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Friction of rubber on ice: A new machine, influence of rubber properties and sliding parameters

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ABSTRACT

Friction of rubber on ice and snow is important for performance of vehicle tyres in winter. We introduce a new linear tribometer that was designed for measuring the friction of rubber on ice. We present a systematic study of rubber sliding on ice, investigating speed, load, temperature and rubber properties. The friction was linked to behaviour at the interface, particularly melt–water formation and real area of contact. Friction tends to decrease with conditions that promote melt–water formation, and tends to increase as real area of contact increases. We observe stick-slip behaviour with high real area of contact and high load.

1. Introduction

The frictional behaviour of rubber surfaces is important for tyre performance in all weather conditions. Typically rubber exhibits high friction, while ice often has very low friction because of a lubricating layer that forms on its surface. The frictional behaviour of both materials individually varies with parameters that are of interest for tyres sliding on icy surfaces; when the materials are combined they create a complex system of high interest.

Dynamic friction coefficient (μ) on ice surfaces is closely related to the thickness of the lubricating layer produced during sliding. Investigations on ice surfaces with various sliders have shown that the thickness of the lubricating layer and thus the frictional force and μ depend on velocity [1–3], temperature [1,4] and load [5–7]. Other parameters that affect friction of ice are real contact area [8] and surface roughness [9]. At very low velocities and temperatures there is little melt–water on the ice surface. Dry friction, during which friction force is governed by solid to solid contact, dominates and this results in higher μ values. At higher velocities and loads the enhanced frictional heating, which accounts for the existence of the lubricating layer [1,10], increases the thickness of the melt–water. Due to this increase there is a significant drop in friction. A further increase in the layer thickness leads to less solid to solid contact and the slider is essentially supported by the water layer. Friction is based on shearing of the liquid layer [11] and increases.

Contrary to other hard solids, the first observations regarding the frictional behaviour of rubber revealed a dependence on load, velocity and temperature [12,13]. Grosch [14] combined speed and temperature using the WLF equation [15] and produced master curves of the friction coefficient that are applicable for low velocities due to lack of frictional heating. He also distinguished the difference in the frictional behaviour depending on the testing surface. Smooth surfaces exhibit a maximum that is associated with adhesion whereas on rough surfaces there is also a hysteretic component connected with the internal friction of the rubber.

Early studies of rubber sliding on ice surfaces revealed a decrease in friction coefficient with increasing temperature [16] and increasing load [17] due to melting of ice asperities. At high and low velocities low μ values are reported and a maximum occurs at intermediate velocities [17]. Southern and Walker [18] created a master curve and attributed the high friction values obtained at an intermediate velocity range to the viscoelastic rubber properties rather than the interface. The viscoelastic effects are more apparent when velocities and temperatures are relatively low so that surface melting of ice is minimised. Furthermore, the viscoelastic effects depend strongly on the specific rubbers used (which are very different in different studies). Stick-slip phenomena that led to a decrease in the friction coefficient were reported for high velocities [18] or very low temperatures [17]. The presence of Schallamach waves at velocities lower than 1 mm/s [19] was interpreted as an indication of increased friction. The comparison of various rubbers with different glass transition temperatures (T_g) at low velocities

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resulted in higher friction for the rubber with the lowest T_g [20]. Rubbers were found to exhibit higher friction with increased softness [21], resilience [22] and compliance [23]. In a previous study in our group [24] we produced a detailed friction map for a specific tyre rubber and reported a localised maximum in friction for low velocities ($\sim$0.01 m/s) at temperatures close to the tyre rubber T_g. We used cryo-SEM imaging of the ice surface after testing, revealing for the first time direct microscopic evidence for the friction mechanisms which can account for all the different friction coefficients measured. We also introduced a simple thermodynamic model to calculate the time it takes for the surface temperature to rise to the melting temperature; this model is based on the unsteady heat flow equation for a semi-infinite solid subject to constant heat generation at the interface.

Building on the insights gained from this earlier work, we now move onto comparing three tyre rubbers with different glass transition temperatures at a relatively high velocity range (0.1–1 m/s) sliding over ice surfaces made of de-ionised and tap water at applied loads between 0.45 and 1.50 kN (corresponding to pressures of 2.8 and 9.4 bar) and temperature range -3.5–-13 °C. In this study we use a new linear friction machine based on pneumatic load application and precise velocity control which is capable of reproducible and reliable measurements at sub-zero temperatures. We now use the thermodynamic model to predict the friction coefficient values which allows us to discuss the friction mechanisms for the different rubbers.

