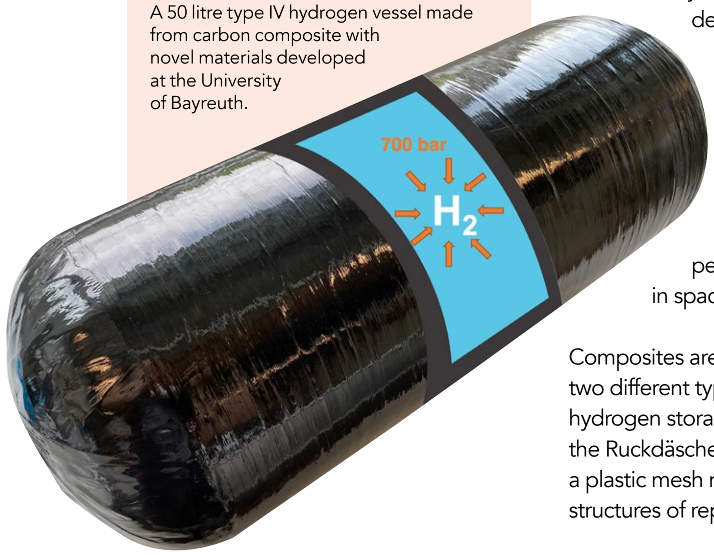
Super-strong materials

Fueling sustainable hydrogen transportation

Hydrogen could kickstart a green revolution in the travel industry – it's a clean, sustainable alternative to fossil fuel powered vehicles. But hydrogen must be stored in tanks capable of withstanding high pressure and low temperatures – challenging requirements that have so far curtailed the advancement of fuel cell electric vehicles (FCEVs). Professor Holger Ruckdäschel, Mr Fabian Hübner, and their team from the University of Bayreuth, Germany, are developing super-strong materials for hydrogen fuel tanks. The cutting-edge technology, using carbon fibre and epoxy resin polymers, could help FCEVs to carry more fuel and travel farther.

A 50 litre type IV hydrogen vessel made from carbon composite with novel materials developed at the University of Bayreuth.



Amid the global climate crisis, many leaders and policymakers view hydrogen as a viable alternative to fossil fuels. Hydrogen fuel cells generate electrical energy through the chemical reaction of hydrogen and oxygen. Unlike conventional combustion engines, they don't emit detrimental waste products, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and soot particles. Despite its potential to kickstart a green energy revolution, however, hydrogen-based technology comes with a set of challenges: green production of the fuel, ease of transport, safe storage, and broad infrastructure availability. To understand the scale of storage and transport challenges, it's important to consider that a hydrogen fuel cell electric vehicle (FCEV), for a typical range of 600km, would need several cubic metres of the element in its gaseous, uncompressed state. To be used efficiently, hydrogen is compressed to 700 bars at room temperature so that its molecules can be condensed together in a fuel tank.

To fulfil hydrogen fuel requirements, Professor Holger Ruckdäschel and Mr Fabian Hübner, from the University of Bayreuth, Germany, have developed high-specific-strength materials made from carbon fibre composites, designed to withstand the high pressure and low temperature of hydrogen stored in high-performance cars, aircraft, or in space travel.

Composites are materials made from two different types of substances. The hydrogen storage tanks designed in the Ruckdäschel laboratory consist of a plastic mesh made of giant chain-like structures of repeating molecular units, which embed a multitude of tough and bulky carbon-fibre strands. The resulting lightweight but incredibly rigid structure retains the low density that characterises most plastic materials, while at the same time being five times stronger than steel. The team optimises the nanomaterial composites for safety, weight, and longevity, investigating the structure–property relationship in detail across nanoscale dimensions and in conditions of extreme temperatures.

