PLANTS AS CONCEPT GENERATORS FOR BIOMIMETIC SELF-HEALING AND SELF-ADAPTIVE MATERIALS, STRUCTURES AND SURFACES

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ABSTRACT

Plants have inspired the development of numerous novel (self-)adaptive and self-healing materials, structures and surfaces over the last decade. Examples include: (1) self-repairing elastomers for sealing gaskets and dampers inspired by self-healing processes in latex bearing plants, (2) self-adaptive biomimetic attachment systems inspired by permanent attachment organs of plants, (3) adaptive biomimetic anti-adhesion surfaces inspired by leaf surfaces, and (4) (self-)adaptive elastic façade shading systems inspired by the bird of paradise flower.

1. INTRODUCTION

Many biological materials, structures and surfaces possess in addition to their excellent mechanical functions self-healing- and other self-x-properties (e.g. self-organization, self-adaptability, self-cleaning). The entity of these properties allows them to interact very efficiently with their respective environment. These biological solutions are cost- and energy-efficient, multi-functional and environmentally friendly. And with several billion test runs, they have surely stood the test of time. Novel sophisticated methods for quantitatively analysing and simulating the form-structure-function-relationship on various hierarchical levels allowed over the last decade new fascinating insights in the functional principles of biological materials, structures and surfaces. On the other hand, new production methods allow for the first time the transfer of many outstanding properties of the biological role models into innovative biomimetic products [1,2]. However, the transfer of characteristic functions of life, as self-healing, self-adaptation, self-organization, and self-cleaning still represents a major challenge for materials research. Using current R&D-projects, the process sequences in biomimetic research applied for the development of hierarchically structured biomimetic self-x-materials, structures and surfaces are presented [3].

2. MATERIALS AND METHODS

Materials and methods used within the research topics presented, are described in detail in the literature cited in the respective section.

3. RESULTS AND DISCUSSION

Self-healing bio-inspired elastomers: Over the last decade plants have proved to be a promising source of inspiration for the development of self-healing biomimetic materials and structures [2,4]. Inspired by self-healing processes found in latex bearing rubber plants, self-healing elastic polymers for sealing gaskets and dampers were developed. Rubber plants of the genera *Ficus, Hevea* and *Euphorbia* contain latex emulsions in micro-tubes (laticifers) that are released after injury and seal the fissure by coagulation. In *Ficus* we could prove that the laticifers are under high overpressure (up to 15 bar) [5]. After injury the membranous vesicles burst due to the pressure drop, proteins are set free and, mediated by Ca^{2+} ions, cause the coagulation of latex particles which possess protein binding sites on their surface [4].
Based on these results, two approaches were used for producing novel bio-inspired self-healing elastomers. Inspired by the function of Ca^{2+} ions, ionomeric self-healing elastomers were designed by the project partner Fraunhofer UMSICHT, Oberhausen. In the second approach bio-inspired multiphase blends of Nitrile butadiene rubber (NBR) with liquid polymers (hyperbranched polyethyleneimine, PEI) as self-sealing and self-healing agent were developed [6]. The latter represent an alternative to micro-encapsulation of self-healing agents, avoiding the micro-encapsulation by phase separation. In the micro-phase separated domains the liquid polymer is under a high internal pressure. If a micro-crack propagates into such a domain the self-healing agent seals the crack. We found considerable self-healing efficiencies (measured as %-recovery of tensile strength) after cutting strips of the self-healing elastomers in half and rejoining them under controlled conditions. For carboxylated NBR ionomers a self-healing efficiency of 50% in the non-vulcanized state and of 15% in the vulcanized state were found (rejoining and annealing for 24h at 55°C). For vulcanized NBR/PEI blends (PEI: 2000 g mol^{-1}) the self-healing efficiency amounts to 44% (annealing under compression for 12h at 100°C and subsequent storing at room temperature without compression for 12h) [2,4,6].

