VALUE EXTENSION OF COMPOSITES VIA THERMOFORMABLE AND RECYCLABLE EPOXY SYSTEM

For applications such as wind energy, automotive and transportation, aerospace, and industrial composites, the ability to modify a cured component can provide additional flexibility throughout its lifecycle. (Courtesy: Shutterstock)

The combination of dynamic reprocessing and chemical recycling provides two complementary pathways for extending the value of epoxy thermoset composites throughout their lifecycle.

By AMIT DIXIT

Epoxy thermosets have long been a material of choice for high-performance composites, structural adhesives, and protective applications. Their unique combination of mechanical strength, thermal stability, chemical resistance, and long-term durability makes them particularly well suited to demanding applications where structural integrity is critical.

However, the crosslinked network that gives thermoset epoxies their exceptional performance also creates a fundamental lifecycle challenge. Once cured, conventional epoxy systems are permanently crosslinked, limiting their ability to be reshaped, reprocessed, or recycled. While thermoplastics offer greater flexibility through their ability to soften and be reshaped with heat, they often cannot match the mechanical performance in many structural applications.

For the composite industry, this presents an important question: Can a thermoset deliver performance expected during service while offering greater flexibility at the end of manufacturing and at the end of its useful life?

The innovative thermoformable and recyclable epoxy system offers a unique solution to extend the value of high-performance composites. Leveraging the proprietary Recyclamine® technology platform, the novel epoxy system incorporates dynamic and cleavable functionality into a single network. This advanced polymer network integrates the performance characteristics of conventional crosslinked thermosets with thermoformable, repairable, and reprocessable functionality, while simultaneously enabling closed-loop chemical recycling and end-of-life material recovery.

By integrating performance and circularity into the same material platform, this next-generation epoxy technology extends the value of high-performance composites across their entire lifecycle. The result is a new approach to epoxy-based composites that supports manufacturing flexibility, facilitates repair and reuse, and creates viable pathways for material recovery without compromising the performance expected of advanced thermoset systems.

THERMOFORMABILITY WITHOUT SACRIFICING THERMOSET PERFORMANCE

The difference between a conventional epoxy matrix and the innovative dynamic thermoformable epoxy becomes particularly relevant during thermal processing.

A conventional epoxy thermoset cannot readily retain or adopt a new defined geometry once it has been fully cured. By contrast, the dynamic thermoformable epoxy system remains capable of reforming and undergoing controlled shape change, allowing components to be formed into a new geometry under appropriate temperature conditions.

Importantly, this capability does not require abandoning the performance characteristics associated with a thermoset network. Tests demonstrate that the grinded material from cured thermoformable epoxy can fuse under heat and compression at 180°C for 30 minutes retaining significant level of its original mechanical performance unlike the conventional epoxy that remains infusible. (See Figure 1)

Figure 1: Comparative thermoformability performance of conventional and dynamic epoxy thermosets.

FROM PERMANENT CROSSLINKING TO DYNAMIC NETWORK FUNCTIONALITY IN COMPOSITES

The key to the propertiary technology lies in response of the crosslinked epoxy matrix to temperature. Under normal service conditions, the crosslinked structure remains stable, providing the dimensional integrity, mechanical performance, and durability expected from a thermoset. When exposed to controlled elevated temperatures, however, dynamic bonds within the network can exchange and rearrange.

This network rearrangement allows thermoset composites to change shape and reform without simply melting, flowing, or degrading. In practical terms, the cured epoxy matrix is thermoformable, enabling controlled shape change and stress relaxation while maintaining the overall integrity of the crosslinked network in composites. (See Figure 2)

The capability opens new possibilities for composite manufacturing and service, including thermoforming, repair, rework, and reshaping of cured components.

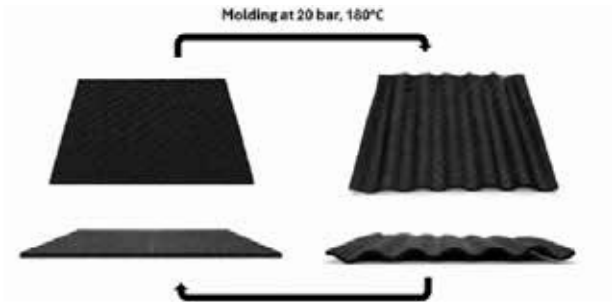

Figure 2: Thermoforming and shape-memory behavior of an epoxy-based carbon-fiber-reinforced (CFRP) composite, demonstrating shape transformation and recovery under controlled heating.

