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Evolution of ice surface under a sliding rubber block

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ABSTRACT

The constant need to improve road safety and the driving performance of winter tires imposes challenging requirements on tire development, especially when considering that one of the key steps, the evaluation of the product itself, is limited by the seasonal changes. This explains why the industry is moving towards indoor testing. An example is the ice performance of tires, which is very frequently characterized indoors or even in the laboratory. The quality of the data thus obtained, however, depends strongly on how well the artificial surface approximates real life. Today, several methods are available to assure the consistency of the test data by controlling the creation and the break-in of the ice track used for testing. At the same time what happens at the surface during its preparation and how this affects the physics of the rubber–ice contact is not yet fully understood. To build this understanding, in the work reported here we were focusing on one of the simplest experiments available. Series of linear friction tests were performed in the laboratory with strict environmental and procedural control. The quasi-real-time microstructural monitoring of the ice surface, together with the friction measurements, allowed the main physical processes that were ongoing during the break-in of the fresh or aged ice surfaces and led to changes in the contact conditions to be identified. The results indicated that there was no large-scale melting of the ice when the rubber was sliding over it. The deformation of the ice and its strong dependency on temperature, on the other hand, may play a significant role in ice friction.

1. Introduction

One of the main steps in tire development is the evaluation of the product candidates and that of the final product. The industry places great emphasis on thorough testing to achieve the highest level of road safety and product performance. In the case of winter tires, an additional challenge is posed by the seasonal evolution of the weather, which limits the availability of outdoor testing. Hence the manufacturers basically have to follow the winter to the northern and southern hemispheres of the globe. Another option, which is to move the activities indoors or even to the laboratory, has been explored with varying success in the past for different winter surfaces. Because it is seemingly simple to generate the ice surface indoors, it was the prime candidate for this move. Currently, one of the key tire performance items, ice traction, is evaluated on indoor ice rinks to a significant extent.

Besides full-scale tire testing, the development of tread block-scale laboratory rubber–ice friction testing also has a long history. Quite early, in the '70s Gnörich [1] introduced one of the first rubber–ice tribometers and developed some of the basic techniques for laboratory ice surface preparation. Somewhat later, on the basis of extensive measurements, Roberts proved the existence of an apparent switch between different friction mechanisms when the temperature increases [2–4]. He also noted that at lower temperatures, where the measured friction is surprisingly high, the properties of the rubber compound also play an important role; when the melting point is approached their influence fades out with the decrease in friction. An important additional observation, later confirmed by several studies, was that the sliding speed and the temperature have very similar roles, so that the ice becomes more slippery not only if the temperature increases, but also if the rubber slides faster. This relation was explained by showing that the main governing factor of rubber–ice friction is the evolution of the temperature in the contact zone [5,6]. Indeed, it was proposed as early as 1939 that frictional heating might be the main contributor to ice slipperiness [7].

The direct observation of the contact was more challenging. Roberts [2] used a transparent rubber hemisphere to gain access to the surface. A higher-resolution but "post-mortem" analysis was made possible with the method developed by the group of Blackford [8], who introduced ice or rubber pins for their experiments. At the end of the tests the pin was then moved to an SEM microscope and examined further.

There is, however, a common limitation of these earlier works, namely that they used rotational friction testers. The big advantage of rotational testers is that they are relatively simple and at

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the same time very scalable, so it is reasonably easy to upscale them even to full tire size [9,10]. Their disadvantage, on the other hand, is that the sample touches the same surface patch repetitively, so that the heat created in the contact zone cannot be dissipated easily, possibly resulting in a relatively quick melting of the ice. This melting can only be avoided by adopting extremely low sliding speeds [1], which, on the other hand, make the conditions very different from those that exist in real tire-road contact [8].

Another way to avoid the repeated contact is to shift from rotational to linear friction testing. Several such devices were reported in the literature [11–14], which are capable of producing different speed and load ranges. In general, they are equipped with sample holders for sample sizes ranging from a tread block to full tire sections. All the linear friction testers reportedly provide very stable, repeatable friction measures which compare well with real-life tire test data.

One should, however, note at this point that neither the laboratory nor the tire test protocols usually followed in the industry claim to reproduce the full range of possible road conditions. Rather, they are meant to provide safe and preferably inexpensive ways of ranking tires by their average performance. Each protocol is defined to ensure that the hypothetical average road performance is captured in a reliable way. This goal is also kept in close view when someone defines the surface preparation, surface conditioning, and testing. The exact protocol is difficult to establish and it is often part of the closely guarded knowledge of the team that is developing it.

