Healable thermoset polymer composite embedded with stimuli-responsive fibres

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Severe wounds in biological systems such as human skin cannot heal themselves, unless they are first stitched together. Healing of macroscopic damage in thermoset polymer composites faces a similar challenge. Stimuli-responsive shape-changing polymeric fibres with outstanding mechanical properties embedded in polymers may be able to close macro-cracks automatically upon stimulation such as heating. Here, a stimuli-responsive fibre (SRF) with outstanding mechanical properties and supercontraction capability was fabricated for the purpose of healing macroscopic damage. The SRFs and thermoplastic particles (TPs) were incorporated into regular thermosetting epoxy for repeatedly healing macroscopic damages. The system works by mimicking self-healing of biological systems such as human skin, close (stitch) then heal, i.e. close the macroscopic crack through the thermal-induced supercontraction of the SRFs, and bond the closed crack through melting and diffusing of TPs at the crack interface. The healing efficiency determined using tapered double-cantilever beam specimens was 94 per cent. The self-healing process was reasonably repeatable.

Keywords: self-healing; macroscopic damage; spider silk; biomimetic; smart fibre

1. INTRODUCTION

Inspired by the self-healing of wounds in biological systems, researchers have developed many materials with self-healing capability, such as microcapsule-based self-healing materials and microvascular-based self-healing materials [1–4]. However, for severe and macroscopic damage, these self-healing systems are facing challenges because macroscopic cracks need a large amount of healing agent to fill in, which may deteriorate the matrix mechanical properties, and, additionally, when the healing agent is released, what is left behind may have large defects such as holes [5,6].

This research group proposed a two-step self-healing scheme, close then heal, for macroscopic damages using shape memory polymers [7,8]. In the first step, the macro-cracks were closed as a result of the constrained shape recovery of the shape memory polymer matrix. In the second step, thermoplastic particles (TPs) that were pre-embedded in the shape memory polymer matrix melted, diffused and bonded the closed cracks through molecular entanglement. However, as indicated by Li & Shojaei [9], this system requires a shape memory polymer as the matrix. However, in engineering structures, conventionally used thermosetting polymers do not have shape memory capability. Because of this, Li & Shojaei [9] proposed that regular thermosetting polymer composite structures may be healed by embedding shape memory polymer fibres. It is noted that Kirkby et al. [10,11] embedded shape memory alloy wires in epoxy matrix to narrow down cracks (about 150 μm) by taking advantage of the shape recovery of the shape memory alloy wires. The limitation of this system is that (i) because of the low recoverable strain of shape memory alloy wires, which is below 8 per cent, the capability for shape memory alloy wires to close macro-cracks in polymer composites is limited. (ii) The shape memory alloy wires do not mechanically match the polymer matrix, particularly at the high recovery temperature. At the high recovery temperature, the shape memory alloy wire is very stiff while the polymer matrix becomes soft, limiting the load transfer capability and crack-closing efficiency.

Therefore, as proposed by Li & Shojaei [9], stimuli-responsive shape-changing polymeric fibres with outstanding mechanical properties may be a viable alternative for the purpose of automatically closing macro-cracks. To develop these synthetic fibres, we can learn from nature. Spider silks possess humidity-responsive supercontraction, in addition to outstanding mechanical properties [12–15]. Unfortunately, natural spider silks cannot be obtained in a large scale because spiders cannot be...
farmed. Although much effort has been made to fabricate artificial spider silks, not much success has been achieved as a result of the extreme difficulty of replicating spider silk proteins and mimicking the exact spinning process of spider silks [16,17].

In this research, we developed a spider-silk-like stimuli-responsive fibre (SRF) by synthesizing a non-protein polymer with a similar molecular structure to silk fibroin protein, and fabricating the fibre from the polymer using a conventional spinning process. The main difference between the SRF and natural spider silk is that the SRF is stimuli-responsive (supercontraction when heated), while spider silk is humidity-responsive (supercontraction when wetted) [18,19]. In this study, we will first study the outstanding mechanical properties of the SRF. Our focus will then be on the feasibility of using the SRFs and TPs to heal macro-cracks in regular thermosetting epoxy composite.

