Francesco Braghin · Federico Cheli
Stefano Maldifassi · Stefano Melzi
Edoardo Sabbioni *Editors*

The Engineering Approach to Winter Sports

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Preface

Why did we decide to write this book? In fact, we had never thought of writing a book on winter sports since our competences were focused just on bobsleigh, skeleton and luge (except Stefano Maldifassi who, being responsible for the research of the Italian Winter Sports Federation, had carried out research in all disciplines but had no time for writing a book). Too less material for writing a book.

One day, however, we took part to a congress with a special session on sports equipment, and there was a great interest in the sensors we had developed and the test campaign we had carried out to characterize the dynamics of the sled coupled with the actions by the athletes. Our surprise was to see that what we had done within our discipline was very similar to what colleagues had done in different disciplines, e.g. in skating. In fact, all winter disciplines have one thing in common: the sliding on a slippery surface (either ice or snow). Thus, to maximize performances, one has to minimize (or control, such as in curling) the friction at equipment—ice/snow interface.

The following question arose: Why not putting the experiences gained in all the various disciplines together to cross-fertilize and provide new ideas? Looking around, however, there was no common archive of the engineering studies done on winter sport disciplines. You had to go around the internet and the various public or private databases trying to collect all the literature. Even more problematic, several colleagues, especially in the past, had published their researches at conferences and the corresponding proceedings were almost lost. Not to talk about brilliant researches done within Ph.D. thesis that had not been published elsewhere.

Thus, we decided to collect all the relevant literature on the engineering studies done in the various disciplines and to write a book summing them up. However, a mere review would have been not that interesting. We therefore tried to highlight the research paths, to critically analyse the obtained results, to show the technological trends, to draw the attention to the open questions, and, even more important, to stress the similarities and the differences between the different disciplines. We decided to split the book into two main sections: the first focusing on the common denominator of all winter sports, i.e. ice and snow as well as their interaction with skis and runners, respectively, and the second focusing on the various disciplines.

We decided to limit our analysis to the most popular Olympic disciplines but interesting hints for disciplines not considered in the book can easily be obtained. At the end, we added a concluding chapter that bridges engineering with the other most relevant science in sports: medicine. In fact, you may have the best equipment but you will win or lose according to your training and your psychology. We hope you will enjoy the reading of this book.

Milano, Italy

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Contents

1 Ice and Snow for Winter Sports 1
Norikazu Maeno

2 Friction Between Ski and Snow 17
Werner Nachbauer, Peter Kaps, Michael Hasler, and Martin Mössner

3 Friction Between Runner and Ice 33
Francesco Braghin, Edoardo Belloni, Stefano Melzi, Edoardo Sabbioni, and Federico Cheli

