present recent work on the topic of nanomechanical testing of third bodies while at the same time identifying the challenges and opportunities this research presents.

1. Introduction

In studying the friction and wear of materials, commonly known as the field of tribology, scientists and engineers have long struggled to fully describe the interfacial processes and related material deformation mechanisms. For sliding contacts between two materials, the region of interest is at or near an interface which remains 'buried' and obscured from view or inspection using traditional surface characterization methods. To overcome this problem, techniques, such as *in situ* tribometry [1–5] and on-line tribometry [1,6], were developed and garnered significant information about mechanical and chemical changes that occur dynamically at the sliding interface. These techniques revealed 'flows' of materials that were hypothesized originally by Godet in his theory of the third-body concept for tribology [7,8]. Even for an unlubricated solid-solid contact, sliding induces significant material modification leading to third bodies (see Fig. 1a), which are often called by many names (e.g. tribofilm, tribolayer, transfer films, mechanically mixed layers (MML), tribologically transformed structures (TTS), etc.). The third body material experiences high hydrostatic stress, but also high shearing stresses that lead to microstructural modifications that are sometimes, but not always similar to materials processed by high plastic deformation techniques (e.g. equal channel angular pressing (ECAP), high pressure torsion (HPT), etc.). They also can react chemically when the two starting 'first bodies' are dissimilar and also with the surrounding environment. Both the mechanical and chemical processes that the third bodies experience contribute to the eventual formation of the somewhat special third body known as debris. That is a loose material that can stay in the contact, recirculate or be ejected entirely. These are some of the 'flows' mentioned earlier that are epitomized in the 'tribological circuit' (see Fig. 1b) [9].

One way of understanding and making use of the third body concept is to consider wear as a thermal, chemical and mechanical processing of a material (see Fig. 1a). Deformation, fracture, oxidation and corrosion occur to materials in the process of creating third bodies. These processes take place primarily at the surface, but the material is modified beneath the surface to a depth that depends on contact pressure, sliding velocity and material properties. Thus, it is often important to examine the changes in the material microstructure from the surface toward the bulk. Advances in microscopy techniques, such as the now commonly used focused ion beam (FIB) microscope, have allowed tribologists to study carefully and thoroughly the microstructure and chemistry of third bodies. Scientifically, these studies are interesting as they often provide a sort of strain history that is connected to the wear process from the early stages of deformation toward highly strained materials and finally detachment of debris. However, it is nearly impossible to model precisely the stress-strain state of third body materials. The material flows (see Fig. 1b) that occur can release debris from the contact of recirculate third bodies and lead to mixing. There can also be significant changes to the stress distribution in the tribological contact due to the presence of the third body materials [10]. As such, another important recent advance was the use of high pressure torsion (HPT) as a method to simulate the stress states commonly found in a tribological contact [11–13]. High hydrostatic stress and high shearing strains and strain rates are possible. Post-inspection of the microstructure can be

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* Corresponding author.
E-mail address: richard.chromik@mcgill.ca (R.R. Chromik).

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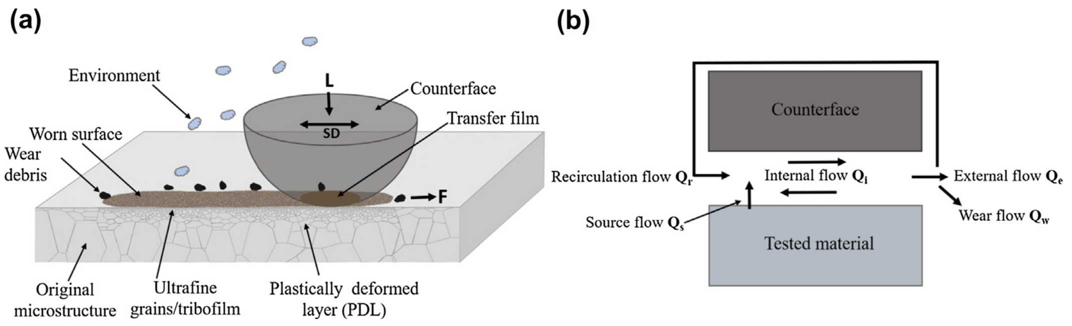

Fig. 1. (a) Schematic illustration of a counterface sliding on a coarse-grained metallic material with the wear surface in contact with the transfer film on the counterface ball. Sliding usually generates tribofilms consisting of ultrafine grains at the worn surface, and a plastically deformed layer (PDL) underneath the tribofilm. A normal load (L) is applied and sliding is in the direction indicated (SD), which leads to a friction force (F). (b) Tribological circuit depicts third body dynamics in the contact: $\mathbf{Q_s}$ represents detachment of tested material to become third bodies; $\mathbf{Q_i}$ is movement of material across the interface; $\mathbf{Q_e}$ is material ejected from the contact; $\mathbf{Q_r}$ is ejected material has been reintroduced to the contact; and $\mathbf{Q_w}$ is material permanently removed from the tribosystem [9].

correlated to the strain history precisely and then finally carefully compared to microstructures found within a real tribo-contact.

