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Effect of material elastic properties and surface roughness on grip performances of ski boot soles under wet and icy conditions

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ABSTRACT

A set of thermoplastic materials employed in soles for alpine skiing boots were characterized in terms of chemical composition, cristallinity, hardness, surface roughness, and grip. The results of friction experiments on different substrates reproducing the real environmental scenarios point out that materials provide more grip as they become softer. Moreover, higher roughness results in lower dynamic coefficient of friction (COF). Finite element simulations corroborate the experimental measures of COF and let to rationalize the role of material elasticity and surface roughness on the frictional characteristics of soles. The measure of grip on an inclined wet surface provides analogous results, indicating that COF can be used as key performance indicator in the design of ski-boot soles and of other anti-slip equipments in wet and icy environments.

1. Introduction

Slips and falls are very common when walking on ice (Fleischer et al. (2014)) and they can be the cause of injuries of skiers in both outdoor environment (e.g., on ski slopes and resort walking areas) and indoor. For example, it is reported by Fleischer et al. (2014) that in Alaska approximately 10% of the injuries related to falling-through-the-ice (FTI) are connected to sport activities such as skiing and other adventure sports. For this reason, it is of crucial importance to identify the factors that influence the grip of the materials used for the production of soles on wet and icy surfaces (Tsai and Powers (2013)). The soles of alpine ski boots are generally made of the same hard materials (polyolefines- or polyurethane-based thermoplastic polymers) used for the main body of the boot, ranging from 50 to 65 Shore D hardness (Colonna et al. (2013); Nicotra et al. (2015); Colonna et al. (2014)), and have a limited tread which result in a limited friction with slippery surfaces (Grönqvist and Hirvonen (1995)). This type of construction aims at reducing the costs and complexity of the moulds used for the production (Colonna et al. (2014)). Nevertheless, in recent years several manufacturers have started to produce boots with interchangeable soles (Colonna et al. (2013)) made of softer materials with respect to the plastics used for the body, in order to improve their anti-slip properties. On the other hand, the soles for ski-touring and freeride skiing boots are made of thermoplastic elastomers or vulcanized (natural or synthetic) rubber, to provide good grip when hiking and climbing.

The sole of a ski boot must have a stiff behaviour in order to efficiently transmit the impulse from the boot to the ski but, at the same time, a good grip on icy and wet surfaces. Generally, stiffer materials have lower friction resistance on hard and wet surfaces

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compared to soft materials (Gao et al. (2003)). The drawback of using soft rubbers is the lack in power transfer between the skier and the ski due to sole excessive bending under load, leading to a less precise control of the skis. Moreover, the efficient and safe behaviour of the binding in releasing the boot during a fall is strongly influenced by the geometry and the hardness of the parts in contact. In recent years some producers have provided the possibility to change the heel and the toe of the sole in order to have boots with desired properties according to the specific application. This type of sole is generally attached to the shell using metal screws. Therefore, alpine ski boots must be realized observing limits and prescriptions in terms of dimensions, materials and design of the boot interface. Two ISO standards (5355 and 9523, ISO (2005, 2008)) rule the design of ski boots (Colonna et al. (2013)), defining the area of the ski boot in contact with the binding. In terms of materials used, both standards require that the hardness of the material at the toe and heel binding interface must be not less than 50 Shore D, measured at a temperature of $+23^\circ$ in accordance with ISO 868 (ISO (2003)). ISO 5355 specifies that the dynamic friction coefficient between the boot material and a low friction element of PTFE must be less than 0.1. Only when materials different from thermoplastic polyurethane (TPU) are used in the heel part of the boot, there must be at least one longitudinal low friction area to act as a bearing surface for the ski-brake. ISO 9523 requires a minimum percentage of the area in contact with the bearing surface of the binding of 25% in the toe and of 40% in the heel but no restriction in the characteristics of the material for the sole are prescribed. Ski-boots producers are currently pushing for the development of new standards that take into account different types of bindings. Since the amount of ski-mountaineering boots produced is less than 5% of the overall ski boots market (Colonna et al. (2013); Nicotra et al. (2015)) the interest of ski boot manufacturers and of researchers is mainly focused toward the study of soles for alpine skiing.

