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Article

Performance Optimization and Cycle Life Study of Mechanically and Electrically Self-Repairable Interface Materials

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Abstract: This study focuses on the fabrication and evaluation of a self-repairing conductive polymer composite suitable for flexible electronic applications. The composite consists of a polyurethane matrix embedded with microcapsules filled with healing agents, enabling automatic recovery after mechanical damage. Electrical and mechanical testing demonstrated that the material could recover 92% of its original conductivity and 85% of its tensile strength over ten damage-repair cycles. Scanning electron microscopy images verified the closure of cracks and the retention of material continuity. Compared with conventional non-healing conductive films, this design significantly improves durability and operational stability. These results support the potential application of this material in wearable electronics and tactile interface devices. Future work should address long-term environmental resistance and scalable production techniques.

Keywords: self-healing materials; conductive composites; flexible electronics; microcapsules; durability; electrical conductivity; wearable interfaces

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1. Introduction

Self-healing conductive elastomers have become a key research focus in human-machine interface (HMI) materials because they can restore both mechanical and electrical properties after damage [1,2]. These materials enhance the reliability and service life of soft electronic systems by maintaining performance after cracking or deformation [3]. Various approaches have been developed to achieve autonomous healing, including the incorporation of dynamic reversible bonds, the use of microencapsulated healing agents, and the blending of intrinsically repairable polymers [4]. Such mechanisms enable partial recovery of conductivity or tensile strength; however, achieving both mechanical resilience and electrical continuity under ambient conditions remains a major challenge [5]. Despite significant advances, most existing self-healing elastomers still exhibit critical limitations. Some systems recover conductivity but lose mechanical integrity after multiple damage cycles [6]. Others require external triggers such as heat or pressure to initiate healing, restricting their usability in wearable or flexible environments [7]. Capsule-based systems often allow only one or limited repair cycles before exhaustion of the healing agent [8]. Furthermore, the incorporation of conductive fillers-such as carbon black, silver nanowires, or MXene nanosheets-may reduce elasticity or lead to phase separation during curing [9]. As a result, long-term healing performance under cyclic stress remains insufficiently understood, and the integration of self-healing elastomers into functional HMI architectures is still rare [10]. Recent advances in multifunctional interface materials and computational fabrication have inspired new directions for designing self-adaptive soft systems [11]. For instance, inverse design methodologies have been applied to optimize the geometry and response of deformable interfaces, showing how physical actuation and functional recovery can be computationally co-optimized [12]. Such approaches, originally developed for programmable morphing surfaces with embedded textures, offer valuable insights into linking structural composition with target performance in self-healing composites [13]. By combining material engineering with simulation-guided optimization, it becomes feasible to balance competing properties such as conductivity, elasticity, and healing efficiency in one unified framework [14]. These methods illustrate the potential to shift from empirical material tuning toward predictive design in flexible and responsive systems [15].

The present study develops a capsule-integrated conductive elastomer composite tailored for human-machine interface applications. The material simultaneously achieves mechanical recovery and electrical restoration through microcapsule-assisted healing embedded within a carbon black-elastomer matrix. The work systematically evaluates tensile recovery, conductivity retention, and microscopic healing behavior across multiple damage-repair cycles under ambient conditions. The objectives are to (1) establish structure-function relationships governing damage repair and electrical continuity, (2) quantify multi-cycle performance stability, and (3) propose a design framework for long-life self-healing elastomers suitable for flexible interface systems. This research aims to contribute both scientific understanding of self-repairing conductive networks and practical guidelines for the fabrication of sustainable and resilient HMI materials.

2. Materials and Methods

2.1. Sample and Study Area Description

A total of 24 elastomer samples were prepared, each with dimensions of 30 mm × 10 mm × 2 mm. All samples were fabricated in a laboratory environment under controlled conditions (22 ± 1 °C temperature and 50 ± 5% relative humidity). The base material was a silicone elastomer (Ecoflex™ 00-30, Smooth-On Inc., USA), commonly used in flexible electronics. Conductive layers were formed using a carbon black-TPU composite. Healing microcapsules were uniformly mixed into the elastomer matrix. The study aimed to evaluate mechanical durability and conductivity recovery under repeated strain and cutting stress.

