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Soft-matter damage detection systems for electronics and structures

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ABSTRACT

Soft-matter technologies are essential for emerging applications in wearable computing, human-machine interaction, and soft robotics. However, as these technologies gain adoption in society and interact with unstructured environments, material and structure damage becomes inevitable. Here, we present a robotic material that mimics soft tissues found in biological systems to identify, compute, and respond to damage. This system is composed of liquid metal droplets dispersed in soft elastomers that rupture when damaged, creating electrically conductive pathways that are identified with a soft active-matrix grid. This presents new opportunities to autonomously identify damage, calculate severity, and respond to prevent failure within robotic systems.

Keywords: Damage detection, liquid metal, soft robots, stretchable electronics, health monitoring

1. INTRODUCTION

Soft materials that sense, actuate, self-heal, and actively tune properties provide opportunities to create highly multifunctional materials.[1–3] This allows for material systems that are highly deformable and mechanically tunable and robust across diverse length scales. The ability for functional materials to bend, stretch, and twist is typically accomplished by utilizing elastomeric substrates as a carrier for active materials. This approach is highly versatile and amendable to diverse materials including deterministically patterned metal wires or wavy circuitry,[4,5] networks of conductive nanomaterials such as carbon nanotubes and graphene,[6,7] and conductive and semi-conducting polymers.[8,9] Another method is to use non-toxic liquid metal alloys such as Galinstan or eutectic gallium indium (EGaIn). This approach has led to highly elastic circuitry,[10] tunable antennas,[11,12] and deformation sensors.[13,14] The use of a conductive liquid combines the desirable electrical and thermal properties of metal with the deformability and softness of fluids, providing an intriguing option for multifunctional soft materials. Such materials can be useful for a variety of applications, including soft robotics[15–17] and "artificial skin" electronics for bio-monitoring and human-machine interaction.[7,18,19]

As these materials move out of the lab and into real-world environments, it is becoming increasingly necessary to monitor material and structural health to detect flaws and the propagation of damage. This is especially important as systems become more complex and performance becomes dependent on the function of individual soft matter components. Conventionally, damage detection has focused on a variety of non-destructive evaluation (NDE) techniques,,[20,21] which we summarize below.

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1.1 Damage Detection

Visual detection can be accomplished through dyes or mechanically induced color change of materials. Liquid dye penetrants can be applied to surfaces, drawn into cracks, and upon the removal of excess dye can be exposed through UV light to reveal flaws.[22] This has been expanded through mechanochemical mechanisms where mechanical force induces chemical bond reformation and color change.[23,24] However, the signal is limited by low contrast and reversible color change, and large strains and concentrated forces are generally required to indicate mechanical damage.[25] Despite their promise for certain monitoring conditions, these techniques often result in a limited visual signal and can require controlled lighting conditions to increase reliability. Micro-capsule techniques have recently demonstrated enhanced contrast with permanent color change.[25] However, visual inspection is best suited for line of sight applications, can be tedious and time consuming, and potentially unreliable, which limits their use in autonomous and deployable systems.[26]

Electromagnetic detection such as Eddy current, magnetic particle inspection, and X-ray techniques interrogate flaws by inducing electric or magnetic fields at the surface or in the bulk of a specimen. In contrast to visual detection, techniques such as Eddy current do not require line of sight and can be performed without contacting the material. However, electromagnetic techniques can have strict material requirements. For example, Eddy current techniques require electrically conductive materials and magnetic field based techniques require the material to be ferromagnetic.[20]

Vibration detection techniques utilize an emitter and receiver pair to detect ultrasonic waves in a structure. For in-situ and compact monitoring, piezoelectric patches have been investigated to simultaneously actuate at high frequencies and sense the dynamic response of the structure or material.[21] Damage can then be detected by comparing to a baseline material through intense signal processing and analysis.[27] This technique utilizes piezoelectric materials such as inorganic PZT transducers and organic PVDF.[28,29] Although successful at detecting damage on inextensible materials and structures, these systems are typically composed of stiff (modulus > 1 GPa) and relatively brittle (strain $< 10\%$) materials such as lead-zirconate-titanate (PZT) or polyvinylidene difluoride (PVDF), making them incompatible with soft and highly deformable materials and structures.[28,29]

Organic materials Due to the advantages of thin-film piezoelectric patches, damage detection systems in recent years have continued to investigate thin-film technology to overcome limitations of the previously mentioned techniques. Recent work has demonstrated the use of photoactive polymers such as poly(3-hexylthiophene) (P3HT) as strain detectors.[30,31] These sensors consist of multiple functional layers including ITO (Indium Tin Oxide) coated polyethylene terephthalate (PET) as an anode and support substrate. These sensors are made of polymeric materials that are only capable of small cyclic extensional strains (0.5%) due to the brittle nature of the materials, limiting their applicability in highly dynamic architectures and deformations.

