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New tribological strategies for cutting tools following nature

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ABSTRACT

The material concept of animal teeth for cutting viscoelastic and abrasive food is completely different to those existing for industrial cutting tools. Biological cutting systems use abrasive wear in order to form sharp cutting edges. This work gives an overview of biological principles and describes a biomimetic approach for designing industrial cutting tools. The developed tools based on nature inspired hierarchic structure and shape show outstanding mechanical properties and provide evidence that self-sharpening effects and high abrasive resistance must not be contradicting.

1. Introduction

1.1. *Cutting of visco-elastic materials*

The process of cutting visco-elastic materials is not completely understood up to now. Although there is a huge difference in the elastic modulus of cutting steel and work piece material the cutting edge is damaged after few cuts e.g. during granulating plastic materials. If the work piece material includes abrasive particles, the irreversible damage is even worse. Functional fillers, fibres and inorganic colour pigments used in plastics show similar characteristics: small particle diameters and high hardness [1]. Titanium dioxide is used in polymer industry as a typical material for white pigments in the form of fine spherical particles with a size below 1 μm and a hardness of about 2150 HV.

To avoid high abrasive wear, cutting materials should ideally be harder than the hardest phase of the work material. But due to high mechanical loads and damageable geometries the cutting tool materials used should be ductile and should provide a high flexural strength. Cold work steels, high-speed steels and even powder-metallurgical steels offer a high toughness and therefore are often used for cutting applications [2]. Due to the fact that these steel qualities exhibit a relatively low hardness below 1000 HV, the tribological system of cutting tool and hard particles in the polymer work piece is exposed to severe wear. The occurring abrasive wear erodes the metal matrix, as a consequence a pull-out of the hard phases starts [1]. To avoid this wear mechanism, often harder materials like WC-Co hard metals and ceramics are used. But with an increase of the material hardness the toughness will decrease. Linear-elastic properties of ceramics cause brittle failure of the cutting edges, thus the potentially high abrasive resistance does not come into play [1]. Today, ultrafinely grained hard metals show a good compromise of toughness and abrasive resistance and are therefore often used in abrasive cutting applications [3,4,5]. Considering the above-mentioned wear situation in cutting visco-elastic materials, the coating of cutting edges with thin layers of hard ceramic materials is not a promising solution. Different investigations show that the use of conventional coatings on cutting edges did not necessarily lead to better cutting qualities or a longer durability [6,7]. Often this is due to the comparatively large cutting edge radius of the coated tools and an associated increase in cutting forces.

The risk of mechanical edge fracturing is even higher due to the coating hardness ranging from 2300 HV (e.g. titanium nitride) to 9000 HV (diamond coatings) [2]. Compared to bulk material hard ceramics offer tough materials behaviour in the form of ultrathin layers but it stands to reason that their wear resistance properties do not last for a long time. As soon as the coating is worn out, the cutting edge is exposed. Thus, it appears that the strategy of minimisation of wear is no long-term solution for abrasive cutting applications. During millions of years of evolution nature has developed better strategies by controlling wear instead of diminishing it.

1.2. *Biting and chewing of abrasive food*

Teeth of herbivores work quite well under abrasive load. Due to the low energy content of grass and plants herbivores have to

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eat a lot. The fibrous structure of plants needs intensive cutting and chewing to prepare food for digestion. At the same time abrasive silica particles embedded in the cell-wall of grass initiate high abrasive loads. In excrements of African herbivores a silica content of 115 g/kg was measured [8]. But obviously the cutting edges of teeth remain sharp (see Fig. 1). Using the example of a rodent incisor, the material concept of self-sharpening teeth can be described: The body of the tooth is made of dentin. Dentin is a bonelike material with visco-elastic mechanical properties caused by 20 wt% of organic matter as well as 10 wt% water. Only the front of the tooth is covered by a thin enamel layer. Enamel is the hardest material in living species. It is hierarchically structured with an organic content of about 1 wt% and 4 wt% of water [9]. Due to differences in abrasive resistance only the hard enamel layer forms the tip of the tooth during wear. The tooth grows permanently [10]. Although enamel is hard, it seems to be very ductile due to the fact that the edge of the tooth does not break brittle and delaminate from the elastic body. Reasons for that can be found in the hierarchic structure of the biological ceramic. Single crystallites of hydroxyapatite are covered with a thin organic protein shell with a thickness of some nanometres. About 100 of these crystallites are clustered to prisms. When teeth are formed these prisms start to grow from the enamel-dentin junction up to the surface of the tooth [11,12]. Ang et al. [13] measured the mechanical properties of human enamel over millimetre and nanometre length scales by indentation. Fig. 2(a) shows that the elastic range of enamel increases by smaller scales. At the scale of prisms (5–6 μm) and those of single crystallites (30 nm) plastic and even elastic-plastic deformations were measured before enamel fractures. According to a model shown in Fig. 2(b), the hard crystallites carry the stresses while the organic protein layers undergo a deformation during mechanical loading. Similar mechanical models in the nanoscale are also discussed for other biomaterials like e.g. bones [14]. But also for technical nanocomposite materials: Nanocomposite ceramic coatings show mechanical properties that are even better than those of their single components [15]. Models of energy dissipation on the scale of nanometres were developed [16]. Thus an analogy between biological and technical systems can be assumed. Taking the differences between biological and technical cutting systems in tribology and mechanical load into account a biomimetic design of cutting tools can be described.

