Wear of ski waxes: Effect of temperature, molecule chain length and position on the ski base

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ARTICLE INFO

ABSTRACT

The effects of snow temperature, wax molecular chain length and position along the ski on the wear of ski waxes due to friction on snow were analyzed in this work. Wear was induced on a linear snow tribometer positioned inside a cold chamber over a length of 9.35 km. Every 850 m, the waxed ski bases were analysed using FTIR-spectrometry and contact angle measurements. The deformation of the snow was investigated using micro-computer tomography. The tests showed that wear was snow temperature dependent, with high wear on cold snow and low wear on snow close to the melting point. Wax molecule chain length had only an effect on cold snow and in the ski tail region, where the wax with shorter chains wore more. It is proposed that the changes in snow and wax hardness, snow roughness and meltwater lubrication are responsible for the different wear behaviours.

1. Introduction

To reduce friction between ski and snow and in some cases also to protect the ski surface from wear and oxidation, skis are coated with ski waxes [1]. Wax manufacturers offer, depending on the snow conditions, a wide range of gliding waxes, which mainly consist of alkanes (paraffins) or (per)fluorocarbons. Especially perfluorocarbons are very popular in today's ski racing due to their ability to increase the water repellence of ski bases [2] and thereby reduce the adhesion between ski and snow or water [3]. According to wax companies and [4,5], wax hardness should be adapted to the snow hardness, meaning the harder the snow, the harder the wax. The wax hardness is usually increased by increasing the chain lengths of the wax molecules [5]. Although waxes improve gliding performance, professional skiers often report a drop of performance over distance. This performance decrease was investigated by [6] using contact angle and dirt attraction measurements. They stated that due to an increase in dirt absorption caused by the wax, friction increased faster for waxed skis than unwaxed ones. The wear of ultrahigh molecular weight polyethylene (UHMWPE) sliding on ice was studied by [7]. They showed that wear of UHMWPE depends on the ice roughness with high wear at high attack angles (blunt ice peaks) and less wear at low attack angles (smooth peaks). However, no studies are known which investigated the wear of wax due to snow friction and which mechanism are accountable for it.

The aim of this study was to investigate the wear of waxes as a function of gliding distance at two different snow conditions using infrared-spectroscopy and contact angle measurements. By performing measurements from the ski tip to the ski tail, also the wear relative to the position on the ski base was studied.

2. Methods

2.1. Skis

Three wooden skis without camber and sidecut with the dimensions of 114×5 cm were used. To ensure a uniform pressure distribution along the ski, the stiffness of the skis was additionally increased by fixing them to a 4 cm thick aluminum carrier. The radii at the tip and the tail of the ski were 20 cm, resulting in a running length of 100 cm. The base material (UHMWPE, IS CB 7515 C10, Isosport, Austria) was fixed to the bottom of the skis with double-sided cellotape. The bases were grinded in gliding direction using a ski grinding machine (Race NC, Wintersteiger, Austria) applying identical grinding parameters. Before waxing, the arithmetic mean roughness Sa, the water contact angle and the friction coefficient at $-5.0\,°C$ snow temperature of the ski bases were measured. All measurements were performed as described in [8]. The measured values are displayed in Table 1. The three skis had almost equal Sa, θ_{Water} and μ, and were, therefore,

Table 1
Measurement results obtained for freshly grinded skis. Sa is the arithmetic mean roughness, θ_{Water} the contact angle between water and ski and μ the friction coefficient.

	Base 1	Base 2	Base 3
Sa (µm)	2.8	3.1	2.8
θ_{Water} (°)	82 ± 4	83 ± 3	82 ± 5
µ (-)	0.059 ± 0.001	0.059 ± 0.001	0.059 ± 0.001

considered to be equivalent.

2.2. Waxes

Two different perfluorocarbon powder waxes were compared to a standard paraffin wax (A1 Allround, HWK, Austria). Wax 1 consisted of shorter perfluorocarbon molecules (melting point: 135 °C), while Wax 2 consisted of longer ones (melting point: 173 °C). The names and other details of the waxes are held back due to confidentiality agreements.

2.3. Preparation

Skis were first cleaned using acetone and fluorine cleaner (HWK, Austria). Then all skis were waxed with the standard paraffin wax using an iron at the temperature of 120 °C. After cooling down to room temperature, the excessive paraffin was scraped off using a polyethylene blade. To uncover the grinded structure from the paraffin, the skis were additionally brushed in gliding direction first with a brass and then with a nylon brush. Therewith, the preparation of the paraffin ski was finished. The other two skis were further prepared by distributing the respective powder waxes uniformly on the ski base. The perfluorocarbon was then molten by an iron with temperatures slightly above the melting point (Wax 1: 140 °C, Wax 2: 180 °C). After cooling at room temperature for 10 min, a fleece roll with a rotating speed of about $1000 \, min^{-1}$ was moved over the ski from the front to the back. Finally, the structure was again uncovered by brushing the skis in gliding direction with a brass and nylon brush. For each wax separate fleece rolls and brushes were used.

