A Healable Resistive Heater as a Stimuli-Providing System in Self-Healing Soft Robots

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***Abstract*—Self-healing polymers can address the damage susceptibility in soft robotics. However, in most cases, their healing requires a heat stimulus, provided by an external device. This letter presents a self-healing soft actuator with an integrated healable flexible heater, functioning as the stimuli-providing system. The actuator is constructed out of thermoreversible elastomers that are crosslinked by the Diels-Alder (DA) reaction, which provides the healing ability. The heater is manufactured from a DA-based composite network filled with 20 wt% carbon black to provide electrically conductive properties for resistive Joule heating. The flexibility of the heater does not compromise the actuator performance upon integration and the self-healing properties of both heater and actuator allow for damage repair. This includes very large damages, as both heater and actuator can recover (near 100%) from being cut completely in two pieces, using Joule heating at 90°C with a bias voltage of about 30 V. The embedded heater avoids the need for external intervention in the healing process, and provides healing quality assessment and a healing on-demand mechanism, paving the way for an optimum healing solution of damage resilient soft robots that require heat as a healing stimulus.**

***Index Terms*—Bending actuator, embedded heater, healable robot, self-healing heater, self-healing polymer, soft gripper.**

I. Introduction

IN THE past decades, soft robotics has pushed developments on material [1] actuator [2] and manufacturing techniques [3] for a large variation of capabilities including gripping [4] manipulation [5] and locomotion [6] However, the inherent vulnerability of these robots towards damage induced by sharp objects, tendon cut, overloading, and fatigue still remains a big challenge [7], [8].

In the early 21st century, the emergence of self-healing polymers brought new strategies for damage resilience [9]. This remarkable artificial healing ability was exploited in soft robotic components by constructing them out of self-healing elastomeric network polymers [10]–[12]. Consequently, these systems can heal from macroscopic damages in the centimeter scale, recovering their functionalities after healing [13]. This artificial healing can be autonomous [14], or non-autonomous [11].

The healing ability is referred to as autonomous, if no external stimulus is required to activate the healing action, other than the damage itself. There exist a wide variety of autonomous intrinsic self-healing polymers, in which the healing is provided via physicochemical crosslinks, including hydrogen bonds [15], metal-ligand complexes [16], and ionic bonds [17]. Although healable at room temperature, the mechanical strength of these networks is in general limited to a few MPa with a limited healing efficiency [7], [18]. One approach to solve the weak mechanical strength of these networks is to tune the properties by adding fillers [19], [18].

Healing can be introduced via reversible covalent bonds as well, resulting in higher mechanical strength [7]. However, their higher bond energy leads to non-autonomous healing in the material. Nonetheless, the covalent Diels-Alder (DA) reaction was used by the authors to demonstrate successful healing at room temperature after one week in a soft bending actuator [14]. Also in this material, the mechanical strength is limited to a few MPa, limiting the force output of the actuator [20]. To conclude, there is a general trade-off between, on the one side mechanical strength and stability and on another side healing time and temperature. In literature, most of the self-healing materials used for robotics applications need stimuli for healing [21].

In non-autonomous systems, an external device such as a heat or a light source is used to trigger the healing procedure. Using light is limited to thin soft robotic structures, due to the limited penetration depth of this system (up to 0.5 mm) [7]. Therefore, most reversible covalent elastomers in soft robotics require heat

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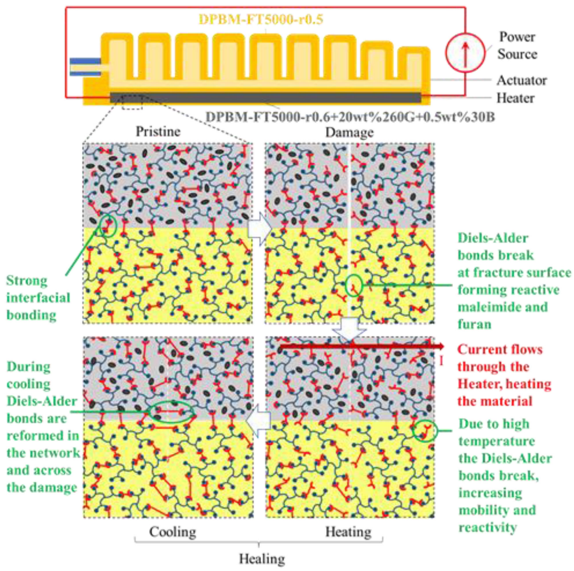


Fig. 1. Schematic of the self-healing bending soft pneumatic actuator, composed of non-conductive DPBM-FT5000-r0.5 and conductive DPBM-FT5000-r0.6+20wt% 260G+0.5wt% 30B. Both materials are self-healing Diels-Alder elastomers, which are covalently bond together at the multi-material interface and can recover from large macroscopic damage.

to heal, which is provided by an external device (e.g., oven) [10], [11], [12].