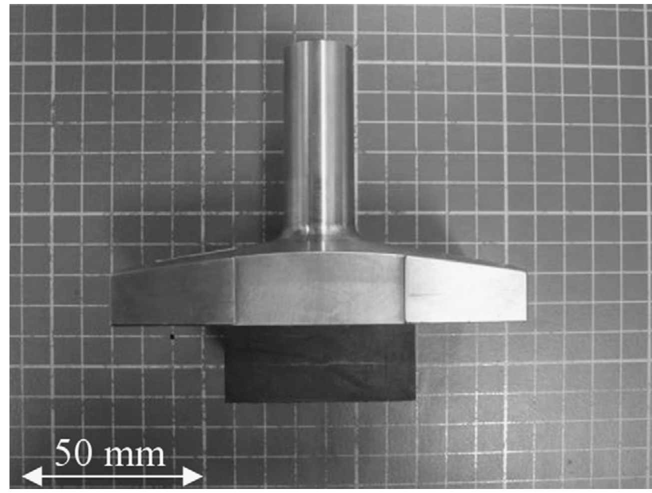

Fig. 1. The sample holder with a rubber block.

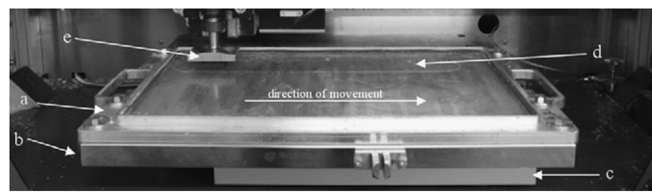

Fig. 2. Photograph of the new linear friction machine. The ice tray is bolted on the test table and the sample holder mounted on the moving part. (a) Tray, (b) aluminium table, (c) measuring platform, (d) milled track in ice, (e) rubber holder and rubber sample.

2. Experimental

2.1. Ice surface preparation

The ice surfaces were prepared in an aluminium tray $0.9 \times 0.4 \times 0.03$ m by freezing several water layers to avoid surface irregularities caused by water expansion during freezing. A foam tape strip was glued to the side walls of the tray to absorb the expansion of the ice. Each ice tray consisted of 7–10 layers of water of about 1 l. The water was first boiled to remove dissolved gases. Ice surfaces were prepared using de-ionised water (resistivity of 18 MΩ cm at 25 °C) and tap water (conductivity of 4×10^{-3} S/m).

2.2. Rubber samples

The rubber samples were provided by Michelin. We used three types of tyre rubbers A, B and C, with glass transition temperatures of -50, -25 and -9 °C, respectively. The rubber blocks were glued to a stainless steel holder before curing. The holder was designed to be rigidly attached to the friction testing machine (Fig. 1).

2.3. Friction machine

The experiments were made with a new linear friction machine in a cold room, operating between 0 and -15 °C (Fig. 2). The machine is bolted rigidly to a substantial concrete block beneath the cold room floor to minimise errors from vibration of the machine itself. The machine has (i) a moving part where the sample holder is mounted and (ii) a table where the ice tray is attached. The moving part has two parallel electromagnetic rails that control the movement of the sample; normally a constant velocity is applied. The velocity range is 0.01 to 2 m/s. A compressed air supply allows pneumatic application of loads that are controlled manually. The sliding distance of the test can be adjusted and for this study was set to 530 mm. The tray containing the ice is bolted to the test table. The table is positioned on a multicomponent measuring platform comprising four three-axis load cells: x is in the horizontal plane in the direction of travel, y is in the horizontal plane perpendicular to the direction of travel and z is vertical. The platform measures three force components and via the software these are linked with the position of sample. In these experiments the initial acceleration was set to ten times the values of the velocity tested. A milling tool can be mounted on the moving part of the machine. This enables us to mill a flat path on the ice, resulting in a controlled surface roughness of the ice and increased repeatability of the tests.

2.4. Testing preparation and procedure

A series of experiments were made to investigate key parameters: rubber type, temperature, velocity, load and ice type. The combinations of parameters are given in Table 1.

The ice tray was prepared at -3.5 °C to avoid cracking of the ice due to its increased brittleness at lower temperatures. After all the layers of water were frozen, the ice surface was machined flat by removing a 1–2 mm thickness of ice with a milling tool and was left overnight. Before the experiments several preliminary ice–rubber friction runs were performed. After experiments at a given temperature the surface was milled again, the cold room temperature was adjusted to the next lower temperature for investigation and the ice tray was left overnight to equilibrate. For a given test temperature the ice surface temperature was stable to ± 0.5 °C.

2.5. Data processing

The coefficient of friction μ was obtained by dividing the component of the force in the x direction with the component of force in the z direction (the normal load). A typical plot of μ against distance is shown in Fig. 3, on which 530 measurement points are plotted; this is for rubber A, speed 0.1 m/s, load 0.7 kN and temperature -3.5 °C. Near the beginning of the test there is a