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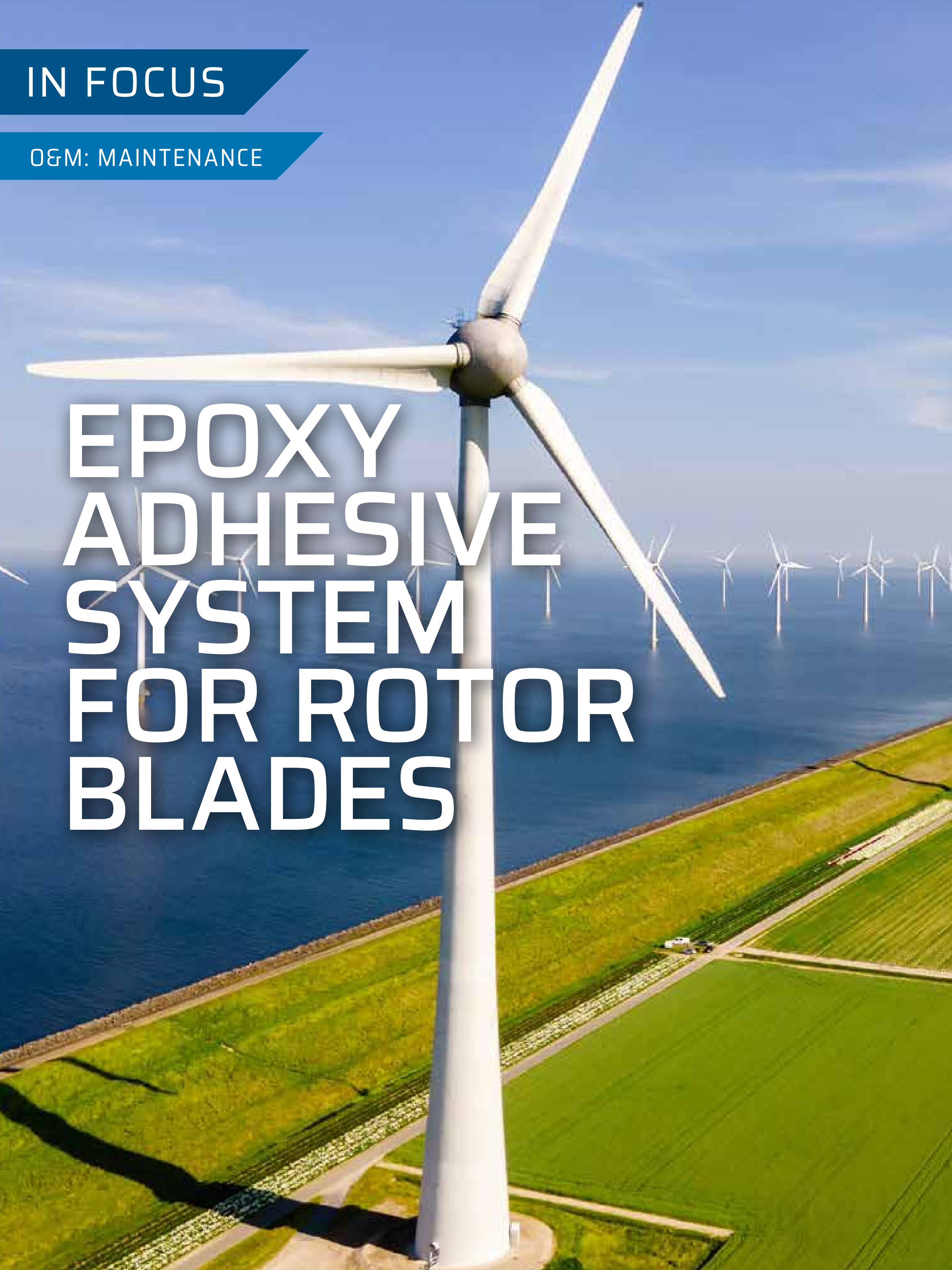
EPOXY ADHESIVE SYSTEM FOR ROTOR BLADES



The growth of the wind industry is duly supported by development of new technologies that enable it to harness more energy with high efficiency. Incidentally, the industry is also facing a compelling issue in end-of-life management of decommissioned rotor blades. (Courtesy: Shutterstock)

A wind turbine rotor blade made from a recyclable epoxy resin system and the recyclable epoxy adhesive system can be fully recycled by a low-energy solvolysis process.