Despite the most common approach for healing activation [10], [11], external heating does not allow for local heating, as such it is not energy efficient. In addition, some parts of the robotic system, like electronics, cannot be heated to high temperature. Therefore, the authors believe that in many self-healing soft robotics applications local heating/healing will be desired.

In robotics, a stimulus providing system (e.g., heater) can be integrated due to the presence of a power supply and a (micro) controller. As such a soft robot with integrated stimuli providing system can heal without human intervention, even though constructed out of non-autonomous self-healing polymer. In addition, using this approach, healing of partially damaged components can be postponed until mission completion. Furthermore, prior to healing, cleaning and alignment can be checked for an optimum recovery.

Joule-effect flexible heaters have demonstrated various practical applications in wearable devices for healthcare [22], [23], [24], variable stiffness structures for foot-drop treatment [25], and electrothermal actuators [26], [27]–[29]. These are usually composed of polymers or fabrics combined/coated with conductive agents, mostly carbon black (CB), graphene, silver nanowires (AgNWs), copper nanowires (CuNWs), or liquid metals [30]–[36]. All are fundamentally soft and consequently safe but also susceptible to failure. Moreover, Tonazzini *et al.* have exploited Joule-effect of a wire for phase changing of a healable low melting point alloy to make a variable stiffness fiber used in robotics applications [20].

Within the domain of repairable materials [37], Tiwari *et al.* [38], Khatib *et al.* [39], and Willocq *et al.* [40], have reported on healable ohmic heaters for applications, such as goggle defogging and scratch removal and healable electronic skins.

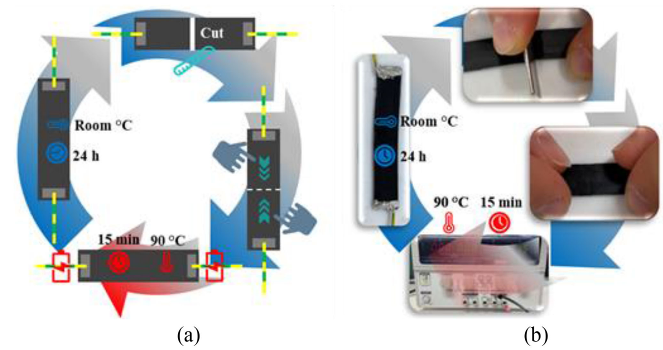


Fig. 2. Steps in damage-healing cycles of the heater (**a**) Schematically, and (**b**) Physically. It includes cutting the sample in two, manually recontacting the two sides, raising the temperature to 90 °C by about 30 V for 15 minutes, and keeping at room temperature for one day.

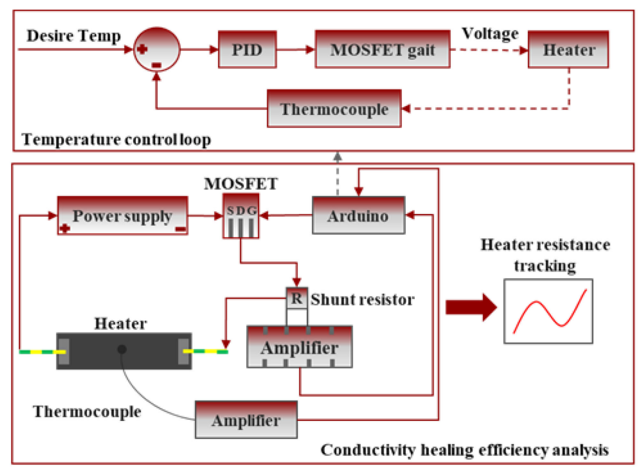


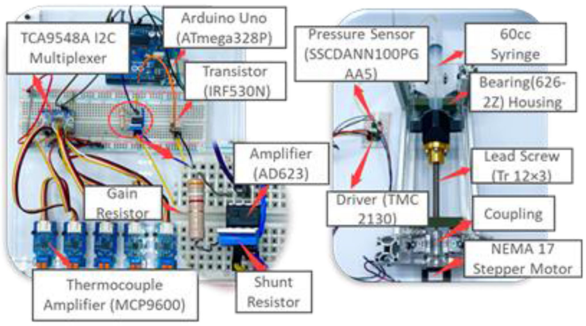
Fig. 3. Circuit diagram of the resistance tracking and temperature control.

Although being able to recover scratches, the ability to heal big-scale damages, for example being cut in two, is still a remaining challenge. In addition, Guo *et al.* [41], have conducted research on a bio-degradable self-healing heater, which is suitable for low-temperature applications as it is decayed at almost 70°C. In general, the concept of a healable heater for healing activation in soft robotics is not yet explored.

