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Relationship between wear rate and mechanical fatigue in sliding TPU–metal contacts

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The present paper reports the process for obtaining a law of wear by friction that reproduces the behaviour of a contact pair between a guide shoe insert, made of TPU, and the corresponding guide, made of steel, in a lift guide shoe application. After an initial identification of the TPU wear type as fatigue wear, the wear law is fitted from tests carried out in a tribometer, obtaining a relationship between the TPU worn volume and two fundamental variables: the travelled distance and the applied load. Archard's law, a relationship commonly used by many authors in the literature, is taken as a starting point, analysing its validity in this case and proposing an improved fitting by means of a potential law.Additionally, in order to analyse in depth the physical phenomena that guide the wear process present in the contact pair under study, and corroborating what was stated by the law fitted previously, the wear process is studied by means of observations by SEM and confocal microscopy by finite element simulations at micro-level, analysing the interaction between material and countermaterial. The results from these analyses are compared with conclusions stated by several authors in the literature in similar studies of other polymers. Finally, this study is completed with an analysis of the analogy between wear and mechanical fatigue, relating both phenomena, in order to confirm the assertion stated in previous studies: the wear process in TPU occurs as a result of repeated crack propagation in the subsurface layer of the material at small scale.

1. Introduction

Thermoplastic polyurethane elastomers (TPU) combine the processability of thermoplastic polymers with the mechanical properties of vulcanized rubber. They substitute other materials, polymers or elastomers, because of their low cost, higher elasticity, greater flexibility and toughness, fast elastic recuperation, high load capacity and resistance to tear, oxidation and humidity. They have a low friction coefficient notwithstanding that the material is elastic, they are good absorbers of noise and vibrations and they have excellent resistance to greases and oils. Another advantage is that they can be repeatedly melted and processed, due to the absence of the chemical networks normally present in rubber, showing typical properties for elastomers in the solid state and able to be processed by methods used for thermoplastic materials at elevated temperatures. Bearing in mind all of these advantages, these materials are widespread in many fields [1–3], some of them implying frictional wear as is the case of the guide shoe insert.

The wear of polymers in general and of TPU in particular is defined as the damage to a solid surface, generally involving progressive loss of material, due to the relative motion between contacting surfaces. Besides, it is determined by the nature of the materials, the surface and bulk mechanical, the physical and chemical properties of the frictionally interacting bodies, the operating parameters, the macro and micro-geometry, and the working environment. Investigations carried out by Rymuza and Viswanath [4,5] show dependencies of polymer properties (surface energy, modulus of elasticity, specific heat, thermal conductivity), of operating conditions (normal load, speed and duration of the test) and of contact variables (counterface roughness) on the dynamic of polymer–metal systems and on the worn polymer material.

A general classification of wear types in polymers is still an open matter. For more than half a century, many researchers have put forward several classification methods from various angles; however, a generally recognized methodology has not yet been achieved. Generally, a classification including abrasive, fatigue, erosive and adhesive wear is accepted, while other wear forms such as corrosive or tribochemical wear are included by some authors [6,7] or fretting wear considered by others [8,9].

Regarding erosive and abrasive wear types, an extensive survey can be found in [10–12] for the erosive wear type and in [13,14] for the abrasive. The wear type to be analysed in the current work is that present in the case of the repetitive sliding process of TPU

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over steel under dry conditions, corresponding to the case of contact between a guide shoe insert and the guide in a lift guide shoe application. This contact takes place usually under lubricated conditions, but the study described in the current paper is done under dry conditions to set up a reference in the analysis of new materials and coatings with the aim of eliminating totally or partially the lubricant from the application. Among all of the types of wear cited before, and bearing in mind the final application of this study, fatigue wear is the type analysed in the present work. Nevertheless, in the literature [7,12] it is indicated that fatigue wear can be treated as abrasive wear at small scale due to the fact that the asperities present in the counterface at micro-level act as sources for the TPU abrasion. Besides, abrasive wear is produced against a rough counterface with sharp texture, unlike fatigue wear which is produced against a rough counterface with blunt projections [7]. Fatigue wear was presented as a concept by Kragelskii in the 1950s [15], being a kind of low-intensity wear by comparison with abrasive wear. Another characteristic of this type of wear is the material damage under the repetitive action of compressive, tensile and shear deformations during cyclic loading caused by the interaction of the polymer with the hard and blunt projections on the rough surface during sliding, which give rise to the generation and development of cracks, and which can be assisted by the presence of defects [14]. Some authors modify the term fatigue wear to frictional or rolling wear if the polymer presents a low tearing strength and slides on smooth counterfaces with high friction coefficient, causing roll formation at the sliding interface and tearing of the rolled fragment [7].