For applications such as wind energy, automotive and transportation, aerospace, and industrial composites, the ability to modify a cured component can provide additional flexibility throughout its lifecycle. Manufacturing defects or design changes can potentially be addressed without replacing the entire component, while repair and reshaping can help extend the useful life of high-value composite structures.

EXTENDING THE COMPOSITE LIFECYCLE THROUGH REPAIR AND REPROCESSING

Thermoformability introduces another dimension to composite lifecycle management: the ability to extend the useful life of a cured composite structure as long as its mechanical properties meet the application requirement.

Rather than treating curing as the irreversible final step in the manufacturing process, the dynamically reprocessable epoxy network enables cured components to be modified, repaired, and potentially repurposed when required. This shifts the perception of a composite part from a fixed, end-state structure to an adaptable asset with continued value beyond its initial manufacture.

In manufacturing, this could help accommodate changes in component geometry or address certain processing issues. During service, the same capability could support repair or rework strategies. For high-value composite structures, extending the useful life of an existing component can be an important part of reducing material consumption and preserving the value embedded in the original manufacturing process. The technology therefore moves the discussion beyond conventional recyclability. Instead of focusing only on what happens after a component becomes waste, it introduces the possibility of maintaining, adapting, and reusing the component before it reaches end of life.

CHEMICAL RECYCLING: RECOVERING EPOXY MATRIX AND REINFORCEMENT IN COMPOSITES

The thermoformable system offers second capability to chemically recycle composites at the end of its service life. The dynamic network incorporates cleavable functionality that enables the cured epoxy matrix to be chemically deconstructed through solvolysis under controlled recycling conditions. This provides a pathway to separate the polymer matrix from the reinforcing material. (See Figure 3)

For composites, this is particularly relevant because, rather than treating an end-of-life component as waste destined for landfill or incineration, chemical deconstruction creates an opportunity to recover the reinforcement and retain more of the material value within the manufacturing cycle.

The solvolysis using a chemically benign solution converts the epoxy matrix into a thermoplastic material while allowing the reinforcements to be recovered. The recovered reinforcements retain their integrity enabling re-use to manufacture new composites. The epoxy matrix recovered as a thermoplastic has inherent properties similar to traditional thermoplastics.

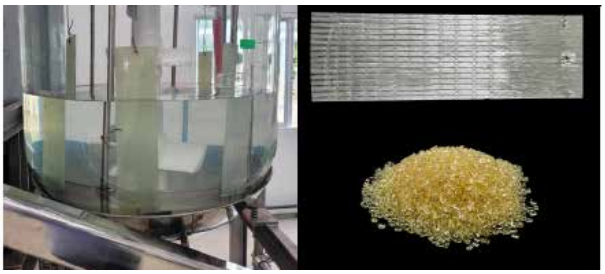

Figure 3: Illustration of the solvolysis-based chemical recycling of glass-fiber-based composite, showing polymer matrix deconstruction and recovery of reinforcement and thermoplastic material.

This creates a potential pathway in which both sides of the composite — the epoxy matrix and the reinforcement — can have a route to a subsequent new life. For composite manufacturers, this distinction is important. Recycling is not simply about diverting material from landfill or incineration; it is about preserving material value and creating viable routes for recovered materials to re-enter manufacturing.

ONE EPOXY PLATFORM, TWO PATHWAYS FOR LIFECYCLE FLEXIBILITY

The combination of dynamic reprocessing and chemical recycling provides two complementary pathways for extending the value of epoxy thermoset composites throughout their lifecycle. During manufacturing and service, thermoformability enables cured components to be reshaped, repaired, reworked or reprocessed under controlled thermal conditions. At end of life, chemical recycling through solvolysis provides a pathway for deconstructing the epoxy matrix and recovering the matrix and fiber reinforcements for subsequent composite applications. Together, these capabilities offer a different way to think about thermoset composites. A thermoset no longer has to represent the end of a material's useful journey once it has been cured.

By combining the high-performance characteristics of epoxy with dynamic network functionality and chemical recyclability, this technology provides a pathway toward keeping composite components in service longer and recovering valuable materials when they ultimately reach end of life.

For an industry increasingly focused on resource efficiency and lifecycle value, the opportunity is not simply to make composites recyclable. It is to design greater flexibility into the material itself — so that one epoxy platform can support multiple stages of a composite's lifecycle. Two capabilities. One epoxy platform. More than one lifecycle.

ABOUT THE AUTHOR

Amit Dixit is senior vice president at Aditya Birla Advanced Materials. He is a global R&D leader with more than 25 years of professional experience in materials science, specializing in advanced polymer and epoxy technologies. He has spearheaded the development and commercialization of multiple applications, breakthrough products, and core industrial technologies on a global scale.