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Links between energy dissipation and wear mechanisms in solid epoxy/epoxy sliding contact

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ABSTRACT

This paper covers wear and energy dissipation of solid epoxy induced by the alternative rubbing between two samples of identical thermosetting polymer. Varying normal load, sliding velocity and sliding distance, the authors were able to define and discuss wear and friction laws and associated energy dissipation. Moreover, traces of several wear mechanisms were distinguished on the worn surfaces and associated with applied conditions. Observed under higher velocity, polymer softening and local state transition were explained by surface temperature estimate and confirmed by infra-red spectroscopy measurements. To conclude this study, all observed phenomena are classified into two wear scenarios according to sliding velocity.

1. Introduction

For many years, tribologists have attempted to predict wear of different tribological systems. In spite of a large number of published experimental and theoretical investigations of this problem, a universal wear law, taking into account all parameters affecting wear, has not yet been proposed. The most famous and one of the oldest wear laws is the law of Archard [1]. Archard considered the hypothesis of plasticized contact, where the real contact area is the ratio of the normal force over the material hardness, and defined the volume of wear V_{wear} as follows:

$$V_{wear} = k_w F_N L_k / H \quad (1)$$

where k_w is the wear coefficient varying from 10^{-7} to 10^{-2} for different materials, H is the hardness of the softest surface, L_k is the relative sliding distance between the materials or kinematic length and F_N is the normal force. The low value of k_w indicates that wear is only caused by a very small proportion of asperity contacts. Furthermore, it does not depend on normal load or sliding velocity.

Many investigators observe similar tendencies in different frictional systems. For example, the use of an energetic approach is able to provide similar answers to various wear problems [2–6]. By using this approach, the dissipated energy (resp. power) is calculated from experimentally measured frictional force and sliding distance (resp. sliding velocity). It is then related to the measured wear volume in order to define the mechanisms of dissipation and wear.

For instance, Ramalho et al. [3] measured a linear wear volume–energy dissipation dependence for a couple of metals using a cross-cylinder tribometer. A similar linear dependency was observed by Fouvry et al. [4,5] for fretting contacts of metals and hard coatings. In their later work on fretting wear [6], the same authors were able to associate the wear mechanisms, such as plastic deformations, formation of tribologically transformed structure and stable wear regime, with the total amount of dissipated energy. Similar results were obtained by Huq et al. [7] in fretting wear during experiments in humid and dry atmosphere.

Aghdam et al. [8,9] recently proposed a method to predict friction power loss and wear rate from measurements of contact temperature. Moreover, in sliding reciprocal friction experiments on steel alloy/brass pin-on-plate couple, they were able to correlate the average power dissipation to average contact temperature rise. As with the other works above-mentioned, these authors also observed a linear correlation between average wear rate and average power dissipation.

The linear dissipated energy–wear rate relationship was also shown to be correct for polymer/metal contacts. In the work of Colaço et al. [10], the worn volume UHMWPE increases linearly with the dissipated energy, independently of the lubricant, material used as a counterbody, and of the surface finishing of both the polymer and the counterbody. To explain their results, these authors assumed a negligible contribution to the wear process of contact temperature rise. According to them, the major mechanisms responsible for energy dissipation of the polymer are viscous or plastic deformations E_{def} and generation of worn particles E_{wear}, i.e.

$$E_d = E_{def} + E_{wear} \quad (2)$$

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Many experiments have been carried out to study PMMA fretting wear [11–15], in which in situ and after test observations revealed a dependence of wear debris shape and surface damage on loading type and conditions. For instance, Geringer et al. [11] investigated a fretting wear of PMMA against a metal. These authors compared cumulated dissipated energy and C–C bond energy in order to verify whether the frictional energy was dissipated in breaking these bonds. Because these values differ by a factor of 1000, they concluded that the dissipated energy is mainly used to mix and transform the third body and to expel worn particles from the contact. The good agreement between the theoretical value of the Fuller-Tabor parameter and that calculated from the experiments encouraged them to consider that only adhesion and separation load due to asperities contribute to the dissipated energy, ruling out the energy dissipation contribution:

$$E_d = E_{adh} + E_{sep} \tag{3}$$

When frictional loading is cyclic and prolonged, fatigue wear mechanism usually appears. The proportion of fatigue wear contribution due to elastic deformations, and abrasive wear contribution due to plastic deformations, depends on elastic modulus and surface roughness. Dubourg et al. [16] investigated nucleation and propagation of fatigue cracks into epoxy under fretting wear conditions. In these experiments, epoxy material had a glass transition above 100 °C and demonstrated brittle behaviour under static fatigue and wear fretting loading. The material transparency helped them to observe that the effects of the material microstructure on crack propagation mechanisms were predominated by the mechanical stress-strain state undergone by the material.

