POAC'25
St. John's,
Newfoundland and
Labrador, Canada

Proceedings of the 28th International Conference on
Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

A Novel Skate Blade and Associated Ice-Crushing Phenomena

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ABSTRACT

Tests and observations conducted at NRC have shown that various characteristics of ice-crushing in the brittle regime (e.g., spallation and related load oscillations), as seen in larger-scale experiments, are also at play beneath ice-skating blades. Furthermore, the NRC results are the first to report a thin slurry-layer of ice particles and melt produced by a skate blade. The slurry-layer was generated at the forward bow of the blade during gliding, and along the blade's edge during lateral shaving motions, where in both cases ice crushing was the progenitor. Since the slurry-layer has been shown to be highly lubricating during ice crushing-friction tests (Gagnon, 2016), even on rough surfaces, its role in ice skating is significant, as has also been shown in a recent analytical study (Lever et al., 2022). The above considerations have led to a novel ice-skating blade (patent pending). Here we describe the novel blade (known as 'Speeder-Blade') and present results from lab tests using a mock blade incorporating the technology. Relevant aspects of the ice/liquid slurry-layer are discussed.

KEY WORDS: Ice skating; Ice/liquid slurry-layer; Novel skate blade.

INTRODUCTION

Ice skating is a fascinating subject, and enjoyable activity for many. Previous studies have described some of the physics of ice skating analytically with varying degrees of success (e.g., Le Berre and Pomeau, 2015; Lozowski et al., 2013; Van Leeuwen, 2017). The earlier theories depend on the generation and action of a thin lubricating melt layer between the blade and the ice, while more recent experimental observations (Gagnon, 2021) and analytical study (Lever et al., 2022) have illustrated the importance of a highly lubricating and dynamic slurry-layer mix of ice particles and liquid (Gagnon, 2016) generated by ice crushing. Here we describe experiments and observations using mock ice-skating blades (one typical and the other novel) that traversed the surface of lab-grown ice samples in the gliding and lateral-shaving orientations, where the intent was to demonstrate the efficacy of the novel Speeder-Blade technology.

FORCE AND DYNAMIC ASPECTS OF ICE SKATING

Figure 1 illustrates some basic aspects of ice skating during an accelerating forward stride (right leg) of a skater. Figure 1a shows the beginning and end positions of a conventional blade and a Speeder-Blade on the ice surface during a pushing stride that accelerates the skater forward (Figure 1b). The novel gripping aspect of the Speeder-Blade, described below, improves the efficiency of the pushing stride. That is, more forward motion is obtained for a given lateral movement length. Note that typically during forceful ice skating both gliding in the skate-blade direction and lateral shaving/crushing of the ice surface occur during pushing strides. Similar improvement in efficiency for stopping and turning maneuvers would be expected for the Speeder-Blade technology.

During a lateral sliding event (e.g., push-off, sharp turn, fast stop) a thin layer is shaved off of the top surface of the ice (Figure 2). The shaving/crushing behavior is facilitated/accompanied by tiny regular ice-spallation events (Gagnon, 2021). The spray ejected from the blade-edge/ice-contact zone consists of small pieces of ice-spallation debris, and a liquid/ice-particle slurry mix (Gagnon, 2021).

EXPERIMENTAL SETUP AND RESULTS FROM THE LAB TESTS

For clarity and ease of reading, we define some technical terminology that relates to the experiments and discussion below. ‘Sliding direction’ refers to the direction that a mock skate blade moves in the horizontal plane across the ice surface when pulled by the test apparatus actuator. ‘Blade orientation’ refers to the angle in the horizontal plane (either 0^o, 45^o, or 90^o in these tests) that the long axis of the blade makes with the sliding direction. ‘Glide’, or ‘gliding’, refers to the movement in the horizontal plane of the blade in the direction of its long axis. ‘Edging angle’ refers to the angle of tilt of the blade from the vertical axis.

Mock skate blades (typical and novel), manufactured from stainless steel, were used for the tests. These had similar dimensions and characteristics in the lateral section as typical recreational blades, however, they were shorter in length (~ 40 mm) in order to optimize the lengths of the ice sample surfaces that were used. The ‘hollow’ on the bottom of the blades had a radius of curvature of 7 mm. Along its length the blade edges were linear in the central 20 mm of length and curved upwards at the 10 mm length segment at each end, with a