This presents an embedded healable heater inside a bending soft pneumatic actuator, being able to repair itself and the actuator from large macroscopic damages, being cut in two (Fig. 1). When damaged, the heater localizes the heating at that site. Several conducted experiments on conductivity and mechanical property restoration in cyclic damage-healing experiments validate its functionality.

II. METHODOLOGY

The actuator is constructed out of a non-conductive self-healing polymer; a reversible DA crosslinked elastomer (DPBM-FT5000) with stoichiometric maleimide-to-furan ratio of 0.5 (Fig. 1) [12]. Upon damage the DA crosslinks break locally (Fig. 1). When heating (e.g., 90°C), inside the damaged polymer a large fraction of crosslinks break reversibly, increasing the reactivity and mobility, leading to the sealing of the damage



(a) (b)

Fig. 4. Actuation and sensing systems (**a**) The circuit for temperature control by voltage tunning via a transistor. Multiple thermocouples are used for temperature distribution analysis running through a multiplexer used for I2C communications of multiple thermocouple amplifiers (MCP9600) with a same address. In series with the transistor, using a shunt resistor and an amplifier (AD623) the current passing through the heater is measured for resistance tracking ($\mathrm{R} = \frac{\mathrm{V}}{\mathrm{I}}$) (**b**) The linear pressure controller system for the pneumatically driven soft actuator.

on microscopic level. Upon cooling to room temperature, the crosslinks are reformed, binding across the damaged site and restoring the initial properties.

To achieve electrical conductivity for the heater, two types of filler were added to a similar DA polymer, DPBM-FT5000-r0.6; 20 wt% of Ensaco 260G Carbon Black (CB) (Imerys) and 0.5 wt% of Cloysite 30B nanoclay (Southern Clay Products).

As a result, the heater can provide enough heat, by Joule-effect, breaking the DA crosslinks (Fig. 1).

Apart from being healable, the covalent bonds among different DA materials makes a strong interfacial connection between the heater and the robot and prevents debonding [10]. In addition, These DA materials are recyclable meaning that they can be remolded or dissolved by an appropriate solvent and reduce environmental footprint of the system [11].

A. *Healing Quality Assessment*

A four-step healing process is applied, after which the healing efficiency is investigated (Fig. 2). First, the heater is completely cut through in the middle using a scalpel blade. Second, the two pieces are manually recontacted. Third, the voltage is applied until reaching 85-95°C and maintaining this for several minutes. This period when current flows through the heater is only 15 minutes for conductivity healing efficiency evaluation (the heater reacts very fast in conductivity recovery) and 45 minutes for mechanical restoration analysis. Finally, the heater is kept for one day at room temperature giving time to reform bonds. By comparing the resistance before damage and after healing, as well as the strain and stress at break, the conductivity and the mechanical healing efficiency are evaluated. Additionally, to verify that the embedded heater can recover its functionality and that of the actuator, the trajectory and bending angle vs pressure are compared before damage and after multiple damage-healing cycles.

It should be noted that one of the most important parameters in healing efficiency is a proper realignment after encountering large damages. As an example of an autonomous approach, Carden *et al.* have developed a magnetic composite material for damage closure [42].

B. *Measurements and Control*

Side reactions and the resulting degradation in healing properties in DA materials owing to overheating necessitates temperature controlling during the heat treatment process.[10] Using a PID loop, the temperature is controlled by tuning the voltage input of a MOSFET transistor, according to the feedback from type-K thermocouple (Fig. 3). Direct contact of the thermocouples' junction with the heater is avoided by LOCTITE 315 thermally conductive/electrically insulation paste to limit noises. In addition, to monitor the changes in resistance in experiments, a current measurement system, including a shunt resistor and an amplifier, is implemented (Figs. 3 and 4a). Moreover, to compare Joule heating with heating by an external device, an LCR meter (Keysight E4980AL) measures the resistance of the samples while they are heated in an oven.

In order to perform tensile tests and assess the mechanical healing efficiency, a Tinius Olsen tension machine is used. We consider $0.5\%.s^{-1}$ rate for the strain in each tensile test. Further, a linear pressure controller system has been developed to drive the bending actuator (Fig. 4b).

III. Self-Healing Heater

A. *Fabrication*

The hybrid composite which is prepared by mixing the CB and the nanoclay with the matrix, is poured in a one-side Teflon mould and placed in vacuum at 90°C for 24 hours. The cast sheets are then ground and put inside the inlet of a two-side pre-heated Teflon mould at 120°C for 30 minutes. Then the particles are pressed and gradually cooled. Finally, two wires are connected to each of the samples using MG Chemicals 9410 electrically conductive adhesive (Fig. 5).