4 Alpine Ski 53
Stefano Melzi, Edoardo Belloni, and Edoardo Sabbioni

5 Cross-Country Ski 107
Peter Carlsson, M. Ainegren, M. Tinnsten, D. Sundström, B. Esping, A. Koptioug, and M. Bäckström

6 Aerodynamics of Ski Jumping 153
Mikko Virmavirta

7 Bobsleigh and Skeleton 183
Edoardo Sabbioni, Stefano Melzi, Federico Cheli, and Francesco Braghin

8 Ice Skating 277
Edoardo Belloni, Edoardo Sabbioni, and Stefano Melzi

9 Ice Hockey Skate, Stick Design and Performance Measures 311
R.A. Turcotte, P. Renaud, and D.J. Pearsall

10 Curling 327
Norikazu Maeno

11 Why Did We Lose? Towards an Integrated Approach to Winter Sports Science 349
Dario Dalla Vedova

Index 379

Chapter 1
Ice and Snow for Winter Sports

Norikazu Maeno

In the past winter sports were played only in cold areas during winter, but the development of techniques to artificially produce snow and ice has changed the situation. Now winter sports are enjoyed even in summer and almost all over the world regardless of season and area. Ice and snow are indispensable to winter sports because they cover a variety of ground surfaces, mountains, forests, lakes and so on, and provide us surfaces on which we can walk and play. Moreover ice and snow prepare slippery surfaces necessary for various kinds of winter sports such as ski, skate, sledge, curling, etc. The slipperiness is the most important property of ice and snow for winter sports. It may be stupid to make a question why ice and snow are so slippery, but this inquiry gives an important key to understand the essential property of ice and snow. In physical sense slipperiness is not an intrinsic property of ice and snow. The reason is as follows. Figure 1.1 shows the homologous temperatures of three familiar materials. The homologous temperature is defined as T/T_m where T is the temperature and T_m is the melting point expressed in the absolute temperature (K). The homologous temperature 100 % means the highest temperature any solid material can attain because it melts away at T_m; it is 1809 K (1536 °C) for iron and 273 K (0 °C) for ice.

For instance, the homologous temperature 80 % is −55 °C for ice and 1174 °C for iron. −55 °C is quite a cold temperature for human beings, but it is extremely high temperature for ice and corresponds to iron heated to 1174 °C. We should remember that ice and snow we see are just like iron heated to red-hot and white-hot above 1000 °C. Another example in Fig. 1.1; imagine an iron pot and knife on a table at room temperature 25 °C. The room temperature corresponds to the homologous

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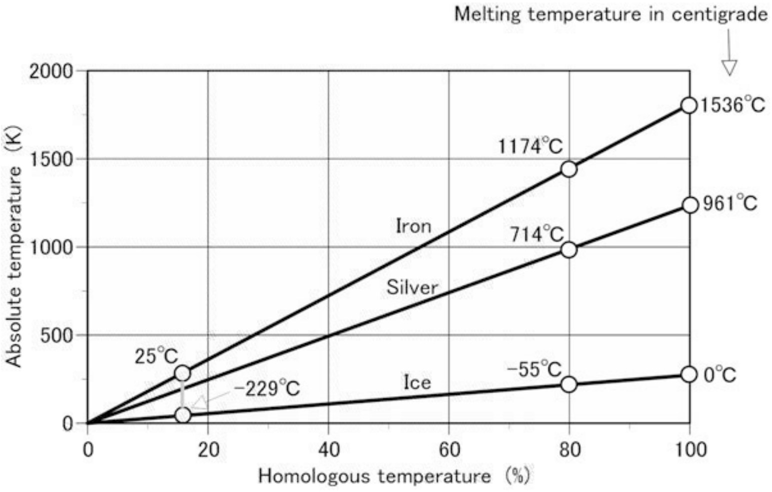

Fig. 1.1 Homologous temperature. Homologous temperature is the fraction of melting temperature of a material, that is, T/T_m where T and T_m represent, respectively, the temperature and the melting temperature of the material in Kelvin

temperature of iron 16 %, which is −229 °C for ice, that is, the iron pot and knife at the room temperature are equivalent to ice cooled to −229 °C.

In winter sports we should carefully understand that we are treating ice and snow at such high homologous temperatures. Slipperiness of ice and snow may be caused by pre-melting near the melting point, and many other processes may be attributed to high homologous temperatures. An example is shown in three sequential pictures in Fig. 1.2, which gives small ice particles in contact at −8 °C. As seen in the pictures bonds between the particles grow with time. The solid-state process below the melting point is known as "sintering," which has been studied extensively in metallurgy and ceramics. As we see in the following discussion, structures and various physical properties of ice and snow vary dramatically with time depending on temperature, humidity, and other factors. In winter sports we should recognize that ice and snow are always changing with time. This is because the situation is just like the iron pot and knife or the ceramic pottery works kept in a firing kiln at homologous temperatures above 80 %. In this sense we may call ice and snow as *pottery works in a kiln* [1]. In the following we briefly review the structure of ice and snow, and then their friction properties.

