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An advanced abrasion model for tire wear

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ABSTRACT

The abrasion processes of rubber or tires are extremely complex phenomena and basically different from those of other materials. Much research in tire industry has been done to predict the wear of a tire tread. However, such studies have not considered the history dependency of abrasion as well as directional effects. This paper is to propose an advanced abrasion model for rubber that will takes these two effects into account. As a result the new model can be applied to predict tire tread wear. Within this model, directional damage will be introduced to characterize the history of frictional sliding contact including the change of slip directions. It also covers local contact conditions such as contact pressure, slip velocity or flash temperature. The model will be analyzed theoretically and numerically. A FEM simulation for the Grosch-wheel with different loading conditions using the new abrasion model is performed and validated by experimental data.

1. Introduction

Wear is a phenomenon of material removal from a surface subjected to a frictional interaction with another surface. This process is therefore associated with friction during sliding between contacting bodies. While friction is useful in many problems in engineering, wear is often referred to as one of the factors that end up the service life of components or machines. Therefore, engineering applications might require high friction for their optimal performance, while wear has to be minimized. One of the important applications focusing on these targets is the wear performance of a tire tread which is particularly considered in this work. Indeed, the tire tread is the only component of vehicles contacting roads and thus its wear performance is a crucial criterion for the tire design.

In general, wear is basically related to sliding friction, but quite more complex since the amount of material removed is often estimated after a sufficient long time in which many different mechanical, physical, chemical and electrical phenomena possibly take place either separately or at the same time, and change irregularly. Therefore, there are various forms of wear observed in the daily life and engineering applications. Several wear classification methods have been addressed so far in the literature in which the fundamental and major wear mechanisms commonly considered are: abrasion, adhesive wear, corrosion, surface fatigue wear. The detailed description of these specific types of wear can be found in e.g. [1–3].

In the context of rubber wear, the problem is even more complicated. This is due to the fact that rubber or a rubbery material is much different from others as it inherently possesses relative high elasticity. In the cases of frictional sliding the wear performances of rubber, in general, strongly depend on the properties of the rubber and the conditions of the rigid surface. Besides the abrasive and fatigue wear like other materials, roll formation are also known as one of the most important wear mechanisms of rubber. This type of wear is the result of the detachment of edge rolls that are formed by tearing and rolling the adhesive parts of the rubber, which has low tearing strength, when sliding on a hard surface. While the abrasion and fatigue wear often occur on the hard relatively rounded tracks, respectively, the roll formation much emerged on the smoothed surfaces. A close relation between friction and wear in rubbers was given in [4]. Accordingly, the abrasion and roll formation are correlated with the adhesion friction, and the fatigue wear for the hysteresis friction.

While the fatigue wear is regarded to a mild material loss but continuous, the abrasion and roll formation are quite serious but often happen in a short duration. Despite the fact that the abrasion is often the most dominant mode of rubber wear, especially for tire wear, the material losses due to other wear mechanisms are also relatively significant if considered for a long duration of sliding or rolling. Therefore, for rubber, abrasion is often not distinguished with wear, but covers all of the above wear mechanisms [5], and accordingly the word "*wear*" and "*abrasion*" will be used alternatively in the rest of the paper.

Besides the relation between friction and abrasion of rubber mentioned above, the phenomenon of waves of detachment existing on the rubber surface when sliding over a hard track, or vice versa, following adhesive effects and buckling of the rubber surface is also identified as a

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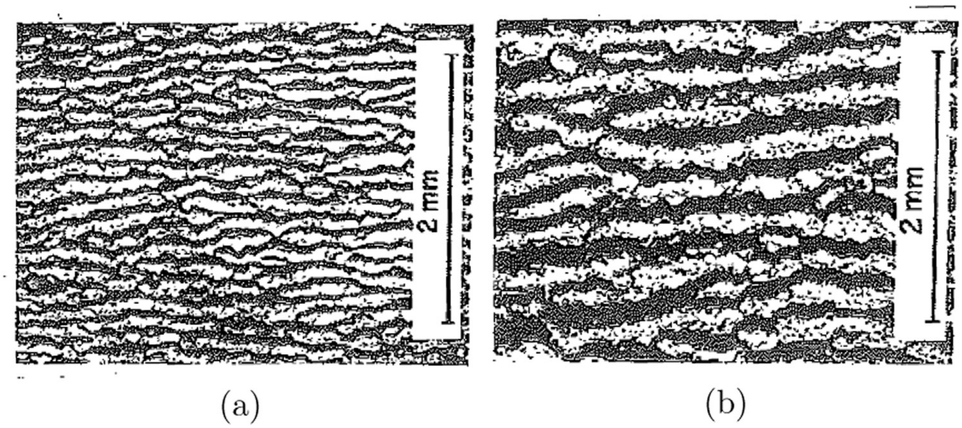

Fig. 1. Abrasion patterns of a type of rubber: (a) on Tarmac and (b) on Concrete (taken from [36]).

feature of rubber abrasion [6]. A correlation between this phenomenon and the abrasion patterns, which are well-known as a characteristic performance in rubber abrasion and will be discussed in detail in the next section, was carried out by [7].