By AMIT DIXIT

In 2023, the wind-energy sector celebrated the landmark figure of 1 TW of global installed capacity. This milestone was a testimony to the fundamental role played by wind energy in decarbonizing the global power system and helping the world reach its climate and energy goals. It took 40 years to reach the 1 TW milestone; however, according to estimates from Global Wind Energy Council (GWEC), the next terawatt installation is projected to take less than seven years on account of high growth forecast for the wind industry amidst the target net zero emissions by 2050. While the electricity generation from wind is increasing year after year, significant capacity addition, with a 17 percent average annual generation growth rate, is required to realize approximately 7,400 TW/h of wind electricity generation by 2030 (IEA).

The growth of the wind industry is duly supported by development of new technologies that enable it to harness more energy with high efficiency. Incidentally, the industry is also facing a compelling issue in end-of-life management of decommissioned rotor blades. It is estimated that 85 percent of the components of a wind turbine can be recycled and re-used except the rotor blades, due to the non-recyclable thermoset matrix. In the last few years, new technologies have been developed that enable inherent recyclability in materials. The Recyclamine® is a disruptive technology platform that enables recyclable epoxy thermosets. Importantly, the technology is adaptable to existing rotor blade manufacturing processes, thus eliminating the need for design or operational changes to implement.

The wind industry has been instrumental in leading and taking a leap forward towards addressing the sustainability concern with successful implementation of Recyclamine® technology and development of world's first recyclable rotor blade. The latest development of Recyclable epoxy adhesive system complements 100% recycling of rotor blade driving circularity.

EVOLUTION OF ADHESIVE TECHNOLOGIES FOR ROTOR BLADES

A wind turbine rotor blade generally consists of two shells bonded together with a structural adhesive, also called a

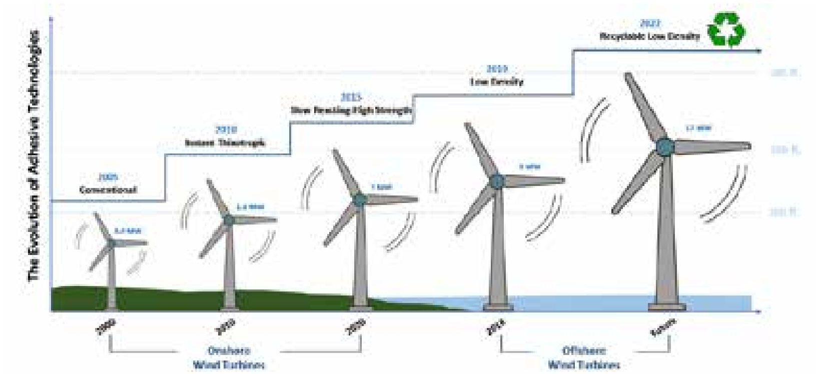


Figure 1:The evolution of adhesive technologies.

SN curve analysis	Results
Regression Equation (y = ax^{-b})	y = 53.204x$^{-0.112}$
Exponent of S-N Curve	0.112
Coefficient of Correlation	0.9947
n = 1/b	8.929

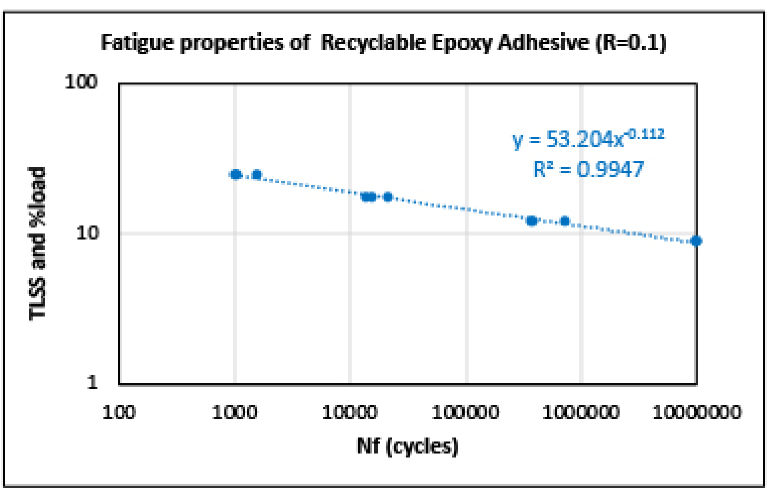


Figure 2: Fatigue behavior of recyclable epoxy adhesive system.

