Towards self-healing actuators:a preliminary concept

Terryn, Seppe; Brancart, Joost; Mathijssen, Glenn; Verstraten, Tom; Van Assche, Guy; Vanderborght, Bram

Published in:
IEEE Transactions on Robotics

DOI:
10.1109/TRO.2016.2558201

Publication date:
2016

Towards self-healing actuators: a preliminary concept

Seppe Terryn, Glenn Mathijssen, *Student Member, IEEE,*
Joost Brancart, Tom Verstraten, Guy Van Assche, and Bram Vanderborght, *Member, IEEE,*

***Abstract*—Natural organisms have a unique property not yet available in robotics, a self-healing (SH) ability. This powerful biological healing function has inspired chemists to impart similar properties to synthetic materials to create "self-healing materials". Recent development in SH-polymers made us investigate the potential of using these materials in robotics. This paper presents an innovative approach of using SH-polymers, based on the reversible Diels-Alder (DA) reaction, in a compliant actuator. Using DA-polymers a sacrificial SH-mechanical fuse (SH-MF) is designed, developed and validated by placing it in a cable driven robotic system. The fuse is designed as weakest element and will sacrificially fail if a damaging overload occurs, protecting the compliant element and other components of the system. The experimental results showed that this SH-MF could be healed at a relatively low temperature, recovering the initial mechanical properties. This first working prototype indicates the feasibility to use SH-materials in robotics. "Self-Healing Robotics" will lead to more sustainable and lighter systems and eventually to more efficient designs.**

***Index Terms*—Self-healing material, Diels-Alder polymers, Compliant Actuators, Robotics**

I. Introduction

In nature, most organisms posses a remarkable advantage compared to human-made objects, the ability to heal themselves when certain damages and injuries occur. Almost in every body part a Self-Healing (SH) system is incorporated: the skin is healing continuously, muscles can recover from ruptures and bones can heal from fractures. Our bodies are not over-dimensioned so fractures, ruptures, and injuries will occur when a body part is overloaded in abnormal, extreme circumstances. After the extreme damaging conditions the healing process will start up autonomously. This healing process will take some time but will, if the damage is limited, recover the body part to its original state. When this recovery is complete the part can fulfill its specific function again until another overload occurs.

So far robots on the other hand do not possess this healing ability. Instead, in order to be able to withstand unexpected loads, robotic systems are over-dimensioned. The different parts have to be designed in such a way that they can withstand numerous extreme circumstances, avoiding any damage. Increasing the safety factor often implies increasing the weight of the system, while in many robotic applications compactness and mass are of great importance. The idea is that by incorporating a SH-ability, robots can be dimensioned based on their performance tasks, instead of on extreme loads. If such an over-load takes place, a robotic part will fail. Using the SH-ability the robotic part can be healed back to its initial state, and this preferentially autonomously. In this way "self-healing robotics" may lead to lighter systems and eventually to more efficient designs. This also benefits the sustainable manufacturing of actuators, since the life span (MTTR: mean time to repair) can be drastically increased.

Recent developments in SH-polymers [1]–[6] have led to commercial applications, e.g., the "Scratch Shield" car body finish of Nissan and AkzoNobel and the SH-cover of LG Flex smart-phones, and are promising for future commercial applications, like puncture SH-polymers in aerospace [7]. Ideally a future robot could be build up with a complete set of SH-materials, meaning that the robot will be build up out of a skeleton, actuators, sensors, a communication/ information processing system, and a cover/skin, all incorporated with a SH-mechanism. However, in literature not much can be found on SH-robotic principles. To the best of the authors' knowledge, only one paper by Hunt et al. [8] can be found in which a SH-principle is used to create a self-healing dielectric elastomer actuator. In work by Wei et al. [9] it is suggested to use a developed self-healing hydrogel in future soft robotics applications. Besides this limited work on the hardware level, SH-principles were recently introduced in robotics on software level. These Modular Self-Reconfigurable Robot Systems [10], [11] contain control architectures where after loss of, for example, a leg or part, the system can take this into account.

SH-concepts have the potential of being introduced in a lot of components of the robot. This paper focuses our study on actuators, in other words, on SH-systems dealing with damage due to the overload of robotic joints. The introduction of the SH-concept in actuators is expected to result in a significant reduction of the overall dimensioning of the robots. Other damaging effects like wear effects, damage by clamping, and scraping occur and might be solved using SH-technology. For example, the skin or cover could be protected with already existing SH-coatings [4], [12], [13] or using the recently developed artificial stretchable SH-film for artificial skin applications [14]. Robotics is a relevant field of application, since robots are an ideal demonstrator, for the introduction of SH-mechanisms in actuation industries. A robot consists of numerous components and materials, making them hard to be repaired since they are generally hard to dismantle.

S. Terryn(*), B. Vanderborght, G. Mathijssen and T. Verstraten: Robotics and Multibody Mechanics (R&MM),Vrije Universiteit Brussel (VUB), Pleinlaan 2, B-1050 Brussels, Belgium. http://mech.vub.ac.be/robotics. *e-mail: seterryn@vub.ac.be

G. Van Assche, J. Brancart: Physical Chemistry and Polymer Science (FYSC), Vrije Universiteit Brussel (VUB), Pleinlaan 2, B-1050 Brussels, Belgium. http://www.vub.ac.be/MACH/FYSC/.

Over-dimensioning of robotic parts is most common for robots that preform a task in highly unstructured, dynamical environments, in which unexpected, potentially damaging loads can occur. In these environments and in places where contact with people is required, compliant actuators [15]–[18] that insure safe interaction are desirable, in order to protect both surrounding and the robotic hardware. With robots more and more present in these settings, compliant actuators are becoming increasingly important. Therefore, this work presents the first concept of a self-healing compliant actuator.

To make a first design of the implementation of the SH-principle in a robotic actuator, a series elastic actuator (SEA) [18] was selected, as it is already deployed in several applications [19]–[21]. This basic compliant actuator consists of a motor, a gear, and a compliant element. The compliant element, often a spring, is placed in series, between the gear train and driven load to intentionally reduce the stiffness of the actuator. In the design, a SH-polymer part will be implemented in the SEA. The idea is to design this part as the weakest mechanical element in the construction, such that when the actuator is overloaded this elements will fail, protecting the other actuator components. The developed prototype was integrated in a cable driven compliant actuator [22].

