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A new rotary tribometer to study the wear of reinforced rubber materials

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ABSTRACT

A rotary tribometer has been developed in order to reproduce abrasion wear at the interface between the reinforced rubber material of a tire tread and the road surface, under controlled environmental parameters. The characteristics of the device are described in this paper. It consists in a spherical indenter sliding on the rubber material under study. The control parameters are the normal load, the ratio between the indenter radius and the sample thickness, the sliding velocity, the number of passages, the time interval between two passages, and the temperature. The friction coefficient and weight loss are measured all along the wear test. Wear patterns are observed in situ with an optical pen. We show preliminary results on reinforced natural rubber materials which illustrate the potentialities of the setup. Different wear patterns could be created and observed, according to the conditions.

1. Introduction

Efforts transmitted by a vehicle are located in the contact zone between the tire tread surface and the road, which is generally of the order of a few hundred squared centimeters. The tread must have high resistance to fatigue, abrasion wear, tearing and impact and should also withstand quite high temperatures [1–5]. Also, the friction coefficient between the tread and the road must be high in order to provide grip and cornering stability. Wear occurs in this contact zone. When expressed in terms of tire thickness loss per revolution, wear rates observed in soft usage conditions are of the order of a few 10^{-10} m per cycle, which is of the order of an atomic dimension, while elementary components of the material (polymer chains, filler aggregates) have sizes from a few nanometers to a few hundreds of nanometers. Also, the size of debris pieces is of the order of micrometers to tens of micrometers typically. It follows that wear is not a continuous process, but is an average result of discontinuous phenomena, at intermediate (submillimetric) scales.

Reinforced elastomers exhibit very specific wear patterns [6]. Wear patterns and abrasion weight loss depend on three sets of parameters [4]: (1) the constitutive equation of the material, which itself depends on material formulation [7–9]; (2) the mechanical loading (normal pressure, sliding velocity, slipped length [10–12], contact surface [13–16]); and (3) the environmental conditions (temperature, hygrometry, atmospheric composition) [17]. The various wear patterns observed in reinforced rubbers may be classified into four characteristic patterns [1–3]: (1) Grooves are patterns parallel to the sliding direction, associated to extremely severe wear conditions on rough surfaces, with dimensions from micrometers to millimeters [18]; (2) Ridges form regularly spaced arrays of asymmetric steps perpendicular to the sliding direction, with the steeper side (riser) facing the oncoming sliding indenter, as shown in Fig. 1 [17,19–22]. The distance between ridges ranges from micrometers to millimeters and their height is typically ten times smaller than this distance. Ridges are created in less severe conditions than for grooves; (3) Craters are roughly circular patterns, with diameters ranging from tens to hundreds of micrometers and a depth of about a tenth of the diameter, associated to very soft wear conditions and small sliding velocities [1]; and (4) Rollers are formed by wear fragments sticking on the rubber surface [23,24].

The few studies on the mechanisms of creation of these wear patterns have been generally focused on ridges [25,2,17,19–22]. One study has been devoted to crater formation [1].

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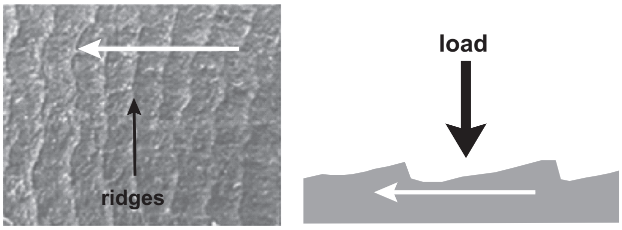

Fig. 1. Left: A representative example of wear ridges seen from above the surface; right: schematics of the lateral view. The direction of the sliding indenter is indicated by horizontal arrows.

In order to model the tread/road contact, several issues, related to the complexities of both the materials and the mechanical problem at the tread/road interface, have to be addressed.

Wear has been generally studied in laboratory conditions using a sliding indenter rubbing on the rubber surface. Contact sliding is a necessary condition to observe wear, i.e. abrasion weight loss. Indeed, it has been shown that wear is univoquely associated to slip and does not occur in indentation experiments in the absence of slip [1,3]. In the tread/road contact zone, sliding may be global, due to wet skid for example. However, it is essential to realize that, even in the absence of skid and of tangential efforts transmitted by the vehicle, some local slippage occurs in the contact zone [26].