B. *Resistive Heating*

Based on the Joule's law ($Q = RI^2t$) and specific heat formula ($Q = mc\Delta T$), the amount of energy Q produced by passing current I through a substance with resistance R, specific heat c and mass m, changes the temperature ΔT. The design of the presented heater is a compromise between the weight percent of added CB and Clay (details of this selection is out of the scope of this paper), the heal-ability of the heater (increasing the CB content compromises the healing efficiency), the desired temperature for healing (85-95°C), the size and topology of the heater that affects the resistance ($R = \frac{\rho l}{A}$) and the required power supply. Considering the target robotic demonstrator, the size of the heater is chosen to be $1 \times 10 \times 60$ mm in thickness, width and length respectively (Fig. 5). In this paper the characterization is performed at 25°C.

C. *Characterization*

Applying 30 V can increase the temperature of the heaters up to 90°C in 8 minutes starting from room temperature. However, as the power relates to the current squared ($P = RI^2$), this

Fig. 5. Processing of the heater. Cast composite is ground and put inside the inlet of the pre-heated mould at 120 °C. After 30 minutes of heating, it is pressed and gradually cooled. Then the mould is opened, and the main section is trimmed. Finally, two wires are attached by a curable conductive paste.

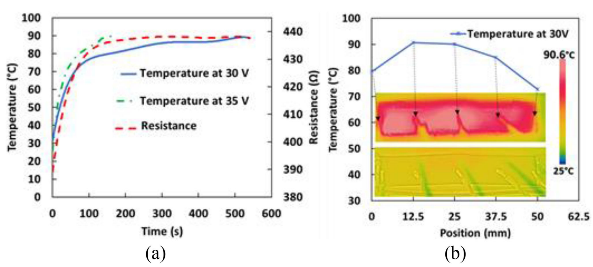


Fig. 6. Heating analysis of the heater (**a**) Comparison of rising rate of temperature with 30 V and 35 V. In parallel with the increase in temperature, the resistance is also increased due to positive temperature coefficient. (**b**) The heater has almost a symmetric heat distribution with 15 °C difference between the highest and lowest temperature.

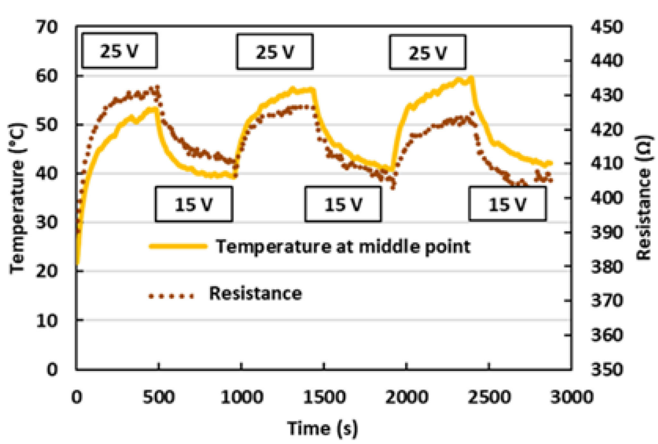


Fig. 7. Behavior of the heater in cyclic heating. As seen, the heater exhibit an stable characteristics when the voltage is shifted between 15V and 25V.

duration sharply decreases to less than three minutes with 35 V (Fig. 6a). When increasing the temperature, the resistance increases which indicates that the heater is a Positive Temperature Coefficient (PTC) heater (Figs. 6a and 7). A possible explanation is that inside of the composite, agglomerates of conductive parts are formed within the non-conductive matrix. Upon heating, the matrix expanses and the distance between the conductive agglomerates increases, leading to an increase in resistance. However, this doesn't mean that the material is instable as this is a reversible and reproducible behaviour. Fig. 7 clarifies this claim where the heater shows a reversible behaviour in cyclic heating between 15V and 25V in 8 minutes interval. PTC heaters have many advantages in comparison with fixed-resistance heaters, as they eliminate the risk of overheating and lead to more even heat distributions, and faster heating response [43].

To visualize the thermal behaviour of the heaters, a FLIR One Pro thermal imaging camera is used. Keeping all the default parameters of the camera, the optimized distance between the camera and the heater was about 15 cm which was calibrated by a thermocouple. As seen in Fig. 6b, except the sides, the heat is almost evenly distributed along the heater. Although the composite is made via extensive mixing using a magnetic stirrer, there are some locations where the heat is more concentrated. Furthermore, owing to the higher amount of heat lose at the connectors, the sides are a bit cooler.

D. *Conductivity Healing Efficiency*

To investigate the recovery of the conductivity and thermal properties, heaters were cut completely in half and healed using Joule heating and external heating for five damage-healing cycles (Fig. 8a and 8b). In all the cycles, the resistance drops from the kilo-ohm scale (when brought back in contact) to few hundred ohms in a few seconds, recovering the conductivity to up to 90% and after 15 minutes it reaches to more than 95% of the initial conductivity measured before the damage (Fig. 8a). It is worth noting that the resistance further decreases during cooling, owing to the PTC phenomenon and crosslinking in the network. After a day the conductivity is restored by near 100%.

