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The role of the sliding direction against a grooved channel texture on tool steel: An experimental study on tactile friction

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ABSTRACT

To control tactile friction, that is the friction between fingertip and counter-body, the role of surface texture is required to be unveiled and defined. In this research, an experimental approach is used based on measuring tactile friction for directional texture (grooved channel) with varying depths. For a reference surface, in this current case a polished surface from the same tool steel is compared. The experimental results are analyzed to explain the observed skin friction behavior as a function of surface texture parameters, sliding direction and applied normal load. Sliding parallel to the groove length shows greater values in COF than sliding perpendicular to the groove direction. Furthermore, parallel sliding reveals a higher dependency of COF on the depth of the grooved channel texture than perpendicular sliding. Application of the two term friction model suggests that the adhesion component of friction has greater impact on parallel than perpendicular sliding direction. According to the observations, grooved channels are well suited to control skin friction in direction dependent sliding, for moderately loaded contact situations. This experimental research contributes to the haptic perception related research, and to the development of other direction-dependent surface structures for touch.

1. Introduction

The study of friction and the role of surface textures in relation to touch perception is the subject of researches in both science and industry for a wide variety of applications (van Kuilenburg et al., 2013; Derler et al., 2009; van der Heide et al., 2013). Tactility is directly related to the functional behavior and perception of products like haptic devices, smartphone cases, tool handles, personal care products and for example kitchenware. In most cases, the exploratory procedure to detect the surface features of various objects consists of a sliding movement of our finger(s) at a moderate load and relatively low sliding velocity (Klatzky and Pawluk, 2013; Barnes et al., 2004). Surface recognition is deciphered by the cutaneous sensory neurons from the specific movement made by our finger during active touch (Fagiani et al., 2012). The touch perception is greatly influenced by the friction generated between the fingertip and counter-surfaces (Darden and Schwartz, 2013; Klatzky and Pawluk, 2013; Liu et al., 2008; Skedung et al., 2011).

Perception can be linked to psychophysical factors such as smooth-rough, slippery-grippy, warm-cold and soft-hard (Liu et al., 2008). The frictional behavior of skin-surface sliding is important in all of these factors (Kuramitsu et al., 2013). Tactile friction requires an in-depth understanding of the contact mechanics and the behavior of human skin. Surface textures can be categorized as deterministic nature or as stochastic nature (Steinhoff et al., 1996). Deterministic textures have a repetition of fixed geometric structure, and stochastic textures are non-deterministic with random surface pattern. Stochastic surfaces typically use roughness parameters based on distribution characteristics and could result in surfaces that are distinctively different in pattern, yet which have the same distribution parameters. In the work of Skedung (Skedung et al., 2011), finger friction measurements are evaluated to determine the relationship between the coefficient of friction (COF) and surface roughness of a series of printing papers. The research found that both roughness and finger friction can be related to perceived coarseness. The topography of paper samples is stochastic and directional-independent. As the relation between distribution related parameters and touch functionality is not known, it seems likely that progress can only be made in this field by using surfaces with pre-defined features. These

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pre-defined features with deterministic nature are better controlled for touch functionality related experiments.

In this research, the directional texture like grooved channel is designed as deterministic surface structures for the purpose of studying the role of sliding direction for tactile friction. The finger friction tests are performed on the steel samples with directional textures. The structures are fabricated as grooved channels by using laser surface texturing technology. The objective is to find the relation between surface topography parameters and COF with the influence of sliding directions (perpendicular and parallel) on directional textures.

2. Skin tribology

Human skin has a layered and complex structure. Each skin layer has a different composition, thickness and hydration degree which results in different mechanical properties (Morales Hurtado et al., 2014). Consequently, the full skin structure shows a viscoelastic, non-homogeneous, nonlinear, anisotropic behavior when skin is under load.

Basically, skin is composed of 3 layers: epidermis, dermis and hypodermis. The stratum corneum is the outermost layer of epidermis which is directly in contact with the surrounding environment. It has an important role in hydration control and tactile friction (Tagami and Yoshikuni, 1985). The next layer in the skin structure is dermis. Sensory receptors have their origin in this layer which have a role in the tribological response (Silver et al., 1992; Edwards and Marks, 1995). Hypodermis is the deepest layer of the human skin. Its role in skin mechanical properties could be neglected for tactile application (Ramsay, 1996). Skin's response to stress depends on the combined behavior of these layers. In addition, the state and properties are a function of the body site, age, degree of hydration or nutritional conditions (Lapière, 1990; Hendriks and Franklin, 2010; Derler et al., 2009; Diridollou et al., 2001; Cua et al., 1990; Veijgen et al., 2013). As a result, a specific value for tribo mechanical properties of skin, cannot be given.