2. SAMPLE PREPARATION

The SRF was prepared from a segmented polyurethane with relatively short polyols as the scarce soft segment, and diisocyanates and small molecular extenders as the rich hard segment. The novel polyurethane was synthesized using poly(butylene adipate) (PBA; Sigma-aldrich, USA), 4,4-diphenylmethane diisocyanate (MDI; Sigma-aldrich) and 1,4-butanediol (BDO; Sigma-aldrich). Dibutyltin dilaurate was used as a catalyst with a content of 0.02 wt%. The average formula weight ratio was (MDI + BDO) : PBA = 1021 : 300. BDO was dehydrated with 4 Å molecular sieves for 1 day in advance. All the chemicals were de-moisturized prior to use in a vacuum oven. Molten MDI was filtered to remove the precipitate dimmers and any impurities before use. The reaction was conducted in a high-speed mixer at room temperature. The obtained polyurethane was further cured in a vacuum oven at 110°C for 12 h. Before spinning, the polymer was dried in a vacuum oven at 80°C for 6 h. The SRF filaments with a diameter of 50 μm were spun by melt spinning. A customer-made extruder heating rate of 10°C/min was used because of the high shear viscosity of the polymer. The laminar air temperature was 22°C. Extruder head pressure was 5.00 MPa. The fibre passed three pairs of rollers before being wound up. The scanning electron microscopy (SEM) image of the SRF is shown in figure 1.

SRF/TP/epoxy composites were fabricated following the flowchart shown in figure 2. Polycaprolactone was chosen as the thermoplastic healing agent because it was reported that it could diffuse and rebind cracked epoxy surfaces with a healing efficiency of about 100 per cent [20,21]. The polycaprolactone (Mn 45 000, Sigma-aldrich) had a melting temperature at around 60°C and density of 1.145 g cm⁻³. The composites were prepared by a dry weaving process per the pin-guided filament winding process [22]. The spacing between the fibre bundles (ribs) was 13 mm. Epoxy was prepared using bisphenol A diglycidyl ether (Dow Chemical Company, USA) and triethylentetramine (The Dow Chemical Company). Bisphenol A diglycidyl ether was melted in advance and mixed with TPs by vigorous stirring for 1 h before triethylentetramine was added. The volume fractions of the TPs and SRF were 12 per cent and 7 per cent, respectively. The mixture was poured into the bay areas of the SRF woven grid skeleton. The composite mixture was degassed in a vacuum oven for 20 min and cured at ambient temperature (22°C) for 40 h. The glass transition temperature of the epoxy matrix was around 75°C.

3. CHARACTERIZATION

3.1. Characterization of stimuli-responsive fibre

The molecular structure of the SRF was investigated using Fourier transform infrared spectroscopy (FT-IR, Nicolet 6700, Thermo Scientific, USA) equipped with a Smart iTR universal sample holder in the region of 700–4000 cm⁻¹ at room temperature. The thermal properties of the SRFs were investigated using a differential scanning calorimeter (PerkinElmer DSC 4000, USA). The sample was cooled from room temperature to −50°C at a speed of 10°C min⁻¹. Then the sample was scanned from −50 to 240°C at a heating rate of 10°C min⁻¹. The phase separation morphology of the polymer was investigated using an atomic force microscope (AFM, SPA-300HV, Seiko Instruments Inc.) in the tapping-mode under an ambient environment (22 ± 2°C, 45 ± 5% RH). In phase images, a higher modulus material induces a higher phase offset and it appears lighter as opposed to a softer phase, which appears darker. SAXS (small angle X-ray scattering) tests of the fibre were conducted on a Nanostar SAXS machine (Bruker, USA). The X-ray source was copper Kα emission and the wavelength was about 0.154 nm. Samples were scanned in the range of 0.5°–3.0° (2θ) at a scanning rate of 0.05° min⁻¹. The detector was a Bruker AXS HI-STAR position sensitive area detector. The SAXS was conducted for 1 h on every sample. The model and calculation equations used to calculate the domain structure can be seen in reference [23]. The orientation function of the SRF of the amorphous phase and crystalline phase was determined by IR dichroism using a Perkin-Elmer microscopy (Perkin-Elmer Inc., USA) equipped with a diamond cryogenic Micro-ATR unit and an IR polarizer [24,25]. The calculation methods of the soft and hard segment orientation can be found in references [26,27].
The tensile properties of the SRFs were tested using MTS (mechanical testing and sensing system; Alliance RT/5, MTS Inc., USA) equipped with a 250 N load cell. Sample clamps specified for fibres were used. The crosshead speed was 80 mm min\(^{-1}\) and the gauge length was 38.1 mm (1.5 inch). A total of 10 specimens were tested. The cross-sectional area of the SRF was obtained using a scanning electron microscope (SEM, JSM-6390, JEOL Ltd., Japan, figure 1). The fibres were coated with gold before observation. The damping property tests were conducted using the same MTS (Alliance RT/5, MTS Inc.). One end of the fibre was fixed in the upper clamps of the MTS. The other end of the fibre was hooked with a mass (222.2 g). The initial force exerted by the mass was set to be zero. A 1 N force was applied to the fibre and then released to record the damping properties of the fibres. The elastic fibre was an XLA elastomeric fibre made of cross-linking polyolefin from Aquafil Group, Italy. The supercontraction of the fibre was evaluated by measuring the shrinkage percentage of the free fibre with increasing temperature. The supercontraction ratio of the SRF was determined by the following equation:

