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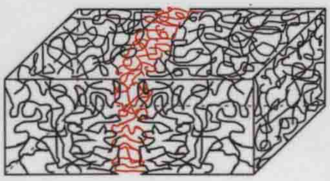

Recent Advances in Smart Self-healing Polymers and Composites

Edited by Guoqiang Li and Harper Meng

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Preface

In the past several decades, the desire for lighter, tougher, stronger, and smarter materials in transportation vehicles, energy production, storage, and transport, military equipment and vehicles, infrastructure, chemical processing equipment, offshore oil and gas platforms, and consumer goods, has driven the use of fiber-reinforced polymer composite materials and polymeric coatings on metallic substrate. Fiber-reinforced polymer composite materials, while they have high specific strength, stiffness, corrosion resistance, and design tailorability, are prone to damage due to the various weak interfaces. Therefore, damage self-healing in polymer composite materials and coatings has been a topic of intensive research over the past two decades. The literature (papers, books, patents) has been growing exponentially. For people who are new to this area, it is difficult to digest the vast volume of literature, particularly when this literature is scattered in various types of journals, conference proceedings, and patents in various languages. Therefore, we feel that there is a need to have a one-stop shopping place so that newcomers and long-time engineers can easily get an overview of the historical backgrounds, on-going activities, and future perspectives in this emerging area of study. To this end, we invited a group of leading experts in various aspects of self-healing polymers and composites to contribute to this edited book. Owing to the time constraints and our limitations in knowledge, we must mention that this book is by no means comprehensive. Some relevant materials may have been overlooked, although that was not our intention.

This book consists of 12 chapters. Guoqiang Li and Harper Meng provide an overview of crack self-healing in polymer composite materials in Chapter 1. Using in-service (under stress, at low temperature, fixed boundary condition, etc.) load-bearing composite structures as an example, a set of evaluation criteria are proposed and the various healing schemes, including both intrinsic and extrinsic schemes, are compared against the criteria. The common requirement for any self-healing scheme to work is to bring fracture surfaces in contact. This requirement is emphasized using the strategy introduced in this chapter. Attention is then paid to healing structural-length scale cracks or wide-open cracks using a biomimetic two-step close-then-heal (CTH) strategy. Future perspectives such as combining hybrid intrinsic and extrinsic self-healing schemes, using artificial muscles, and employing hybrid artificial muscles and shape memory polymer fibers, are discussed. We believe that this chapter will provide an overall picture of the various self-healing schemes, challenges, and potential strategies to deal with the challenges.

After this introductory chapter by the two editors, we start with modeling of self-healing composite materials. Amir Shojaei in Chapter 2 covers the recent theoretical developments in the field of continuum damage-healing mechanics of self-healing materials. The mechanisms associated with the damage and healing are utilized to propose the damage and healing parameters. The evolution laws for the damage and healing processes are developed within the continuum damage healing mechanics (CDHM) framework, which are calibrated in accordance with the experimentally measurable properties such as changes in the elastic moduli. We feel that this chapter will provide the skill set needed in modeling damage healing behavior.

In Chapter 3, Frank Jones and Russell Varley present solid-state healing of resins and composites. Solid-state healing represents a unique field of self-healing materials research characterized by the use of solid-state additives that impart inherent healing functionality to a given polymer matrix. As healing generally requires external intervention or activation, these systems are often referred to as mendable resin systems, but confer several advantages compared to other mechanisms. Some of these advantages are that healing is typically repeatable; able to repair damage to the same location time and again yet remaining indefinitely dormant until required. They are also convenient to incorporate into traditional fabrication technologies, enhancing their potential commercial application. Both one-phase and two-phase solid-state healing processes are discussed. Healing of fiber-reinforced polymer composites are also explored. We are optimistic that this chapter will provide our readers with critical knowledge and skills on successfully implementing healing by a solid healing agent.

Extrinsic self-healing by microcapsules is one of the most popular strategies in the literature. It is also one of the first strategies, if not the first scheme, to do damage self-healing. Dong Yu Zhu, Min Zhi Rong, and Ming Qiu Zhang provide a comprehensive review of microcapsule-based self-healing composite in Chapter 4. The review discusses the recent progress in this field from the viewpoint of material design and preparation. The challenges and future research opportunities are summarized at the end of the chapter. We believe that readers of this chapter will be provided with a grasp of the achievements to date and an insight into the future development in this fast growing field.

Christopher Hansen focuses on microvascular-based self-healing materials in Chapter 5. Inspired by the repair functionality of biological systems, self-healing by microvascular components is an approach to directly mimic the autonomic healing abilities of biological organisms. In this chapter, biological microvascular systems are briefly reviewed with respect to key design elements and considerations for functional and reliable synthetic microvascular systems. Fabrication using both subtractive and additive manufacturing techniques is discussed. The self-healing efficacy in terms of restoration of mechanical strength is evaluated. It is envisioned that the field of microvascular self-healing has significant potential for continued growth.

As an intrinsic self-healing strategy, reversible chemical bonds have been widely studied. In Chapter 6, Pengfei Du and Xinling Wang focus on reversible cross-linking polymer-based self-healing materials. They start with reviewing the autonomous self-healing polymers with embedded microencapsulated healing agent. They then focus on the cross-linked healable polymeric materials based on reversible noncovalent bonds, including hydrogen bonds, π–π stacking interaction, and metal–ligand coordination. Finally, they review the cross-linked healable polymeric material containing reversible covalent bonds (DA adducts). We believe that this healing scheme will help eliminate hidden hazards, prolong service life, and expand the application area of polymeric materials.