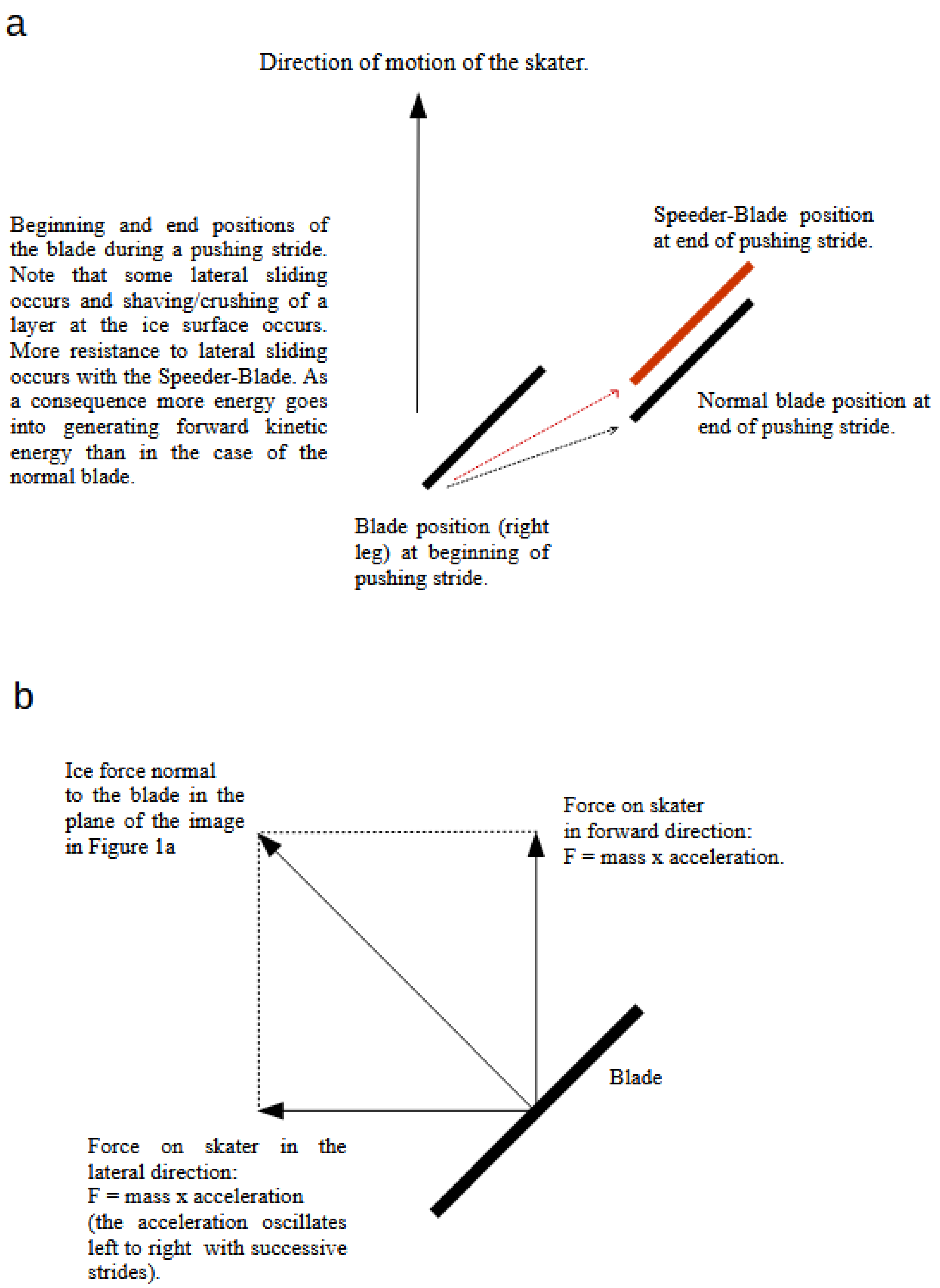

Figure 1. Schematic of ice-skating dynamics: (a) Pushing stride dynamics; (b) Lateral and forward forces on the skater (and blade) during the pushing stride.