\[
\text{supercontraction ratio} = \frac{L - l}{L} \times 100\%,
\]

where \(L\) is the original fibre length; \(l\) is the length after shrinkage. The supercontraction stress of the SRF was tested using MTS (Qtest/150, MTS Inc., USA) equipment with a thermal chamber (10–162; Thermodynamic Engineering Inc., USA). To determine the thermal-induced supercontraction stress, the fully restrained SRF was heated up from the ambient temperature (25°C) to 170°C at a heating rate of 5°C min\(^{-1}\). The contraction stress of the SRF was recorded. To improve the contraction stress, the second set of samples was cold-drawn with a strain of 150 per cent. The samples were held for 30 min at the strain to partially fix the deformation. Then the strain-hardened fibres were heated so as to test the contraction stress. The experiments were repeated five times.

The cyclic thermomechanical behaviour of the SRF under tension was determined by Instron MTS (Instron Inc., USA). First, the SRF was stretched to 50 per cent elongation ratio at the ambient temperature at a drawing speed of 10 mm min\(^{-1}\). Second, the strain was maintained for 15 min. Third, the upper clamp was returned and the SRF was heated up to 80°C for contraction. Fourth, the SRF was cooled down to ambient temperature. After the cycle was completed, a second cycle began. To study the interface between the SRF and the polymer matrix, the prepared composite was broken in liquid nitrogen to create fracture surface. The interface between the SRF and the polymer was observed using SEM (SEM, JSM-6390, JEOL Ltd., Japan). The fracture surface was coated with gold before observation. Shape memory alloy wires/TP/epoxy composites were also prepared to study the compatibility in comparison with that of SRF/TP/epoxy composite.

### 3.2. Characterization of the self-healing composite

To demonstrate the self-closure of macro-cracks upon heating, specimens of \(8 \times 15 \times 80 \text{ mm}^3\) were cut from the composite panel. A macro-crack was first created on the specimen using the MTS (Qtest 150, MTS Inc., USA) by tension. The crosshead speed was 10 mm min\(^{-1}\). The specimen with the macro-crack was put on a hot plate (CORNG 6795-420D, USA) to trigger the supercontraction of the SRF. A high-resolution charge-coupled device camera (Sony XCD-CR90, Sony Inc., Japan) with a resolution of 3.7 × 3.7 µm/pixel was used to record the closure of the macro-crack. Tapered double-cantilever beam (TDCB) specimens were used to determine the healing efficiency and repeatability of the healing. The specific geometry of the TDCB can be seen in the electronic supplementary material, figure S1a. The healing efficiency was evaluated by tensile test using an MTS Qtest150 machine (MTS Inc., USA) with laboratory-made sample holders (see electronic supplementary material, figure S1b). The protocol for evaluating the self-healing efficiency using the TDCB sample can be seen in reference [28]. The self-healing of the TDCB sample was achieved simply by keeping the cracked TDCB samples in a preheated oven (Grubenlyberg Model L34HV104 from Lunaire Limited, USA) for 15 min at 80°C (greater than \(T_c\) of the SRFs and \(T_m\) of the TPs). The oven was power off after 15 min, and the mechanical property tests on the...
4. RESULTS AND DISCUSSIONS