SPACE INSPIRES HYDROGEN REVOLUTION

Several countries are opting for battery-powered transport to meet strict environmental targets set in recent years, and to curb the effects of CO_2 emissions on global warming. However, electric mobility does not come without challenges. One of the main problems affecting potential customers is the long charging times required to power a journey over a modest range. Storing enough energy to increase the range in mileage (while decreasing charging time) requires the right combination of fuel and materials used for fuel storage. Hydrogen fuel cells have the advantage of being recharged during operation, eliminating the need for long charging times. On the other hand, liquid hydrogen storage requires the use of materials that can resist cracking under harsh conditions of temperature and pressure.

Ruckdäschel, Hübner and their team took inspiration from the space industry, designing hydrogen storage tanks made with lightweight materials that don't lose their strength and durability. The team uses epoxy resins, widely used polymers known for their role in the production of adhesives, coatings, and housings. Due to their low viscosity, they are the ideal material for manufacturing lightweight composites. Epoxy composites are made of a resin and a hardener; once the two components are mixed, stable bonds are formed, meaning that the plastics cannot be melted any longer and acquire exceptional strength. When designing vessels aimed at containing pressurised fuels, it is important to consider the vessel geometry and size, as well as important functional properties of epoxy resins, such as tensile strength (the amount of stress a material can endure before breaking) and fracture toughness (the capacity of a cracked material to resist further fracture).

Hydrogen: fuelling sustainability.

CRACKING CONTAINER CONUNDRUM

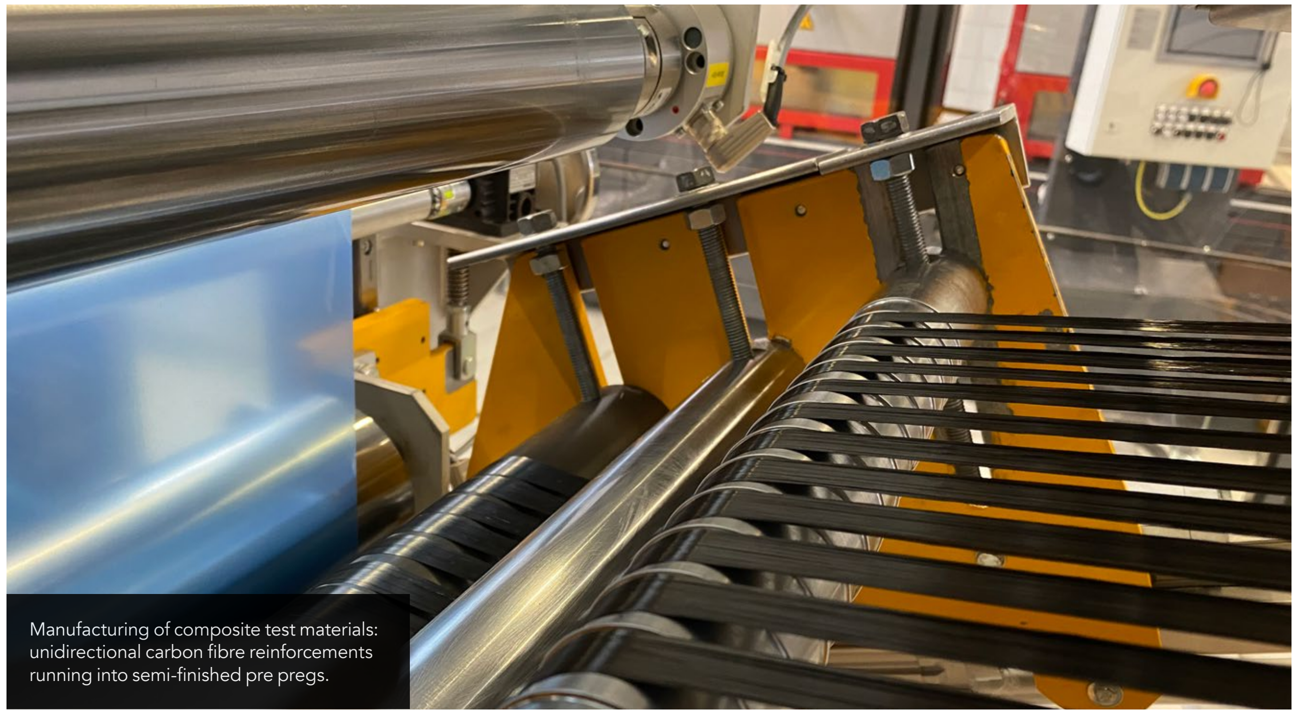
Ruckdäschel and Hübner investigate the physical and chemical resilience of toughened epoxy-amine formulations under a broad range of chemical and environmental conditions. They report the findings of their study in a paper published in 2021, focusing on the mechanical behaviour of the toughened composites at low temperatures and compared to a non-toughened reference material. The fatigue crack propagation, a property indicating the tendency of a solid to fracture under mechanical stress through tension, pressure, bending or torsion, was investigated at -50°C and at 20°C. The low temperature value was chosen specifically as a first step towards testing conditions that have relevance to vessel-filling procedures adopted in space travel, where liquid hydrogen is stored at cryogenic temperatures of around -253°C.