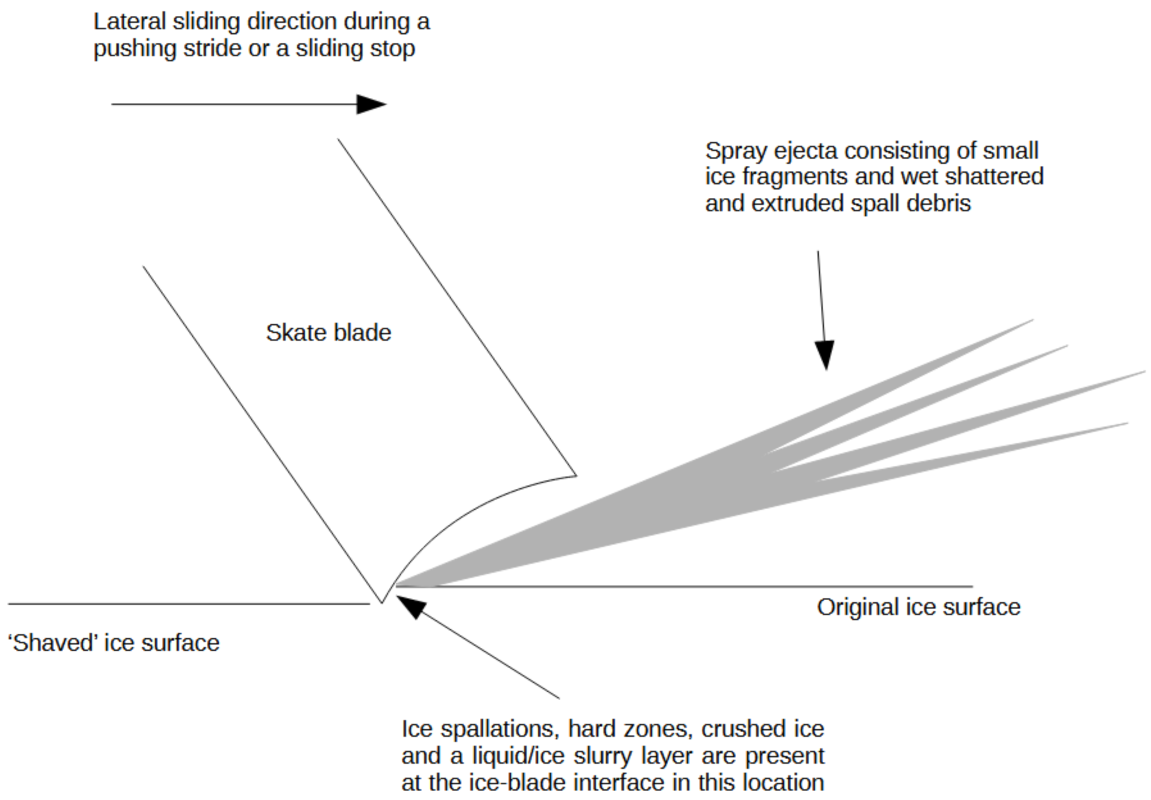

Figure 2. Skate blade on edge during a lateral sliding movement. A certain thickness of ice is removed/shaved from the original ice surface. The shaving, though on a small scale, involves common aspects of ice-crushing in the brittle regime at larger scales. These features include repetitive spallation, and a high-pressure zone of intact ice where a thin squeeze-film liquid/ice-particle slurry layer is generated (Gagnon, 2021).

curvature radius of 50 mm. Figure 3 shows a 'conventional' blade sliding from left to right on the flat surface of a columnar-grained freshwater ice sample, which was grown in a large insulated container with no top. The track left on the flat ice surface following a glide test is shown in Figure 4, where the depth of the track was determined from the actuator displacement of the MTS loading apparatus. The reader can expand this image on-screen to see details discussed below. As noted by Gagnon (2021), '...when the wispy material is swept away from the blade track after a test, one observes that the track is very smooth and has a consistent profile. There is no evidence of distorted grain boundaries from the original surface, or bulging of ice at the sides or in the center of the tracks, that would suggest actual plastic behavior, as classically defined.' In other words, the track depression left on the surface of the ice is due to ice crushing at the bow of the blade and the erosive action of the associated thin liquid/ice-particle slurry layer.

Figure 5 shows schematics of the novel modified blade with the four notches on one blade edge. Each notch penetrated 0.5 mm into the metal at an angle of 36^{o} from the blade wall. The length of each notch was 1 mm and the spacing between the notches was 0.5 mm. Figure 6 shows photographs of the novel 'Speeder-Blade' and a typical unmodified blade.

A set of tests was performed with the blade on edge (~ 21^{o} to vertical) while oriented perpendicular to the sliding direction, and the conclusion was that the novel-blade edge provided positive results. That is, the blade edge provided more grip (~ 24 %) during lateral sliding/ice shaving tests (Figures 7 and 8) than a regular blade edge for two levels of ice

Figure 3. Mock ice-skating blade gliding from left to right on a columnar-grained freshwater ice sample. (From Gagnon, 2021)

Figure 4. Blade track left following a number of gliding tests. Note that the vertical load is borne on the symmetric contacting portions of the blade's edges. The thin white wispy material is frozen extruded slurry (discussed below).