The relationship between skin structure, hydration and skin friction response is the subject of several experimental studies, see e.g. the work of Derler (Derler and Gerhardt, 2012). From the review, it is concluded that for both dry and humid conditions, the adhesion component is dominant in sliding contacts between skin and other surfaces. In this research, the experiments are conducted based on the skin in dry conditions, because most sliding touches for consumers' products occur in dry conditions.

The friction force (F_f) between human skin and a counter-surface can be composed of an adhesive term ($F_{f,adh}$) and a term resulting from deformation ($F_{f,def}$) as in Eq. (1) (Greenwood and Tabor, 1958).

$$F_{f,tot} = F_{f,adh} + F_{f,def} \tag{1}$$

The adhesion force from Eq. (1) can be predicted by the following equations (Greenwood and Tabor, 1958; Johnson et al., 1993; Adams et al., 2007).

$$F_{f,adh} = \tau \cdot A_{real} \tag{2}$$

Where A_{real} is the real contact area; τ is the shear strength of the interface.

The deformation term depends on the actual contact situation. The real contact area is more important compared to apparent contact area in order to predict the friction due to adhesion component of friction and it is difficult to be measured experimentally (Derler et al., 2014). The apparent contact area is defined as the area of the fingertip in contact with the counter-surface (Bowden and Tabor, 1950; van Kuilenburg et al., 2012). The real contact area is constituted by the sum of all contacted spots between two surfaces and it is a function of surface texture, material properties and interfacial loading conditions (Bowden and Tabor, 1950; Zahouani et al., 2011).

3. Experimental method

3.1. Materials

The experimental work was conducted by using samples from tool steel WN 1.2510. The grooved channels with varying depths D (see Fig. 1) were produced as the deterministic pattern by using laser surface texturing technology. The surface topography of each sample was examined by using a confocal laser scanning microscope (VK 9700 KEYENCE, Japan) (refer to Table 1). For the sample with stochastic surface roughness, arithmetic mean (Ra), the root-mean-square roughness (Rq) and maximum peak to valley height (Rz) were obtained from the surface area. Deterministic surface patterns were described by the top to valley distance (D), spacing (λ) and width (w), and the surface roughness and horizontal distance for the high portions on the top of the grooves are shown as well.

3.2. Experimental set-up and preparation

Friction measurements on skin in vivo were carried out by using a load cell (ATI Gamma three-axis force/torque transducer, ATI Industrial Automation, Apex, NC, USA). The ATI force transducer uses six degrees of freedom to measure the forces (normal force in z-direction, tangential forces in xy-plane and torques around x, y and z axes). The force measurements have a resolution of 25 mN in normal direction and 12.5 mN in tangential direction, with a sampling rate of 100 Hz. The sliding velocity was calculated from the displacement of initial contact position and final position over time.

Each sample was fixed to the top of the friction transducer using double sided tape. For the group of samples with deterministic surfaces, each counter-body was aligned with a parallel or perpendicular orientation to that of the moving axis of the finger. The middle finger of the non-dominant (left) hand of a healthy female adult (25 years old) was used for all the experiments reported here. One experiment consisted of three repetitive single strokes of the finger, sliding towards the body. The stroke length on each sample depended on the size of the surface and shape. For the samples with deterministic surface pattern, the stroke length was 25 mm. For the samples with stochastic surface pattern, the stroke length was 45 mm.

The normal load was controlled by placing a mass on the top of the sliding finger as shown in Fig. 2(a). Once the normal load was

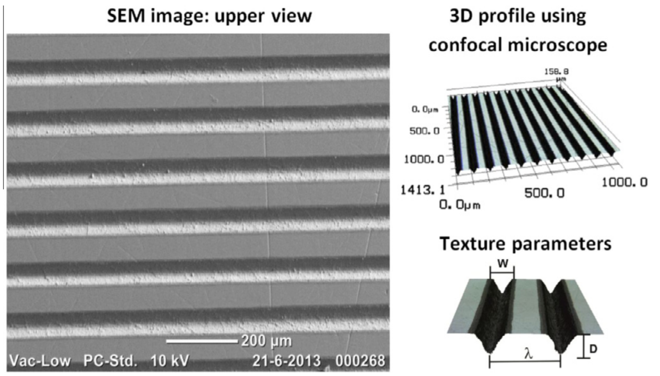

Fig. 1. Grooved channel texture on tool steel samples (a) SEM image: upper view; (b) 3D profile using confocal microscope; (c) texture parameters.