Despite its potential to kickstart a green energy revolution, hydrogen-based technology comes with a set of challenges.

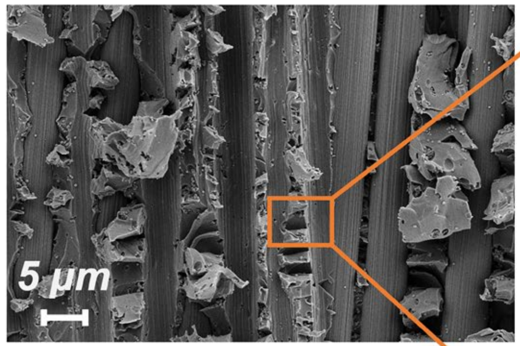
A special requirement for pressure vessels is enhanced resistance to microcracking at cryogenic temperatures. The goal is to achieve highly stable and leakproof resin-based tank systems. The microcracking phenomenon might be the result of a mismatch in thermal expansion between the fibres and the matrix in the resin. The authors found that the toughening of the epoxy resins led to a dramatic increase in functional properties, like strength under tension and compression. More importantly, at -50°C the crack growth rate is decreased drastically when the material is toughened. However, the researchers caution that more studies will be needed. Further investigations of cracking phenomena in epoxy resins at low temperatures are essential to prevent catastrophic failures.

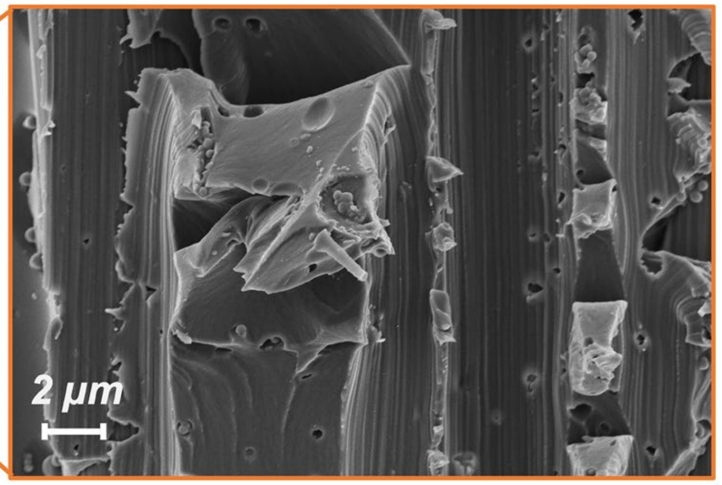
FUELLING HYDROGEN SUSTAINABILITY

Many questions still need to be resolved about using hydrogen fuel cell technologies efficiently and sustainably



Manufacturing of composite test materials: unidirectional carbon fibre reinforcements running into semi-finished pre pregs.





Scanning electron microscope images. Fracture surfaces of composite test specimen: an insight into nanotougheners used for epoxy matrices to enhance micro-cracking resistance.