1.1 Structure and Friction Properties of Ice

1.1.1 Structure of Ice

Hexagonal ice is the crystal form of all natural snow and ice on Earth, on which we play winter sports. It is a stable phase of ice at atmospheric pressures and called

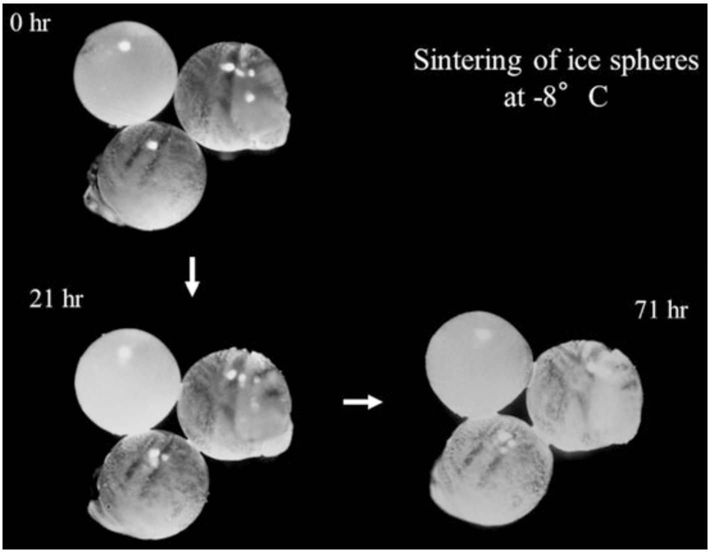

Fig. 1.2 Sintering of ice particles. The diameter of ice particle at the *top left* is 0.9 mm and temperature is −8 °C. The bond growth process below the melting point is called sintering

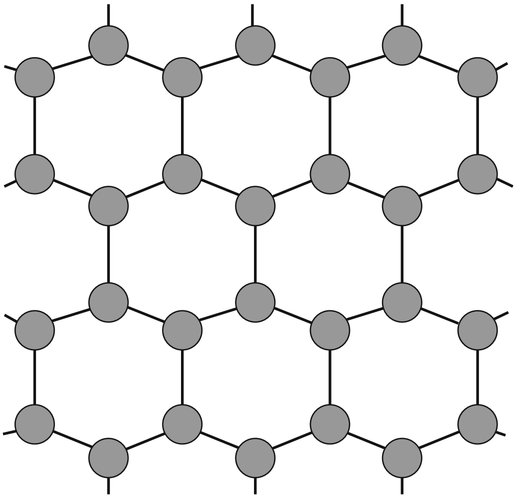

Fig. 1.3 Arrangement of water molecules in a basal plane of ice Ih. *Dark balls* are water molecules and *solid lines* are hydrogen bonds. The layer of six-fold symmetric rings is the "basal plane" and the normal direction to the plane is the *c*-axis

"ice Ih" to distinguish from other ices. All other ices appear only at extremely high pressures or low temperatures [2]. The arrangement of water molecules in Ice Ih is schematically illustrated in Fig. 1.3.

Water molecules, shown by dark balls, are arranged in a layer of hexagonal or six-fold symmetric rings. Lines connecting water molecules are hydrogen bonds. The crystallographic layer is called "basal plane," and the normal to the basal plane is the *c*-axis or the optical axis of the crystal. A single crystal or monocrystalline

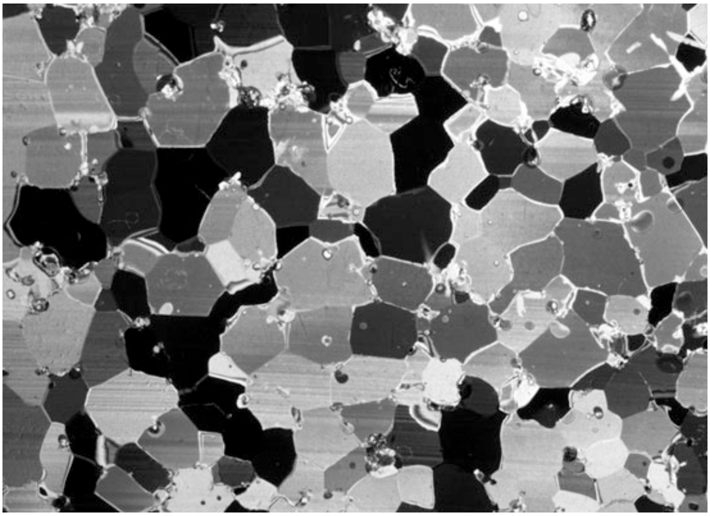

Fig. 1.4 Cross section of ordinary ice (polycrystalline ice)