4.1. Molecular structure and aggregate structure of the stimuli-responsive fibre

The molecular and aggregate structures of the SRF were studied using differential scanning calorimetry (DSC), atomic force microscope (AFM), small-angle X-ray scattering (SAXS) and Fourier transform infrared spectroscopy (FTIR) dichroism. The similarity between SRF and natural spider silks in the primary and aggregate structure is shown in the electronic supplementary material, figure S2. Spider silk molecules are sequences of different long chain amino acids mainly consisting of highly repetitive alanine and glycine blocks [29,30]. The alanine mainly forms the crystalline domains with a dimension of about 2 × 5 × 7 nm. The glycine with larger side-groups forms most of the amorphous phase [30]. The crystalline domains are embedded in the amorphous phase (see electronic supplementary material, figure S2c). The segment assembling into crystalline rigid beta sheet domains can be regarded as the hard segment. The segment forming helical and beta turn amorphous phase can be regarded as the soft segment. The interplay between the crystalline hard region and the soft amorphous region endows spider silks with the extraordinary toughness and strength. The hydrogen bond in spider silks is one of the basic chemical bonds that play a vital role in the mechanical properties of spider silk, as demonstrated by Buehler’s research [31–34]. In the spider silk, the hard segment and soft segment are partially orientated.

Like spider silk, the SRF undergoes microphase separation into crystalline phase and amorphous phase, as demonstrated by the DSC results in the electronic supplementary material, figure S3. This is because of the low compatibility of the rich hard segment and the scarce soft segment. The hard segment phase forms crystalline domains that can act as reinforcing nanofillers, stiffening and strengthening the SRF [35]. The phase separation structure of the polymer was observed using AFM, as shown in the electronic supplementary material, figure S4a. The darker areas are indicative of soft segment phase, and lighter areas may represent hard segment phase [36]. The SAXS profile of the SRF with a scattering shoulder in the electronic supplementary material, figure S4b also implies that the SRF is phase separated. The calculated interdomain spacing based on Bragg’s Law is 7.95 nm. The abundant hydrogen bonding in the SRF was demonstrated by FTIR (see electronic supplementary material, figure S5). The shift of the stretching vibration of N–H from high wavenumber to low wavenumber indicates the hydrogen bonding between the N–H…O=C. The ‘bifurcated’ C=O stretching vibration suggests that the C=O groups are mostly hydrogen bonded [37]. Both the shift of the N–H and C=O stretching vibration to low wavenumbers indicates abundant hydrogen bonding in the SRF. The soft segment and hard segment orientation of the SRF were determined using IR dichroism, as shown in figure 3. The significant differences between the two profiles A// and A⊥ suggest the orientation of the macromolecules in the SRF. The soft segment orientation function was calculated to be 0.19, and the hard segment orientation function was calculated to be 0.56.

4.2. Mechanical properties of the stimuli-responsive fibre

Spider silks—in particular, dragline silk—exhibit a unique combination of high tensile strength and extensibility. This enables the unbeatable toughness (area under a stress–strain curve) of spider dragline silks [29,35]. However, because of the difficulty of replicating spider silk proteins and mimicking the exact spinning process of spider silks, the research on fabricating artificial spider dragline silk is not very successful. One of the best achievements to fabricate artificial spider silk is to use recombinant spidroin-like protein to prepare fibre through wet spinning. Elices et al. [39] prepared artificial spider silk recombinant spidroin-1 and spidroin-2 (dragline spider silk) in the major ampullate gland of the spider Nephila clavipes. The maximum mechanical strength of the recombinant spider dragline silks achieved was only one-fifth of natural spider dragline silk [39,40].