In a parallel research [23], [24] we developed a first proof of concept of a soft pneumatic actuator, built entirely out of SH-elastomers, which can heal damages caused by sharp objects; e.g. cuts, punctures and perforations, using a SH-process .

This paper is organized as follows. In Section II two SH-concepts are introduced. In Section III, a brief overview will be given on the different SH-mechanisms in polymers described in literature. This is followed by a general discussion on the SH-principle of the Diels-Alder (DA) polymers used in this research for a first implementation in a robotic actuator. In Section IV the characteristics of the DA-polymers will be presented. Section V describes the design of the first prototype, the self-healing mechanical fuse. Experimental results are provided in Section VI and VII and finally Section VIII and IX presents conclusion and future work.

II. Conceptual Design of the SH-Mechanism

In traditional “stiff” actuators, safety towards overloads and active compliance can be provided by software control. However, because of shortcomings of the control approach in applications [16] such as robots in close human/robot proximity, legged autonomous robots, and rehabilitation devices and prostheses, the field of compliant actuation emerged recently. In addition, intrinsic compliance can be used in robotic applications, in which safety has to be provided when the system is not powered. The SH-approach for safety fits more the applications in which these compliant actuators are preferred, in which safety is provided by the mechanism itself instead of by the control. This is why we concentrated on the integration of SH-polymers in compliant actuators. To integrate an intrinsic SH-mechanism in a compliant actuator, like the SEA, two main concepts were considered: the self-healing compliant element concept (Fig. 1a) and the self-healing mechanical fuse concept (Fig. 1b).

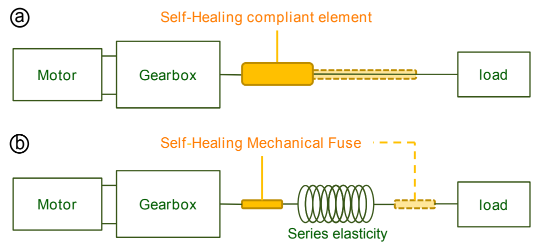


Fig. 1. a) Self-healing compliant element concept. b) Self-healing mechanical fuse concept.

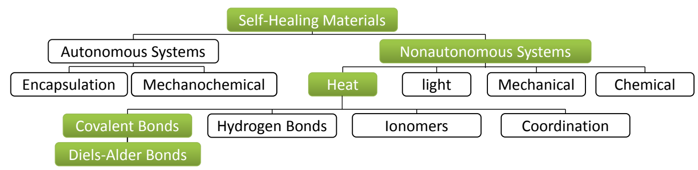


Fig. 2. Overview of the self-healing (SH) materials available in literature [1].

In the SH-compliant element concept, the compliant element is replaced by a SH-compliant element constructed out of a SH-material. The principle works as followed: when an overload is applied to the actuator, the SH-compliant element will fail. A detection system detects this failure and the actuator is brought in an unstressed, predefined position where the SH-process is carried out. The SH-mechanical fuse concept has the same working principle as the first; however a SH-material is used in series with the original compliant element. The sacrificial part will have no (or minimal) mechanical contribution to the overall system, but will fail when the actuator is overloaded. The element is designed to be the weakest element and therefor will protect the compliant element and other components of the system.

This principle of using a sacrificial component already exists, known as mechanical fuses [25]. Most of these fuses have a lifetime limited to one fail cycle, although there are fuses that can be reassembled after an overload [25]. Besides these sacrificial components, other principles to protect both the environment and the robotic hardware components against overloads were developed, like the nonlinear spring system for collision safety [26] and locking mechanisms [27].

III. Overview Self-Healing Materials

A. Selection of SH-mechanism

A broad range of SH-materials has been developed over the last 15 years, based on a variety of chemical principles [1], [4]. Two distinct SH-mechanisms can be defined (Fig. 2): autonomic and non-autonomic ones. Autonomic systems require no stimulus (other than the formation of damage) for operation. They most closely resemble biological systems, delivering healing agents to compromised regions as soon as damage is initiated. Non-autonomic systems require some type of externally applied stimulus (heat, light, a mechanical or chemical) to activate their healing function. Yet this allows the healing process to be performed in a controlled way. From a first analysis [23], Diels-Alder (DA) SH-polymers were chosen

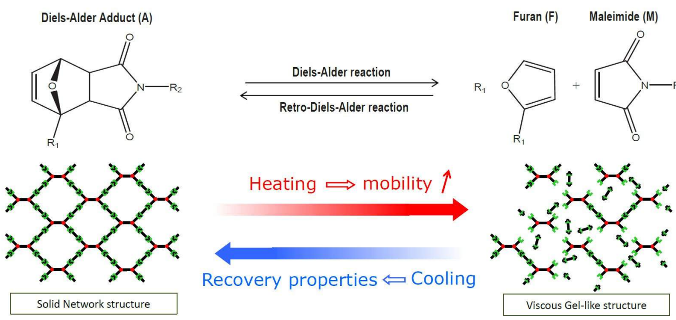


Fig. 3. Equilibrium DA-reaction [13], function of temperature. At T_{low} the network is formed due to a high conversion to DA-adducts. At T_{high} these DA-adducts fall apart and the mobility of the polymer chains increases.

for a first implementation of self-healing in a compliant actuator. The SH-process of these non-autonomous DA-polymers requires a heat stimulus (starting from 70 °C) and is based on reversible covalent bonds. Their mechanical properties are almost completely recovered after healing; the number of SH-cycles for a polymer part is not limited. A second advantage of the DA-polymers is the strong reversible bonds of which the network consists of. Due to these, compared to other SH-polymers [1], [4] (Fig. 2), DA-polymers have a relatively high modulus and strength and high ultimate tensile strength, required for the compliant actuator applications.

