

Recyclable Type IV hydrogen storage pressure vessel for fuel cell electric vehicles



6 min · AMIT DIXIT,, Senior vice president, Advanced Materials-Aditya Birla Chemicals



Hydrogen mobility is emerging as a key zero-emission technology, but its environmental impact depends on the entire lifecycle, from manufacturing to end-of-life. A new recyclable epoxy system for Type IV pressure vessels enables material recovery and circularity, reducing CO₂ emissions linked to hydrogen storage in fuel cell vehicles.

Transportation plays a vital role in daily life and the global economy, but also contributes massively to global warming. Mobility from land, air and sea is still heavily reliant on polluting Internal Combustion Engines (ICEs). The automobile or transportation industry is responsible for 10% of the world's carbon dioxide (CO₂) emissions by producing an estimated 80 million vehicles yearly. A typical passenger vehicle emits approximately 4.6 MT CO₂ per year. This compelling issue has resulted in regulatory changes with governments tightening emissions standards and embedding sustainability into policy frameworks. European Emission Standards (EES) and Corporate Average Fuel Economy (CAFE) regulations impose binding CO₂ reduction targets, compelling manufacturers to accelerate the adoption of Zero Emission Vehicles (ZEVs) and improve overall fleet efficiency. The European Commission has proposed lifecycle-based regulations aimed at enhancing material circularity and resource efficiency including mandate for 25% of plastic components to be sourced from End-Of-Life Vehicles (ELVs), a minimum

30% recycling rate for ELV plastics and product design requirement that facilitate reuse, disassembly and recycling.

In recent years, 2 alternate fuel technologies, Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV) have emerged as alternatives to the conventional ICEs. The FCEV use hydrogen (H_2) fuel stored in Type IV composite pressure vessels for powering. These vessels are made from epoxy thermoset resins due to their high mechanical strength and endurance. The use of epoxy however makes the pressure vessels non-recyclable thereby resulting in CO_2 emissions caused by the End-of-Life (EoL) management. A novel recyclable epoxy system leveraging disruptive Recyclamine® technology is developed used and for manufacturing Type IV H_2 pressure vessel of 52 lit. capacity and 700 bar working pressure. The vessel is performance tested for drop, cyclic and burst strength in accordance with ISO/FDIS 19881:2018(E). The pressure vessel can be recycled at EoL by low energy solvolysis to recover carbon fibre reinforcement, liner and the epoxy matrix as a thermoplastic. Reuse and repurposing of recovered materials enables significant reduction in CO_2 emissions and leads to circularity.

Fuel cell electric vehicles and hydrogen storage pressure vessel

As global decarbonisation efforts accelerate, FCEVs have emerged as a key zero emission technology in the transportation sector. In order to fully assess its environmental impact, a life cycle perspective is essential, capturing emissions from manufacturing, operation and end-of-life phases. Manufacturing includes the energy intensive production of fuel cells, while operational emissions depend on the carbon intensity of the H_2 supply. End-of-life considerations involve the emissions associated with the disposal, recycling or reuse of vehicle components. FCEVs are zero emission systems that convert H_2 gas into electricity through A Proton Exchange Membrane (PEM) fuel cell, combining stored H_2 with ambient oxygen to power electric motors, emitting only water vapor as a byproduct. Unlike BEVs, which store electrical energy directly, FCEVs offer faster refuelling and longer ranges,

making them ideal for high utilisation or long-distance applications such as transit and freight. A core engineering challenge in FCEV design is H₂ storage due to the low volumetric energy density, small molecular size and high diffusivity that makes it prone to permeation and material degradation, including embrittlement of susceptible metals. Safe and efficient storage requires high pressure vessels capable of withstanding up to 700 bar while resisting permeation and maintaining structural integrity under cyclic loads.