Figure 4a shows the tensile properties of the SRF in comparison with natural spider dragline silk (adapted from [41, fig. 1C,D]), recombinant dragline silk (adapted from [39, fig. 2A]), other high-performance fibres (adapted from fig. 2.5, [42]) and steel bar (standard tensile specimen, cold drawn steel 18 (STFC18), cold rolled steel, USA). The tensile strength of the SRF approaches, but is still lower than, that of the spider dragline silk. The tensile strength of the SRF is three times that of the recombinant fibres. Both the
fibre (high modulus (HM)). Experiments mimicking high strength (HS) and 30 times that of carbon bar (STFC18), six times that of glass Kevlar fibre (intermediate modulus (IM)), five times higher than natural spider dragline silk and Kevlar has a toughness value of 245 MJ m$^2$

The mechanical strength of the SRF is approaching tensile strength of the spider dragline silk and SRF is much higher than that of steel bar. Both the tensile strength of the spider dragline silk and SRF is much higher than that of steel bar. Kevlar fibre, spider recombinant dragline silk and other high performance fibres. (Online version in colour.)

Figure 4. (a) Stress–strain curves of the SRF compared with spider (Araneus major ampullate silk) dragline silk [adapted from Omenetto & Kaplan [41] fig. 1C,D], spider recombinant dragline silk [adapted from Elices et al. [39] fig. 2A], other high performance fibres [adapted from ACI Committee 440 [42] fig. 2.5] and steel bar (STFC18). (The curves and data are intended to indicate relative magnitudes rather than exact values). The mechanical strength of the SRF is approaching though is still lower than that of spider dragline silk. Both the tensile strength of the spider dragline silk and SRF is much higher than that of steel bar. (b) The toughness values of the SRF in comparison with spider dragline silks. Kevlar fibre, spider recombinant dragline silk and other high performance fibres. (Online version in colour.)

4.3. Stimuli-responsive supercontraction of the stimuli-responsive fibre

A free spider dragline silk shrinks up to 50 per cent in length when wetted. The mechanism is the plasticizing effect of water and disruption of hydrogen bonds in spider silk, leading to the formation of less-organized silk protein [19]. No obvious water-induced supercontraction was observed on the SRF because the SRF is not as hydrophilic as spider silk. The SRF showed thermal-induced supercontraction as a result of its special two-phase structure. During the spinning process, at a temperature above the melting temperature of the crystalline hard segment phase, the fibre is extruded from spinneret. Upon cooling to ambient temperature, the fibre is wound up. The molecules of SRF are slightly oriented resulting from the spinning process. When the SRF is heated up, the soft segments in the amorphous phase have enough mobility. The hydrogen-bonded crystalline hard segment phase has a tendency to contract the fibre, which leads to shrinkage of the fibre. Cold-drawing leads to more alignment of the amorphous phase and thus more supercontraction. Further increasing the temperature leads to the melting of the hard segment phase, which result in the further shrinkage of the SRF.

Figure 5a presents the thermal-induced free supercontraction ratios of the SRFs at different temperatures. Figure 5b shows the contraction stress curves of the restrained SRF. The SRF has a contraction stress of 1.8 MPa. The contraction stress of the SRFs can be improved by strain-hardening through cold-drawing. As shown in figure 5c, after one-time of 100 per cent strain-hardening by cold-drawing, the contraction stress of the SRF reaches 7.8 MPa.

4.4. Cyclic thermo-mechanical tensile test

Figure 6 shows the cyclic thermo-mechanical tensile testing curves of the SRF. As shown in the figure, if a crack is created in a composite embedded with the SRFs, the fibre will be deformed by stretching (similar to cold-drawing programming). Upon heating, the contraction of the SRF with outstanding mechanical properties may close cracks in the composite by recovering the strain to 0. Furthermore, because the SRF with supercontraction has a tendency to shrink further, the fibre may exert a compressive force on the closed crack interfaces. The cyclic thermo-mechanical cycles are repeatable; therefore, the capability of the SRF to heal macroscopic damages may be repeatable.
4.5. Thermal-induced self-healing of the stimuli-responsive fibre composite