Supramolecule chemistry is another fast-growing area in the intrinsic self-healing field. Wenwen Deng, Yang You, and Anqiang Zhang focus on supramolecular network-based self-healing polymer materials in Chapter 7. Supramolecular polymers could form a dynamic network, which exhibits the ability to heal their damages. In this chapter, some recent advances in supramolecule self-healing materials based on noncovalent interactions, including hydrogen bonding, π–π stacking, metal–ligand complexes, and ionomers, are discussed. Furthermore, the self-healing properties and self-healing mechanisms of these materials are described. In addition, the challenges and future perspectives are discussed. We believe that this chapter provides fundamental knowledge on this emerging research area.

Chapter 8 focuses on self-healing coatings. Corrosion of metallic structures has been a challenging problem for centuries. Coatings with polymers have been popular in recent decades but suffer from damage in the coating layer. A.E. Hughes addresses this issue by developing self-healing polymeric coatings. In this chapter, a wide variety of self-healing approaches to coatings is investigated. Other healing mechanisms that have potential applications in coatings are also explored. A broad range of coating applications are discussed with particular attention to coatings where the polymer acts as the resin or binder. We believe that self-healing coatings represent considerable opportunities for future research and development. We envision that applications to real-world structures will become available in the foreseeable future.

Except for a limited number of healing systems, most intrinsic and extrinsic self-healing systems need some external help such as heating to increase the mobility of molecules so that molecular interaction can occur. For these systems, like human skin, the damage needs to be sensed before healing occurs. In Chapter 9, Simon Hayes, Timothy Swait, and Austin Lafferty discuss self-sensing and self-healing in composites. They introduce the principles of self-sensing, both optically and electrically, and show in each case how the sensor utilizes the reinforcing fibers of the composite in order to determine the damage state. Intrinsic self-healing is then discussed, presenting different ways of incorporating a self-healing response into resins that are suitable for use as matrix materials for composites. Strategies for combining electrical self-sensing with systems requiring thermal activation and optical self-sensing with those requiring optical activation are discussed. We believe that self-sensing will have a significant impact on enhancing the self-healing systems, particularly on extrinsic self-healing systems.

As a comparatively new member in the self-healing family, self-healing of shape memory polymers or self-healing of conventional nonshape memory polymers by shape memory effect has been intensively studied by several groups in the past several years. In this book, we devote three chapters to this emerging research field.

In Chapter 10, Haibao Lu, Wei Min Huang, Zhen Ding, Chang Chun Wang, Hai Po Cui, Cheng Tang, Jun Wei, Yong Zhao, and Cheng Li Song focus on rubber-like polymeric shape memory hybrids with repeatable heat-assisted self-healing and joule heating functions. The fabricated hybrids are not only rubber-like from above to below their shape recovery temperature, but also have repeatable heat-assisted self-healing functionality. By incorporation of carbon blacks in the polymer matrix, the hybrids maintain highly elastic, and are able to be directly joule heated for shape recovery. The major parameters, which affect the performance of the hybrids, are experimentally investigated in a systematic manner. We are confident that this chapter will deepen understanding and enhance application of shape memory assisted self-healing in rubber-like hybrid polymers.

In Chapter 11, Gefu Ji, Pengfei Zhang, Jones Nji, Manu John, and Guoqiang Li focus on self-healing of impact induced cracks in rigid and stiff thermosetting shape memory polymer matrix. Several fiber-reinforced thermosetting shape memory polymer structures, including composite sandwich structures, grid-stiffened composite structures, and 3-D woven fabric-reinforced composite structures, are fabricated, low-velocity impact tested, and healed per the biomimetic CTH scheme. Several impact–healing cycles are conducted to demonstrate the healing repeatability. Repeated damage sensing by a percolated carbon nanotube network is also presented. It is validated that the CTH scheme can heal structural-length scale crack in fiber-reinforced thermosetting shape memory polymer composite structures repeatedly, efficiently, timely, and have potential to heal autonomously.

In Chapter 12, Harper Meng, Pengfei Zhang, Oludayo Ajisafe, and Guoqiang Li further show that structural-length scale cracks in conventional thermosetting polymers, which do not have shape memory effect, can be repeatedly healed by embedding a small amount of prestretched shape memory polymer fibers and thermoplastic healing agent. Shape memory polymer fibers in 1-D, 2-D, and 3-D configurations are investigated. Specimens with both free boundary conditions and fixed boundary conditions are tested, which confirms that tensile-stressed specimens or specimens under in-service conditions can also be repeatedly healed with proper programming of the shape memory polymer fibers. We believe that this study provides a new and cost-effective way of repeatedly healing wide-open cracks in conventional thermosetting polymer composite structures.

The guest editors of this edited book are confident that this collection of highly relevant and impactful contributions will be of interest to many diverse audiences, be they in academia or industry. We are grateful to have achieved such a high-quality collection of chapters and would like to thank the authors for their contributions. We would also like to thank the Woodhead Team for their assistance during the course of organizing this book. We would like to encourage the whole field to continue the progress in all fronts related to self-healing polymers and composites.

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Harper Meng, Ph.D.

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