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Self-healing soft robots

Seppe Terryn[*12], Joost Brancart[2], Ellen Roels[12], Guy Van Assche[2] & Bram Vanderborght[1]

[1] Brubotics, Vrije Universiteit Brussel (VUB) and Flanders Make, Pleinlaan 2, B-1050, Brussels, Belgium.
[2] Physical Chemistry and Polymer Science (FYSC), VUB, Pleinlaan 2, B-1050, Brussels, Belgium.
[*] seterryn@vub.be

The need for robots that can safely interact with humans has led to the development of the novel field of "soft robotics". In soft robots, compliance is integrated through flexible elements, which are in many cases elastomeric membranes. Because of their intrinsic flexibility these robots are suitable for applications in uncertain, dynamic task environments, including safe human-robot interactions. However, the soft polymers used are highly susceptible to damage, such as cuts and perforations caused by sharp objects present in the uncontrolled and unpredictable environments these soft robots operate in. In contrast with stiff robots, in soft robotics a large part of the robot's body will experience dynamic strains. As a result, fatigue will occur throughout the entire soft robotic body. In many soft robotic designs weak interfaces that rely mainly on secondary interactions, are created due to multi-material designs or multistage molding. After a limited number of actuation cycles, interfacial de-bonding leads to delamination and eventually failure. These damaging conditions lead to a limited lifetime of soft robotic components. Most flexible polymers currently used in soft robots are irreversible elastomeric networks, which cannot be recycled. Therefore, damaged parts are disposed after a limited life cycle as not recyclable waste.

In our research we propose to increase the lifetime of soft robotic components by constructing them out of self-healing polymers, more specifically out of reversible Diels-Alder (DA) networks. Based on healing capacities found in nature, these polymers are given the ability to heal damage. As an additional benefit, these polymers are completely recyclable and can pave the way towards sustainable, ecological robotics. A variety of DA-networks was synthesized and characterized that vary in concentration, functionality and (non)stoichiometry ratio of the maleimide and furan reactive components. The knowledge of the direct effect of these three network design parameters on the material properties allow the design and preparation of DA-networks with customized mechanical properties for dedicated applications. A new manufacturing technique "folding & covalently bonding" that exploits the healing ability was invented. In addition, fused filament fabrication is developed, which allows to 3D print DA-networks into 3D objects with isotropic mechanical properties. These novel manufacturing techniques were used to develop the first healable soft robotic components including; soft grippers, soft robotic hands and artificial muscles. These components, of which some consist of multiple DA-materials, were designed through finite element modeling and their mechanical performances were characterized using customized dedicated test benches. It was experimentally validated that the healing ability of these components allows healing microscopic and macroscopic damages with near complete recovery of initial characteristics after being subjected to a healing process that requires mild heating. Integrating a healing capacity increases the lifetime of soft robotic components and in addition the self-healing polymers used are completely recyclable, potentially reducing further the ecological impact of soft robotic systems.