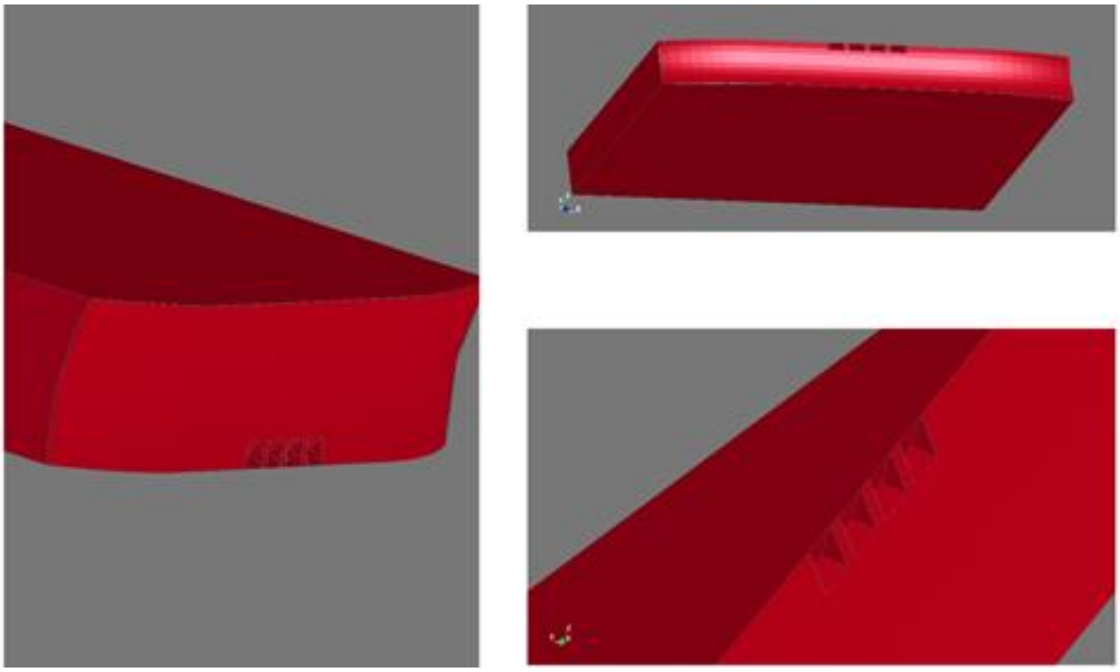

Figure 5. Three schematic views of the novel blade that was used for the lateral sliding (shaving) tests and the forward gliding tests. Four notches on one edge of the blade are evident. For the perpendicular lateral sliding tests the blade was put on edge (~ 21^{o} to vertical) using either the notched or conventional edge. The same strategy was used for sliding tests where the blade was oriented at 45^{o} to the sliding direction. Note that the notches are oriented at 36^{o} to the side wall of the blade. Also note that for a skater's 'Speeder-Blade', the notches would be on both blade edges. The thickness of the skate blade is 4 mm. In reality (Fig. 6), the notches have some inner curvature due to the roundness of the tiny machine tool that was used.