It is expected that the SRFs with the outstanding mechanical properties and thermal-induced supercontraction can close macroscopic cracks if they are embedded in composites. The SRF and TPs were incorporated into a regular epoxy for the self-healing of macroscopic damages. Electronic supplementary material, figure S8 shows the interface between the SRF and polymer matrix in comparison with that of shape memory alloy wire and the polymer matrix. The interface between the SSLF and the matrix is not clear, while the interface between the shape memory alloy wire and the polymer matrix is clear. The shape memory alloy wire is pulled out of the matrix. These results indicate that in comparison with shape memory alloy wire, the SRF has better compatibility with the polymer matrix. Figure 7a shows the schematic self-healing process of the SRF/TP/epoxy composite with a macro-crack. The healing process consists of two steps. In the first-step, the damaged sample is heated to a temperature ($T_1$) above the glass transition temperature of the SRF to trigger the thermal-induced supercontraction of the SRFs. The supercontraction of the SRFs closes the macro-crack. In the second step, the composite is further heated up to the bonding temperature ($T_2$) of the TPs. The molten TPs flows into the narrowed crack by capillary force, fuses into the fractured epoxy matrix by concentration gradient and forms physical entanglement and solid wedge when the sample is cooled down. Figure 7b presents the typical load-deflection curves of the original and healed TDCB samples after different fracture/healing cycles. According to figure 8b, after the first two-step healing process, 94 per cent of the strength of the sample was recovered. After four rounds of cracking/healing cycles, the healing efficiency can reach 80 per cent. The healing process is reasonably repeatable. To conduct more precise healing efficiency evaluation, the healing efficiency can be further calculated following energy-based approach for proposed by Rule et al. [46].

5. CONCLUSIONS

SRFs with superior mechanical properties and thermal-responsive supercontraction were fabricated for the purpose of healing macroscopic damages in composites. The SRF has superior toughness, which is 1.4 times of spider dragline silk, five times of that Kevlar fibre (IM), six times of that of glass fibre (E), 11 times of...
that of carbon fibre (HS) and 30 times of that of carbon fibre (HM). SRF-grid-stiffened epoxy composite with embedded TPs was fabricated for healing macroscopic cracks in regular epoxy. Following the two-step biomimetic self-healing scheme, the SRF and TPs healed macroscopic crack in epoxy with a healing efficiency of over 90 per cent. The healing process was also repeatable. It is believed that the SRFs provide a new way to repeatedly, efficiently and molecularly heal macroscopic damages in regular thermosetting polymer composites.

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REFERENCES

I. Introduction

The research field of self-healing materials has gained significant attention in recent years, particularly in the context of thermoset polymers. These materials are characterized by their ability to initiate a healing process upon the onset of a crack, thereby restoring their mechanical properties to some extent. This self-healing capability is achieved through the incorporation of healing agents that are either pre-mixed with the polymer matrix or encapsulated within microcapsules.

The healing process in thermoset polymers typically involves the interaction of healing agents with the polymer matrix, which can be triggered by external stimuli such as heat, light, or mechanical stress. The healing mechanism can range from simple adhesion to more complex processes involving the diffusion of healing agents, the dissolution of the polymer matrix, and the re-aggregation of the damaged regions.

II. Healing Mechanisms

A. Superelastic Shape Memory Polymers

Shape memory polymers (SMPs) are capable of undergoing large deformations and then returning to their original shape upon application of a stimulus such as temperature or mechanical stress. This property makes them attractive for applications requiring self-healing capabilities, as the thermally induced shape change can be harnessed to heal cracks in the material.

B. Hydrogen-Bonded Polyurethanes

Hydrogen-bonded polyurethanes are known for their toughness and ability to form strong intermolecular interactions, which can be exploited for self-healing purposes. The healing process in these materials often involves the reformation of hydrogen bonds upon the application of a stimulus, leading to the realignment of the polymer chains and the repair of damaged areas.

C. Epoxy-based Self-Healing Materials

Epoxy resins are commonly used in self-healing applications due to their high strength and toughness. The incorporation of microencapsulated healing agents, such as silane or metal organic frameworks, can provide a sustained release of healing agents that can diffuse into cracks and promote healing.

III. Examples of Self-Healing Thermoset Polymers

A. Healable thermoset polymer with SRF


B. Infrared and Raman spectroscopy of polymers


IV. Future Directions

The field of self-healing thermoset polymers is rapidly evolving, with ongoing research aimed at improving the efficiency and effectiveness of healing mechanisms. Challenges include the development of materials that can heal at higher speeds, at lower temperatures, or under more extreme conditions. Additionally, there is a need for materials that can heal not only cracks but also other types of damage, such as tears or holes, to fully realize the potential of self-healing technologies.

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