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Structural evolution and wear of ice surface during rubber–ice contact

András Kriston [a,b], Nihat Ali Isitman [a,*], Tibor Fülöp [a], Ari J. Tuononen [b]

[a] Goodyear S.A., Colmar-Berg L-7750, Luxembourg
[b] Department of Engineering Design and Production, Aalto University, Espoo 00076, Finland

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ABSTRACT

This study investigates different possible contact mechanisms of rubber–ice sliding friction using in-situ and ex-situ ice microscopy at test temperatures below melting point. Several frictional processes were identified based on the evolution of ice surface morphology. The nature of rubber–ice contact is significantly different for softer and stiffer rubber compounds. For softer compounds the ice microstructure evolves through frost rounding/removal, surface scratching by hard filler plowing, and shearing of quasi-liquid layer by capillary drag. Cold recrystallization and local melting/refreezing of ice was not found to occur owing to homogenous pressure distribution. For stiffer compounds, the pressure distribution is uneven and contact is more localized, resulting in enhanced local deformation features such as subgrain boundaries, visible etch pits and large-scale melting/refreezing.

1. Introduction

The tire industry places strong emphasis on improving winter driving conditions. These ongoing efforts include developing the tire-road tribology, specifically, a more complete understanding of the rubber–ice friction processes. This is essential to describe the behavior of tires on road surfaces covered with winter contaminants, mainly made up of solid or granular ice. The increased understanding is not only important to improve the grip behavior of rubber compounds on icy surfaces but also necessary in order to better plan road surface maintenance activities, such as de-icing or cleaning.

The study of rubber–ice contact is not a recent endeavor, though. One of the earliest works attempting to characterize rubber–ice friction dates back to the 1970s [1]. The experiments were performed at unusually low sliding speeds ($\sim$10 mm/s) with the idea of eliminating frictional heat generation. Under these conditions, the ice was said to be kept “stable”. The authors found high friction coefficients that were greater than $\mu = 1.0$ and concluded that ice behaves like a solid surface with a very low roughness, in analogy to polished metal or glass. This allowed for the interpretation of the friction mechanism solely on the basis of rubber viscoelasticity ruling out the potential effects of interaction between the rubber and the ice surfaces. Importantly, the authors also clearly noted a difference in the frictional behavior of “freshly formed ice” as compared to “polished ice”.

In real life, however, the study of very low sliding speed regimes does not suffice to explain the simple physical observation, namely that ice is often slippery. Therefore it is fair to say that a more complete description of rubber–ice friction is essential. This description shall contain several parameters associated with rubber compound properties such as stiffness, hysteresis, surface chemistry, and surface roughness, to name a few, but also those governed by the ice surface characteristics, such as the grain structure, frost deposits, or the temperature and time dependence of its mechanical properties. The main research fields related to friction on ice are linked to the tire industry [2–6], sports industry [7–9], and fundamental nano- and microscopic scale friction studies [10,11]. The ongoing Arctic boom emphasizes the importance of sea ice friction in many applications [12,13].

The present paper aims to describe the different wear and contact features that can be observed on ice surface after the passage of a block-shaped rubber sample. The study utilizes a combination of in situ optical microscopy and ex situ characterization techniques. The latter relies on capturing the topography of the ice surface using dental replication material [3,14,15], allowing detailed examination of a durable replica ice surface by optical and Scanning Electron Microscopy (SEM) or by White Light Interferometry (WLI) techniques. The classification of the different types of contact features helps to provide a better understanding of the principal mechanisms active during the rubber–ice contact

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[*] Corresponding author. Tel.: +352 8199 3915; fax: +352 8199 3856.
E-mail address: nihat_isitman@goodyear.com (N.A. Isitman).

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process, taking into account many influencing factors, such as the surface and material properties, and also the loading conditions.

2. Materials and methods

2.1. *Ice preparation*

The ice surface, built up from several layers, was made from distilled water using a flooding technique [16]. During the preparation of the ice the flooded water was evenly distributed using a straight rubber spatula. After the preparation of the ice, a rest period was allowed to condition the surface.

2.2. *Friction testing and ice surface characterization*

2.2.1. *Friction test*

The Mini-mu-Road tester (Aalto University, Helsinki, Finland) was used for the rubber–ice friction measurements. The device was installed in a cold chamber in which the ambient temperature was set to −10°C. The relative humidity was monitored, but not actively controlled. A schematic view of the test device and the individual measurement steps is shown in Fig. 1. The kinematics of the device included horizontal and vertical motion along the ice table. During a single sweep, the sample was loaded using a predefined normal force, then swept until the end of the track with a given velocity. At the end of the track it was moved out of contact and then back to the start position.