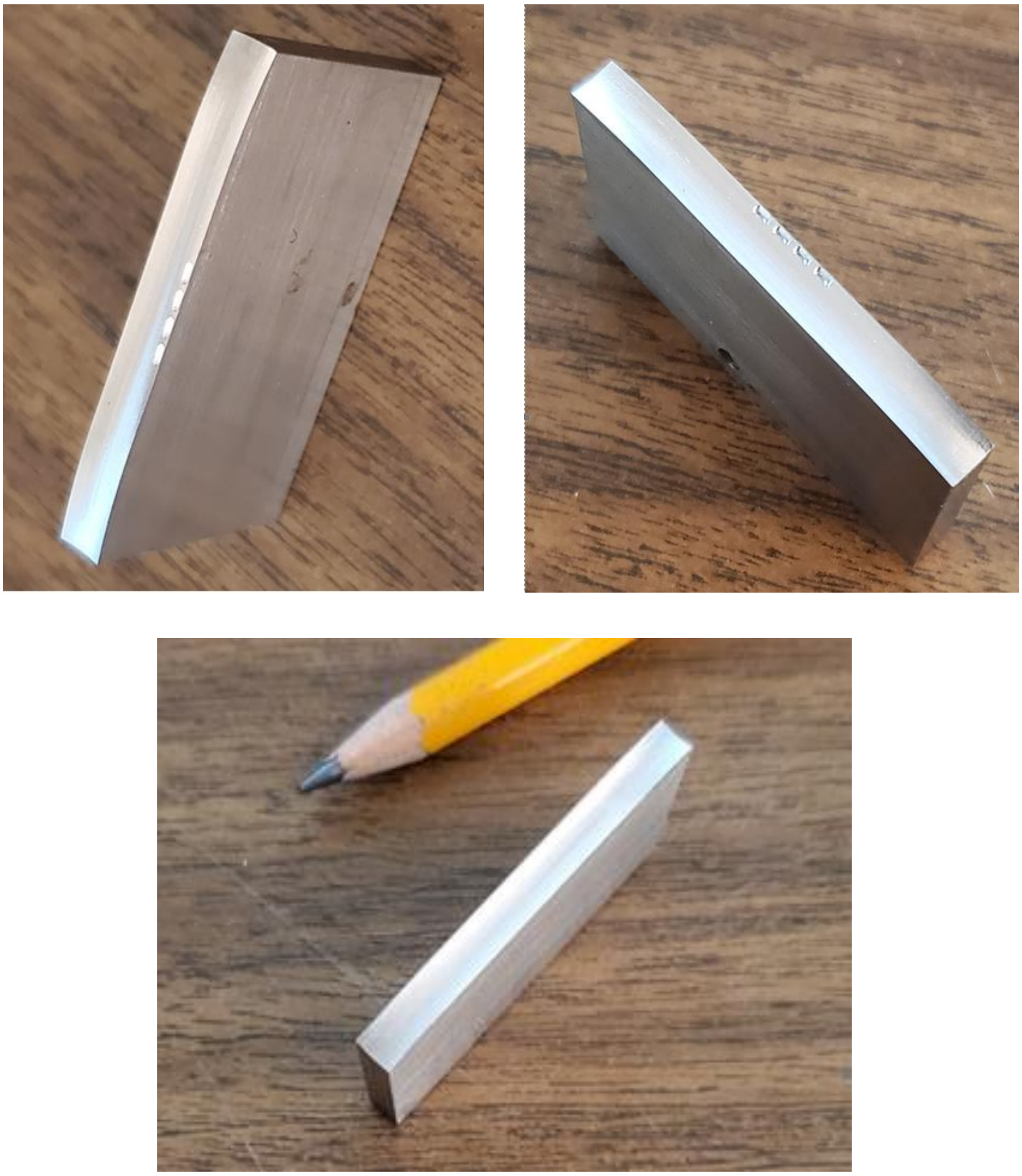

Figure 6. Two photographs of the 'novel blade' with four small notches on one edge (top left and right images) and a conventional blade without notches (bottom image), which were used for the lateral sliding (shaving) tests and the forward gliding tests. For the perpendicular lateral sliding tests the novel blade was put on edge (~ 21^{o} to vertical) using either the notched or conventional edge. The same strategy was used for sliding tests where the blade was oriented at 45^{o} to the sliding direction. Note that the notches are oriented at 36^{o} to the side wall of the blade. Also note that for a skater's 'Speeder-Blade', the notches would be on both blade edges. The thickness of the mock skate blade is 4 mm.

penetration (0.05 mm and 0.1 mm), and furthermore did not create any additional significant friction during forward gliding. In fact, the gliding friction appeared to have reduced (Figure 9). Tests were also performed with the blade oriented at 45^{o} to the sliding direction to determine if the novel-blade edge led to any additional friction in the forward-glide

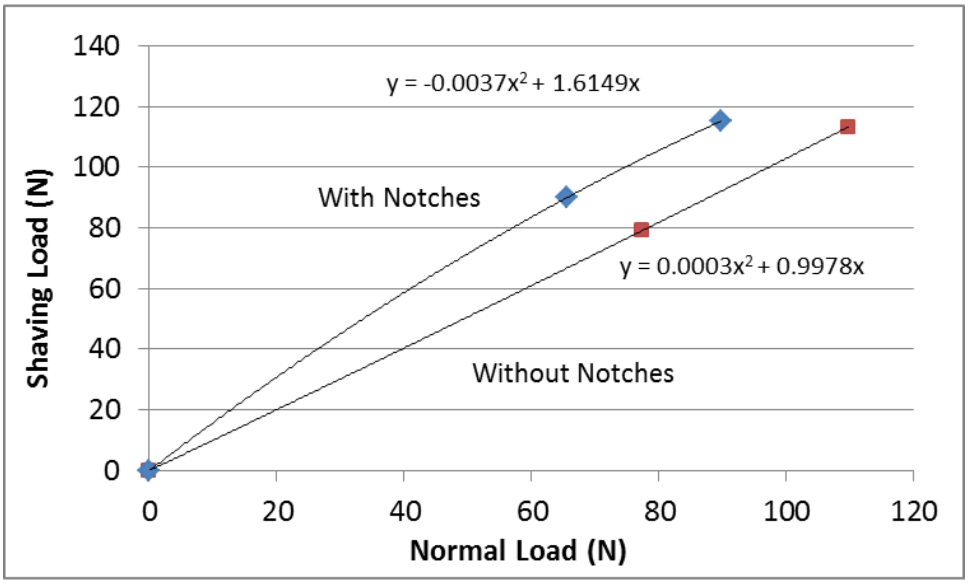

Figure 7. Shaving Load vs Normal load for blades with and without notches during lateral sliding tests. The blades were oriented perpendicular to the sliding direction. More 'grip' is exhibited by the blade with the notches for any given normal load. Each data point represents the average value from three or four tests.