Type IV composite pressure vessels are now standards in FCEVs as they offer the highest gravimetric efficiency and corrosion resistance. Their multilayer composite architecture ensures thermal stability, fatigue resistance and minimal H₂ permeation, critical for enabling safe, reliable H₂ mobility. The fabrication of Type IV composite pressure vessels can be achieved through various fibre winding techniques, with wet winding being widely adopted due to its cost effectiveness and adaptability. Wet winding also offers flexibility in resin formulation and fibre architecture, making it a proven solution for high pressure H₂ storage applications in FCEVs.



Fig. 1: Type IV recyclable H₂ pressure vessel

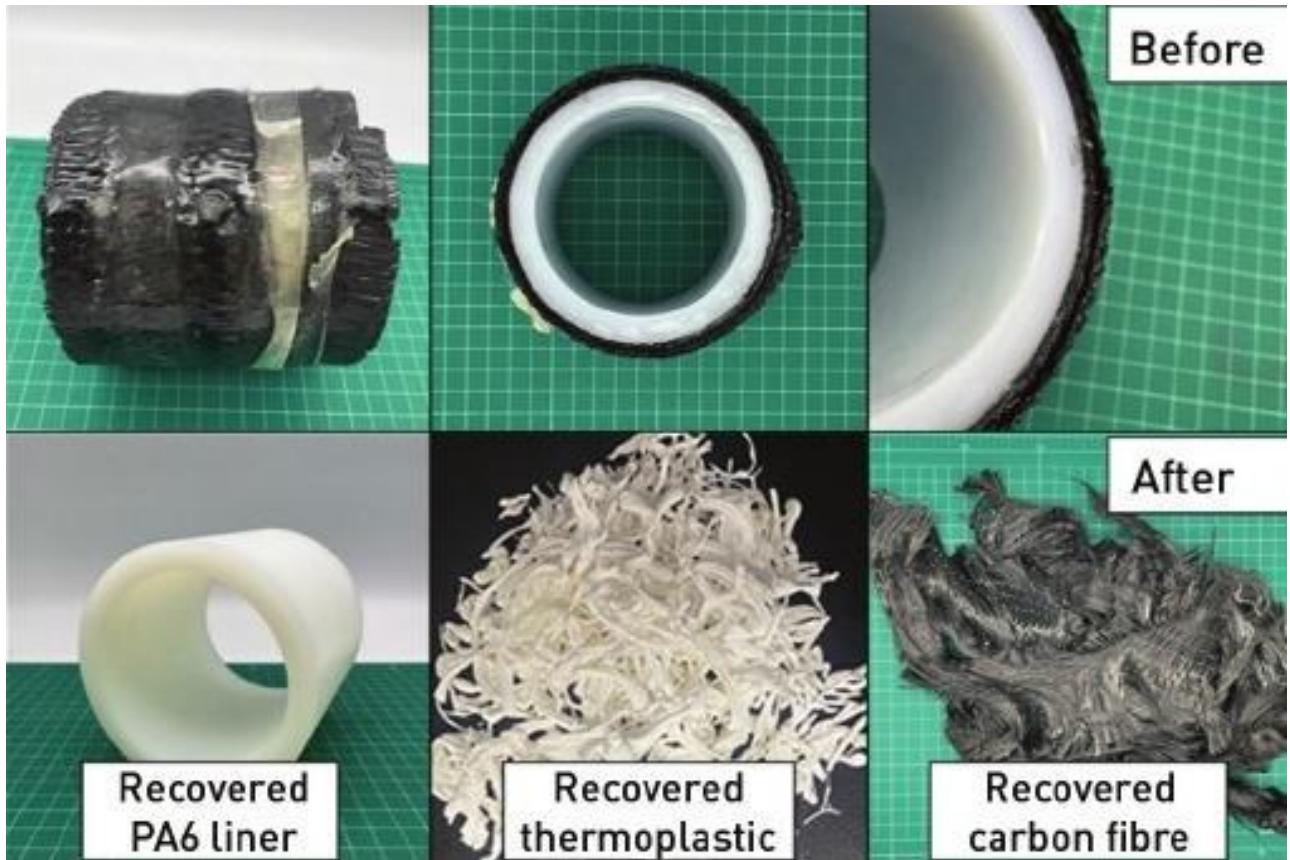


Fig. 2: Composite vessel specimen before and after solvolysis recycling

Circularity in hydrogen storage with Recyclamine® technology

Recyclability is an increasingly important consideration in the design of Type IV H₂ pressure vessels for FCEVs, as conventional epoxy thermosets are non-recyclable due to their permanent cross-linked structures. Recyclamine® technology overcomes this by incorporating cleavable linkages in the matrix enabling mild condition solvolysis to recover reinforcement in near virgin form and convert the matrix into a reusable thermoplastic.

The novel recyclable epoxy system leveraging disruptive Recyclamine® technology developed for wet winding process provides optimum combination of process and mechanical performance (Table 1). A fully recyclable 52 l, 700 bar Type IV vessel fabricated using wet winding meets ISO19881 standards, demonstrating both mechanical reliability and circularity in H₂ storage (Figure 1). The pressure vessel exhibits outstanding performance across multiple qualification tests, confirming both its mechanical reliability and recyclability. It achieved a burst pressure of 1,641

bar, significantly exceeding the nominal working pressure, indicating a robust safety margin. Drop impact testing from a height of 1.8 m onto a concrete surface revealed no leakage, visible damage or interlaminar delamination, verifying structural resilience under accidental impact conditions. Pressure cycling conducted at -40, 25 and 85°C simulated real world service environments. At 25°C, the vessel completed 32 cycles between 20 and 875 bar without failure and additional test at -40°C showed stable behaviour under thermal fatigue.