2.4. Friction measurements and wear of wax

The wear of waxes was induced under laboratory conditions with a large-scale linear tribometer (Technology Centre of Ski and Alpine Sports, Austria) [9]. It consists of a 24 m long trough filled with a layer of snow on which the skis were tested. The total wear distance was 9350 m and the test velocity $5 \, ms^{-1}$. The normal force was 290 N, resulting in a uniform pressure along the ski of 5.8 kPa. The distance was divided into 11 tests, resulting in 850 m per test. Each test was conducted on a new, untouched track and consisted of 50 runs (17 m per run). While going backwards, skis were lifted up from the snow surface by a motor, and thereby any wear in the opposite direction was avoided. During each run F_n and the friction force F_r were measured by load cells (S2M, HBM, Austria). The coefficient of friction µ was then calculated using Eq. (1).

$$\mu = \frac{F_r}{F_n} \qquad (1)$$

For easier comparison μ_{rel} was calculated (Eq. 2), with μ_{Fluor} being the coefficient of friction of the respective perfluorocarbon waxed ski and $\mu_{Paraffin}$ the one of the paraffin waxed ski. The runs 40–50 were then used to calculate the mean value $\overline{\mu_{rel}}$ and the standard deviation s_μ.

$$\mu_{rel} = \frac{\mu_{Fluor} - \mu_{Paraffin}}{\mu_{Paraffin}} \cdot 100\% \qquad (2)$$

The snow was produced in a cooling chamber with a snow lance at temperatures between −17.5 and −14.0 °C. The snow was sieved, then

Table 2
Snow characteristics measured before the tests. Snow temperature was measured with a PT 1000 element and snow density by weighing a 14.4 cm³ snow cube. Snow hardness was measured with a spring-loaded aluminum cone (cone angle = 30°). Out of the penetration depth, the penetration force was calculated, which is reliable measure for the snow hardness. All measurements were done according to [10].

Snow Temperature T_{snow} (°C)	−2.0	−18.4
Snow Hardness H (N)	6.7	16.4
Snow Density ρ (kgm⁻³)	359	364

filled into the trough and finally straightened by a steel blade. The tests were performed at two different snow temperatures of −2.0 and −18.4 °C. Table 2 shows the measured snow parameters. While snow density ρ stayed nearly constant, snow hardness H increased strongly by over 200% with decreasing snow temperature.

2.5. Wear analysis

After each test (every 850 m), the waxed ski bases were analyzed at room temperature by Fourier transformed infrared (FTIR) spectrometry and contact angle measurements. Both measurements were performed in 10 cm steps from the tip to the tail of the ski. The freshly waxed and finally worn skis were additionally examined using FTIR-microscopy. Since it was impossible to distinguish the paraffin from the polyethylene background, FTIR-spectrometry and -microscopy were only applied on the perfluorocarbon waxed skis.

2.5.1. FTIR-spectrometry

The infrared spectrometry analyses were performed using the Alpha FTIR-spectrometer (Bruker, USA) in the external reflection mode. The mean value of 100 spectra, recorded between the wave numbers $400–4000 \, cm^{-1}$ with a resolution of $4 \, cm^{-1}$ was used for each measurement point. Using the idea of infrared reflection absorption spectroscopy (IRRAS) [11], the absorption spectra of the perfluorocarbon-coatings are obtained. After vector normalization, the spectra were analysed using the CF_2 stretching peaks between the wavenumbers 1050 and $1300 \, cm^{-1}$ (Fig. 1). By integrating over the infrared curve in this area, the peak area A was calculated. Beer-Lambert's law states that the observed peak intensity and therefore the observed peak area of an infrared band, associated with a specific component, is proportional to the concentration of this component in the sample [12]. Therefore, the calculated A is then proportional to the amount of wax on the ski base and the ratio A/A_0, with A_0 being the peak area of the unworn ski, proportional to the remaining wax quantity.

2.5.2. FTIR-microscopy

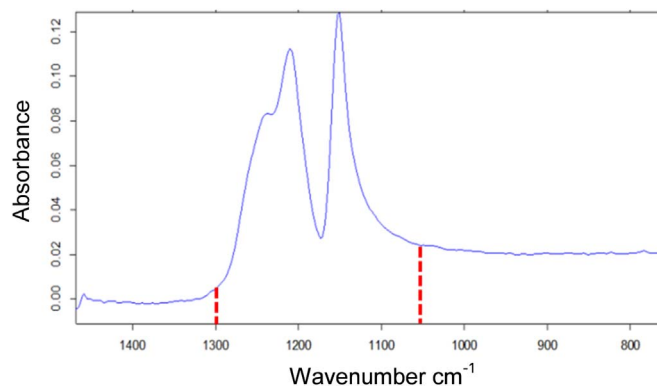The distribution of perfluorocarbon wax was measured using a

Fig. 1. Example for a measured IR-spectrum. The dotted lines indicate the integration boundaries. The peaks at 1150 and 1210 are, respectively, due to the symmetric and antisymmetric CF_2 stretching modes [13].