In recent years a significant work was performed in order to understand and model the friction behaviour of elastomers, mainly due to the interest of the automotive industry on this topic. For example, Heinrich and Klüppel (2008) have investigated the role of rubber friction on tire traction, focusing on the load and velocity dependence of the friction coefficient. Attention has also been given to the study of materials used for the sole of shoes. Especially, Derler et al. (2008) have studied the influence of abrasion and temperature on grip, combining measurements of friction and hardness. Li et al. (2006) have investigated the correlation between the tread groove depth and the coefficient of friction on different wet and water-detergent covered floors, finding to be not significant in those conditions.

Some authors have focused their attention on soles friction on ice. For instance, Grönqvist and Hirvonen (1995) have tested 49 types of winter footwear on dry and wet ice. From their evaluation, material type and hardness, as well as cleat design, were the most important factors on dry ice. On the other hand, only on wet ice the tread design had an influence on the friction properties. The high slipperiness of melted or wet ice was confirmed by Gao et al. (2003) who measured the effect of sole abrasive wear on the coefficient of friction on dry and melting ice. The results proved that artificially induced abrasive wear of soles increased slip resistance on hard ice, but not on melting ice. In the end, the chemical composition and the hardness (the latter dependent from the first) have an effect also on the scratch resistance that may affect the surface roughness in the long term (Budinski (1997)). Thus, it is clear the need of a study that takes into account different material parameters (namely chemical composition, hardness, and surface roughness) in order to obtain the best balance in terms of energy transfer and of grip on wet and icy surfaces.

The exploitation of numerical simulations in the realization of sports equipment is widely acknowledged by the industries and it represents an unavoidable step for the design of optimized and high performance products, limiting the cost of physical experimentation and prototyping to few calibration and verification tests. Regarding ski boots a number of work has focused on the structural design and optimization (Corazza and Cobelli (2005); Parisotto et al. (2012); Natali et al. (2014)). However, to the best of authors' knowledge, no specific application of computational tools was use in the study and design of the grip performances of soles.

The aim of this work was to evaluate the friction performance of different materials used in ski boot soles on wet floors and icy conditions, correlating the performances with the chemical composition of the material, with its elasticity (hardness) and with the sole surface roughness. Finite Element Method (FEM) numerical simulations were used to fit the experimental results in order to understand general trends and extend the investigation domain.

2. Materials and methods

2.1. Materials characterization

A total of six different mould injected soles were tested: soles 1 and 2 are bi-injected with a geometry (design 1) shown in Fig. 1(a) while soles from 3 to 6 are mono-injected with a geometry (design 2) shown in Fig. 1(b). Materials for sole groups 1–4 and 5–6 were provided by two different manufacturers. All the soles are conform to the ISO 5355 standard.

The chemical composition of all the soles was determined via Fourier Transform Infrared Spectroscopy (FT-IR) using a Perkin Elmer Spectrum One spectrometer equipped with an Attenuated Total Reflectance (ATR) detector. The Shore D hardness of the materials was measured according to the ISO 878 standard at $+23$ °C and at -10 °C in order to evaluate the temperature dependence of hardness. Calorimetric measurements were carried out in order to measure the crystallinity and melting temperature of the materials, using a Perkin Elmer DSC6 differential scanning calorimeter (DSC) equipped with a liquid sub-ambient accessory and calibrated with high purity standards. Weighted samples of approximately 10 mg were encapsulated in Aluminum pans and heated up to 250 °C order to evaluate the temperature at a rate of 20 °C/min.

2.2. Surfaces characterization

The contact area between the boot sole and the ground was measured with an image analysis technique, usually used in biological sciences, performed on a PMMA transparent platform (see Supplementary Fig. 1(a)). The image analysis and processing was done using an open source software (*Image J*) which, through its threshold colour plugin, allows the selection and isolation of specific colours or grey-scale tones and its area measurement (see Supplementary Fig. 2). In order to have a good contrast between the areas in contact with the Plexiglass® surface and those not in contact, a solution of water and black wall paint (with a concentration of 1.3 g/L) was used (see Supplementary Figs. 1(b) and 2). A total of 5 measurements for each sole were preformed and the final area determined as the average.

The sample surface texture characteristics were evaluated using an optical profilometer LEICA DCM 3D (Leica Microsystems), using a confocal objective with 20× magnification. The areal surface roughness parameters, in particular the arithmetic average height of the surface S_a and the root mean square gradient S_{dq}, were measured according to ISO 25178 (ISO (2012)) over a sampling length of 900 μm. The acquired areas were also processed through binarization, setting a threshold value of 12 μm for the distinction