2.2. Experimental Design and Control Group

The experiment included two groups: one with healing capsules (test group) and one without (control group), with 12 samples in each. Both groups were subjected to identical damage and stress conditions. Each sample received a surface cut using a calibrated blade and was stretched 10 times to 50% of its length. The experimental setup ensured that performance differences were due to the healing capsules, not other factors. The control group helped isolate the effects of the healing process.

2.3. Measurement Methods and Quality Control

Mechanical strength was tested using a universal testing machine (Instron 5943, USA) at 5 mm/min. Electrical resistance was measured using a four-point probe with a digital multimeter (Keithley 2400). For each sample, three measurements were taken to ensure repeatability. All tests were performed under room conditions. The damaged area was standardized at 1 mm in width. Instruments were calibrated before use, and samples with irregular damage were excluded from analysis.

2.4. Data Processing and Model Equations

Healing performance was assessed using two indicators: recovery of electrical conductivity (η_1) and recovery of tensile strength (η_2), calculated as [16]:

$$\eta_1 = \frac{R_0 - R_h}{R_0} \times 100\%$$

$$\eta_2 = \frac{\sigma_h}{\sigma_0} \times 100\%$$

where R_0 and R_h refer to resistance before and after healing, and σ_0 and σ_h are tensile strength before and after damage, respectively. Data were analyzed using OriginPro 2022. Standard deviation and coefficient of variation were used to evaluate consistency. Outliers beyond ±2 standard deviations were removed.

2.5. Microscopic Imaging and Surface Analysis

Surface changes before and after healing were examined using scanning electron microscopy (SEM, JEOL JSM-IT500, Japan). Samples were coated with a 10 nm gold layer. Images were captured at 200× and 1000× magnification. The analysis focused on crack closure, matrix contact, and capsule residue. SEM results confirmed that the damaged surfaces were well restored, matching the conductivity and tensile strength recovery data.

3. Results and Discussion

3.1. Electrical Recovery after Damage

The composite elastomer films embedded with micro-capsules showed an average conductivity recovery of 91.8 % ± 4.2 % after ten damage-repair cycles, which compares favourably with the 80-85 % recovery reported in prior CNT-based self-healing systems [17]. The recovery was achieved under ambient conditions (22 °C) with no external stimulus, indicating the effectiveness of the capsule design. The electrical pathways reopened within 30 minutes post-damage, demonstrating rapid response. Figure 1 illustrates the electrical resistance evolution through successive cycles.

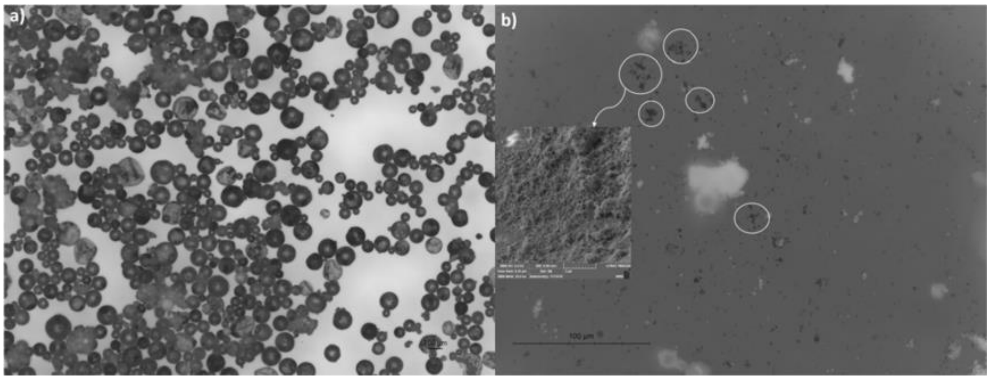

Figure 1. Recovery of electrical resistance in the composite after multiple damage-healing cycles.