2.2.2. *Ice surface replication*

Different casting techniques are suggested in the literature for the ex-situ investigation of ice surface. In the current study, a dental casting material, vinyl polysiloxane, was used [15]. It is available as precision casting material for surgery-level treatments. Its considerable advantage is that it can be used at very low temperatures, although the polymerization takes a remarkably longer time to complete (4–5 h at −10 °C instead of 1–2 min at 25 °C). The casting material is optimized to generate only negligible heat during polymerization which helps avoid severe thermal impact on the surface characteristics of ice. The long-term dimensional stability is an additional important advantage of this particular casting material; furthermore, contrary to a real ice surface, the replica surface is insensitive to the heat input expected during a normal microscopy analysis.

The negative imprint of the ice surfaces made by casting can also be used as a mold to cast a positive surface replica with another casting material. In this study, polyurethane was used for this purpose. Fig. 2(a) shows the casting method used to prepare the positive imprint of the ice surface. A metal ring was placed on the vinyl polysiloxane (silicon) replica in order to keep the liquid polyurethane casting material on the surface during curing. A previous study performed on different casting methods [17] states that the resolution of the silicon and polyurethane casting material is finer than one micron.

2.2.3. *Microscopic and surface topology techniques*

A variety of imaging methods were used to characterize the ice surface. Optical microscopy technique was the basis for the in-situ observation of the ice track before and after sliding sweeps. An X-Loupe A-series portable microscope was used for this purpose. Fig. 3 shows a representative image of an original ice surface, as taken by the portable microscope. Although providing high quality, this technique has some drawbacks such as small observable surface area and limited time available for image recording without damaging the ice surface.

To balance the inconveniences of the in-situ observation, ex-situ methods were also applied to surface replicas where the ice

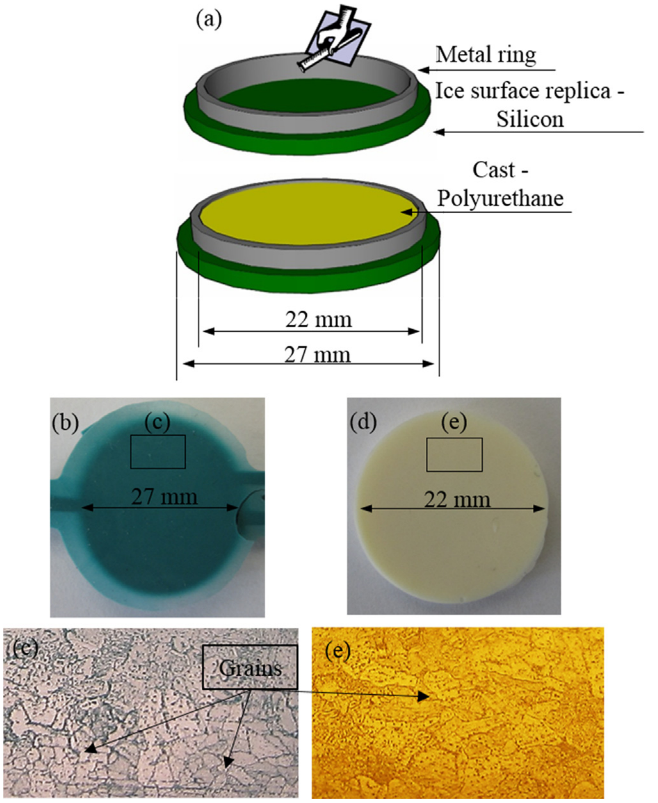

Fig. 2. (a) Replication of the ice surface (positive replica); (b, c) negative, (d, e) positive imprints of the surface.

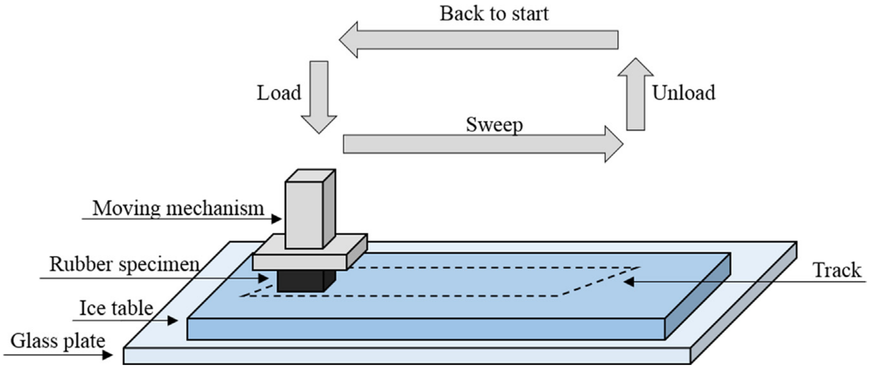

Fig. 1. Schematic drawing of the test device and procedure.