The preparation of the ice surface, especially the surface conditioning, is aimed at predetermining the contact conditions. This “break-in” aims to clear the ice of frost and on outdoor tracks to remove snow particles blown by the wind. If this is compared with real road conditions, during break-in the surface state moves from a rarely trafficked icy road to a busy but icy highway. Obviously, both extreme sets of conditions are of interest for traffic safety. We should look more deeply into the contact process itself, however, if we want to understand how and why they differ. In particular, we have to understand how the ice surface evolves during the break-in phase.

Because of the relative difficulty of directly observing the ice surface, only a relatively limited number of studies have been published in the open literature. The earliest method, the replication of the surface features with Formvar™ solution, was developed by Sinha [15] and later used by, for example, Klein-Paste [16] to study aircraft landing safety in the Nordic countries. Another and surprisingly precise method involves replication with dimethyl siloxane resin, which is used in dental healthcare, and was introduced by Bäurle [17]. Both of these have the same disadvantage, however, namely that the casting process is quite long and in many cases it is destructive. In a very extensive study Higgins [8] followed a different approach, first introduced by Marmo [18], which consists of using ice pin sliders in contact with rotating rubber disks. The pin can then be moved to a scanning electron microscope and studied in detail. Although the method is able to give a very precise picture of the surface, it is quite cumbersome and clearly it cannot be applied in the case of real-life ice surfaces.

In this paper we present a method which aims to overcome one of the biggest inconveniences of these studies, namely their inability to perform quasi-real-time characterization of the evolution of the ice surface during rubber–ice friction testing. The in situ microscopy introduced in the next section, together with the use of a linear friction tester located in an environmental chamber, allows us to follow the evolution of the ice surface during break-in. We will then connect the surface observations to the frictional performance of the samples that were tested.

2. Materials and methods

A linear friction tester called Mini-Mu-Road (MMR), installed at Aalto University, was used for the tests reported here. Since a detailed description of the device and its development was already given elsewhere [19–22], here we only recall its main characteristics. The application of the image acquisition system, a new element of the measurement system used here, will be described in greater detail.

2.1. Ice surface preparation

The ice surface was prepared from distilled water on a glass plate with a flooding technique by making several thin ice layers [20].

After the base ice surface had been prepared, a thermocouple was placed on the surface of the ice and covered with additional ice layers. It was placed in the path along which the rubber would slide to the region where the rubber–ice kinetic friction is stabilized on a constant level. The thermocouple is installed as close to the surface as possible without risking it being destroyed during the friction testing as seen in (Fig. 1).

The ice was prepared at $-10\,^{\circ}$C, and left uncovered overnight before testing. This standard aging process, which is regularly used during friction testing, was followed here to allow comparison with older results. During the one-night aging, the temperature was maintained at a constant $-10\,^{\circ}$C. Since the air moisture level was reasonably low, no additional surface protection was necessary.

Before the tests, the glass plate containing the ice layer was moved onto the friction tester. No additional pre-treatment was applied, so the ice was used in an “as received” state. This aim was to approximate the conditions found on an outdoor test track prepared in the evening and used for tire testing the day after.

The MMR friction tester device itself is located in a climatic chamber with massive wall insulation. This isolation allows all the measurements to be made under reasonably stabilized temperature and humidity conditions, especially when compared, e.g., to climatic containers where air-conditioning control measures may dominate the results.

2.2. Friction measurement and ice surface monitoring

Before testing, the rubber sample that was used (with a contact surface of 60×60 mm^2) was glued to a sample holder. The design of the holder allows it to be clamped quickly to the measuring unit, so that the test samples can be exchanged rapidly when necessary. The sample surface was cleaned (chemically with ethanol) and slightly roughened with a sand paper before it was brought into the cold chamber. It was then mechanically broken in on the friction tester to ensure that for e.g. Payne-effect will not disturb the friction measurements.

The horizontal and vertical forces acting on the rubber sample were measured with piezoelectric force transducers. A pneumatic

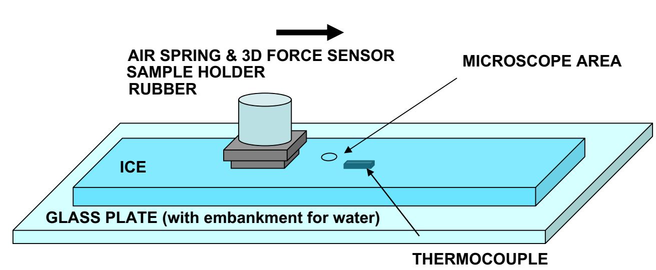

Fig. 1. Experimental setup used in the study: MMR, thermocouple under the ice, and microscope.