To benchmark the Joule-effect healing mechanism, its healing was compared with heating by an external device and one sample was healed in an oven. Fig. 8b shows that at least 45 minutes is required to restore near 95% of the conductivity. This figure is reduced to 70% at the fifth damage-healing cycle. Note that the final healing efficiency also depends on how well the two damaged sides are aligned.

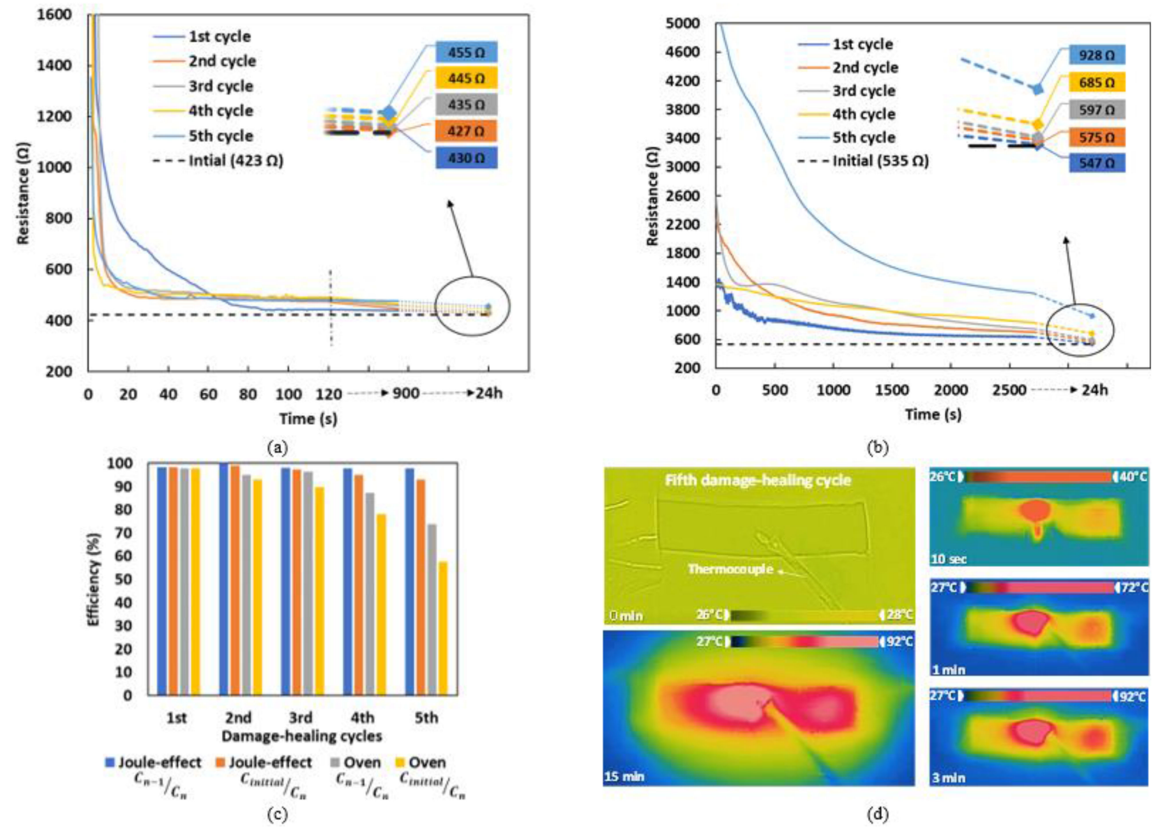


Fig. 8. Conductivity healing efficiency analysis. **(a)** Tracking the changes in resistance in five damage-healing cycles of a sample heated by Joule-effect shows recovery of more than 90% in less than two minutes and near 100% after one day. **(b)** The recovery of another sample in five damage-healing cycles heated in an oven at 90 °C is slower. **(c)** Comparison of the conductivity healing efficiency of the two methods using different stimuli providing system. **(d)** Joule-effect provides localized heating around the damage site. Due to healing, the temperature distribution evolves gradually from localized to evenly distributed along the heater.

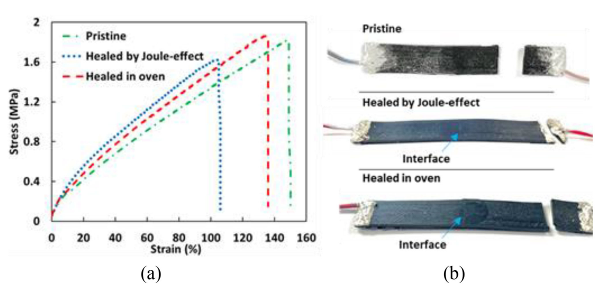


Fig. 9. Mechanical healing efficiency analysis (a) Tensile test of three samples with a strain rate of 0.5%.s-1. The variations between the graphs can be addressed to tiny bubbles inside the samples, as well as the changes in manually clamping the samples in the tensile machine. (b) None of the healed samples broke at the healed damage site (interface).

