Cold Regions Science and Technology 115 (2015) 1–8

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Onset of frictional sliding in rubber–ice contact

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A R T I C L E   I N F O

Article history:
Received 12 December 2014
Received in revised form 16 February 2015
Accepted 7 March 2015
Available online 14 March 2015

Keywords:
Ice friction
Rubber friction
Onset of sliding
Detachment front
Precursor
Dwell time

A B S T R A C T

The onset mechanism of frictional sliding is essential in understanding frictional strength between materials. In particular, the static friction coefficient is a very important but often overlooked indicator for the emergency braking performance of tyres. In ABS braking a significant area of the tyre contact patch is locally stuck to the road and becomes detached to frictional sliding when the local shear stresses exceed the local friction potential. The detachment phenomena were studied for rubber–ice contact by means of a high-speed camera and image processing. The image sequences of the contact were combined with friction force data. It was observed that for a smooth rubber sample a horseshoe-shaped detachment front was produced. The last contact point was always at the trailing edge or side of the sample. The textured sample had a ring-like detachment front that located the last contact point in the centre of the contact area. The dwell time had a logarithmic dependency on the static friction of the rubber–ice contact. Two different types of precursors were found. The first precursor occurred when the first signs of detachment were observed visually. The second precursor was found when the static friction rose so high that the movement of the sample was nucleated by the breaking of the ice rather than the detachment of the contact.

1. Introduction

The friction between tyres and the road plays an important role in traffic safety (Brentin and Sarnacke, 2011; Crisman and Roberti, 2012; Klein-Paste et al., 2012; Ripka et al., 2012; Strandroth et al., 2012). Tyre manufacturers develop their products constantly to provide safer and better-performing tyres. One of the most critical properties of a tyre is its ability to generate a decelerating force when a vehicle is braking. This is important in all road friction conditions, but especially in icy (low-friction) conditions tyre performance is crucial. When emergency braking is performed, it is important that the tyres generate as much force as possible to stop the car before an obstacle. In emergency braking, the tyres are kept at a longitudinal slip ratio of 5–10% by ABS (Anti-lock Braking System) (Van Zanten et al., 1996) in order to compromise between lateral stability and the braking distance. The operating range of ABS in terms of the slip ratio depends on the vehicle in question, but it is rather wide because the inertia of the wheel and torsional stiffness of the tyre cause rotational vibrations and create challenges for the driver. In addition, different tyres and road conditions generate the maximum force in slightly different slip regions.

The longitudinal slip ratio of 5–10% of a rolling tyre does not, however, mean that the whole contact area of the tyre is sliding on the road. During braking, the sliding nucleates from the trailing edge of the tyre contact patch, and as the longitudinal slip ratio increases, more of the contact area is in sliding contact. In fact, the leading edge of the contact patch can be in a static friction condition while the trailing part is in kinetic friction condition (Kidney et al., 2011; Pacejka and Sharp, 1991).

In order to illustrate the importance of the static friction coefficient for the braking grip of tyres, a simple example is given here. The Treadsim model (Pacejka, 2002) is a brush model of a tyre extended with carcass flexibility. In this model, the forces on the tyres and the proportion of the contact area that is sliding can be simulated for different static and kinetic friction parameters. In tyre research and development, the static friction coefficient is a very important but often overlooked indicator of the emergency braking performance of the tyre. Indeed, very often the linear friction testing of rubber samples focuses on ranking sliding friction coefficients (Fülöp and Tuononen, 2013). However, the results gained with a Treadsim model (Fig. 1) clearly show that, especially in ABS braking, the static friction coefficient of the tyre plays a more important role in the overall tyre friction than kinetic friction does.

The figure shows that an improvement of just the kinetic friction behaviour can lead to significant improvements in the braking force at high longitudinal slip, but only to a slight improvement within the ABS operating region. Meanwhile, increasing the static friction shows a more significant effect on the friction force in the ABS region. It should be noted that in the operating region of ABS only about 50% of the tyre contact area is sliding, according to this simplified model of a rolling tyre. This implies a continuous process of frictional detachment in the rolling tyre contact patch. Therefore, studying the transition phase from static to kinetic friction could lead to significant improvements in tyre performance.