B. DA-polymers

The DA-polymer [13] selected, is a (thermo-) reversible polymer network, formed by the DA-cross-linking reaction between a synthesized furan functional compound and a bismaleimide (Fig. 3). The DA-reaction is an equilibrium reaction for which the extent of the reaction is a function of temperature. The equilibrium is shifted from Furan and Maleimide towards the cyclo-DA-adduct (and backward) by decreasing (increasing) the temperature. The DA-reaction is reversible, which implies that, given enough time, a temperature-dependent equilibrium state will be reached at each temperature. At low temperatures the DA-adduct is formed. As the temperature is increased the equilibrium is shifted towards the breaking of the reversible bonds (Fig. 3).

The SH-procedure is based on the reversible network and can be divided into three stages (Fig. 4), extensively discussed in [23]. The first step is a heating process (Fig. 4: t1 - t0 = 7 min). At higher temperature a lot of DA-adducts will break. The DA-polymer will still have a network structure, however, enough DA-bounds are broken to give the polymer chains the necessary mobility to induce healing and to seal/close microscopic and macroscopic gaps. It has to remain at high temperature until the macroscopic gap is filled entirely. The duration of this isothermal process (t2 - t1 = up to 40 min) depends on the DA-polymer (Section IV) used and the dimensions of the macroscopic damage, but is relatively fast. Once the gap is sealed, the polymer can be brought back to room temperature with a slow, controlled cooling process (t3 - t2 = up to 130 min). This slow cooling is extremely important and will affect the recovery of the initial material properties since the reforming of the polymer network by the DA-reaction

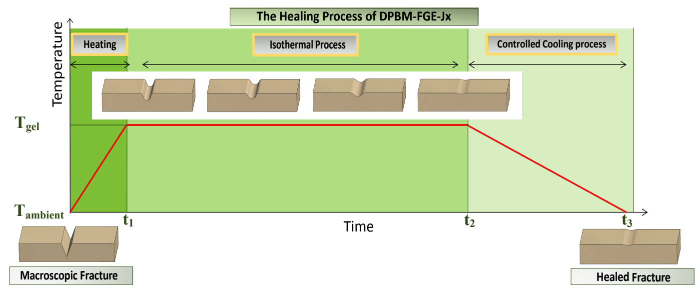


Fig. 4. Schematic illustration of the SH-procedure: Illustrating the heating part, the isothermal part and controlled cooling part.

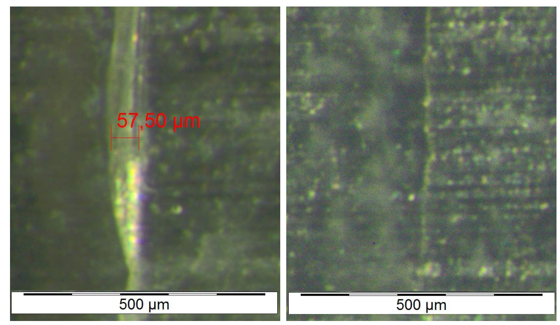


Fig. 5. Pictures, taken with an optical microscope, of a DPBM-FGE-J2000 DA-polymer sample before and after the SH-process took place. In the 0.75 mm thick sample a macroscopic gap of 57.50 μm was made. Movie of this SH-procedure: https://www.youtube.com/watch?v=jR6ddEfdPbs&list.

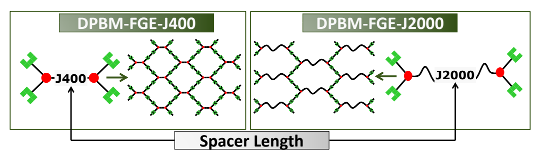


Fig. 6. Varying the spacer length of the poly(propylene oxide) chain results in reversible polymer networks with different mechanical properties.

requires some time. In Fig. 5 the actual SH-process of a macroscopic gap is illustrated.

IV. CHARACTERISTICS OF THE DIELS-ALDER POLYMER

In the course of earlier work [13], a series of three DA-polymers was synthesized using different furan-functionalized compounds (Fig. 6), which differ in furan spacer length, the polymer chain length of the hydrocarbon chain (R1 in Fig. 3). By varying this, polymers were synthesized, with different mechanical properties but with the same SH-mechanism incorporated, the reversible DA-bonds. The three materials are DPBM-FGE-J400, -J2000 and -J4000 [13], [23], [24]. These can be classified in two groups, based on their thermo-mechanical behavior (Fig. 7): J400 contains furan compounds with short polymer chain length. Due to these short chains, the network has a high cross-link density, leading to (brittle) glassy thermosets. J2000 and J4000 on the other hand are built up out of furan compounds with longer polymer chain length, limiting the cross link density. The latter materials are elastomers with ductile characteristics. In Table I the T_g as well as the T_{gel} [13], and the density of the three DA-polymers are presented.

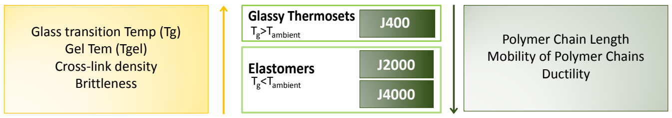


Fig. 7. Classification of the DPBM-FGE-Jx series into 2 groups: Glassy Thermosets and Elastomers (at ambient temperature).

TABLE I
MATERIAL PROPERTIES OF THE DPBM-FGE-JX SERIES.

Properties of DPBM-FGE-Jx (mean of 4 samples + STDev)				
Classification		Glassy Thermoset	Elastomeric Thermoset	
DPBM-FGE-Jx Material		J400	J2000	J4000
Transition Temperatures				
DSC: Tg [14]	°C	55,5	-55,3	-64,6
DMA: Tg	°C	74,7 ± 1,7	-43,6 ± 2,4	-59,9 ± 3,1
Tgel [14]	°C	119,5	98,5	81,0
Visco-Elastic Properties at 25°C				
Storage Modulus	MPa	1602,5 ± 431,5	107,4 ± 26,0	10,00 ± 1,34
Loss Modulus	MPa	79,6 ± 21,7	19,3 ± 2,9	1,13 ± 0,10
Tan(δ)		0,055 ± 0.026	0,183 ± 0,021	0,114 ± 0,015
Fracture Properties at 25 °C				
Fracture Strain	%	1,24 ± 0,69	131 ± 29	450 ± 112
Fracture Stress	MPa	17,7 ± 9,7	3,10 ± 0,30	2,41 ± 0,44
Density				
	g/ml	1,19 ± 0,01	1,13 ± 0,02	1,05 ± 0,03

In order to determine the viscoelastic behavior of the SH-polymer series at ambient temperature, Dynamic Mechanical Analysis (DMA) was carried out on the three materials (extensively discussed in [23], [24]). In Table I the Storage modulus, Loss modulus and their ratio, the tan(δ) are presented. To derive the fracture stress and strain, a static stress-strain test until fracture was carried out in tension. This table clearly indicates that DA-polymers can be synthesized with mechanical properties that vary over a broad range.