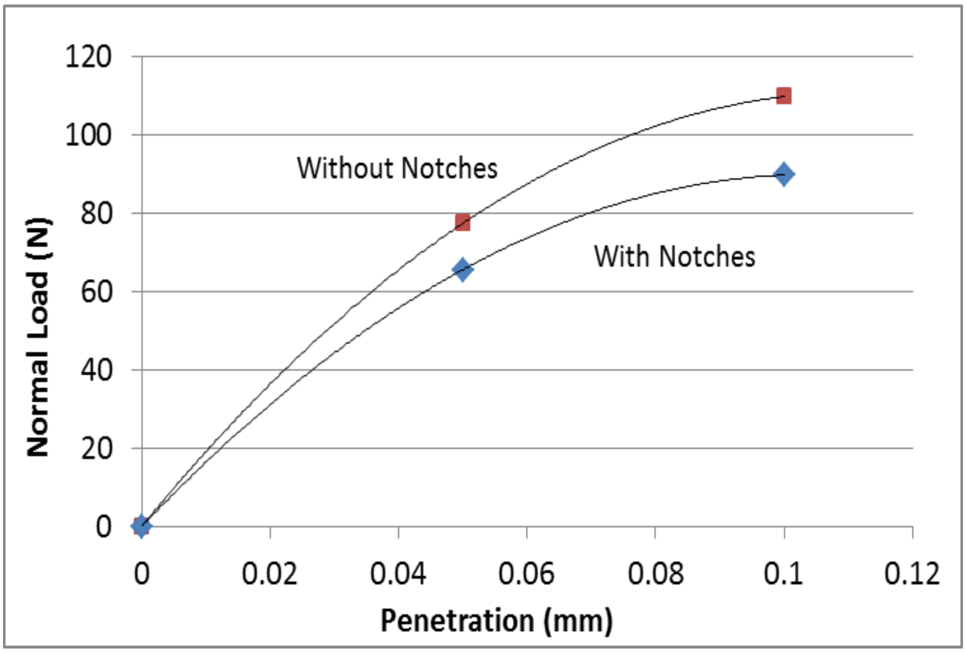

Figure 8. Normal Load vs Ice Penetration for blades with and without notches during lateral sliding tests. The blades were oriented perpendicular to the sliding direction. More normal load was required by the blade without notches for any given ice penetration. Each data point represents the average value from three or four tests.

component of the blade movement during lateral sliding/shaving of ice. In that case the blade caused no additional friction for a blade penetration of 0.05 mm and a small amount (~ 8 %) for a penetration of 0.1 mm (Figures 10 and 11), yielding an average value of 4 % for the two ice penetrations.

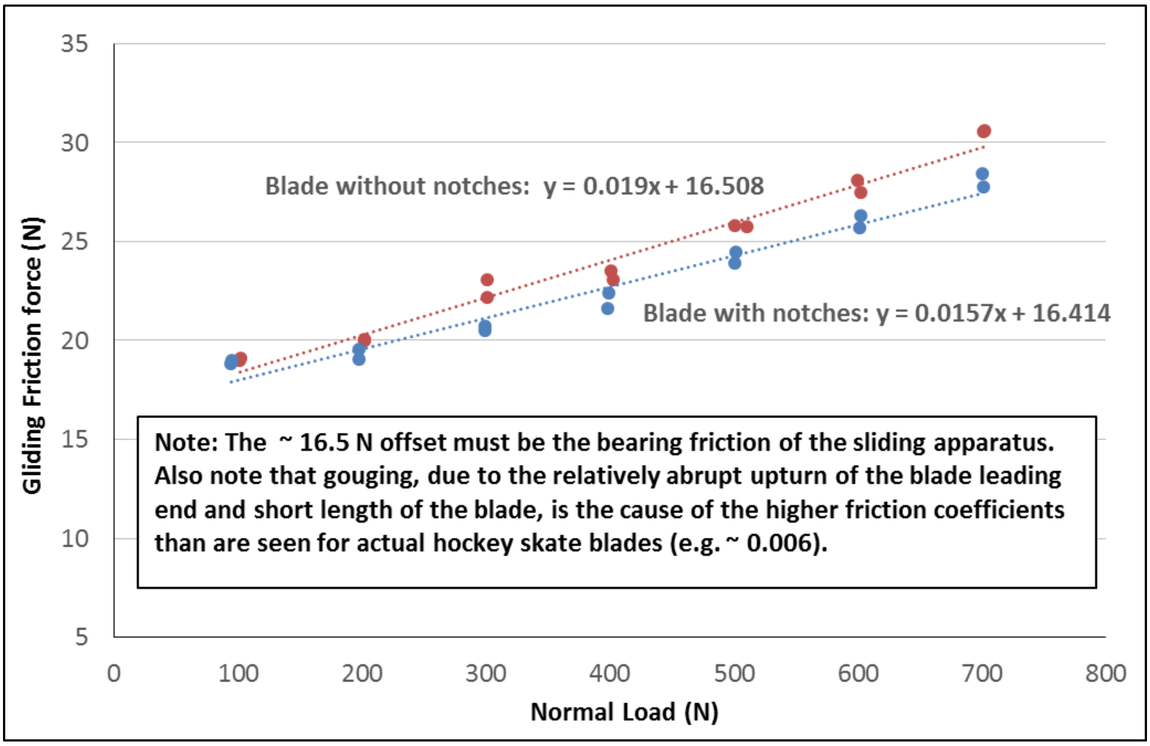

Figure 9. Gliding Friction Force vs Normal Load for blades with and without notches during forward gliding tests. The blades were oriented parallel to the sliding direction.