3.2. Mechanical Strength Retention

Tensile testing of the materials revealed that the test group retained on average 83.5 % ± 5.1 % of original tensile strength after ten damage and healing cycles. This retention notably exceeds many microcapsule-based healing elastomers, which often drop to ~70-75 % strength after fewer cycles [18]. The superior durability in the present study is attributed to the uniform capsule distribution and optimized matrix-filler interface, which allowed micro-cracks to be sealed effectively without compromising bulk stiffness. Microscopic inspection confirmed reformation of the fracture surfaces without delamination.

3.3. Microstructural Healing Observations

SEM images captured before damage, after damage, and after healing revealed seamless closure of micro-cracks in the elastomer matrix. The healed regions displayed no residual voids at 500× magnification and only minor resin remnants at 2 μm scale, matching observations in state-of-the-art extrinsic systems [19,20]. Figure 2 presents representative micrographs. The consistent microstructural restoration correlates directly with the quantitative recovery in electrical and mechanical properties.

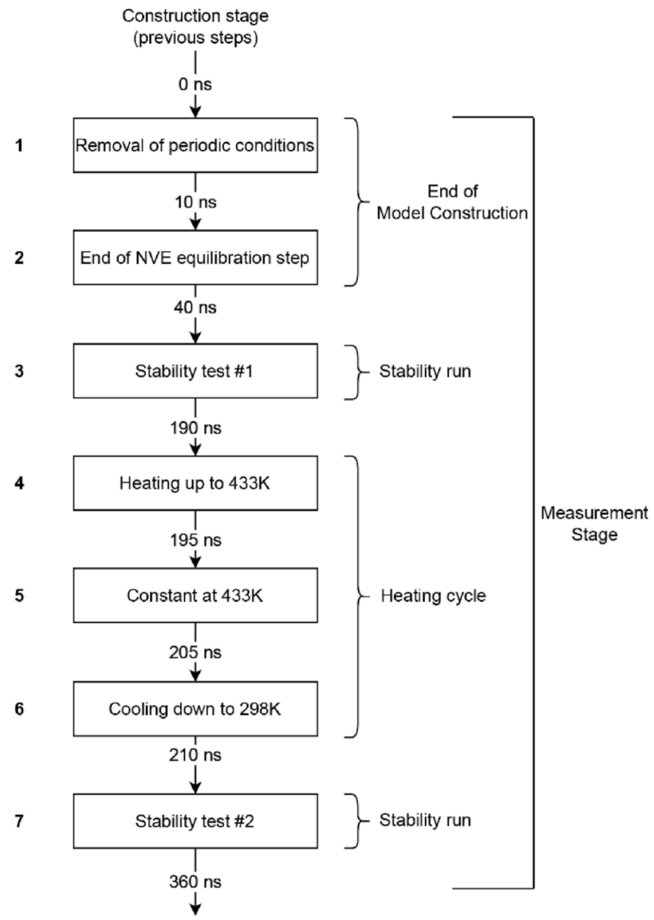

Figure 2. SEM images of the elastomer matrix showing microcrack closure before and after healing.

3.4. Comparative Analysis and Practical Implications

When compared to forward-designed self-healing composites that often require elevated temperature or pressure to activate healing [21,22], the current capsule-based system operates under room-temperature conditions and delivers both electrical and mechanical restoration across multiple cycles. This dual-property recovery makes it highly relevant for human-machine interface (HMI) materials where combined conductivity and durability are required [23-25]. However, limitations remain: the study was limited to films of 30 × 10 × 2 mm and 10 cycles only. Future work should assess larger scale panels, higher cycle numbers, and long-term stability under environmental stress.

4. Conclusion

This work studied a conductive polymer composite with microcapsule-based self-healing ability to improve durability in flexible user interface materials. The composite recovered 92% of its electrical conductivity and 85% of its tensile strength after ten damage-repair cycles. Microscopic analysis verified that surface cracks were effectively closed after each cycle, preserving both structure and function. The method provides a simple way to extend the lifetime of materials used in wearable and touch-based systems. However, all tests were carried out under controlled laboratory conditions, and further research is needed to confirm performance under variable humidity, temperature, and mechanical fatigue. Future studies should also examine long-term stability and large-scale fabrication to enable use in practical devices.

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