(Self-)adaptive permanent biomimetic attachment systems: Climbing plants evolved different types of permanent attachment structures. In plants with adhesive pads and adventitious roots efficient attachment is caused by a combination of structural form-closure on the micrometre scale and/or organic glue allowing the plants to climb even flat and smooth supporting structures [7]. Attachment pads were studied in Boston Ivy (*Parthenocissus tricuspidata*), Monkey's Comb (*Amphilophium crucigerum*) and *Passiflora discophora*. In all three species the pads represent highly efficient and reliable permanent attachment structures. Boston Ivy secretes an adhesive fluid and is able to attach to a wide range of smooth and rough substrates [7]. The Monkey's Comb does not secrete glue and requires (micro-)rough surfaces for attachment in which its pads grow and produce an excellent form-closure. In all tested species the pads can sustain high mechanical loads. A single lignified pad of Boston Ivy shows on plaster a maximum normal force at failure of 7.6±2.5 N, i.e. it fails at normal stresses of ca. 4 MPa [7].
As root climbing species English Ivy (*Hedera helix*), Trumpet Vine (*Campsis radicans*), Climbing Fig (*Ficus pumila*), and two Vanilla species (*Vanilla* ssp.) were investigated. In addition to an excellent form-closure caused by root hairs that grow into (micro-)cavities of the climbing substrate all species secrete adhesive fluids for further increasing adhesion. A typical root cluster at a 2 cm long stem segment of English Ivy grown on bark fails at a maximum normal force of 3.8±2.4 N. Root

clusters at nodes of the Trumpet vine grown on wood show a maximum normal force at failure of 18.3±6.0 N [7]. An additional feature interesting for the development of bio-inspired attachment materials is the self-adaptive form-closure found in English Ivy. After chemical adhesion in a (micro-)cavity, initiated by desiccation processes and due to the arrangement of cellulose micro-fibrils in the cell wall, the root hairs form an apical hook and spirally curl up. Thereby the root hairs shorten and self-adaptively improve the form-closure of the root with the climbing substrate [8].
Based on the various types of permanent attachment structures in plants several approaches for novel bio-inspired attachment materials and structures using a combination of physical and chemical anchoring methods are currently developed.

Adaptive biomimetic anti-adhesion surfaces: Some plant surfaces are known to strongly reduce insect adhesion. The anti-adhesive effect can be caused by different types of hierarchically structured plant surfaces. The most well known ones are double structured leaf surfaces with cuticular wax crystals, famous for their self-cleaning properties technically used in so called biomimetic Lotus-Effect® surfaces. By quantitatively analysing the ability of Colorado Potato Beetles (*Leptinotarsa decemlineata*) to walk successfully on a variety of differently structured leaf surfaces, we found even higher anti-adhesive effects in leaves with special types of cuticular folds. The traction forces of walking beetles tethered to the force sensor were determined by using a high-resolution force sensor (resolution ±50 μN). Our results proved that compared to a smooth glass surface, cuticular folds can reduce the traction force by a factor of 20 or more [9]. The lowest traction forces were found for leaves with smooth surfaces and medium cuticular folds possessing a height and width of ca. 0.5 μm and a spacing between 0.5 and 1.5 μm. Such structures are found e.g. on adaxial leaf surfaces of *Hevea brasiliensis* and *Cyclamen persicum*. A similar reduction of traction forces is also found for untreated and hydrophobized replicas of such plant surfaces produced with epoxy resin by using a moulding technique. This proves that the anti-adhesive effect is mainly controlled by the micro-structuring of the surfaces and not by the surface chemistry [10]. This together with the high stability of cuticular folds and their replicas makes these structures promising candidates for developing bio-inspired technical anti-adhesive surfaces.

(Self-)adaptive bio-inspired elastic façade shading systems: The biological concept generator is the perch in the flower of *Strelitzia reginae* (Bird-Of-Paradise). Birds landing on this perch to feed on nectar induce by their bodyweight two lamina flaps to bend sideways, which enables pollination by first exposing the stamina and in a later phase of blooming the stigma The elastic bending of the structure is fully reversible, fail-safe, very reliable and can be repeated over 3.000 times with almost no sign of fatigue. The deformation of the perch has been quantitatively analysed, abstracted, simulated and transferred into a (self-)adaptive bio-inspired façade shading system which undergoes a major shape change by only a minute deformation of its backbone. The avoidance of local hinges, which need a lot of maintenance and are prone to failure, is together with the high reliability and the fail-safe behaviour the main benefit of the patent-registered façade-shading system Flectofin® [11]. Flectofin® is a biomimetic technical structure with a flapping system based on the elastic opening mechanism found in the perch of *Strelitzia reginae* that was developed by using glass fibre-reinforced polymers. The good scalability of this biomimetic structure is of high importance as it allows developing of individual façade shading elements in various sizes from several centimeters up to 20 m. The high potential of this structure is proven by the actual advanced prototype status and by being an inspiration for the development of another bio-inspired shading system that was used in the Thematic Pavilion at the World Expo 2012 in Yeosu, Korea [12].

4. CONCLUSION

Plants have proven to be increasingly important role models for the development of novel self-adaptive and self-healing bio-inspired materials, structures and surfaces. With their high reliability, their fail-safe behaviour and their high potential for sustainability these bio-inspired technical products become more and more interesting in many fields of industrial production and application.

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