Chapter 11
Concluding Remarks and Future Perspectives

11.1 Advantages and Disadvantages of Self-Healing Engineering Materials and Future Research Directions

Mimicking natural vascular systems in engineering materials is achievable by using core-shell nanofibers (NFs) whose cores are filled with self-healing agents (e.g., resin monomer and curing agent, or epoxy and hardener). This is beneficial for the following reasons: (i) uniformly distributed versus localized healing elements (as in the case of microcapsules containing healing agents), and (ii) nanoscale instead of microscale healing elements (as in the case of microcapsules). Nanoscale healing elements can fit ply areas in layered composites and avoid weakening the surrounding matrix. Another benefit of NF-based self-healing systems is that the dispersion of additional components required for self-healing reactions in the surrounding matrix is unnecessary. Specifically, a self-healing system should use two types of interwoven NFs with two complementary healing agents present within their cores, namely, a resin and its curing agent or an epoxy and its hardener. When released from the damaged core-shell nanofibers, these components react with each other to form polymerized, solidified stitches that connect the crack banks. The stiffness and self-cohesion of the damaged material can thus be restored. However, the prevention of delamination and the recovery of adhesion to surfaces of different compositions remain issues to be resolved that require additional future research efforts.

In fabrication, it has been demonstrated that the solution blowing of core-shell NFs encapsulating healing agents is a much more effective process than either co-electrospinning or emulsion spinning. However, although the solution blowing of various polymers and biopolymers has already been demonstrated on the industrial scale using commercially available equipment, it remains to be employed for fabricating core-shell NFs containing healing agents. Only after solution blowing of self-healing NFs can be achieved will self-healing engineering materials find widespread use in engineering practice. Electrospun and solution-blown fibers are usually randomly oriented and deposited unevenly on surfaces. Moreover, it remains non-trivial

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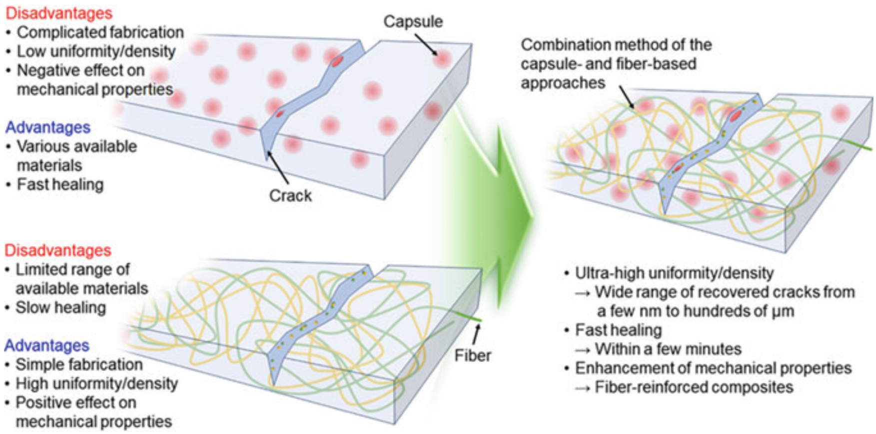

Fig. 11.1 Schematics for capsule-based, fiber-based, and hybrid self-healing approaches and the corresponding advantages and disadvantages of each method. Reprinted with permission from An et al. (2018b)

to ensure the continuous and uniform encapsulation of healing agents within core-shell NFs when using these techniques. This is an additional obstacle to the industrial fabrication of self-healing materials while maintaining high production quality. The development of three-dimensional self-healing nanotextured vascular materials has only begun recently and should attract wider attention in the future.

Although numerous self-healing materials have already been developed, it remains unclear whether the methods proposed for fabricating these materials are economically feasible and industrially scalable. Capsule-based self-healing methods have several disadvantages, such as low uniformity of the dispersed capsules and complicated fabrication processes (Fig. 11.1). To overcome these drawbacks, several fiber-based self-healing approaches have been introduced recently: the method of solution blowing has already been performed at the industrial scale, as mentioned above. Nevertheless, the range of materials that can be used as the shells for encasing the core materials in these core-shell NFs remains limited. On the other hand, capsule-based methods allow the use of a wider range of materials, despite their other limitations.

Several additional goals must be pursued in future studies. First, it would be highly desirable to be able to consistently (in all cases on demand) decrease the outer diameters of the shells from the microscale to the nanoscale, in order to enhance the self-healing performance by increasing the specific surface-area-to-volume ratio (S/V). Second, the development of core materials with shorter healing times of a few hours or less is essential. The core and shell materials currently available for the fiber-based approach to self-healing possess healing times on the order of hours in the best cases. Third, fabrication processes for self-healing composites that are industrially scalable and economically viable must be developed to allow greater use of self-healing techniques in the aeronautical and automotive industries. The recent development of multi-nozzle coating systems and roll-to-roll devices for the fabrication of NFs is encouraging and should help in addressing the scalability challenge.

Simultaneously, hybrid methods incorporating both capsule- and fiber-based approaches (see Fig. 11.1) should be developed further to maximize the advantages of both approaches. For example, self-healing composites using both rapidly healing capsules and miniscule self-healing core-shell NFs could be used for damage recovery of a wide range of cracks of many length scales, from a few nanometers in size (by the NFs) to hundreds or thousands of nanometers wide (by the capsules). In addition, such a hybrid approach would not exhibit the limitations related to slow healing, because of the use of the capsules, or low uniformity, because of the presence of NFs. Finally, adding corrosion inhibitors or using pH- and redox-responsive polymers could lead to additional improvements in the self-healing performance, particularly in the field of corrosion protection.

The interfacial toughening of composite laminates, for the aeronautical and automotive industries as a measure of protection against impact damage and fatigue cracking, will be important. Accordingly, nanotextured self-healing interleaved structures aiming the interfacial toughening will be sought. Proliferation of soft robotics and actuators, as well as products based on them, requires innovative flexible self-healing composites, which can withstand multiple operation cycles without growth of fatigue cracks (An et al. 2018a, Kang et al. 2019). A remedy to the electrodes and solid electrolyte interphase of Li-ion batteries, which crack because of cyclic loads during charging and discharging can probably be sought in the form of embedded self-healing elements (Jin et al. 2017).

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