While promising for inextensible structures or systems where the sensors will be loaded in mild bending modes, all the above-mentioned approaches have limitations when implemented into deformable systems for continuous monitoring. Additionally, these existing methods are typically required to be powered to detect damage. This active approach to sensing leads to an indeterminate expenditure of energy. For true autonomy, the material should be electrically passive and only react (and engage the supporting electronics) when damage occurs.

Soft Materials For soft material systems, damage detection architectures must be mechanically compatible with the host structure, which requires high compliance, flexibility, and stretchability. Nervous tissue provides an example of a soft responsive material system capable of detecting, communicating, and responding to external stimuli. The pathway for such a response is initiated from a distributed network of receptors called nociceptors,[32] which fire action potentials to relay the response to the cortex of the brain. The body then responds by triggering motor pathways to move away from the negative external stimuli. This interconnected response in biological systems has inspired a wide range of stimuli-responsive materials that adapt or respond to environmental changes including temperature, mechanical or physical, optical, and chemical.[33–36] Bio-inspired soft materials that exhibit similar response and which also interface with existing technologies provide a path forward to enable

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intelligent, programmable interactions between external stimuli and dynamic material properties.[1] Recently, autonomy has been incorporated in soft-matter systems through intelligent mechanical design with pre-planned tasks and on-board actuation, power, and computation.[2,37–41] While promising, these systems lack the necessary hardware and sensing to provide critical run-time feedback to modify the pre-planned task. Additionally, for wireless machines in remote areas, power consumption needs to be minimized. This is critical for long-term remote monitoring of deployed systems to achieve system autonomy. The comprehensive system-level integration of components to enable soft-matter robotic materials to be fully self-aware of their current state still remains a significant challenge.

1.2 Present work

In this work we present a soft and elastically deformable "artificial nervous tissue" that can detect and localize multiple forms of damage. The material is composed of micron-sized liquid metal (LM) droplets embedded within a soft silicone elastomer matrix. Previously, the authors and other researchers have shown that LM-embedded elastomer (LMEE) composites can be engineered to exhibit a wide range of material properties – from dielectric insulators[42] with high thermal conductivity[43–45] and toughness[46] to electric conductors[47–50] that autonomously form new conductive pathways when the material is torn, punctured, or removed.[51] Electrical conductivity is only possible with certain compositions and requires extreme pressure or stretch in order to rupture the embedded LM droplets and induce percolation. While these previous efforts have examined the conductivity and electromechanical properties of LMEEs, the electrical response to damage is rarely studied and none of them have explored how load-controlled LM droplet percolation can be harnessed to detect and localize damage within a soft material system. In this study, we show that LMEEs can be incorporated into a soft materials architecture that electrically registers the occurrence and location of mechanical damage caused by compression, fracture, or puncture (Figure 1). When damaged, LM microdroplets within the LMEE will rupture and cause *in situ* conductive pathways between neighboring droplets to form. The damage-initiated change in electrical conductivity can be actively detected and localized through an array of LM soft sensing electronics (Figure 1).