The studied polymers differ only in spacer length, which makes it possible to mix furan compounds having a different degree of polymerization, during the synthesis of the SH-material. Using this mixing method a DA-polymer is obtained with a mixture of spacer lengths and with desirable, intermediate material properties lying in the broad interval between the two extremes (J400 and J4000). This mixing ability is a great advantage since it provides a certain degree of freedom in the design of future self-healing actuator applications.

V. DESIGN SELF-HEALING MECHANICAL FUSE

A. Concept choice

First, a suitable mechanism for the first implementation of the DA-polymers in an SEA had to be selected. As thermosets as well as elastomer-like DA-polymers can be produced by varying the spacer length, the DA-polymers can be used for the two SH-concepts: the SH-mechanical fuse concept and the SH-compliant element concept.

In the SH-mechanical fuse concept a thermoset DA-polymer, the -J400, will be used. At room temperature this elastic polymer possesses a high storage modulus (2840 MPa) and exhibits almost negligible strains before fracture. Due to the stiffness of the material, the mechanical fuse, placed in series with the original compliant element, will have no (or minimum) mechanical contribution. In the other concept, the SH-compliant element will be based on an DA-elastomer: -J2000 or -J4000, or an elastomeric mixture of different Jeffamines, providing the required elasticity in the actuator.

To create a SH-actuator that can function entirely independent, the fracture surface will be a very important design parameter. After fracture the two fracture surfaces need to be brought together to start the healing process by local heating. It is preferable that the two surfaces fit properly, such that minimal local heating is required and that the healing process can be carried out in a static joint position. This implies that the polymer should not undergo a plastic deformation before fracture occurs, as this may result in local necking.

Due to necking the fracture surfaces will not fit properly and therefore, an automated, stand alone, healing process will become more complex, because it is important to obtain the initial shape and cross-section of the fuse after healing to maintain the same mechanical fuse properties, namely fracture tensile strength. To heal a fracture after necking requires more precise position control and heating over a larger area in comparison with the healing of clean, brittle fracture surfaces.

The elastomers -J2000 and -J4000, which will be used in the compliant element concept, possess a non-negligible viscous component at ambient temperatures (Section IV). This viscous component is probably responsible for the necking before fracture, observed for these materials. In contrast, the brittle -J400 material, used in the mechanical fuse concept, has a negligible viscous component and will break with a clean fracture surface, without the occurrence of necking.

An additional benefit of the SH-mechanical fuse concept is that it is more compatible with other types of compliant actuators and can also be used for stiff actuators. Taking this into account together with the necking issue, the discussion is focused on the SH-mechanical fuse concept. However, this does not imply that the SH-compliant concept is not feasible. In addition, the DA-polymers have potential to be used in other robotic applications; in a parallel reseach we developed a first proof of concept of self-healing soft pneumatic actuators using SH-elastomers, -J2000 and -J4000 [23], [24].

B. Conceptual design

The mechanical fuse, as the name indicates, will protect the expensive and difficult-to-replace components of the compliant actuator, more specific: the motor, the gearbox and the compliant element. The fuse should break sacrificially before a potential damaging overload occurs on one of the three previously mentioned components. Once the fuse is broken, the compliant actuator will be put into an offline mode, in which the SH-procedure can be started. When the healing of the fuse is completed the actuator can be put online again, with the same mechanical performance as before. Using this principle all components are protected and there is no need for these to be over-dimensioned to withstand the over-loads. The objective is to design this SH-cycle to be fully autonomous, such that no human interference is required. The SH-MF can be placed into one of the most simple compliant actuators, the Series Elastic Actuator (SEA) (Fig. 1b), in series in front

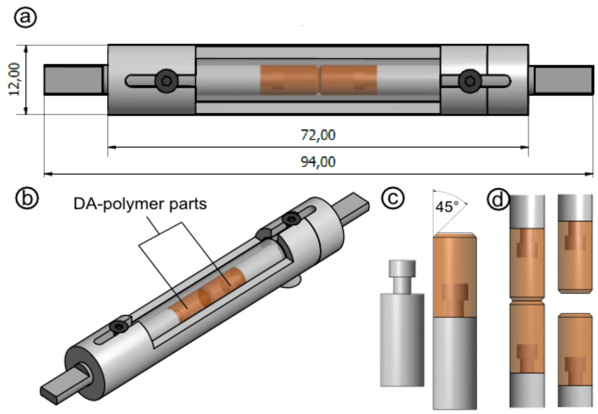


Fig. 8. SH-MF design, dimensions are in mm: a) Top view, b) 3D view. c) -J400 SH-cylindrical part. d) SH-fuse core: healed together and fractured.

Fig. 9. Pictures of the assembled Self-Healing Mechanical Fuse.

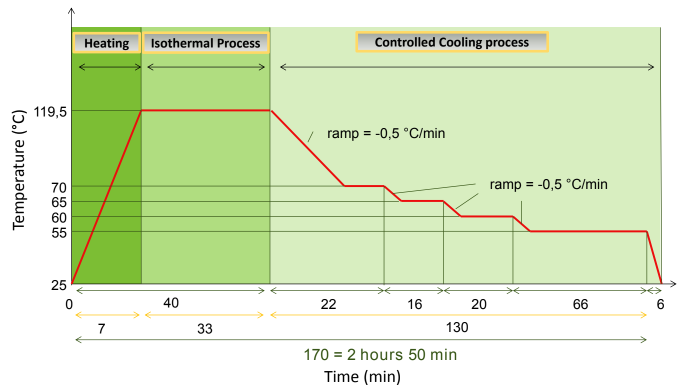


Fig. 10. T-profile of the SH-procedure of -J400 used for the SH-MF.

or behind the compliant element, which is usually a spring. However, the SH-MF principle could also be used in stiff actuators or other, more complex compliant actuators: e.g. in a MACCEPA [28] or a SPEA [29].

