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Abrasion by a blade scraper compared with abrasion by a rough surface

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ABSTRACT

Rates of abrasion by a blade scraper are compared and contrasted with those obtained using an abrasive surface (a DIN abrader) for six rubber compounds: carbon black filled and unfilled vulcanizates of NR, SBR and cis-polybutadiene (BR). Results from the DIN abrader were found to be less sensitive to the amount of frictional work, and less discriminating between different compounds, than those obtained with a blade scraper. These differences are attributed to somewhat different mechanics of tearing in the two cases, even when the same fracture criterion is employed. For a blade, the length of the contact line is unchanged as the applied load increases, whereas for an asperity an increase in load causes an increase in length of the contact area, tending to mitigate the effect of the increased load. Approximate relations are developed along these lines to compare the tearing action of many sharp asperities to that of a blade. The results account reasonably well for the observed differences between rates of abrasion in the two cases. It is also pointed out that the rate of abrasion is not a unique function of the amount of frictional work expended.

1. Introduction

Soft rubbery materials abrade in a characteristic way, forming protruding ridges lying at right angles to the sliding direction [1]. Abrasion occurs at the base of the ridges, which are then bent backwards by the frictional force and protect the surface behind them from abrasion, Fig. 1. As abrasion continues, the tips of the ridges become undermined and are eventually torn off as large debris particles, up to some mm in size. Ridge crests account for most of the rubber lost, typically more than 90 per cent [1–3]. This mechanism of abrasion applies whether rubber is scraped by a sharp blade, as shown schematically in Fig. 1, or abraded by a rough abrasive surface. In the former case, a theoretical treatment proposed by Southern and Thomas [4] accounts reasonably well for the rate of abrasion of rubber compounds in terms of the rate of propagation of a fatigue crack under repeated stressing. Corresponding relations for abrasion by a surface of protruding asperities, as in the case of a DIN abrader [5], were obtained by Ramakrishnan, Donovan and Medalia [7]. We compare measured rates of abrasion in the two cases for a number of representative rubber compounds, in the light of these theoretical predictions.

We first review the theory for abrasion by a scraper blade [4], to make clear the assumptions on which it is based. Abrasion by a plane of asperities [6] is then analyzed on the same general lines. The predictions are significantly different, in particular giving a different dependence of the rate of abrasion on the frictional work expended in sliding. This was made clear in the theory of Ramakrishnan, Donovan and Medalia [7], although they focused on the effect of abrasive particle size on the rate of abrasion.

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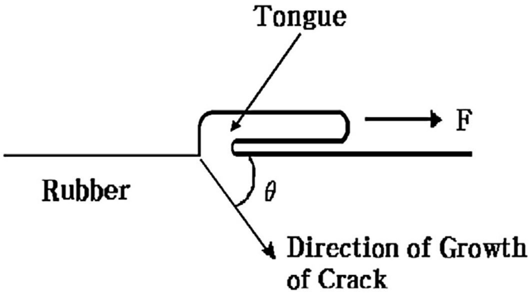

Fig. 1. Model for crack growth under abrading force, F, showing crack propagation at an angle, **θ**, to the surface.

Another important general conclusion also emerges from these theoretical considerations, and is supported by the experimental results: the amount of abrasion is not directly related to the frictional energy input [7,8].

2. Theoretical considerations

2.1. Abrasion in terms of fatigue crack propagation [4]

When a blade scrapes across a rubber surface, Fig. 1, energy is expended against friction. Fracture energy **G** (J/m^2) is also made available to cause tearing at the base of the ridges (Fig. 1), where **G** is given approximately by:

$$G = 2F/w \tag{1}$$

F is the frictional force and **w** is the length of the contact line between the blade and the rubber surface. In other cases (for example, if the ridges do not bend over backwards), the tear energy is much smaller under the same frictional force [9].

When **G** exceeds a minimum (threshold) level necessary to cause any molecular fracture, a crack at the base of a ridge will grow by a small distance **dc** on each pass of the scraper blade. Fatigue crack growth is found to depend on **G** roughly in accordance with a power law [10,11]:

$$dc/dn = B(G/G_o)^{\beta} \tag{2}$$

where **n** is the number of stress applications and $\mathbf{G_o}$ is the threshold tearing energy with a value of the order of 50 to 100 J/m^2 [12,13]. [Note that we have employed a non-dimensional measure of the severity of the applied force in Equation 2: the ratio $\mathbf{G/G_o}$. The fatigue constant **B** then has dimensions of length, and is found experimentally to be of the order of 1 Ǻ [8,9]. Thus, at the lowest energy levels that can cause fracture, the crack growth steps are smaller than the size of molecular strands in the network.]

The index β is found to depend inversely on the tendency of the material to dissipate strain energy under large deformations [10,11]. It is about 4 for polybutadiene (BR) compounds that show little dissipation of energy, about 3 for SBR compounds and about 2 for natural rubber which, although not normally regarded as dissipative, can crystallize at high deformations, when it becomes markedly inelastic [14].

Now, the rate of abrasion, represented by the loss **h** in rubber thickness on each pass of the blade, is found to be related to the frictional force **F** by a similar power law:

$$h = A(F/w)^{\beta'} \tag{3}$$

and the values of β′ are somewhat similar to the indices β relating the growth of fatigue cracks on each application of stress to the tear energy **G**, Equation 2. A quantitative treatment of abrasion as a fatigue process has been developed by Southern and Thomas on this basis [4]. They considered the loss in thickness **h** caused by abrasion to be equivalent to the growth of fatigue cracks at the base of Schallamach ridges at a shallow angle θ to the surface, as shown schematically in Fig. 1. Thus, the rate of abrasion was predicted to be:

$$h = \left(B \sin\theta / G_o^{\beta}\right)(2F/w)^{\beta} \tag{4}$$

of the same form as Equation 2, with the abrasion coefficients **A** and β′ now interpreted in terms of fatigue crack growth parameters, **B** and **β**. Measurements of rates of abrasion by a blade scraper were shown to be in reasonable agreement with the predictions of Equation 4 over a range of frictional forces [4]. We now consider corresponding relations for an abrading surface of protruding asperities[7], as in the case of a DIN abrader, instead of the linear contact geometry of a blade, and then compare measured rates of abrasion in the two cases for a number of rubber compounds.

2.2. Tearing action of a surface of rigid asperities

Assuming, for simplicity, that abrasive asperities can be represented by conical protuberances, sufficiently far apart that the amount of indentation caused by pressing them into an elastic substrate is not affected by their proximity, then the depth **d** of indentation is given by [15]:

$$d^2 = (3\pi/8)p/E \tan\theta \tag{5}$$

where **p** is the normal load per asperity, **E** is the elastic (Young) modulus of the rubber, assumed incompressible in bulk, and **θ** is the half angle of the cone. Assuming a proportionality between normal load **p** and frictional force **f** per asperity, with a coefficient of friction μ:

$$f = \mu p \tag{6}$$

In order to evaluate the tearing energy **G** associated with the frictional force **f**, using Equation 1, we need to assign an effective width **w** to the contact between rubber and asperity. Following Ramakrishnan, Donovan and Medalia [8], we assume that it is equal to the diameter 2**a** of contact given for a conical indentor by [15]:

$$2a = d \tan\theta \tag{7}$$

Thus, from Equation 1,

$$G = f/a = 2\mu p/d \tan\theta \tag{8}$$

The amount of indentation **d** is given in terms of the normal load **p** by Equation 5, or in terms of the frictional