The process of rubber abrasion can generally be divided into three continuous stages: the initial, steady and damage stages. A large number of publications dealing with the formation of abrasion patterns, the intial stage, can be found in, e.g. [8,9,5,10]. Since the most of service time of common rubber components like tires, sealing is on the stationary abrasion stage, a large variety of studies have been done to investigate the performance of rubber abrasion at the steady state, see e.g. [11,7,12,10,13,5,14–16].

Each wear mechanism discussed so far often relates to a specific wear model that is referred to as a set of variables affecting wear and their assembly in a mathematical form. Various wear models have been developed to describe the amount of worn material. According to the survey of Meng and Ludema [17], wear equations can be established from empirical observations (e.g. [18]), or based on contact mechanics (e.g. [19]) or involving material failure mechanisms (e.g. [20,21]). In the context of rubber abrasion and tire wear, the similar models have also been obtained, see e.g. [22,11,23]. Although these existing models, which are mostly only dependent on contact pressure and sliding velocity, can be used to determine the material loss of a particular wear mechanism, they cannot describe the history of the abrasion process, especially in the initial and stationary stages which are of importance in an abrasion process. Furthermore, they have not considered directional effects and flash temperature that crucially influence the wear performance. The former will be discussed in detail in the next section and the latter can be referred to [24,23], where the effects of the flash temperature on friction and abrasion were investigated.

The modeling of wear is very important in the development of an engineering product, like tires, which are usually subject to wear throughout their service time. In the recent decades, with the rapid evolution of computers and numerical analysis techniques, for example the finite element method, a large number of studies on this topic have been done, which usually employed simple wear models such as [19] or something like that. For example, such these models are used in [25–29] to simulate the formation and progress of rubber abrasion. Concerning the whole simulation of a contact problem involving frictional wear, several numerical modeling techniques were presented e.g. in [30–32] for non-rubbery materials and in [33,34] for rubber abrasion or tire tread.

This paper is concerned with an abrasion model for rubber that is applicable to predict the tire tread wear. It has to describe the history dependency of the abrasion process, and capture directional effects as well as flash temperature which the existing models have not handle. The model will be validated in simple numerical applications and in the FEM simulation of the Grosch wheel.

The structure of the paper is as follows. After the introduction, a statement of the problem is provided in Section 2, where we focus on the Grosch wheel experiment and Schallamach's observations as the major motivations for a new abrasion model. Section 3 introduces the advanced abrasion model and deals with its features completely to cover the previous requirements. Afterwards, the attention is laid on the analysis of the capability of the proposed model through some numerical examples (Section 4), and then followed by the Grosch wheel simulation (Section 5). Finally, Section 6 summarizes the core results of the paper and outlook for further works.

2. Statement of the problem

One of the most vital performance of rubber abrasion is the appearance of abrasion patterns or shortly called patterns. Studies on abrasion patterns started in the early 1950s, with pioneering achievements by Schallamach, see e.g. [35]. Schallamach pointed out that under unidirectional abrasion, rubber samples are abraded with formation of surface abrasion patterns. The appearance of such abrasion patterns is regarded as a result of relative friction sliding of an elastomer characterized by low elasticity modulus over another harder counterface and is therefore refered to as a very important abrasion characteristic or often specified as the so-called pattern abrasion, a special wear mechanism, of rubber and tires. According to Schallamach ([35]), these patterns are characterized by almost parallel asymmetric ridges which depend on both the hardness of the rubber and the roughness of the track, see Fig. 1. They are obviously perpendicular to the direction of abrasion as shown in Fig. 2 for the profile of abrasion patterns of an unfilled natural rubber and a worn tire tread. Fig. 2 also

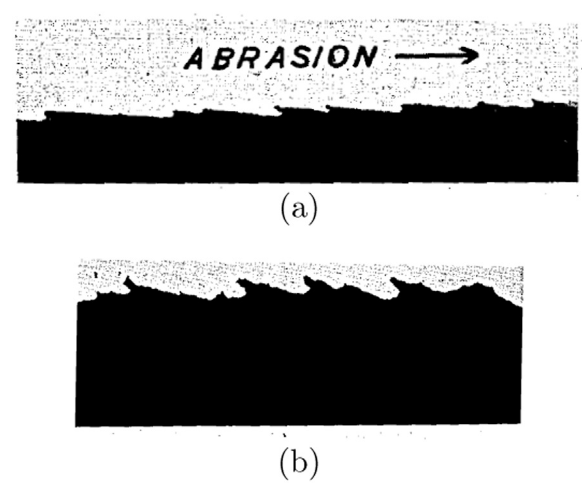

Fig. 2. Profile of abrasion patterns: (a) unfilled Nateral Rubber and (b) a worn tire tread (taken from [35]).