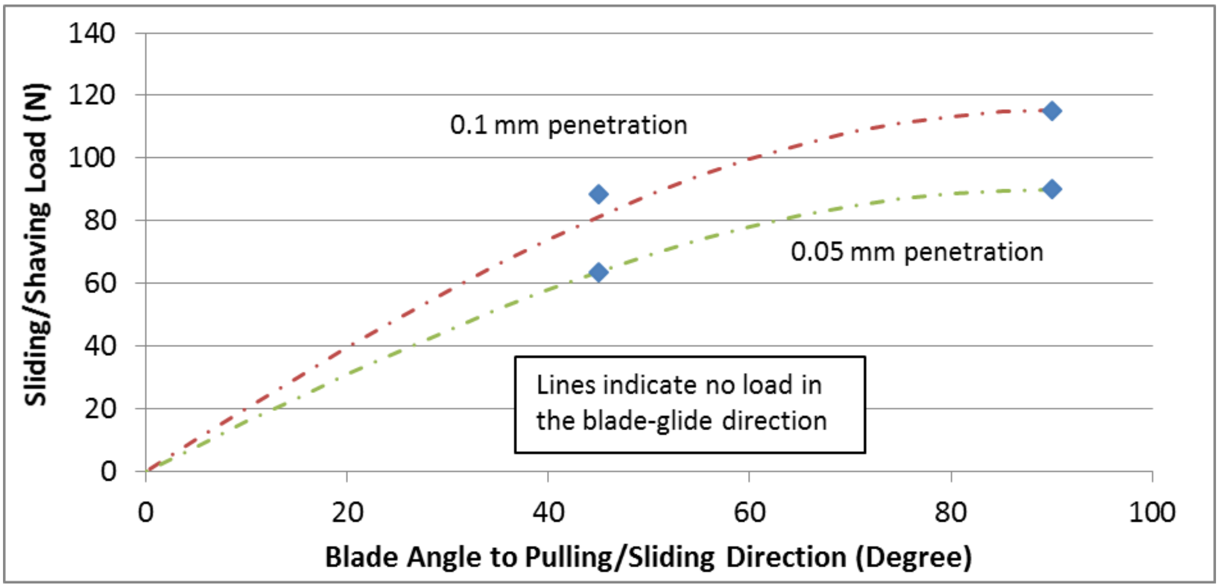

Figure 10. Sliding/Shaving Force vs Blade Angular Orientation for the blade with notches. The angular orientation of the blade is with respect to the pulling/sliding direction. The red and green dashed lines correspond to the theoretical case of there being no frictional load in the blade-glide direction associated with the notches.

Note that for both the perpendicular and 45^{o} ice shaving tests the normal load was applied to the ice surface by the blade by controlling the ice blade penetration, that is, the MTS test apparatus was in displacement control. This was necessary because the MTS device could not control load quickly enough to account for small spallations of ice from the ice surface along

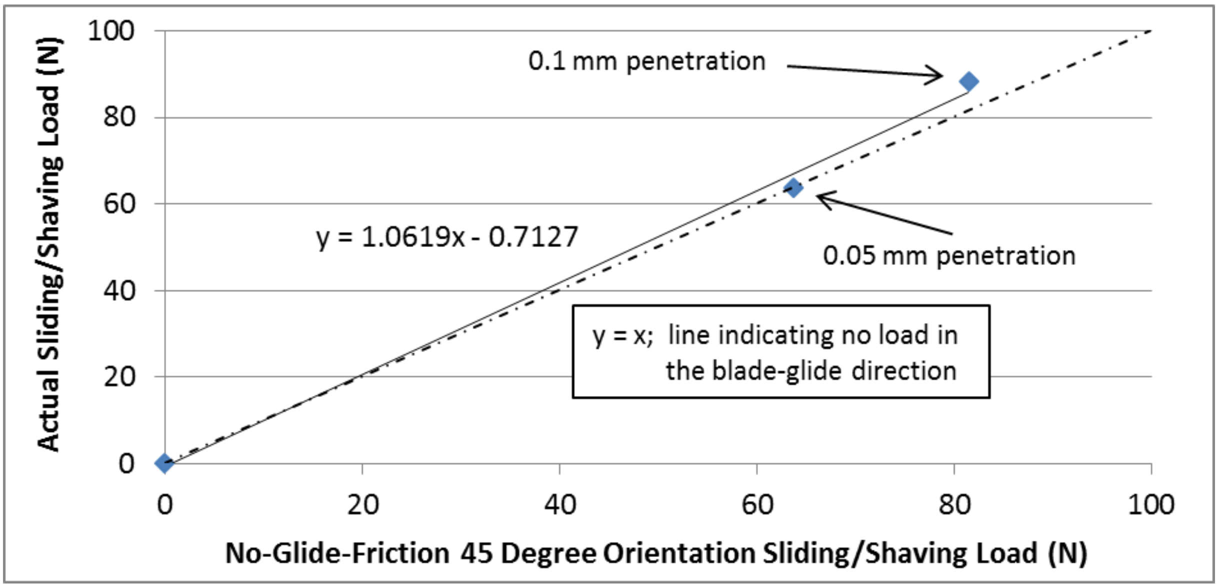

Figure 11. Actual Sliding/Shaving Load vs No-Glide-Friction 45° Sliding/Shaving Load for the blade with notches. The angular orientation of the blade is with respect to the pulling/sliding direction. The dashed line (y = x) corresponds to the theoretical case of there being no frictional load in the blade-glide direction associated with the notches.

the whole contacting blade edge that would cause small sudden changes in the load during the sliding/shaving tests. The gliding tests, on the other hand, did not cause spallations, and load fluctuations, from the side edges of the blade, so the tests were conducted in load control.