bonding paste. The adhesive is load bearing; therefore, higher mechanical performance is required and, consequently, epoxy adhesive systems are used. Further, the profile of rotor blade and the application process necessitate the adhesive to be slump resistant, exhibiting low curing shrinkage and higher resilience.

Over the years, adhesive technologies have evolved with the development of new blade designs and the growth of the offshore platform (Figure 1). The conventional epoxy adhesives were designed with resin and hardener components that were thixotropic and mechanically reinforced. These adhesives provided optimum performance properties; however, the processability by a two-component dispensing machine caused increased wear on the parts and drives. This concern was addressed by the development of instant thixotropic adhesive that are comprised of low viscosity, flowable resin, and hardener components, which, on mixing, provided the same level of thixotropy as conventional adhesive. Increase in blade lengths resulted in development of slow reacting-high strength adhesive that enabled longer open time and low density adhesive that provided higher ductility, toughness, and lowered contribution to weight of the blade.

RECYCLABLE LOW DENSITY EPOXY ADHESIVE

With the development of the world's first recyclable rotor blade from the infusion system, the industry has taken a leap forward towards addressing the sustainability concern; however, since the majority of the rotor blades are constructed in two shells, it is imperative the epoxy adhesive is also recyclable.

The recyclable epoxy adhesive system leverages from the Recyclamine® technology that enables debonding of the two shells under specific conditions facilitating recycling of the rotor blade. The adhesive aligns with the industry trend of longer, lighter, and aerodynamically stable blades. Process and performance properties of the recyclable low-density epoxy adhesive are comparable to the conventional low density non-recyclable epoxy adhesive in terms of rheological characteristics, working time, static, mechanical, and adhesion properties. (Table 1).

The fatigue behavior of recyclable low density adhesive system determined by plotting stress-number of cycles to failure (S-N) curve and slope exponent (Figure 2) also confirms equivalence to conventional structural adhesive (Figure 2).

DEBONDING OF ADHESIVE JOINT FOR RECYCLING & RECOVERY

The proof of concept for the recycling of a wind blade is demonstrated by preparing an adhesive joint simulating the joining of the two shells of rotor blade prepared by gluing

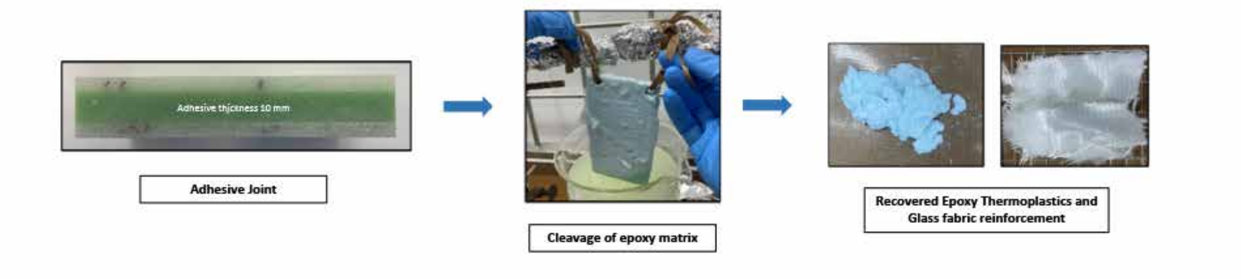


Figure 3: Debonding of adhesive joint and recycling and recovery.

