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Abrasive wear of embossed surfaces with convex domes

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ABSTRACT

Some soil-burrowing animals and other biological organisms living in contact with abrasive materials have surfaces optimized for reducing drag and wear. In this study, bio-inspired embossed surfaces consisting of an array of convex domes are investigated to quantify their abrasive wear resistance properties. The experimental procedure proposed in this work is based on sliding seven different embossed surface specimens against an abrasive material for distances up to 3948.9 m with sliding velocities up to 3.02 m/s. The seven specimens consist of 20 mm-wide convex domes made of bakelite and calcium carbonate fixed to flat steel substrates. Quartz sand particles having three different sizes are used as abrasive material for the tests. Experimental results are analyzed and guidelines for designing embossed surfaces, which are optimized to minimize abrasive wear, are proposed.

1. Introduction

There is a strong interest both from the farming industries and governments to enhance performance of agricultural tools for increasing production and countries' wealth [1]. In this work, we propose a new strategy for reducing the wear, and consequently also improving the lifetime, of agricultural tools in contact with the soil. Most of the research performed in this field has focused on improving wear resistance by coating the agricultural tools with thin layers of different hard materials [2], or modifying the chemical compositions and/or lattice of their substrate [3]. It should however be noted that in the case of abrasive wear, the geometry of the tool's surface also plays a main role. In nature, for instance, there exist numerous cases of soil-burrowing animals having peculiar surface geometries specifically evolved to resist against soil wear and prevent soil to adhere to the animals' bodies. Animals that have recently been investigated include the dung beetle (*Copris ochus* Motschulsky), the ground beetle (*Carabidae*), the earthworm (*Lumbricidae*), the *Oniscidae*, the *Diplopoden*, the centipede (*Chilopoda*), the ant (*Formicidae*), and the mole cricket (*Gryllotalpidae*) [4,5]. The outer body surfaces of these animals have specific geometrical features consisting of regularly or randomly arranged geometrical units, which may be of different shape, size and number. According to the shape of these geometrical units, which could assume either macroscopic or microscopic scales depending on the specific habitat these animals live in, the outer surfaces can be categorized in two main classes: (1) corrugated surfaces, in which ridges are present, and (2) embossed/dimpled surfaces, which have convex or concave domes. There are numerous examples of corrugated surfaces. Marine biological systems, such as seashells and whelks, also have corrugated shells optimized to survive in highly abrasive slurry environments [6].

It should be noted that beaches have surfaces with similar ridged geometries. Also some plants have ridged surfaces with particularly remarked wear-resistive properties. The composite structure of the bamboo [7,8], for example, has been analyzed in several studies investigating its mechanical [9,10] and tribological properties [11–14].

In this study, we specifically investigate embossed surfaces having, as geometrical units, convex domes. An example of convex domes is shown in Fig. 1, which represents the labrum and pronotum of the dung beetle *C. ochus* Motschulsky [15]. The convex domes present on the dung beetle's shell confer hydrophobic properties to the surface and also improve wear-resistance [16,17].

This paper is organized as follows: Section 2 discusses background on abrasive wear of ridges and their guiding effect; Section

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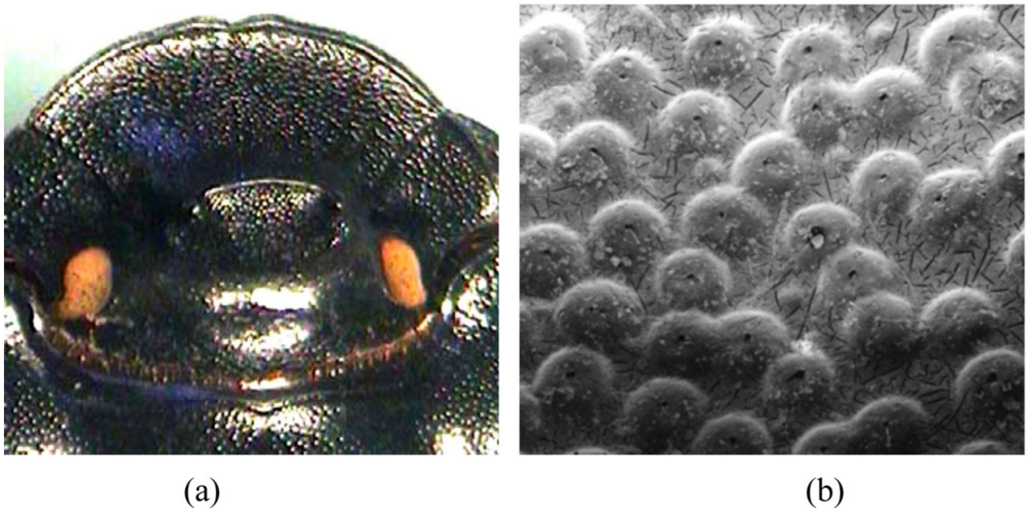