The importance of characterizing third bodies is self-evident to tribologists. But to researchers from other disciplines, some key points may need to be reviewed. Firstly, in the early tribology literature one will find attempts to correlate the wear and wear rate of a material to the hardness. This is one of the feature of Archard's equation for wear [14], which is still commonly used. However, the relationship to hardness expressed in this equation is largely understood to not always be true [15,16]. That is, the initial material hardness may correlate inversely to the wear rate, but this is typically in some narrow range of contact conditions beyond which researchers find the relationship no longer holds. One reason this occurs is that in-service or during testing, the material is being 're-processed' in a way that creates new materials, which are the third bodies proposed by Godet [7,8]. These third bodies can have a profound effect on the ability of the materials to resist or not resist the damage and wear. We can provide two well accepted examples of this found in the tribology literature, one which makes use of *in situ* tribometry and one that may be observed with standard techniques. Firstly, we consider fretting wear, which is a type of wear induced by small displacement, but potentially high frequency oscillations of the tribo-contact. One mechanism for a long-lifetime material that resists fretting wear is for there to be a high wear rate early in the test that leads to the formation of a stable debris bed. Essentially, as stated by Berthier, the "surface sacrifices itself to save the bulk" [17]. The second example is for sliding contacts on solid lubricant materials. Using *in situ* tribometry, many researchers demonstrated that for maintaining low friction and minimal wear, a transfer film must be formed on the countersurface [4,18–21]. The stability of this transfer film, where a low friction interface of solid lubricant versus solid lubricant is maintained, is key in minimizing the wear. Essentially, materials flows (see Fig. 1b) are minimized with this low energy interfacial sliding mechanism. Interestingly, when solid lubricants are incorporated in metal matrix composites (MMCs) instead of used as blanket films, transfer films cannot be maintained and instead the mechanisms for low friction rely on smearing and transfer of solid lubricant back to the MMC from the countersphere [22–24].

From the above discussion, the importance of third bodies becomes clear, which includes the study of how they form, their stability and their microstructures. The characteristics of the third bodies govern why a particular material in a given application may be a very good candidate or a very poor candidate, in terms of low wear, long lifetime materials. One of the most recent developments in understanding of third bodies is measurement of their mechanical properties. This development comes after many years of using nanomechanical testing techniques for bulk materials and thin films, not necessarily for tribology applications. As this review will present, the nanomechanical testing of third body materials has a significant role to play in closing the loop for tribologists in developing some firm theories and models to explain third body behavior. Many authors have attempted to model third bodies. It is possible to demonstrate and characterize the formation of third bodies by molecular dynamic (MD) simulations [25–27]. It is also possible to include third bodies in finite element modeling (FEM), and to account for how they change the stress of the contact [10,28]. However, while MD can adequately show the formation of transfer films, it is relatively small scale compared to a real tribological contact. And while FEM can present a larger scale, it is difficult to include fracture mechanics and plasticity theories accurately enough to mimic the dynamic nature of third bodies. Some researchers turned to discrete element modeling (DEM), which allows one to include physics related to adhesion, fracture and flow of third bodies, which would be treated as particles [29,30]. However, these models too have their drawbacks in not being able to account well for plasticity. More recently, researchers have attempted multiscale or coupled models [31–33]. For future models of third bodies to be more predictive and accurate, an extremely useful input would be measurements of the mechanical properties of third bodies themselves. Ideally, including this level of detail could further explain why in some instances third bodies form that are wear resistant, cohesive and hardened and, in other instances, the third bodies are unable to form with any cohesive strength that lends stability and wear resistance. However, while the inclusion of mechanical properties of third bodies into models can be highly advantageous, the research that actually measures the properties of third bodies is in very early stages. Because there is a need for a high level of care in the measurements along with high resolution microscopy to link to the microstructure, it is a challenging endeavor that only recently has been undertaken by tribologists.

This review is focused on nanomechanical testing of third bodies, primarily for metals in dry sliding contact. In the following, there are three major sections to the review. Firstly, a review of typical third body microstructures and their relationship to tribology performance will be presented. This is followed by a review of research using the two major nanomechanical tests available: nanoindentation and micro-/nano-pillar compression. Lastly, the summary and future directions section will make recommendations for experimental approaches and future research that could help the community make best use of this knowledge to advance the field of tribology for its best economic, environmental and societal impact [34–37].

2. Microstructure observations of third bodies

In sliding contacts, plastic deformation, adhesive transfer and mixing are common features of tribological interactions, from which wear debris is developed and removed from the near-surface material [38]. The repeated tribological loading typically results in subsurface layers whose microstructures and/or chemical composition that are