The principle by which the novel skate blade works is fairly simple. For any given normal load the novel blade enables the blade, while on edge, to penetrate further into the ice and thereby create more grip during lateral sliding/shaving that occurs during push-offs, stops and turns. This is due to the removal of metal from the blade edge, due to the notches (gaps), that would otherwise have applied load on the ice during penetration (see Figures 5 and 6). The notches may be separate or may be combined to produce one longer notch along the blade edge. Indeed, one can imagine one single 'notch' that spans the full length of the blade. Such a notch, however, would likely provide much more grip than is required. But the idea of a single full-blade-length 'notch' can be configured to achieve the desired degree of grip by tuning the angle between the notch face and the original blade metal face (Figure 12). This configuration of the technology completely eliminates any additional friction in the blade-gliding direction that would have been associated with multiple notches during push-offs where the blade is not perpendicular to the lateral sliding/shaving direction.

Here we note that even in the case where a set of notches is present on the blade edge (e.g., Figure 5), the portion of the side faces of each prominence between the notches that crushes ice when the blade is primarily shaving ice laterally while on edge, but with a component of forward glide, amounts to a small area. The ice crushing against this small area will only generate a small force. For example, the area of the four forward facing faces of the notches on the blade edge in Figure 5, for a penetration of 0.1 mm, amounts to $< 4 \times 10^{-8}$ m^2. Assuming a typical ice-crushing pressure of 30 MPa over that area yields a force of 1.2 N opposing the forward glide component of the blade movement. Recall that the force in the sliding/shaving direction (~115 N) was roughly two orders of magnitude greater than this. In fact, the opposing force will likely be even smaller than this due to extraordinary characteristics of ice crushing-friction that show that friction on very rough surfaces with regular arrays of prominences (much larger than the prominences on the novel blade edges) is very low (Gagnon, 2016). The physics of ice crushing, determined from the published ice crushing-friction experiments, indicates that the leading faces of the notch prominences experience the full ice-crushing pressure (~ 30 MPa for these tests). This is due to the thin pressurized melt/ice-particle slurry layer that is generated at the metal/ice interface during ice crushing. At the leeward faces of the prominences a small gap is created by the relative movement of the notches and the ice. The gap fills with flowing pressurized slurry to impose a back-pressure on the trailing faces that partially balances the pressure on the leading faces, thereby reducing the net friction force.

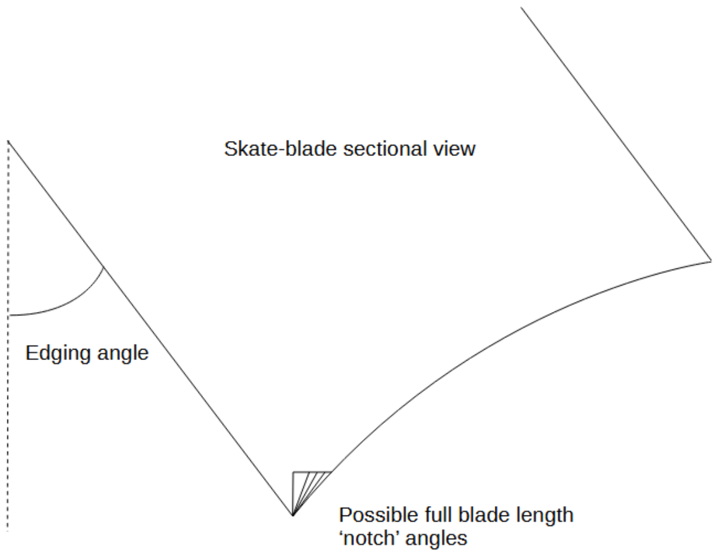

Figure 12. A schematic of a novel blade illustrating a range of possible notch angles.

The above considerations imply that the friction in the blade glide direction associated with blade notches during sliding/shaving will either be negligible, or at most a relatively tiny effect compared to the 'gripping' benefit of the technology.

CONCLUSIONS

Here we have shown consistent results from approximate-full-scale repeatable lab tests of a novel skate-blade concept (patent pending), where the novel aspect, i.e., the notches, was shown to increase the grip of a mock skate blade. This suggests that the same benefits, with respect to more efficient pushing strides, fast turns and sliding stops, could be experienced by actual skaters. The notches could be included in the fabrication process of new skate blades, or applied to existing skate blades with a tool similar to that used here. The technology has tunable aspects, in that the number of notches employed, and their dimensions and notch-angles are adjustable. Hence, the technology could be tuned to suit the particular skating activity, and the particular skater. Such tuning, and the issues of notch wear and blade maintenance, while beyond the scope of the present study, are sensible avenues for future study, possibly including 'field trials' with skaters. Recognizing that there are variations in existing skate-blade characteristics, depending on the activity, the mock skate blade characteristics we chose, i.e., where the blade has parallel side-walls and a hollow on the bottom, are roughly representative of the majority of skates used for recreation and sport.

ACKNOWLEDGEMENTS

The author is grateful to NRC for accommodating this endeavor, and would like to thank Austin Bugden for expert technical assistance during the experiments.

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