ice can be thought of as consisting of these basal planes. Normally single crystal deforms by gliding on its basal planes just as a pack of cards is deformed by sliding cards each other. This means that the mechanical property of a single crystal of ice is different in different directions, or anisotropic, and the anisotropy can be described by the orientation of the *c*-axis. Anisotropy is also found in other physical properties such as optical refractive index, thermal conductivity, and so on.

Actual ice in our daily life, however, is usually polycrystalline, that is, a block of ice is composed of several single crystals. Figure 1.4 shows an example, a thin section of an ice cube made in a home-refrigerator. We see that the block is composed of small single crystals with different sizes, shapes, and *c*-axis orientations. The difference of orientations gives the different colors to individual crystals; the picture was taken by placing the thin section between two crossed polarization filters. Strictly speaking, the physical properties of the ice cube are dependent on sizes, shapes, and orientations of composing crystals, but we consider that usual polycrystalline ice we treat is composed of many single crystals with *c*-axes in different orientations so that its physical properties are isotropic in average.

1.1.2 Compressive Strength of Ice

Mechanical strength of ice can be tested by applying compressive, tensile or shear force on an ice specimen. We consider here only the compressive strength. The compressive strength of polycrystalline ice has been measured by many

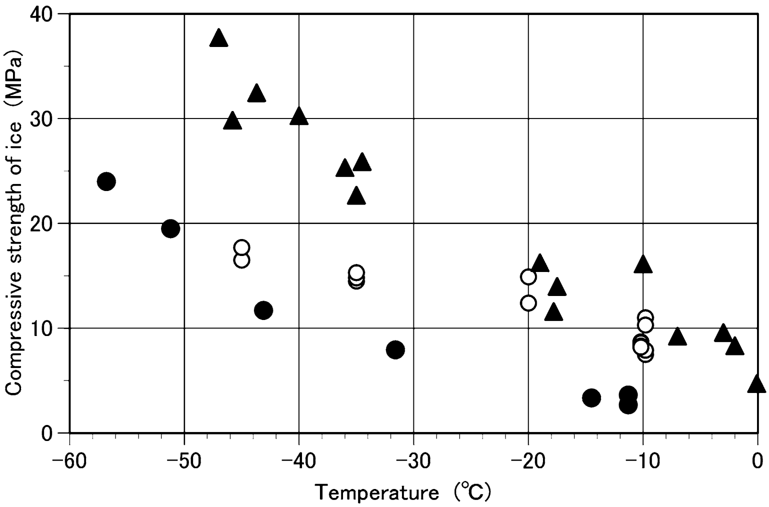

Fig. 1.5 Compressive strength of ice versus temperature. Data obtained by three different research groups are shown. *Filled triangle*: [3], strain rate $10^{-2}\,s^{-1}$; *open circle*: [10], $10^{-3}\,s^{-1}$; *filled circle*: [11], $10^{-5}\,s^{-1}$

investigators but reported data show wide range of scatter mainly because the strength depends on many variables such as temperature, strain rate, ice grain size, and tested volume (see [3–12]).

Figure 1.5 shows the temperature dependence of compressive strength measured at three strain rates from 10^{-5} to $10^{-2}\,s^{-1}$. We can see that the compressive strength is larger at larger strain rates and increases with decreasing temperature from about 5 MPa at 0 °C to 20–40 MPa at −50 °C.