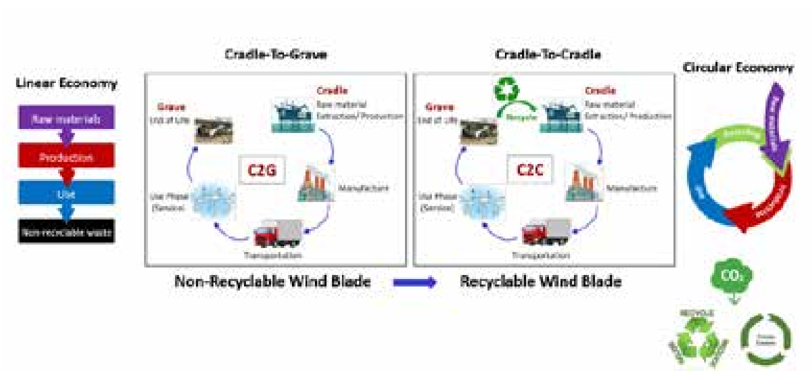


Figure 4: Circularity in wind industry with recyclable epoxy systems.

Property	Test method	Unit	Non-Recyclable Epoxy Adhesive	Recyclable Epoxy Adhesive
Mixing Ratio	-	by weight	100:43	100:43
Viscosity @ 25°C, 2.5 s⁻¹	by rheometer	Pa.s		
- Resin			561	554
- Hardener			468	456
- Mix			180	263
Ultimate Tg	ISO 11357-2	°C	86.90	92.14
Pot Life, 100 gms. mix @ 35°C	ASTM D 2471	minutes/°C	138.8/ 104.2	153.5/ 63.0
Curing Shrinkage @ 60°C/ 5hrs.	ABC-ADC-001	mm^2	2,465	2,127
Tensile Test	ISO 527-2			
Tensile Strength		MPa	53.09	52.43
Fracture Strain		%	4.19	3.64
Elongation at Break		%	6.06	6.06
E-Modulus		MPa	2,778	2,847
Tensile Lap Shear Strength (GRE/GRE)	ISO EN 1465	MPa	26.53	25.24
Fracture toughness	ISO 13586			
Critical Stress Intensity Factor (K1c)		$MPa.m^{1/2}$	2.89	2.77
Critical Strain Energy Release Rate (G1C)		J/m^2	5,645	5,327
Heat Distortion Temperature	ISO 75-2	°C	74.40	77.97
Glass Transition Temperature (Tg)	ISO 11357-2	°C	79.90	82.38
Cured Density	ISO 1183-1	gm/cm^3	1.18	1.16

Note: Test results of typical batch.

Table 1: Comparative properties of non-recyclable and recyclable epoxy adhesive.

two glass reinforced epoxy substrates made from recyclable epoxy infusion. The joint after immersion in solvolysis solution at the temperature range of 75-90°C, debonded with the cleavage of the epoxy adhesive followed by the cleavage of the epoxy infusion system used as a matrix for substrates.

The recycling process resulted in recovery of the glass fabric reinforcement and epoxy thermoplastic after the neutralization and coagulation of the solvolysis solution.

CONCLUSION

A wind turbine rotor blade made from a recyclable epoxy resin system and the recyclable epoxy adhesive system can be fully recycled by a low-energy solvolysis process. The recycling leads to recovery of the epoxy matrix as a thermoplastic and the reinforcement such as glass or carbon fabrics in cleaned form.

The thermoplastic recovered from the recycling process can be re-used and re-purposed to manufacture thermoplastic objects, whereas the reinforcements can be re-used to manufacture new composite parts.

The comparative life cycle impact assessment studies (LCIA) of wind-turbine rotor blade made from Recylamine® enabled recyclable epoxy system and recyclable adhesive indicates a more than 35 percent reduction in the global warming potential measured in terms of gm CO2 equivalent, vis-a-vis a wind-turbine rotor blade made from conventional, non-recyclable epoxy systems.

Further, the 100 percent recycling of wind turbine rotor blade enables a closed loop and drives circularity by transforming from linear economy, cradle-to-cradle (C2G) to circular economy cradle-to-cradle (C2C), (Figure 4). Importantly it addresses the wind industry's global concern on end-of-life management of wind-turbine rotor blades.

ABOUT THE AUTHOR

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Note: Recyclamine® is a proprietary technology of Advanced Materials-Aditya Birla Chemicals.