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New insights about ice friction obtained from crushing-friction tests on smooth and high-roughness surfaces

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ABSTRACT

Ice crushing occurs in many situations that involve a sliding frictional component such as sports involving ice-contact, ice interaction with ship hulls, and ice-on-ice sliding/crushing within glaciers and between interacting sea ice floes. Ice crushing-friction tests were conducted in the lab at −10 °C using a set of acrylic ice-crushing platens that included a flat smooth surface and a variety of high-roughness surfaces with regular arrays of small prominences. The experiments were part of Phase II tests of the Blade Runners technology for reducing ice-induced vibration. Ice was crushed against the platens where the ice movement had both a vertical and a horizontal component. High-speed imaging through the platens was used to observe the ice contact zone as it evolved during the tests. Vertical crushing rates were in the range 10–30 mm/s and the horizontal sliding rates were in the range 4.14–30 mm/s. Three types of freshwater ice were used. Friction coefficients were extraordinarily low and were proportional to the ratio of the tangential sliding rate and the normal crushing rate. For the rough surfaces 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

As pointed out by Gagnon (2016), the frictional behavior of ice has been studied in many contexts, such as in relation to cold-environment sports involving friction on sled runners, skate blades and curling rocks, in the automotive industry concerning rubber tire performance on ice, in shipping regarding friction on hulls of icebreaking ships and other vessels in cold regions, in construction regarding the friction of moving ice on concrete such as piers, bridges and other fixed river and marine structures, in the movement of glaciers 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. 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.

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

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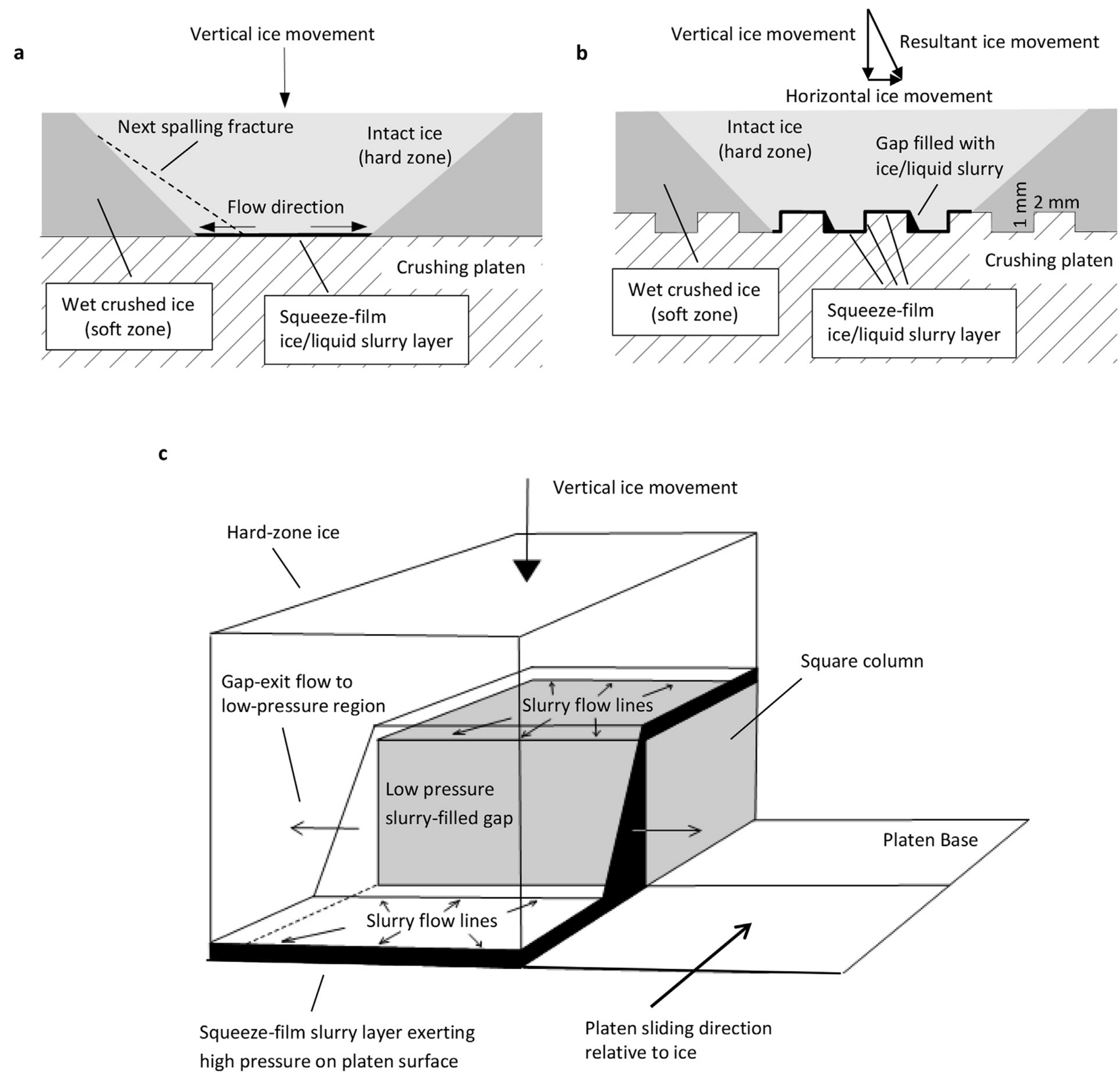

Fig. 1. Schematics showing aspects of the ice behaviour during the crushing-friction experiments. **(a)** Schematic showing the essential characteristics of ice crushing against a flat rigid surface. **(b)** A 2D Schematic depicting ice crushing against a platen surface with square columns. The ice has both a vertical and 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 Fig. 1b. 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. From Gagnon (2016).

shattered spalls that have previously broken away sequentially from the intact hard zone. Fig. 1(a) 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, 1994) 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 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.

3. Slurry layer details

Details of the thin layer have been the subject of investigation in four previous studies. Gagnon (2016) has summarized the results and provided a general view of the nature of the slurry layer during crushing for tests at a similar scale to that of the present ones. We can surmise that the slurry layer thickness in the present tests is somewhere in the approximate range 0.02 mm–0.17 mm, and the liquid fraction of the layer is about 16%. We may think of the slurry layer as a self-generating squeeze film that is powered by the energy supplied by the loading system that causes the ice crushing.