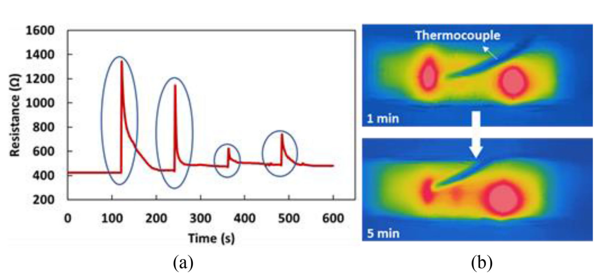


Fig. 10. Heater as a damage detection sensor **(a)** Damage can be detected by sharp increase in resistance. **(b)** Right-side damage shows misalignment as it is not healed after 5 minutes unlike the left one which has been aligned well.

Fig. 8c compares the conductivity healing efficiency of both methods by calculating the recovery of the initial conductivity of the pristine sample ($C_{initial}$) or the conductivity prior to the cycle n ($C_{n\text{-}1}$). Based on the speed of recovery and the final recovery of the conductive properties, it can be concluded that healing via Joule heating is superior to healing via an external heat source.

Fig. 8d shows that there is a transition of concentrated heat generation (localized increase in the resistance by damage) at the damage site (3 min) to a more evenly heat distribution later in the treatment (15 min). This illustrates the localized healing in the heater.

E. Mechanical Healing Efficiency

To investigate the recovery of the mechanical properties, three samples are subjected to tensile tests (Fig. 9a): One pristine heater, one heater that was healed by Joule-effect and one that was healed in an oven. Fig. 9b shows that none of the heaters have been broken at the healed damage site.

Nevertheless, there are some differences in the fracture strain and stress between the three samples. As seen, the sample that was healed by Joule-effect broke sooner than the two others from the electrical connectors. These variations can originate from the existence of bubbles or small defects inside the samples and due to the changes in manually clamping in the tensile test setup.

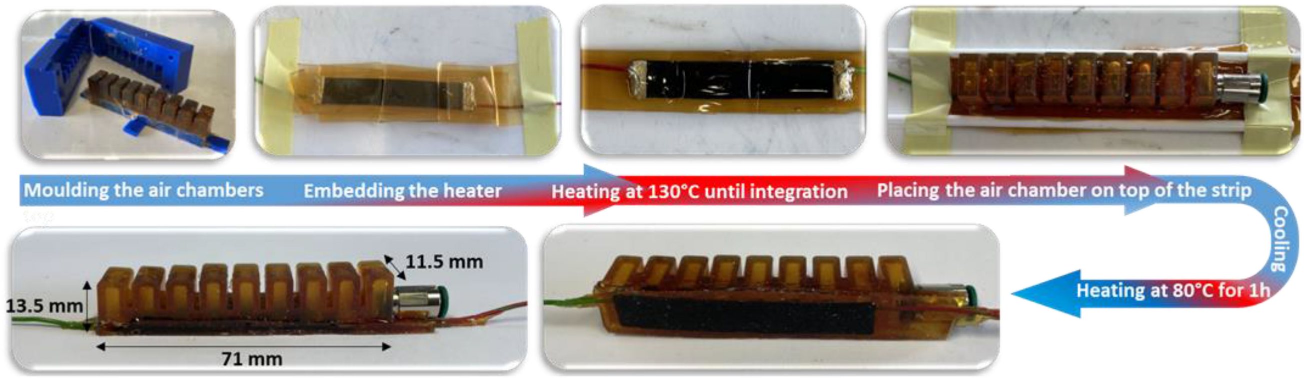


Fig. 11. Embedded heater in the soft actuator. The air chambers are made by a two-side plastic mould like the technique used to process the heater. The strip is then fabricated by embedding the heater between layers of DPBM-FT5000-r0.5 and heating to 130 °C, above the degelation temperature. As a result the viscous DPBM-FT5000-r0.5 flows around the heater. While the strip is still a viscous fluid, the air chambers are placed on top of it and the assembled part is kept for one day at room temperature. At last, the whole actuator is heated for an hour at 80°C, to ensure sufficient covalent bonding between the assembled parts and strong interfacial strength due to Diels-Alder bonds.