The present paper is aimed at introducing some new insights on the wear mechanisms occurring during the friction of solid thermosetting polymer against similar polymer. The evolution of these mechanisms during sliding and increase of surface damage under different tribological conditions is a key to understanding and prediction of failure of these materials. Plane/plane configuration is chosen as it is more representative of real problems. In addition, a wide range of rather severe tribological conditions is applied in order to let the system develop the maximum of wear regimes under given geometrical and loading configuration. One can notice, that the conditions applied in this study are at the same time close to fretting, because the amplitude of the sliding motion is just a triple of the contact width, and different from it, because of the macroscopic size of our plane/plane system.

The energetic approach is adopted in order to link the dissipated energy to wear. Firstly, a relationship between the wear rate and dissipated energy is examined. Secondly, we relate the dissipated energy to the damaged surface area, which seems more appropriate in this case of severe wear and surface deformations. This approach allows us to discuss the energy necessary to develop surface damage by different wear mechanisms which are detected on thoroughly examined worn surfaces after different numbers of sliding cycles. An additional surface analysis is performed on the worn specimens. Polymer softening and yielding observed on worn surfaces, as well as sliding-induced crosslinking, had suggested possible polymer state transformations, which encouraged us to estimate contact temperatures during the sliding under different conditions. Finally, all observed wear mechanisms are classified into two qualitatively different types, and a wear retrospective is proposed to evaluate the scenarios of the genesis of both types.

2. Materials and methods

2.1. Materials

All friction experiments presented in this paper are carried out on cross-linked epoxy resin HexPly® RM10.1. This epoxy resin is moulded into a large flat plate of 4 ± 0.5 mm thickness, which is cut into rectangular samples with the approximate dimensions of $30 \pm 4 \times 15 \pm 2$ mm^2 for the largest specimens and $8 \pm 2 \times 6 \pm 1$ mm^2 for the smallest ones. The apparent sliding area of each slider is carefully measured using image treatment technique and taken into account in the following calculations. All sample surfaces are successively polished with P600, P1200, P2400 and P4000 abrasive silicon papers. The sample surface profiles are measured with Surfascan Somicronic tactile profilometer with a stylus of 2.5 μm radius tip and a step of 4 μm. The RMS roughness R_q is 0.07 ± 0.003 μm. The average RMS waviness W_q is 0.05 ± 0.001 μm.

The glass transition temperature of this cross-linked epoxy material is 68.8 ± 0.2 °C as measured by several tests of Differential Scanning Calorimetry with heating rate of 10 °C/min. Nanoindentation tests are carried out on the CSM Ultra Nanoindentation Tester with Berkovitch indenter tip under ambient environmental conditions. The penetration velocity of loading and unloading for these static indentation tests is 10 mN/min. A pause of 20 s is made after total loading for all indentations. These measurements are treated by the Oliver and Pharr method [17] using the value of epoxy Poisson's ratio of 0.4. Values of elastic modulus of 4.5 ± 0.1 GPa and of hardness of 256.7 ± 8 MPa of the epoxy material are obtained. The physical characteristics given by the supplier as well as surface mechanical properties measured with nanoindentation technique on polished samples are given in Table 1.

2.2. Experimental setup and tribological conditions

This tribological study is carried out on a linear tribometer developed in LTDS and whose principle is detailed in [18]. In this paper, the contact configuration on the tribometer is schematized in Fig. 1. A sinusoidal reciprocating motion between two flat samples fixed in stationary and moving parts of the tribometer is performed. Hereafter, the largest fixed sample will be called '*track*', while the small sample sliding upon the track will be referred to as '*slider*'. The normal load, tangential force, position and sliding velocity are continuously measured and recorded with 1 kHz sampling frequency as depicted in Fig. 1.

Four tribological conditions, summarized in Table 2, are applied in order to point out the effect of normal load and sliding speed on energy dissipation and wear. The sliding distance for all experiments is 10 mm. The applied sliding frequencies of 1 and 6 Hz correspond to the mean sliding velocity of 20 and 120 mm/s, or the maximal sliding velocity of 30 and 170 mm/s, respectively. The constant normal force is either 20 or 50 N, which corresponds to apparent contact pressure of 0.7 and 1.8 MPa, respectively. The test duration under each condition is varied between 10 and 1000 cycles in order to study the wear and friction evolution with the sliding distance. All the tests are carried out under ambient humidity and room temperature.

Table 1
Physical and mechanical properties of the epoxy resin.

Density ρ (kg/m^3)	Thermal conductivity k (W/m K)	Specific heat capacity c_p (J/kg K)	Thermal diffusivity χ (m^2/s)	Glass temperature (°C)	Elastic modulus (GPa)	Hardness (MPa)
1.1×10^3	0.19	1×10^3	0.17×10^{-6}	68.8 ± 0.2	4.5 ± 0.1	256.7 ± 8