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http://dx.doi.org/10.1016/j.coldregions.2015.03.003
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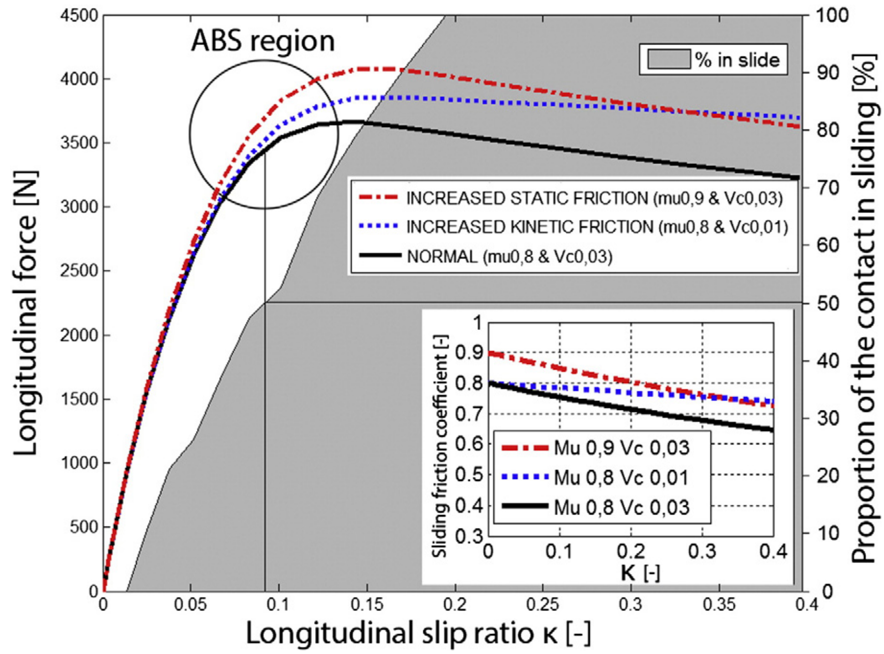

Fig. 1. A Treadsim simulation graph. The graph shows the total longitudinal force and the proportion of the contact area that is sliding, as a function of the longitudinal slip ratio. An ordinary tyre produces the maximum longitudinal (braking) force close to a slip ratio of 0.1, after which the force decreases. ABS systems try to keep the force at the maximum level by adjusting the brake pressure. The proportion of the contact that is sliding (grey area) increases when the slip ratio increases, so that at the maximum longitudinal force only about 50% of the contact area is sliding. Throughout the ABS operating region, an increase in the static friction has more influence on the longitudinal force in the ABS region than an increase in the kinetic friction.

The transition between static and kinetic friction has been of interest in geology, in the context of studying the mechanisms of earthquakes (Ben-Zion, 2008; Scholz, 1998). There have also been slip propagation studies for polymers that clearly show how the slip propagates and the contact area is reduced during the transition from static to kinetic friction (Ben-David et al., 2010; Rubinstein et al., 2004, 2007).

Rubber detachment and stick–slip was studied on transparent glass surfaces (Tuononen, 2013, 2014) and with means of optical microscopy (Brörmann et al., 2013). The phenomena in contact area of a rolling tyre have been studied optically (Wallaschek and Wies, 2013). The rubber–ice friction has been studied optically through a transparent rubber hemisphere for low sliding velocities (Roberts and Richardson, 1981). However, there are no studies of the transition between static and kinetic friction for rubber sliding on ice that would show the physical detachment mechanism.

This article presents an optical imaging method as a tool to study rubber–ice contact behaviour. We show the effect of simple rubber surface texturing on the propagation of the detachment front, and connect the precursors of frictional sliding seen in the friction build-up phase to local detachments in the contact area.

2. Methodology

The rubber samples were produced by vulcanizing a rubber compound in a mould. The contact area of the samples was 60 mm × 60 mm and the sample height was 10 mm. Two tread compounds that are typical for the tyre industry were tested: soft (52 ShA) and hard (67 ShA). Some of the samples were textured by cutting grooves (1 mm deep) into the rubber using a scalpel blade that was precisely controlled using a milling machine. Two longitudinal and two lateral grooves were made in each of the textured samples, 10 mm from the sample edge. The samples are referred as the smooth sample without any grooves, the narrow-grooved sample with grooves made in a single pass, and the wide-grooved sample with grooves 1 mm wide, as shown in Fig. 2.

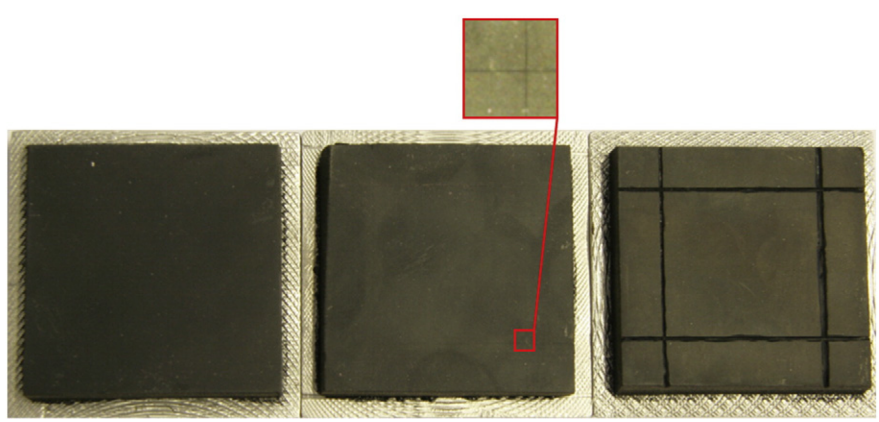

Fig. 2. Picture of the smooth sample, the narrow-grooved sample, and the wide-grooved sample, from left to right. The narrow grooves are hard to notice but the pattern is the same as in the wide-grooved sample.