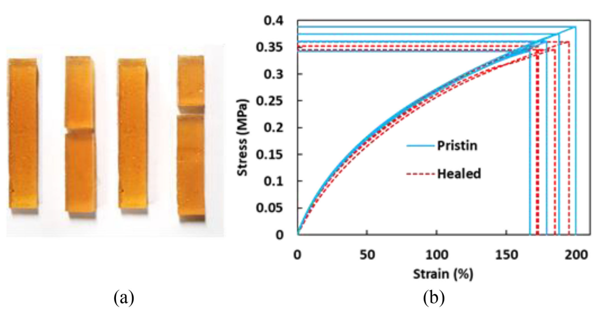


Fig. 12. Heal-ability of the matrix **(a)** Pristine, damaged, healed and fractured samples of DPBM-FT5000-r0.5 used to construct the actuator **(b)** Comparison of the mechanical properties of pristine sample and four healed samples shows a mean healing efficiency of 96%.

Overall, after healing, heater can be strained completely without fracture to more than 100% and bear over 1.6 MPa stress.

IV. Heater as Damage Detection Sensor

As the resistance of the heater changes upon damage, towards the kiloohm region and decreases during healing until the initial resistance at full recovery (Fig. 10a and 10b), the heater can be used as a damage detection and localization sensor, as well as a healing monitoring sensor. In a robotic system the resistance can be checked upon operation. Damage can be measured as a sharp increase in resistance (Fig. 10a). During heating/healing, the damage location can be detected by checking the heat distribution (Fig. 10b).

In addition, the recovery of the conductivity can be a valuable parameter for the healing monitoring. Misalignment or incomplete healing leads to an increase in resistance and can be detected by the heater as well. In Fig. 10b, due to misalignment, the right-side damage is not healed as the left one. Consequently, in the future the heater can not only be used to provide stimulus but also for health and healing monitoring.

V. Self-Healing Soft Robot

A. Fabrication and Heater Integration

The actuator demonstrator is based on the previously designed bending pneumatic actuators [10]. It has a length, height and width of 71 mm, 13.5 mm and 11.5 mm respectively. The wall thickness of this actuator is 1.75 mm. It is composed of two main sections: the air chambers (top) and a strip (bottom). When used in a soft gripper or bionic hand [11], the bottom surface of the strip will be in contact with the grasped objects, making it the most vulnerable part of the actuator. Hence, the heater is embedded inside this bottom strip (Figs. 1 and 11). As seen in Fig. 11, the air chambers are first manufactured via compression moulding of grinded elastomer [44]. The heater is then sandwiched between layers of the DPBM-FT5000-r0.5 elastomer and placed in an oven at 130°C. At this temperature the material degels, flowing around the heater and providing excellent contact between the stacked sheets. The top and the bottom part are joined by placing the top section on top of the bottom layer right after taking the embedded heater out of the oven and by leaving it for several hours at room temperature. Finally, for a better integrity, the entire actuator is heated for one hour at 80°C. Upon cooling, the assembled parts are covalently bond together via strong covalent DA bonds, which leads to robust interfaces inside the multi-material actuator (Fig. 1) [10].

B. Healing of the DA Elastomer

To illustrate healing of the DA elastomer by which the actuator was constructed (Fig. 11), tensile samples of DPBM-FT5000-r0.5 with a gauge length of 7.5 mm, a thickness of 5.5 and a width of 1 mm were made (Fig. 12a). Four pristine samples were subjected to a tensile test with a strain ramp of 1% s^{-1}, until fracture. As illustrated in Fig. 12b, the material has an elastomeric behaviour, characterized by large strains before fracture (up to 200%). Another four samples were cut completely in half (Fig. 12a). After cutting, the parts were brought immediately back in contact, and placed in a hot oven at 80°C for 40 min.