C. Prototype design

The prototype of the SH-MF that was developed has a length of 94 mm and a width of 12 mm (Fig. 8). For the implementation of the SH-MF in the robotic actuator it would be more ideal if the fuse would be smaller, but for practical reasons this first prototype was designed in the centimeter scale. In the schematics, presented in Fig. 8b, two cylindrical self-healing DA-polymer parts are indicated. These two cylindrical parts will be joined together using the SH-property to form the center of the fuse, the "SH-fuse core". Before discussing in detail the mechanical design of the fuse, as well as its SH-mechanism, the shape of these DA-polymer parts will be explained. A cylindrical shape was selected for the SH-fuse core (diameter: 5 mm, length: 10 mm), because misalignments during construction and healing, due to small rotations of the parts relative to one another, are not an issue. To induce the brittle fracture at a desired precise location and not for example at the connection of the SH-material to other system parts, a groove was made into the SH-fuse core. A V-groove of 0.25 mm deep and with an angle of 90° was chosen, resulting in a stress concentration factor K_t = 2,2 (Fig. 8c).

The DPBM-FGE-J series adheres very well on glass and metal. This property is used to connect the SH-polymer part to a steel pin. To create a solid connection, which will not break when the mechanical fuse is put under a load, the steel pin is provided with a T-shape end, over which the SH-material was pressure molded (Fig. 8c). Two of these SH-cylindrical parts are inserted and can slide into a glass tube (Fig. 8a), which is placed in an aluminum cover. Rotation of the SH-cylindrical parts around the axial axis is prevented by screws that slide in grooves made in the cover.

Before the fuse can be used, the two SH-parts (Fig. 8c) are joined together by a SH-process and form the SH-fuse core (Fig. 8d and Fig. 9). This healing process can be done before inserting the fuse in the SEA, or afterwards if the SEA is containing a controlled heating device that can function fully autonomously. Once healed, the actuator can be put online. Whenever an overload occurs, it will make the tensile stress acting on the fuse exceed the maximum tensile strength, and the joined SH-part will brake at the location of the V-groove. Due to this V-groove and the brittleness of the material, the two SH-parts, with just about the same shape as the initial ones, will be retrieved after fracture. The two screws inserted into the cover not only prevent rotation of the SH-parts but will also limit the sliding of the two components in the cover. When implemented in an actuator the length of the SH-MF will be measured continuously to check its status. If the SH-MF is fractured, adequate actions will be taken by the system and it will be put as fast as possible in an offline, safe mode.

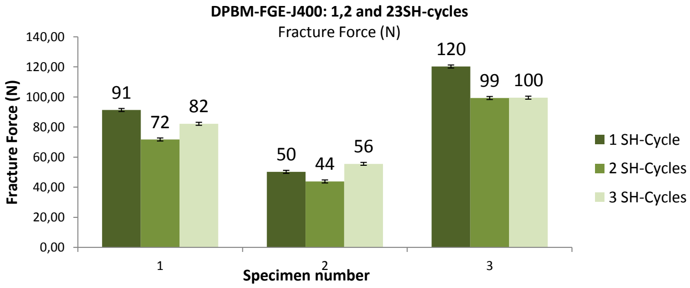
The idea is that when the SH-MF is fractured the actuator system will start the SH-procedure fully autonomously. To do this, a heating device with a programmed controller should be implemented in the SH-actuator system, producing a specific temperature profile required for the SH-process.

The temperature profile of the SH-procedure used to heal the SH-fuse core is presented in Fig. 10. This profile is a trade off between the theoretical requirements, discussed in Section IV, and what is manageable with the heating devices used. It was developed using the simulation tool provided by Scheltjens et al. [13]. The entire SH-procedure takes 170 minutes, after which the SH-MF is ready for use (Fig. 9).

VI. Experiments

A. Experimental method and data

To determine the fracture tensile force of the SH-MF, a "stress/strain tensile test until fracture" was used. SH-



Specimen number	Mean fracture force (N)	Standard deviation (N)
1	82	8
2	49	7
3	106	10

Fig. 11. Fracture force measured by the stress/strain tensile test until fracture of the 3 SH-fuse core specimens inserted in the mechanical fuses. The fracture force was measured for the each specimens after 1, 2 and 3 self-healing cycles.

cylindrical parts were made and joined to form three SH-fuse core specimen, using the SH-procedure described in section IV. Due to practical reasons, the stress/strain tensile test was carried out one or two days after the SH-procedure and at room temperature. Three SH-fuse core specimen were repeatedly self-healed and fractured for three times, to evaluate the mechanical properties after multiple fracture and healing cycles. The stress/strain tensile tests were performed with a controlled rate of extension of 0.01 mm/min and the tensile force is measured with a sample frequency of 10 Hz. The results of the stress/strain tensile test are summarized in the block diagrams in Fig. 11.

B. Discussion

The mean fracture force of the different specimen varied over a broad range, between 106 N and 49 N. These large variations are mostly due to the shaping of the SH-parts, which was done manually. There might be small defects, impurities or solvent bubbles on the contact surface, which interfere with the SH-process, influencing the fracture force. In addition, the chamfer at the edge of the SH-part, was also made manually.

What is more important is the reproducibility of the mechanical properties of the specimens after a SH-cycle. When comparing the fracture parameters after each SH-cycle for the specimens individually, the fracture force after consecutive SH-cycles varies not more than 21 %. These variations can be attributed to the pressure/force during the SH-procedure used to join the SH-parts together, which is not measured, small defects on the contact surface, and small deformations of the SH-parts that took place in the previous SH-procedure. For increasing SH-cycles, there is no decreasing trend detected in the fracture force, which is crucial for the functioning of the SH-MF. A decreasing trend would mean that the mechanical properties would deteriorate after each SH-cycle.