As regards materials, reinforced elastomers used in tire treads are cross-linked (vulcanized) elastomers reinforced by solid particles or aggregates (fillers). They show remarkable, complex mechanical properties [27–30]. First, reinforcement (as quantified by the ratio of the elastic modulus of the material to that of the pure, unfilled matrix) may be very large (up to a factor 100) in a limited temperature range just above T_g and it extends over a broad temperature range, with smaller values however. In practical applications, reinforced elastomers are often used in this broad temperature range. Then, the elastic modulus drops quite strongly at a few percents strain amplitude (Payne effect) [31]. These materials can sustain elastic deformations up to a few 100 percent, with a non-linear constitutive law and large dissipation. After large amplitude strain, they show partially recoverable softening (Mullins effect), as well as a significant residual strain (plasticity or residual set) [32,33] and long relaxation times [34,35]. Finally, they exhibit an outstanding resistance to tear and wear. All these features are of primary importance as regards rolling resistance, grip and durability [30].

To obtain high reinforcement, reinforcing fillers must be typically 100 nm in size, and strong enough filler/matrix interactions must be promoted [33]. Carbon black (CB) aggregates have predominantly been used [33,36]. Using silica may provide an enhanced compromise of usage properties [37], essentially because it offers more flexibility to finely tune the dissipation in various temperature and/or frequency domains.

Several models have been proposed to rationalize this remarkable mechanical behavior. It has been proposed recently that all these effects may be explained by the presence of a glassy (immobilized) layer of elastomer matrix around filler particles, which can build glassy bridges between particles on nanometric distances and are plasticized under local stress [38,39].

The objective of this paper is to present the characteristics of a new experimental device (tribometer), which has been developed in order to mimic the interface between the reinforced rubber material of a tire tread and the road surface (in soft driving conditions and in straight line), under controlled environmental parameters. It is a sphere-on-plate device operating on a thin layer sample, which allows applying a relatively high contact pressure and a long slip length. The involved contact mechanics is discussed in details. Preliminary results obtained on some representative materials are shown. We claim that this device has a number of characteristic features which make it suitable to generate and characterize wear patterns representative of real usage conditions and to allow proper identification and characterization of these wear patterns.

The paper is organized as follows. The studied materials are described in Section 2.1, their mechanical properties are described in Section 2.2. The tribometer is described in Section 3.1. The working conditions are discussed in details (Section 3.3). Results of representative tribological tests realized in reinforced natural rubber samples are presented in Section 4.

2. Materials

2.1. Formulations

The studied materials are Natural Rubber (NR, grade SMR 5L) vulcanized with a conventional sulfur/accelerator process and with two types of reinforcing systems: carbon black N234 (CB sample); precipitated silica (Z1165MP from Rhodia, specific surface 160 m^2/g) treated with triethoxysilylpropyltetrasulfur (TESPT), which covalently links the silica surface to the NR matrix. Two different volume fractions of silica have been used (SIL-1 and SIL-2 samples). The materials are mixed in an Internal Mixer (Banburry 1 l) and vulcanized in the form of 2 mm thick sheets. We know that homogeneous cross-link densities are obtained in the processing conditions which are used [40,41]. Formulations are described in Table 1. Note that mechanical data obtained in a non-reinforced (unfilled) Natural Rubber sample vulcanized in similar conditions (1.5 phr Sulfur, 2 phr CBS) are also shown for comparison in Section 2.2.

2.2. Mechanical characterization

The mechanical behavior of the materials is important to understand the wear behavior and has been extensively characterized in the linear and non-linear regimes. The CB and SIL-1 samples have been formulated in order to have the same Shore hardness, while material SIL-2 is slightly harder (see Table 1). These formulations have been chosen in order to illustrate the effect of changing the type of filler (carbon black vs. precipitated silica)

Table 1
Formulations of the studied materials CB, SIL-1 and SIL-2. Units are in phr (grams per hundred grams of rubber).

	Ingredients	CB	SIL-1	SIL-2
Matrix	NR (SMR 5L)	100	100	100
Filler	Silica Z1165 MP		50	55
	Carbon black N234	50		
Additives	TESPT		4.0	4.4
	6PPD[a]	1.9	1.9	1.9
	Stearic acid	4.0	4.0	4.0
	ZnO	4.0	4.0	4.0
	Sulfur	1.5	1.5	1.5
	CBS[b]	1.5	2.0	2.2
	TBzTD[c]	0.2	0.2	0.2
	Filler volume fraction	0.22	0.20	0.22
	T_g (°C)	−47	−47	−47
	Hardness (Shore A)	70	70	72

[a] *N*-(1,3-dimethylbutyl)-*N′*−phenyl−*P*−phenylenediamine (antioxidant).

[b] *N*-cyclohexyl-2benzothiazyl (primary accelerator). Amount is tuned to compensate for adsorption by silica.

[c] Tetrabenzylthiuram disulfide (secondary accelerator). Some characteristic data are shown also (three bottom lines).