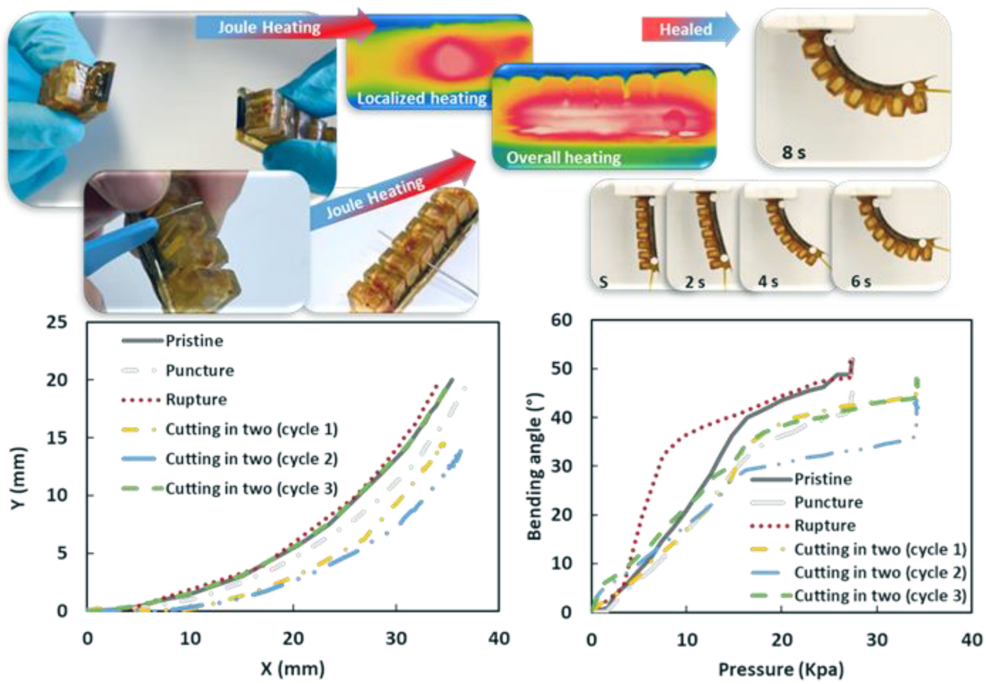


Fig. 13. Soft bending actuator analysis in damage-healing cycles. The embedded heater is able to heal the actuator even if they are completely cut in two. When the heater is damaged, it provides localized heating. The motion of the finger is analyzed via VideoReader in Matlab. Video: https://youtu.be/SX8Sz8WgbCA.

When cooled, the damage is completely healed and the initial mechanical properties are completely recovered. Based on the recovery of the fracture stress, a mean healing efficiency of 96% is measured (Fig. 12b).

C. Soft Robot Performance Recovery

To ascertain the functionality of the heater as a stimuli providing system for self-healing soft robots, it was integrated in a bending actuator (Figs. 1 and 11). The actuator is characterized prior to damage and after five damage-healing cycles. This characterization is performed by tracking the fingertip trajectory and bending angle as a function of the over-pressure, increasing from 0 to almost 30 kPa in 8 seconds. To push the healing to its limits, the actuator and the embedded heater are completely cut in half (Fig. 13). The two sides are brought in recontact and a voltage of 30-35 V is applied to increase the temperature until 90°C. Fig. 13 includes all the variations in the trajectory of the soft actuator and the bending angle relation with pressure after 5 damage-healing cycles. Two types of damage (puncture and rupture) are made in the cell chambers and three times of cutting the finger in two are applied in the backbone of the finger, each time from a different location. There is a noticeable resemblance in the graphs, confirming the heal-ability of the robot with the joule- effect.

VI. Conclusion

Non-autonomous self-healing materials need an external device to trigger the healing. Nonetheless, there are multiple advantages linked to the use of these polymers in healable soft robots, as it permits a higher degree of freedom in inspection and scheduling of the healing and non-autonomous self-healing polymers have in general higher mechanical strength in comparison to autonomous intrinsic self-healing materials. However there is a need for embedded stimuli providing systems that do not compromise the performance of the soft actuator. In order to not influence the flexible characteristic of the actuator in which the heater is integrated, the heaters must be soft and flexible themselves. Being flexible, the heaters are susceptible to damage like the actuators. Consequently, there is a need for embedded heaters that are flexible and healable.

This research proposed a self-healing resistive heater as stimuli provider, embedded in a healable soft robot. The heater was made by combining conductive carbon black particles and clay in a Diels-Alder polymer matrix, being able to reach 90°C at 30 V. The newly integrated healing ability was validated on three levels. On the material level (i), the non-conductive elastomer used to construct the healable actuator, shows excellent healing capacity, with healing efficiencies up to 96% when healing large cuts by external heating (90°C).

On the heater level (ii), it is shown that the conductivity recovers with high healing efficiencies (>95%) after five damage-healing cycles, in which the heater was completely cut in half and healed via Joule heating (15 min at 35V). The heater demonstrated localized heating at the location of severe damages and later a distributed heating after recovery.

Moreover, using Joule-effect made the healing procedure several times faster than typical external heating methods. Considering a higher final recovery of the electrical properties, Joule heating is superior to external heating. The recovery of the mechanical properties was checked via tensile testing on the heaters until fracture. As the fracture does not occur at the location of the healed damage, it could be concluded that for both external heating and Joule heating, no weak spots were created at the location of the healed damage. On the actuator level (iii), the healing ability was pushed to its limits, as both the actuator and the embedded heater were cut completely in half. The actuators performance was almost completely recovered after Joule heating for five damage-healing cycles. Exploiting the presented assistive healing mechanism, permits to make soft robots that can heal fully autonomously from damage, while being constructed out of self-healing polymers that are categorized as non-autonomous, excluding the need of human intervention. Furthermore, the heater can be used as damage detection sensor, as well as a sensor that monitors the healing.

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