It should be mentioned that environmental temperature can affect the mechanical results. For the glassy DA-thermoset - J400, the reactions will strongly slow down when the material vitrifies, which happens when the increasing Tg reached the healing temperature (in the isothermal segment at 55 °C). As a result, specimens that have been healed one or two days before still have approximately a conversion equal to the equilibrium conversion at 55 °C. Therefore, the three specimens tested had approximately the same conversion during the tests. However, if specimens remain at room temperature for a long period, weeks or months, the conversion will have slowly increased, affecting the mechanical properties. Temperature changes during storage may also affect the properties. The effect of ageing and the thermal history on the properties of the SH-MF still has to be investigated, and possibly new approaches will need to be developed to make the system more robust for temperature changes.

VII. Integration in cable driven systems

Despite over-dimensioning, some really compact, lightweight designs, have been developed. However in these complex structures, the components become less accessible for maintenance [15]. For instance, the actuation of the compact humanoid iCub [30] is based on cable differential mechanisms and tendon driven mechanisms. Occasionally one of the (steel) cables breaks, due to a high impact or an overload, and it is necessary to replace it, which implies disassembling part of the robot and then assembling it again, a costly and time consuming intervention done by specialists [31], [32]. Partly due to this problem, in the successor of iCub, cCub (Coman) [33], the cables were replaced for by a fixed linkage. The integration of a sacrificial system, based on the SH-MF, in cable driven systems, found in iCub [31] and advanced robotic hands [34], [35] can have a beneficial impact on the life span of these systems, reducing the required maintenance drastically.

In order to validate the SH-MF in a cable driven system, the fuse was integrated in an antagonistic compliant actuator, which drives a pendulum and is extensively described in [22] (Fig 12). The SH-MF was placed in series with one of the springs. These springs were pre-tensioned to 29.3 Newton. The motor and load shaft position are measured by encoder 1 and 2 and the tension force in the SH-MF is derived from torque sensor measurements. In the experiment the motor shaft angle follows a modulated sine wave (Fig 13a). Consequentially, the tension force in the SH-MF is gradually increased with every swing (Fig 13c). The test was done with and without an integrated SH-MF.

The SH-MF fractured at a tension force of 49.6 Newton (Fig 13c), which coincides with the values measured in Section VI. When the fuse fractures, the two broken polymer pieces slide in the fuse holder and the fuse length increases. As a result the pretension is reduced, decreasing the torque in that swing direction. In this experiment the fracturing of the SH-MF was performed in a controlled way, however, this principle can be used to protect the actuator components from damages caused by external impacts or overloads, since these will also fracture the fuse.

VIII. Conclusion

The novelty of this paper is the first concept, design and validation of a Self-Healing (SH) element which can be integrated in a compliant actuator, and more specifically in a Series

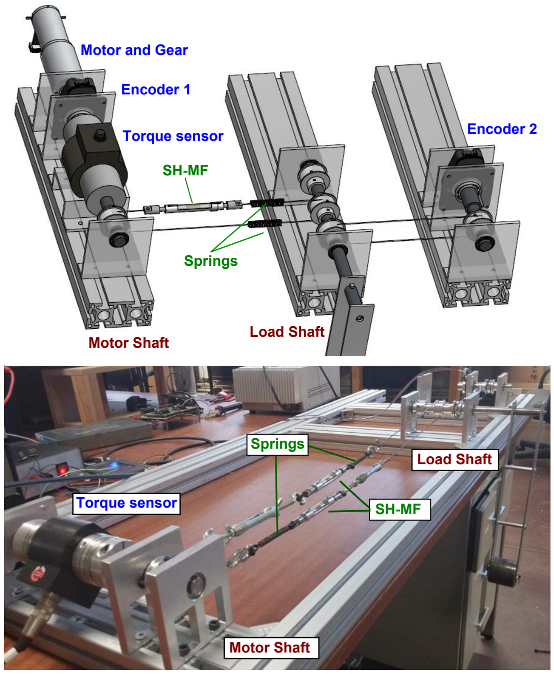


Fig. 12. Pendulum setup: pendulum driven by an antagonistic compliant actuator, in which the SH-MF is integrated. https://www.youtube.com/watch?v=997LjfAgXyw

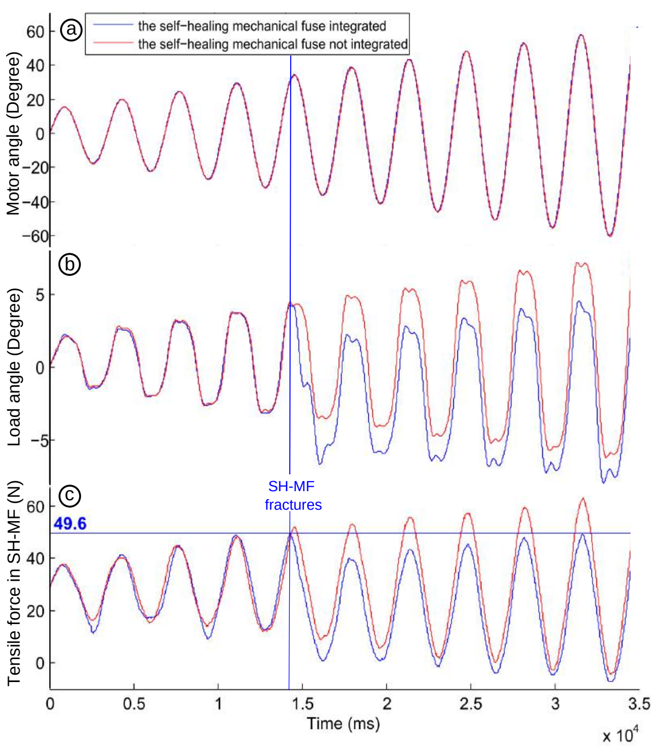


Fig. 13. Dynamic testing of the SH-MF in the pendulum setup. a) Motor shaft angle, b) Load shaft angle and c) Tensile force in the SH-MF: the fuse fractures at a force of 49.6 Newton. A movie of the fracture of the SH-MF: https://www.youtube.com/watch?v=uF71y0QWqks

Elastic Actuator (SEA). Different SH-materials, available in literature were analyzed and after careful consideration, Diels-Alder (DA) self-healing polymers were chosen for a first implementation.