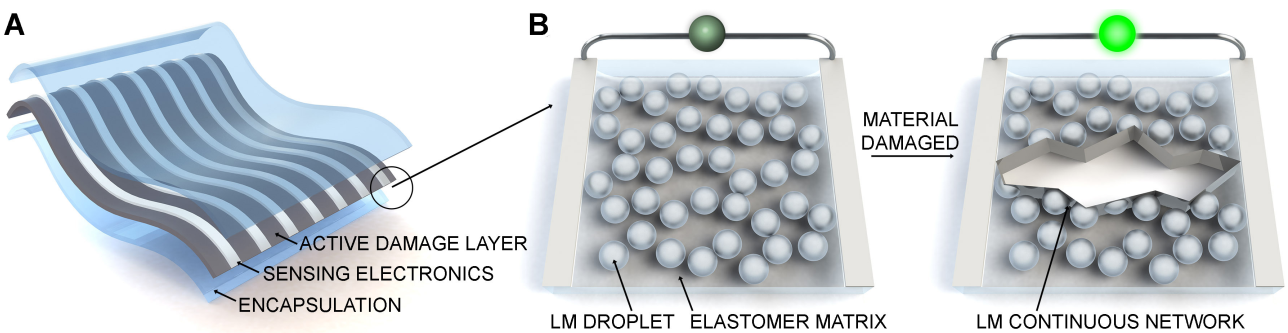

Figure 1. A) Sensing architecture consisting of an active damage layer of LM composite with LM sensing electronics encapsulated in soft elastomer. B) Schematic showing the structure of the active damage layer with LM droplets are dispersed in an elastomer matrix. Prior to damage the droplets isolated and the material is electrically insulating. C) When damage is induced the LM droplets rupture, connect together forming a percolated, electrically conductive network.

2. RESULTS AND DISCUSSION

2.1 Materials

We realize this damage detecting material system using a LMEE material architecture, where Ga-based LM is shear mixed with uncured silicone elastomer at a 1:1 volume ratio ($\phi = 50\%$), forming a suspension of LM microdroplets ($\sim$45 μm particles).[51] This architecture provides significant stress shielding from unintended activation over other droplet film type architectures.[10] We utilize an elastomer blend of Sylgard 184 and Sylgard 527[52] to tailor the mechanical characteristics of the solid-liquid hybrid composite and its sensitivity to mechanical damage. Specifically, we create controlled blends of Sylgard 184 and Sylgard 527, which we quantify by the mass

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percentage of Sylgard 184 within the blend (α). In its undamaged state following synthesis, the composite is electrically insulating ($\sigma < 10^{-7}$ S·cm^{-1}), even at high LM loading ($\phi \geq 50\%$). Once activated, the conductivity for a ϕ=50% composite is $\sigma = 1.37 \times 10^3$ S·cm^{-1}.

2.2 Damage Detection

Upon the application of a critical stress, the microdroplets rupture and are observed to form locally conductive pathways at the point of damage. This transformation enables the detection of a locally damaged region by monitoring the electrical resistance through a sensing layer. The LM traces for the sensing layer are applied directly on top of the damage detection material through a masked spray coating technique. As an example, the composite material is cut and then material damage is electrically detected through a sensing network and communicated in real-time (Figure 2) through LEDs and by monitoring electrical resistance at each trace. As observed in Figure 2C, the traces in the sensing layer are electrically connected by the conductive LM network, which is created by damage from the cut. The signal is a digital response, as the percolation transforms the material from electrically insulating to electrically conductive.

Compression damage can also be sensed in this system. We find that a cylindrical indenter (3 mm diameter) pressed into the material will activate the material at a load between 20-60 N depending on the elastomer blend. However, a $\alpha = 20\%$ blend will not activate under compression and the material will fracture before conductivity is measured in the sensing electrodes.