According to several studies, the interaction of the abrasive particles with the TPU produces deformation and tensile, compressive and shear stresses in the worn surface layer, forming in it fatigue cracks due to the repetitive action of these interactions [9]. Other investigations indicate that the largest shear stress takes place at a certain depth under the surface, this point being nearer to the surface as the friction force increases [16,17]. On the other hand, the deformation of the material is greatest at the surface, which is propitious to the formation of cracks, but at the same time the compressive stress is also at its greatest in this area and restrains crack formation. With the increase of distance to the worn surface, the compressive stress decays faster than the strain, so that at some depth in the worn surface layer, the stress is almost pure shear stress and cracks are able to form more easily. Another effect to take into consideration is the influence of the temperature, caused by the friction and deformation hysteresis which produces the effect of heating and temperature increase in the worn surface layer. At the surface, heat easily dissipates and the temperature rapidly falls; however, in the worn surface layer, the heat dissipation is more difficult and the temperature is higher, which reduces the cohesive energy of the material and involves the formation of cracks. Finally, as a result of the repetitive action of many abrasive particles, the formed cracks extend and intersect, leading to the formation of wear debris.

Other studies, confirming the facts explained above, state that the cracks formed in the subsurface are helped to develop during application cycles by means of the plastic deformation caused by the surface traction, propagating to neighbouring cracks and leading to the material detachment by means of sheared sheets, a process named material delamination by Suh et al. [2,18,19]. Any wear particles generated at the surface cause greater ploughing and increase the frictional force, which accelerates the delamination process. Another important parameter is the temperature attained by the TPU material at the worn surface, explained by Stachowiak et al. [20]. The low temperature at which most polymers melt as well as their low thermal conductivity ensures that frictional contact temperatures can easily reach the melting point of the polymer, causing its surface to melt by means of prow formation. The whole effect of prow formations over all the contact surface of the polymer is known by other authors, such as Bartenevev et al., as fatigue wave formation [21].

The aim of this work is to develop a law of wear by friction that reproduces the behaviour of a contact pair between a guide shoe insert and the corresponding guide in a lift guide shoe application. To carry out this task, and after the identification of the TPU wear type as fatigue wear, a data fitting is done from tests in a tribometer, able to reproduce the behaviour in the contact between a guide shoe insert and the corresponding guide in a lift guide shoe application. Besides, in order to analyse in depth the physical phenomena that guide the wear process present in the contact pair under study, several additional analyses of the contact pair behaviour at micro-level are carried out. These analyses include experimental observations, via microscopy, of the TPU and countermaterial surfaces, as well as numerical studies by means of finite element simulations at micro-level of the contact interaction between material and countermaterial. Finally, this study is completed with an analysis of the analogy between wear and mechanical fatigue phenomena established in polymers by several authors in the literature.

2. Setting up of TPU wear tests in a tribometer: obtaining of a wear law

2.1. Wear laws for TPU

The Tribotests were planned firstly to gain knowledge about the wear characteristics associated to a TPU-steel contact pair, examining the different dependencies observed in the wear behaviour of TPU, and secondly, once a wear test methodology is set up, to include the dependency of the most significant variables in the wear law. These tests, unlike the current conditions of the guide shoe insert which slides over the guide under lubricated conditions, are developed under dry conditions due to the final aim of the project in which this study is being developed, which consists in the partial or total elimination of the lubricant from the application by different treatments to the TPU or countermaterial surfaces. Besides, to emphasise this, it is necessary to bear in mind the difficulty of measuring the wear as weight loss in a wet environment, where the polymer can take up lubricant while swelling up, it being hard to separate the effect of the polymer debris loss and that of the swelling. At the same time, and once the tests are performed, the worn TPU surface is analysed via microscopy to compare the type of wear with that established by other authors in the literature.

The most extensive survey of wear modelling was carried out by Meng and Ludema [22], who catalogued over 300 equations of wear models and equations developed over a long period during the last century. They considered three main approaches to wear modelling: models based on empirical relationships, common up to 1970 and directly constructed with data taken from tests in which few testing conditions were varied (typical models are those proposed by Barwell [23], Rhee [24] and Kar and Bahadur. [25]); models based on contact mechanics, common in the years 1970–1980 and which are models of a particular system that assume simple relationships among working conditions; and models based on material failure mechanisms, common from 1990 up to now and which include material parameters such as dislocation mechanics, fatigue properties, shear failure and brittle fracture properties. Other authors, such as Viswanath [5], have recently developed dimensional analyses based on the previous methods, in this case the equation proposed by Kar and Bahadur. [25], in order to characterize the phenomenon in a smaller number of terms than the original physical variables and to include additional variables not included initially such as the counterface roughness.