Compressive stress–strain curves show ductile behavior at lower strain rates than about $10^{-4}\,s^{-1}$, and brittle behavior at higher strain rates at −10 °C [13]. The relation between the strength and grain size has not been studied in detail, but according to the measurement by Currier and Schulson [5] at $10^{-6}\,s^{-1}$ and −10 °C the tensile strength of ice decreases with increasing diameter. We may assume that the compressive strength is similarly smaller for ice composed of larger grains.

1.1.3 Friction Coefficient of Ice

Slipperiness is of the most important characteristics of ice for winter sports. The degree of slipperiness is expressed by the friction coefficient, μ, which is defined as the ratio of the force of friction and the force pressing the two surfaces. Compared to other materials μ of ice is much smaller, as small as 0.01, and a number of friction measurements of ice have been carried out as found in references of [14–16]. However, most of them were made using sliding surfaces of ice and

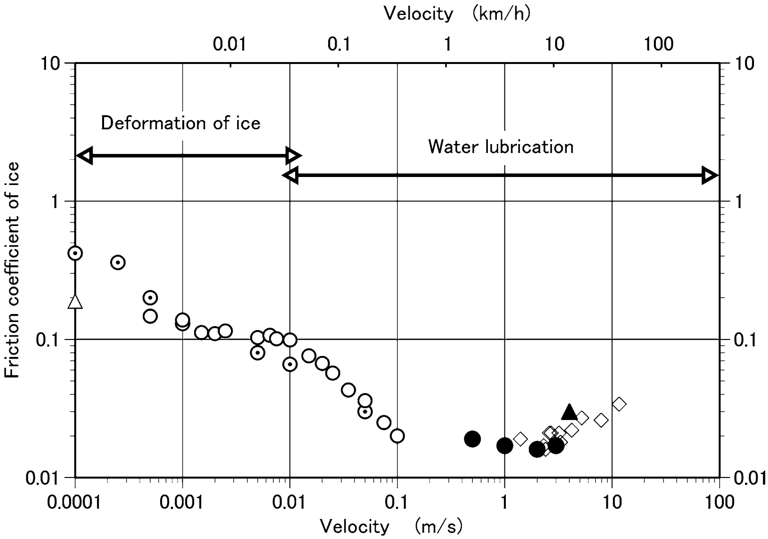

Fig. 1.6 Friction coefficient of ice versus sliding velocity. Data of ice–ice friction coefficient are shown. *Filled triangle*, [17]; *filled circle*, [18]; *dotted circle*, [19]; *open diamond*, [20]; *open circle*, [21]; *open triangle*, [22]. From [23] and [24] with changes

different materials mainly because of practical application needs to skates, skis, and other various structural interactions in ice environments. But ice surfaces show different friction behaviors to different materials, e.g. wood, polymer, metal, etc., and at different sliding velocities. Accordingly each result gave different explanations and could not lead to the systematic understanding of the intrinsic friction property of ice.

Figure 1.6 shows the friction coefficient of ice measured in a wide range of sliding velocity, from 0.0001 to 100 m/s. In the figure only the data obtained by sliding an ice block on ice at about −10 °C are selected to look into the intrinsic friction property of ice. It is clear that the velocity dependence of μ of ice is not simple but quite complicated, but we can explain the behavior by two physical mechanisms working in two different regions of sliding velocity, as indicated in the figure. One is the water lubrication mechanism above roughly 0.01 m/s, and the other is the plastic deformation of ice at the friction interface, which works below roughly 0.01 m/s. Here we discuss briefly the implication of the ice friction behavior to winter sports before we make more detailed explanation of the two mechanisms in the next section.

Ice friction in the velocity region above 0.01 m/s is more important for winter sports. In the region as the sliding velocity increases from 0.01 m/s the magnitude of μ decreases due to the increase of production of frictional heat to form water film as lubricant, and at higher velocities it increases again with increasing velocity. It is noted that there is a somewhat constant value region in between. The V-shaped relation between μ and velocity (U) can be expressed with the following theoretical equations discussed in the next section: