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New friction mechanisms revealed by ice crushing-friction tests on high-roughness surfaces

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ABSTRACT

Ice crushing occurs to varying degrees in many situations including those that involve a sliding frictional component, such as in sports involving ice contact, ice interaction with bridges, piers, ship hulls, vehicle wheels, rock beds under glaciers and ice-on-ice sliding/crushing interaction within glaciers and extraterrestrial ice masses (on Saturn's moon Enceladus). Here results of ice crushing-friction experiments on high-roughness surfaces with regular arrays of small prominences are presented. Friction coefficients were extraordinarily low and were proportional to the ratio of the tangential sliding rate and the normal crushing rate. All of the friction coefficient variation was determined by the fluid dynamics of a slurry that flowed through channels that developed between leeward-facing facets of the prominences and the moving ice. The slurry originated from a highly-lubricating self-generating squeeze film of ice particles and melt located between the encroaching intact ice and the surfaces.

1. Introduction

The frictional behavior of ice has been studied in many contexts, such as in relation to cold-environment sports involving friction on sled runners (Poirier et al., 2011), skate blades (Lozowski et al., 2013) and curling rocks (Maeno, 2014), in the automotive industry concerning rubber tire performance on ice (Klein-Paste and Sinha, 2010), in shipping regarding friction on hulls of icebreaking ships (Scarton, 1975) and other vessels in cold regions, in construction regarding the friction of moving ice on concrete (Møen et al., 2015) such as piers, bridges and other fixed river and marine structures, in the movement of glaciers (Cohen et al., 2005) regarding ice-on-rock and ice-on-ice friction, and even in relation to extraterrestrial ice-on-ice friction in tectonically active regions of the icy Saturnian moon Enceladus (Nimmo et al., 2007). Over the past few decades ice crushing and indentation have also been studied intensively, mostly in relation to ice engineering associated with offshore oil and gas resources. The main characteristics of the ice behavior consistently recur during field and lab studies and at various scales (Gagnon, 1999). While ice friction in nature often involves some degree of crushing, as in most of the cases above, only a few studies have been conducted specifically on the topic of ice crushing friction where substantial crushing is an integral component (Gagnon and Mølgaard, 1989). Here we present results from ice crushing-friction tests, using novel apparatus, on high-roughness surfaces that reveal new friction mechanisms where the friction coefficient depends on both the normal crushing rate and the tangential sliding rate, and is extraordinarily low.

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2. Preliminary considerations

To set the stage for discussing ice crushing friction we first consider an ice feature crushing against a surface where no lateral sliding of the ice feature is involved. Many studies (Gagnon, 1999; Riska et al., 1990; Fransson et al., 1991) have shown that during the crushing there are regions of relatively intact ice, small compared to the nominal contact area, in the contact zone that are surrounded by crushed ice which flows away from the intact zones (Fig. 1a). The peripheral crushed ice is essentially the debris of shattered spalls that have previously broken away sequentially from the intact hard zone. Fig. 1a shows a spall-creating fracture (dashed line) that is about to occur. When the spall forms (to the left of the fracture) and separates from the intact bulk ice it immediately shatters and pulverizes to become crushed ice. Thin section analysis from lab tests confirmed the intact nature of the ice (Gagnon, 1994a) and thin and thick sections from the Hobson's Choice Ice Island indentation tests (Gagnon, 1998) showed similar features. The pressure on the intact ice zones (hard spots) is very high (30–70 MPa) and changes abruptly to low values (0–10 MPa) when crossing the boundary between intact ice and the crushed material at the perimeter. The high-pressure zones have been shown to be regions where a thin squeeze-film slurry layer of pressurized melt and ice particles is present between the intact ice and the surface (Fig. 1). The viscous flow of this slurry layer generates heat that accounts for the rapid melting component of the removal of ice from the hard zones during

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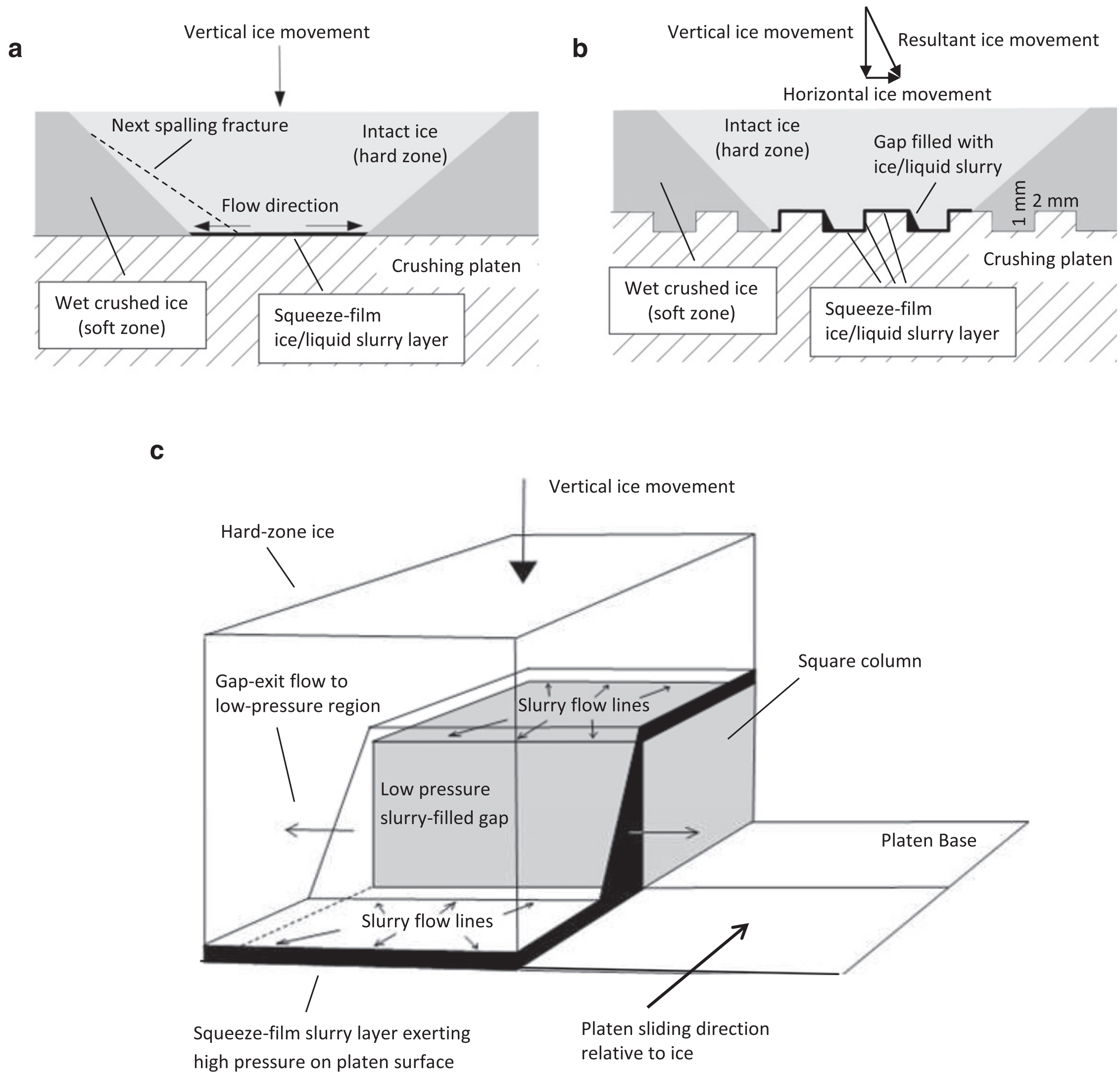

Fig. 1. Schematics showing aspects of the ice behavior during the crushing-friction experiments. (a) Schematic showing the essential characteristics of ice crushing against a flat rigid surface. (b) A 2D schematic depicting ice crushing against a platen surface with square columns. The ice has both a vertical and a horizontal component of movement relative to the crushing platen, where the resultant movement is as indicated. (c) A 3D schematic showing a small portion, a unit area containing one square column, of the view of the ice and platen shown in panel b. The schematic depicts the time-averaged general flow characteristics of the self-generating squeeze-film slurry as it moves from high-pressure regions, where it is generated, into the lower-pressure gap space and eventually out through the gap exits where low-pressure crushed ice is present.

ice crushing. A similar process occurs at ice-on-ice contact (Gagnon, 2013) of ice fragments in the surrounding crushed ice matrix as it flows away from the high-pressure zones.

2.1. Slurry layer details

Details of the thin layer have been the subject of investigation in a few studies. In one case the liquid portion of the layer through-thickness, amounting to about 21 μm during significant spalling events and 3 μm during time intervals between spalling events, was determined from electrical conductance measurements between two conductors on the surface of an ice-crushing platen (Gagnon, 1994b). In another study, using very high speed imaging (30,000 images/s), a direct visual estimate for the layer thickness (~0.17 mm) was obtained by measuring the thickness of a small thin plate of ice/liquid slurry that formed at, and was ejected from, the periphery of a hard zone at high speed (15 m/s) during a significant spalling event in a crushing test (Gagnon, 2010). Hence, when comparing the liquid fraction of the layer thickness during the spalling event from the electrical conductance measurement with the thickness from the direct measurement it is clear that ~12% of the layer is liquid and the rest must consist of ice particles. Another piece of evidence that roughly fits this perspective comes from estimating the amount of energy that is expended by the apparatus during a spalling-event load drop in removing the associated volume of hard-zone ice through the viscous flow of the thin slurry layer, as has been done by Gagnon (1994a). This was achieved by first obtaining the actual hard-zone areas, from video images of the ice contact zone, and the corresponding load measurements. The loads and areas correlated well and the linear fit could be used to estimate the area for any particular load. The area, as a function of load, multiplied by the compliance of the apparatus/ice system was then integrated to get a typical volume of hard-zone ice that is removed during a typical drop in load associated with a spalling event. This volume was multiplied by the estimated pressure on the hard-zone ice (70 MPa) to yield the energy absorbed, although the paper further states that the pressure on the hard-zone ice was likely even higher during the load drop. It was determined that there is enough energy to melt roughly 19% of the hard-zone ice that is removed, implying that the slurry layer through-thickness is about 19% liquid.

Taking the average of this estimate and the former one determined from the conductance measurement and visual observation we get 16% as the through-thickness fraction that is liquid during a spalling