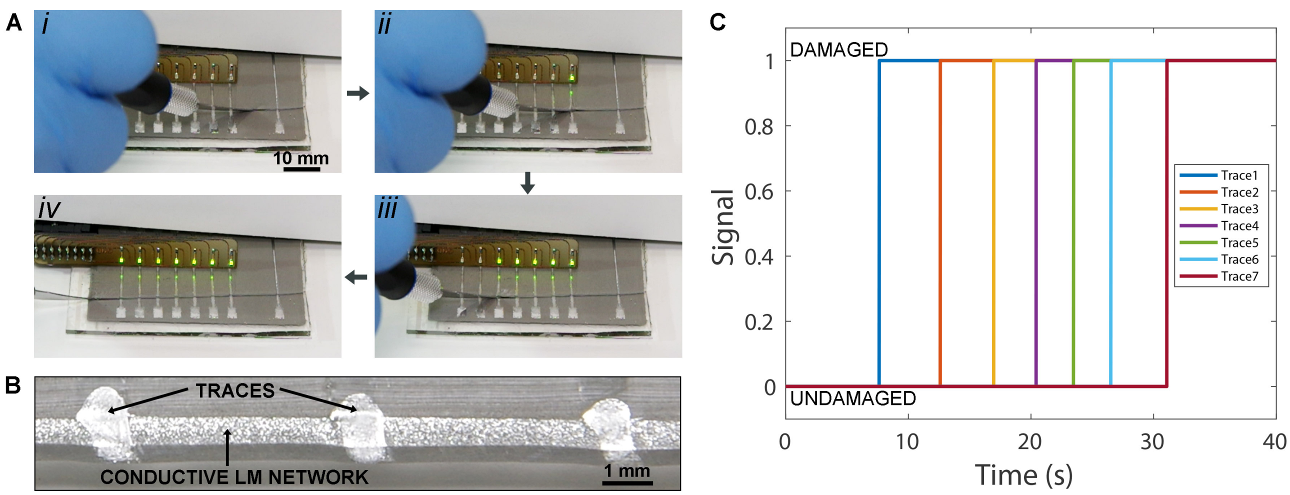

Figure 2. A) Time sequence showing the cutting of a film and damage indication by LEDs. B) Cross-sectional micrograph showing the conductive LM networks upon damage which are sensed by the LM traces. C) The damage detection signal as a function of time as the knife moves across the sensing array.

2.3 2D Damage Detection

To detect damage in 2D, we create sensing electrodes on either side of an active damage detection layer. We choose a row/column electrode configuration so that damage can be detected in a two-dimensional plane to the level of a row/column pair, as seen in Figure 3. By serially measuring the conductivity of each row/column pair, damaged regions can be identified when a row/column pair is electrically connected. This is due to the electrical percolation of the damage sensing layer, which connects the electrodes through the thickness of the damage sensing layer.

To highlight the feasibility of this sensing, communication, and fabrication approach, ballistic damage is inflicted to a 2D damage detection film through a ballistic impact (.22 round). Here damage is inflicted on the material, the damage is localized in two dimensions through the sensing layer, and then a damage response is communicated in real-time over Bluetooth Low Energy to a portable computing device (Figure 3).

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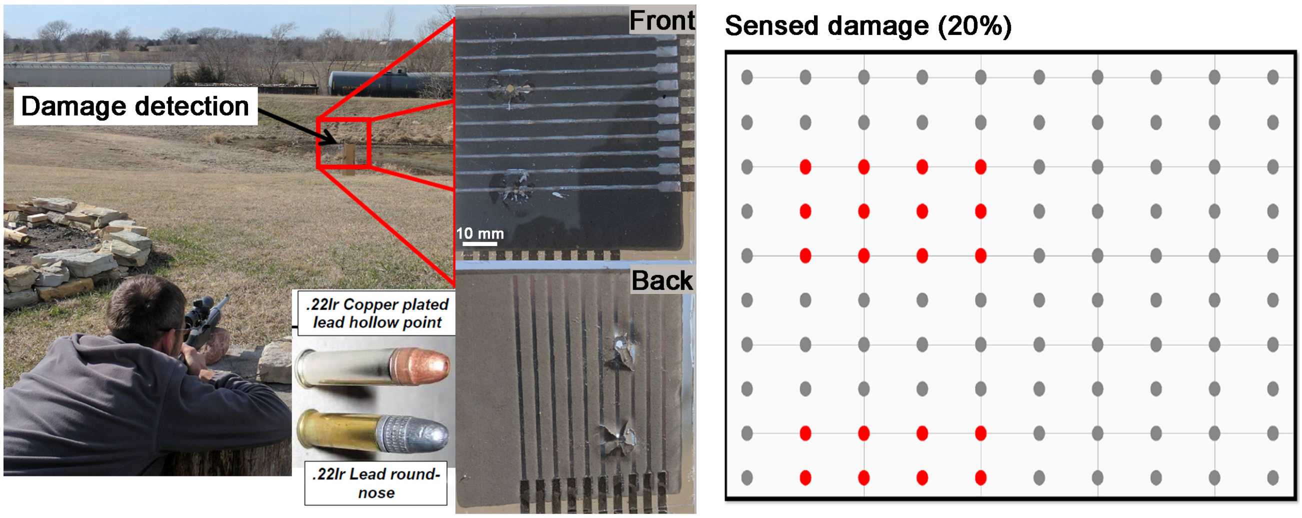

Figure 3. Multiple ballistic damage points identified, quantified (plot), and communicated in real-time. The front and back images show the damage inflicted in the soft matter damage detection system with ballistic impact.