The proof-of-concept studies to evaluate end-of-life recovery by mild solvolysis cleaved the epoxy matrix within 40 h. Post process analysis confirmed that PA6 liner remained chemically and physically intact and the recovered carbon fibres were free of residual resin (Figure 2), ensuring high quality reuse. These results highlight the pressure vessel's structural integrity, thermal durability and compatibility along-with efficient recycling, supporting its potential in sustainable, high performance pressure systems.

Tab. 1: Process and mechanical performance properties

Property	Test method	Unit	Result
Mixing ratio	-	by weight	100:26
Viscosity @25°C of resin	ASTM D 2196-18 ^{E1}	mPa.s	9,226
Viscosity @25°C of hardener	ASTM D 2196-18 ^{E1}	mPa.s	8.64
Initial mix viscosity @25°C	ASTM D 2196-18 ^{E1}	mPa.s	873.4
Glass transition temperature (Tg)	ISO 11357-2	°C	110.2
Tensile test			
Tensile strength	ISO 527-2	MPa	72.49
Tensile strain	ISO 527-2	%	5.30
E - modulus	ISO 527-2	MPa	2,838
Flexural test			
Flexural strength	ISO 178	MPa	119.70
Flexural strain	ISO 178	%	6.48
E - modulus	ISO 178	MPa	2,986
Fracture toughness			
K1c	ISO 13586	MPa.m ^{1/2}	1.50
G1c	ISO 13586	J/m ²	723.91

Towards zero-emission mobility

Sustainable transportation requires solutions that meet both regulatory and environmental goals. FCEVs play a key role, but their success depends on safe, efficient and recyclable H₂ storage. Type IV composite pressure vessels, produced via wet winding, offer high performance and are now enhanced by Recyclamine® technology, enabling full recyclability. The demonstrated durability, safety and end-of-life recovery with circularity demonstrate strong potential for the recyclable hydrogen Type IV composite pressure vessel for circular H₂ systems. These

advancements align with global emission targets and support the shift to zero-emission mobility and reinforce establishment of ecosystem for green-hydrogen economy.

More information: www.adityabirla.com