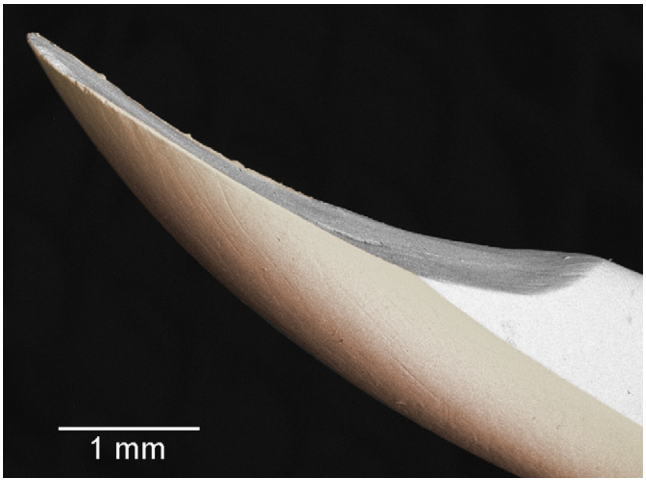

Fig. 1. Rodent incisor of a vole (Arvicolinae), coloured SEM-picture.

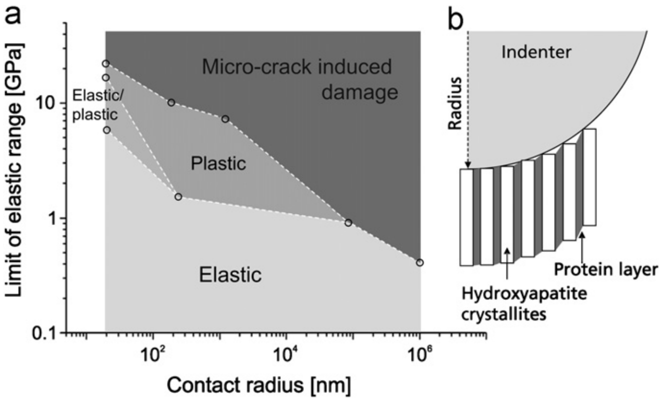

Fig. 2. A map of regions of the most probable deformation behaviours of enamel: elastic, plastic or micro-crack induced behaviour [11].

To be analogous to the dentin body of rodent incisors a biomimetic cutting tool should be produced of tool steel with sufficient toughness so that the rake surface of the tool is able to wear in a controlled way. Only the flank surface should be coated with a thin ceramic layer. This layer must provide high abrasive resistance by combining a sufficient toughness and hardness in order to avoid the brittle failure of the cutting edge [17]. Therefore the concept of the enamel's hierarchic structure is transferred into the architecture of the coating using a combination of ductile and hard phases on the nanoscale (see Fig. 3). In order to develop an optimised cutting system it is necessary to define appropriate mechanical properties of metal body and ceramic layer as well, thus allowing a controlled wear process. This is very specific to the according cutting tribology and requires that the wear and failure mechanisms is completely understood. The following experiments and results are described in detail in [18].

2. Experimental details

2.1. Test set-up

In this work a granulator for plastics provided a basis for tribological analysis. The set-up of the test unit used three cutting tools, installed on a rotor system. The clearance angle of all tools was 10° while the wedge angle was 30°. Cutting speed was 8 m/s. The stator was equipped with two piezo electronic load cells. Applying a measurement system with amplifier vertical cutting

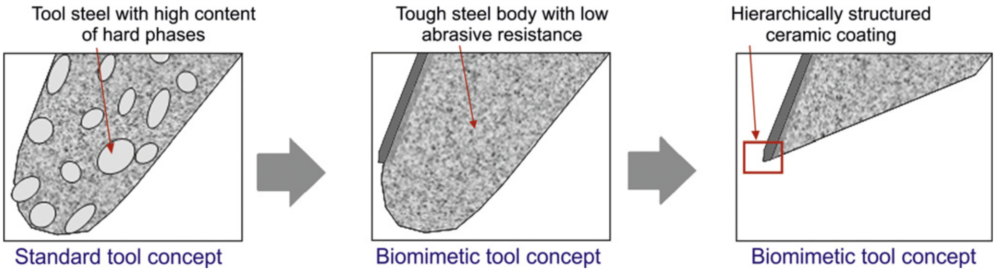

Fig. 3. Concept of biomimeti cutting tool design.