2.4 Damage Selectivity

Damage sensing materials that can differentiate between multiple damage modes can provides tools to evaluate damage severity and size. In our system, to differentiate between indentation and cutting/puncture damage, an $\alpha = 20\%$ composite is layered with a $\alpha = 100\%$ composite (Figure 4). Here, LM electrodes are coated on the two different damage sensing layers and each are individually addressed. During indentation with a cylindrical indenter, it is found that the $\alpha = 100\%$ damage sensing layer activates, while the $\alpha = 20\%$ does not activate (as indicated by only the LED on the $\alpha = 100\%$ layer turning on). The materials are then cut with a razor blade, with an elliptical section of material removed, and both composites activate (as indicated by illumination of LEDs on both composites).

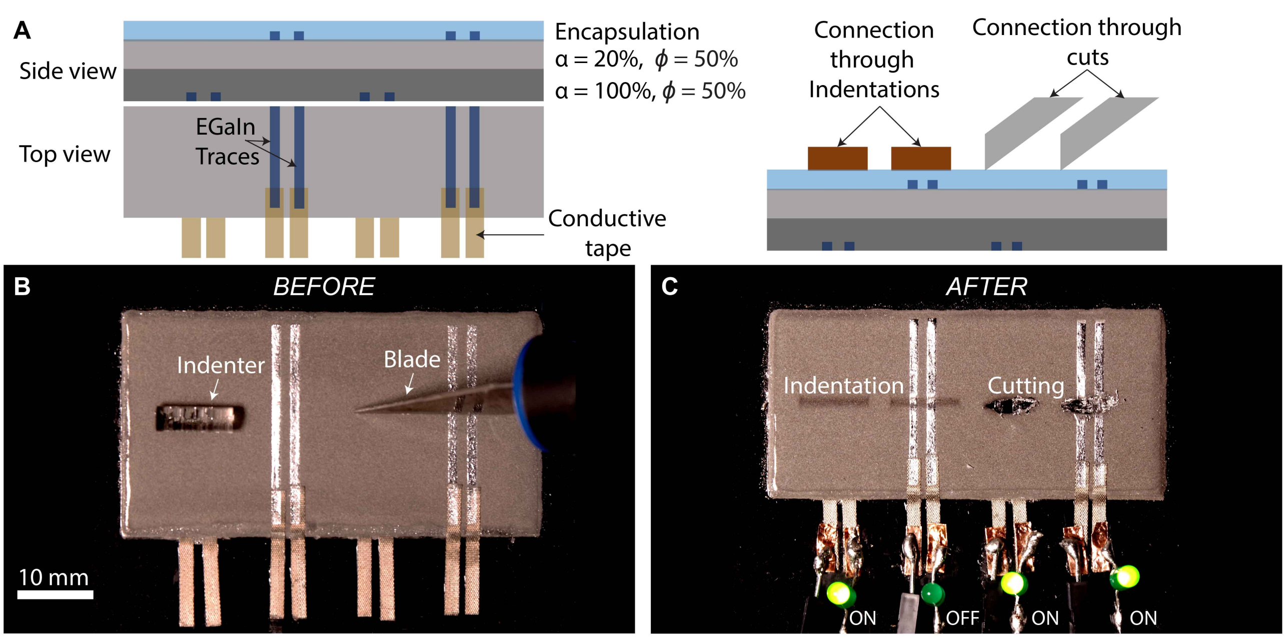

Figure 4. A) Damage selectivity architecture. B) Material before damage and C) Material after indentation and cutting damage with selectivity where compression is sensed when only one LED turns on, and cutting when both turn on.

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3. CONCLUSION

Soft matter damage detection materials can integrate into soft, flexible, or rigid materials without contributing to mechanical stiffness and detect damage under extreme deformation. This versatility can support many emerging technologies like multifunctional and programmable materials or wearable sensors while being compatible with mature technologies like composite and metallic structures.

Another important application is in the robotics domain. Over the past few decades robots have increasingly moved into more autonomous applications. Monitoring material and structural integrity and responding to damage in these systems is essential to successful deployment and continued operation. These damage detection materials are also ideally suited for the emerging area of soft robotics. The high deformability and low mechanical stiffness, will allow integration into soft material structures, actuators, programmable matter, and artificial muscle systems incorporating multifunctionality into these systems.

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