To create a SH-compliant actuator a Self-healing Mechanical Fuse (SH-MF), was introduced as the weakest mechanical element in the construction. The fuse acts as a sacrificial part and will fail first if the actuator is subjected to an over-load, protecting the other components of the actuator. Once fractured the fuse can be healed using a SH-procedure. The center of the SH-MF contains a cylindrical SH-part, the SH-fuse core, made of the glassy thermoset DPBM-FGE-J400 Diels-Alder polymer. A first prototype of this SH-MF was developed. Its mechanical properties and the SH-ability of the fuse were analyzed by repeatedly fracturing the SH-MF in a tensile test and self-healing (non-autonomously in a furnace).

The SH-MF could be healed with a relatively low maximum temperature of 120 °C over a period of 170 min. The mechanical properties after three SH-cycles remain near the initial properties and depend mostly on the quality of the SH-procedure. There was no decreasing trend of the fracture force observed, indicating that the mechanical properties of the fuse remain stable for at least three SH-cycles. The SH-MF was integrated in an antagonistic compliant actuator, which showed that the fuse functions in an operating cable driven actuator.

Finally it can be concluded that the DA-polymers can be processed into macroscopic shapes, which can be implemented and used in compliant actuators. This preliminary concept study lead to a working prototype: the SH-MF. This indicates that it is worthwhile to continue this study and to investigate if the Diels-Alder or other available self-healing polymers can be used for parts and robotic applications. In addition, other actuation fields, like the automation, automotive, machines and aerospace, can also benefit from this new approach.

IX. Future Work

The SH-MF design can be fine-tuned, to reduce its dimensions. The shaping process of the SH-parts and the SH-procedure should be done in a more controlled way, to limit the influence of the shape of the chamfer at the edge of the SH-part. In this way the variations of the fracture parameters between different SH-MF specimen should decrease.

For further evaluations, the effect of a large number of fracture and healing cycles on the functionality and properties of the SH-MF will be evaluated. Therefore, an automated test setup will be developed, consisting of a universal testing machine (UTM) and a programmable furnace, in which the SH-MFs can be sequentially self-healed and fractured in a tensile test, fully autonomously. In this setup the SH-procedure will be performed entirely autonomously and in a more controlled way. We believe this will reduce variations in fracture force a lot. This setup will provide expertise for the development of the fully autonomous SH-compliant actuator.

So far the SH-process of the SH-MF is non-autonomous: the fuse is placed manually in an oven. In a following prototype, a controlled heating device (e.g., ohmic heater mats), using a temperature sensor, will be implemented in the design. This heating device will contain a controller, which allows the heating device to produce the temperature profile, required for the SH-process. To make the actuator system completely autonomous, a sensor has to be placed, which measures the length of the SH-MF continuously, to check whether the fuse is fractured or not. Whenever the fuse is fractured the actuator will be put in an offline mode, in which the SH-procedure can be started. If the SH-procedure is terminated, the actuator will be re-activated. This series of events will be done completely autonomously by the SH actuator system.

ACKNOWLEDGMENT

This work was funded by the European Commission ERC Starting grant SPEAR (no.337596). Seppe Terryn, Glenn Mathijssen and Tom Verstraten are funded by PhD Fellowship of the Research Foundation Flanders (FWO).

REFERENCES

[1] K. K. A. Williams, D. D. R. Dreyer, and C. C. W. Bielawski, "The Underlying Chemistry of Self-Healing Materials," *MRS Bulletin*, vol. 33, no. 08, pp. 759–765, 2008.

[2] S. R. White, N. R. Sottos, P. H. Geubelle, J. S. Moore, M. R. Kessler, S. R. Sriram, E. N. Brown, and S. Viswanathan, "Autonomic healing of polymer composites." *Nature*, vol. 409, no. 6822, pp. 794–797, Feb. 2001.

[3] R. Wool, "Self-healing materials: a review," *Soft Matter*, vol. 4, no. 3, pp. 400–418, 2008.

[4] D. Y. Wu, S. Meure, and D. Solomon, "Self-healing polymeric materials: A review of recent developments," *Progress in Polymer Science*, vol. 33, no. 5, pp. 479–522, May 2008.

[5] S. Van der Zwaag, "Self-Healing Materials: An Alternative Approach to 20 Centuries of Materials Science," *Springer Science+ Business Media BV*, vol. 30, 2008.

[6] S. D. Bergman and F. Wudl, "Mendable polymers," *Journal of Materials Chemistry*, vol. 18, no. 1, pp. 41–62, 2008.

[7] K. L. Gordon, R. K. Penner, P. B. Bogert, W. T. Yost, and E. J. Siochi, "Puncture Self-Healing Polymers for Aerospace Applications," *Conference of NASA: American Chemical Society National Meeting and Exposition*, vol. 242, pp. NF1676L–12 452, 2011.

[8] S. Hunt, T. G. McKay, and I. A. Anderson, "A self-healing dielectric elastomer actuator," *Applied Physics Letters*, vol. 104, no. 11, pp. 413–420, Mar. 2014.

[9] Z. Wei, J. He, T. Liang, H. Oh, J. Athas, Z. Tong, C. Wang, and Z. Nie, "Autonomous self-healing of poly(acrylic acid) hydrogels induced by the migration of ferric ions," *Polymer Chemistry*, vol. 4, no. 17, pp. 4601–4605, 2013.

[10] G. Arunalatha and C. Jhoncy, "Self-healing robots," *Proceedings of International Conference on Emerging Trends in Robotics and Communication Technologies (INTERACT), IEEE*, pp. 283–287, Dec. 2010.

[11] M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian, "Modular Self-Reconfigurable Robot Systems [Grand Challenges of Robotics]," *Robotics & Automation Magazine*, vol. 14, no. 1, pp. 43–52, 2007.

[12] S. H. Cho, S. R. White, and P. V. Braun, "Self-Healing Polymer Coatings," *Advanced Materials*, vol. 21, no. 6, pp. 645–649, Feb. 2009.