Fig. 1. Domes in the surface of the dung beetle (*Copris ochus* Motschulsky). (a) Surface morphology of the pronotum and labrum (digital camera photograph); (b) SEM image of the pronotum surface [15].

3 presents the experimental setup and procedure used to perform abrasive wear tests; and Section 4 discusses the obtained results. Conclusions are drawn at the end of the paper.

2. Abrasive wear and guiding effect of ridged surfaces

The friction force acting between a flat surface of a solid material and the soil, which can be simulated by using abrasive particles, is uniformly distributed [18–20] and the solid material therefore wears uniformly. However, if the solid has a corrugated or embossed surface, friction is not equally distributed and the solid wears unevenly. Fig. 2 shows, for example, a cross-section of a ridge before and after abrasive wear (it is assumed that the ridge is fixed and abrasive material flows as indicated by the arrow); it can be noted that the ridge wears on the side facing the flux of the abrasive material whereas its lee side is preserved.

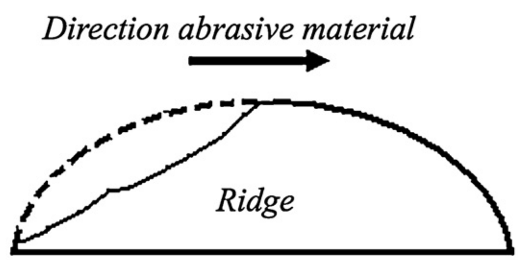

Fig. 2. Schematic diagram representing the cross-section of a ridge or dome after abrasive wear.

The presence of a ridge would reduce wear of surfaces in a distal position respect to the ridge itself. This effect, which was investigated in [19,21], is characteristic of corrugated surfaces and is called the *guiding effect*. Fig. 3 shows the results of a two-dimensional simulation presenting the interaction between abrasive particles and three ridges [22]. It can be seen that the number of particles impinging the second and third ridges (shown in Fig. 3 as ridges #2 and #3) is greatly decreased by the presence of the first ridge. In fact, abrasive particles rebound backwards after impinging the ridges thus deviating the flux of the abrasive material. As a result, the density of the abrasive material in proximity to the surface is reduced and wear is decreased.

It is expected that embossed surfaces with convex domes would act similarly to corrugated surfaces with the advantage that the domes would also provide a symmetrical guiding effect, namely they would be effective for any azimuthal direction of the abrasive material flux. In the following sections, we investigate the implications related to the position of the convex domes fixed to rigid

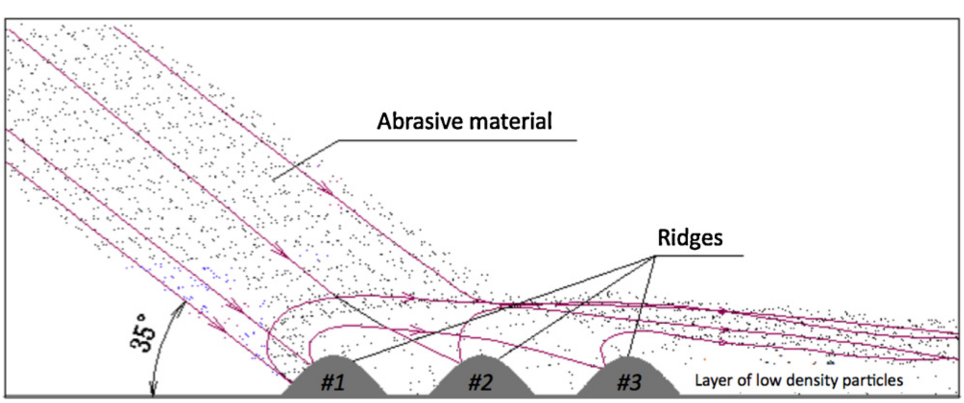

Fig. 3. Schematic diagram showing the interaction between ridges and soil particles [22].