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Self-healing soft robots: from new polymers and processing techniques to autonomous healing soft robots

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Abstract— In order to develop self-healing soft robots, we developed an integrated approach consisting of several essential building blocks from new intrinsic autonomous and non-autonomous self-healing polymers with fillers for additional functionality, different processing techniques to autonomous healing soft robots with embedded self-healing sensors and heaters. This technology was experimentally validated in several soft robotic demonstrators.

I. SELF-HEALING MATERIALS

While healing mechanisms have been incorporated in ceramics and metals most progress has been made in SH polymers due to their higher molecular mobility. We synthesized and characterized self-healing polymers based on Diels-Alder network and with combined reversible crosslinks to make benefit of complementary advantages, both healing autonomous as non-autonomous (requiring external stimuli to control start of healing) [1]. In our review paper on self-healing polymers for soft robots [2], potential material candidates were categorized and compared, based on performance parameters, including mechanical strength, the required stimulus, healing time and healing efficiency. Moreover they were assessed based on criteria for integration in robotic and mechatronic systems as capability to heal macroscopic damages, multiple healing cycles, recovery of initial properties, elastomers with high strength and reprocessable and recyclable. There exists a general trade-off between mechanical strength/stability of the elastomeric network and the intensity of the healing stimulus or the healing duration. This is translated into soft robotic prototypes that can heal autonomously but have a limited force and power output due to their hyper elastic bodies and others that have a higher mechanical performance but require thermal or UV irradiation in order to heal. Judicious design of the polymer network structure (molecular weight and functionality of the monomers, maleimide-to-furan ratio, backbone chemistry) allowed us tuning of chemical and viscoelastic properties and the mechanical and self-healing behaviour. An important characteristic of our material is that the reversible bonds are the same, regardless of the resulting properties and the interface when joining multiple materials is perfectly covalently bonded [3]. Where classical multi-material components often fail at the interface, our materials make innovative multi-material designs feasible.

II. PROCESSING TECHNIQUES

In our review paper “Processing of self-healing polymers for soft robotics” we investigated and validated the potential of

different processing techniques present in the literature for manufacturing self-healing soft robots. We started our classification from the reversible chemistry and microstructure of the regular soft robotics materials and self-healing materials. We validated the potential of each technique and the advantages that self-healing polymers can give, stemming from their chemical nature, and how they open up new processing opportunities. Self-healing elastomers, based on reversible physicochemical or covalent bonding, blur the line between the two traditional categories of thermosetting and thermoplastic elastomers. Thermosetting elastomers cannot be reprocessed (eg needed for 3D printing), and are thus processed using a reactive method, whereas thermoplastic elastomers can be reprocessed by heating them above their transition temperature. Self-healing polymers can also be reprocessed, but the principle behind the reprocessing is now based on the (often thermo-) reversible reaction. This allows them to be processed using both reactive and thermal methods. We demonstrated that our SH material is suitable for different needs of the end application (large scale production or prototyping, isotropy, multi-material, filled composites, hollow structure, surface finish) as additive manufacturing [4], laser cutting and welding, moulding etc.

III. SELF-HEALING SOFT ROBOTS

In the past decade, advances in smart soft materials and fabrication techniques enabled a tremendous expansion in the development of soft devices such as actuators, sensors, electronic skins and wearable devices [5]. These soft devices find applications in personal care and health monitoring, human-machine interactions and soft robotics, and a wide variety of sensory applications, among others. We demonstrated the successful implementation our self-healing materials, and most relevant other mechanisms especially the combination of materials with different mechanical and electrical properties, in self-healing soft robotic grippers and hands [6], also with embedded sensors and heaters. Also the magnetic fillers in the self-healing matrix allow a wide variety of applications both on actuation as sensing level [7]. As stated in Sitti 2021 [8] in addition to computational intelligence (CI), it is essential to advance the physical intelligence (PI) encoded in the body of human-man agents by smart materials as found in biological agents to create autonomous machines to operate in complex real-world environments.

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