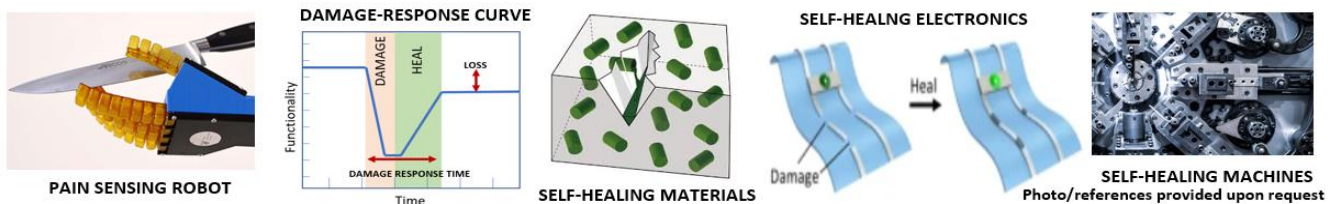


FROM SELF-AWARE TO SELF-HEALING FOR “PERPETUAL” MANUFACTURING

An aircraft that can restore its structure and heal potentially fatal cracks in flight—whether from repeated fluctuations in air pressure, weather, or something more serious—is emotionally and intellectually appealing. Future cars that are fender-bender proof will have assured commercial success. And the world’s first living, self-healing robot called the xenobot—a programmable, hybrid “living machine”—is capable of cleaning up radioactive waste and delivering medicines throughout the human body. All of these advances point to a self-healing future beyond intelligent manufacturing. The concept of self-healing is an idea still new enough that there is no consensus of definition other than that the machine—be it an airplane, a milling machine, a living machine, or an industrial robot—has self-awareness of its own state of operational health and the ability to sense “pain” as a trigger for self-healing responses that restore operational health and function, however defined.

Self-healing for manufacturing is a big idea full of smaller big ideas that inform many of the domains that comprise manufacturing today, but especially machining dynamics, material deformation, electronics, and information systems. Self-healing machine tools can anticipate failure or damage. Rather than alerting humans for intervention, they can manage their own repair by parametric adjustments to assure process stability. The replacement of steel bearings with ceramic bearings made of silicon nitride continuously burnishes the raceways “healing” any surface damage and extending useful life. A next generation of “soft machines”—robots that are mechanically compliant, deformable, and safe for physical interaction with the human body—use sensors and self-healing actuators for damage detection, localization and self-healing. Similarly, new self-healing electronics, both in equipment and sensors, can maintain and recover functionality when damaged. Researchers are exploring batteries that self-repair using a process called coulombic attraction. And self-healing has restorative capabilities in cybersecurity—detecting network flaws and restoring operability without human intervention.



As the above examples illustrate, self-healing in a manufacturing system occurs at different scales that need to be integrated to achieve full power. At the *microscale* level, materials self-repair to maintain and restore function. Most self-healing materials today are polymers and elastomers, but there is growing focus on metals and ceramics which is a critical challenge for manufacturing applications. When composites are damaged, for example, functional microcapsules rupture to release healing agents that coalesce forming new connections that reestablish solid structure. At the *mesoscale* level, machines and parts-in-process self-heal through process adjustments enabled by electronics and self-actuation. Self-healing robots that can feel “pain” and sense degradation were recently announced. A key challenge is to create programmable *and* self-healing materials with electronics that not only control their own healing but also communicate “pain” to the machine tool so that the parameters can self-adjust—reducing damaging forces and torques. Or imagine an incorrectly machined part with the ability to return to specification through self-healing. At the *macroscale* factory level, the system approaches full autonomy, integrating self-healing materials (both machine and part), processes, electronics, and information technology. The key challenge is system-wide synchronization of any damage detection with latencies in the healing processes. Self-healing at the macroscale also provides additional layers of cybersecurity for system defense.

Thus, while the big idea is self-healing, the bigger idea—and challenge to future manufacturing—is to integrate and exploit emerging self-healing capabilities across these scales into a new industrial platform for self-healing manufacturing systems. With their continued development and seamless integration within an AI and IIoT-enabled manufacturing environment, transformational change is inevitable. If trends continue, we can anticipate that biology-inspired technologies and new tools of artificial intelligence will play a dominant role—driving performance and production advantages such as mechanical robustness, assured one-shot-part-to-print precision, maximum productivity, fully autonomous functionality and most importantly a platform for “perpetual” manufacturing shaped by knowledge learned through continuous and dynamic cycles of damage and self-healing.