[13] G. Scheltjens, M. Diaz, J. Brancart, G. Van Assche, and B. Van Mele, "A self-healing polymer network based on reversible covalent bonding," *Reactive and Functional Polymers*, vol. 73, no. 2, pp. 413–420, Feb. 2013.

[14] C. Hou, T. Huang, H. Wang, H. Yu, Q. Zhang, and Y. Li, "A strong and stretchable self-healing film with self-activated pressure sensitivity for potential artificial skin applications." *Scientific reports*, vol. 3, no. 1, pp. 3138–3142, Jan. 2013.

[15] P. Beckerle, "Practical relevance of faults, diagnosis methods, and tolerance measures in elastically actuated robots." *Control Engineering Practice*, vol. 50, pp. 95–100, 2016.

[16] B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, E. Burdet, D. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, M. Garabini, M. Grebenstein, G. Grioli, S. Haddadin, H. Hoppner, A. Jafari, M. Laffranchi, D. Lefeber, F. Petit, S. Stramigioli, N. Tsagarakis, M. Van Damme, R. Van Ham, L. Visser, and S. Wolf, "Variable impedance actuators: A review," *Robotics and Autonomous Systems*, vol. 61, no. 12, pp. 1601–1614, Dec. 2013.

[17] M. Van Damme, P. Beyl, B. Vanderborght, R. Versluys, R. Van Ham, I. Vanderniepen, F. Daerden, and D. Lefeber, "The Safety of a Robot Actuated by Pneumatic Muscles: A Case Study," *International Journal of Social Robotics*, vol. 2, no. 3, pp. 289–303, Jan. 2010.

[18] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *Intelligent Robots and Systems 95. Proceedings of IEEE/RSJ International Conference on Human Robot Interaction and Cooperative Robots*, vol. 1, Aug. 1995, pp. 399–406.

[19] G. Carpino, D. Accoto, F. Sergi, N. Luigi Tagliamonte, and E. Guglielmelli, "A Novel Compact Torsional Spring for Series Elastic Actuators for Assistive Wearable Robots," *Journal of Mechanical Design*, vol. 134, no. 12: 121002, Oct. 2012.

[20] N. G. Tsagarakis, M. Laffranchi, B. Vanderborght, and D. G. Caldwell, "A compact soft actuator unit for small scale human friendly robots," *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, pp. 4356–4362, 2009.

[21] N. Paine, S. Oh, and L. Sentis, "Design and Control Considerations for High-Performance Series Elastic Actuators," *Proceedings of IEEE/ASME Transactions on Mechatronics*, vol. 19, no. 3, pp. 1080–1091, 2014.

[22] T. Verstraten, R. Furnemont, G. Mathijssen, B. Vanderborght, and D. Lefeber, "Energy Consumption of Geared DC Motors in Dynamic Applications: Comparing Modeling Approaches," *IEEE Robotics and Automation Letters*, vol. 1, no. 1, pp. 524–530, Jan. 2016.

[23] S. Terryn, G. Mathijssen, J. Brancart, D. Lefeber, G. Van Assche, and B. Vanderborght, "Development of a self-healing soft pneumatic actuator: a first concept," *Bioinspiration & Biomimetics*, vol. 10, no. 4:046007, 2015.

[24] ——, "Investigation of self-healing compliant actuators for Robotics," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 258–263.

[25] A. J. Flocchini, "Mechanical fuse," *Washington, DC: U.S. Patent and Trademark Office.*, no. Patent No. U.S. 4,716,635., 1988.

[26] J.-j. Park, H.-s. Kim, and J.-b. Song, "Safe robot arm with safe joint mechanism using nonlinear spring system for collision safety," *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, vol. May, pp. 3371–3376, May 2009.

[27] M. Plooij, G. Mathijssen, P. Cherelle, D. Lefeber, and B. Vanderborght, "Lock Your Robot: A Review of Locking Devices in Robotics," *Robotics & Automation Magazine*, vol. 22, no. 1, pp. 106–117, 2015.

[28] B. Vanderborght, N. G. Tsagarakis, R. Van Ham, I. Thorson, and D. Caldwell, "MACCEPA 2.0: compliant actuator used for energy efficient hopping robot Chobino1D," *Autonomous Robots*, vol. 31, no. 1, pp. 55–65, 2011.

[29] G. Mathijssen, D. Lefeber, and B. Vanderborght, "Variable Recruitment of Parallel Elastic Elements: Series-Parallel Elastic Actuators (SPEA) With Dephased Mutilated Gears," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 2, pp. 594–602, 2014.

[30] N. G. Tsagarakis, G. Metta, G. Sandini, D. Vernon, R. Beira, F. Becchi, L. Righetti, J. Santos-Victor, a. J. Ijspeert, M. C. Carrozza, and D. G. Caldwell, "iCub: the design and realization of an open humanoid platform for cognitive and neuroscience research," *Advanced Robotics*, vol. 21, no. 10, pp. 1151–1175, Jan. 2007.

[31] S. Hernàndez and J. G. Alenyà Ribas, "iCub Platform IIT Workshop in Genova a Ribas," in *iCub platform: IIT workshop in Genova.*, 2010.

[32] K. a. Wyrobek, E. H. Berger, H. M. Van der Loos, and J. K. Salisbury, "Towards a personal robotics development platform: Rationale and design of an intrinsically safe personal robot," in *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, May 2008, pp. 2165–2170.

[33] N. G. Tsagarakis, J. Saglia, and D. G. Caldwell, "The design of the lower body of the compliant humanoid robot cCub," in *Proceedings of IEEE International Conference on Robotics and Automation (ICRA)*, no. February 2016, May 2011, pp. 2035–2040.

[34] M. Grebenstein, M. Chalon, W. Friedl, S. Haddadin, T. Wimbock, G. Hirzinger, and R. Siegwart, "The hand of the DLR Hand Arm System: Designed for interaction," *The International Journal of Robotics Research*, vol. 31, no. 13, pp. 1531–1555, Nov. 2012.

[35] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive synergies for the design and control of the Pisa/IIT SoftHand," *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, Apr. 2014.