– for example, how to generate, store, and use the energy needed to produce hydrogen at sufficient scale for the operation of everyday vehicles. Despite these challenges, however, several types of engines powered by hydrogen fuel cells are already being used successfully on buses, trains, and ships. With further research, hydrogen fuel cells could lead to the widespread use of eco-friendly electric engines for public and private transport.

The researchers at the Ruckdäschel laboratory caution that the source of hydrogen production needs to be carefully considered before environmental benefits can be assessed. The most environmentally friendly source of the precious gas is 'green' – purely CO_2-neutral produced hydrogen. Green hydrogen is formed through the process of splitting water (H_2O) into the two elements that make it up – hydrogen (H_2) and oxygen (O_2); this is achieved through a process called electrolysis, which is powered by renewable energy. Hydrogen can also be 'grey' or 'blue'. Grey hydrogen is extracted from a natural gas mixture via the steam reforming process, a production method associated with significant CO_2 emissions, which negatively impacts the climate – especially when copious quantities of hydrogen will be required in the future. Prompt removal and sequestration of CO_2, produced via steam reforming, leads to the production of blue hydrogen, a more eco-alternative.

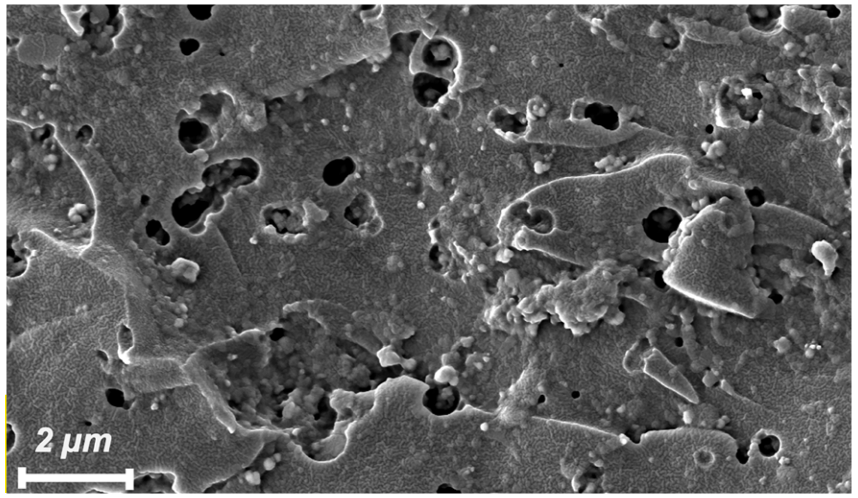
Ruckdäschel and Hübner took inspiration from the space industry, designing hydrogen storage tanks made with lightweight materials that don't lose their strength and durability.

NEW SUPER-STRONG MATERIALS

Ruckdäschel, Hübner and their polymer engineering team take inspiration from materials used in space travel to design hydrogen storage vessels that will enable consumers to use hydrogen-fuelled vehicles every day.

While fossil fuels can be used in an uncompressed state, hydrogen needs to be highly pressurised to be stored and burnt efficiently. For this purpose, the team designed toughened epoxy amine resin systems, investigating their mechanical behaviour and resistance to cracking at low temperatures relevant to the vessel-filling procedures of cryo-compressed hydrogen gas. These composite materials, reinforced by carbon fibre, can withstand standard pressures of 700 bars and can keep their structural integrity at extreme temperatures – even with an overall tank-wall thickness of less than 10mm.

These strong, lightweight materials will establish hydrogen fuel cell technology in the automotive market. Ruckdäschel and his team's achievements are a super-strong step forward in improving sustainability for everyday transport.



Scanning electron microscope image of the surface of an epoxy tested at low temperature along its fracture toughness. Nanoparticles used for energy dissipation of a crack.

Behind the Research

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Bio

Prof Dr-Ing Holger Ruckdäschel
After studying materials science and earning a PhD in the Department of Polymer Engineering at Bayreuth in 2009, Ruckdäschel worked as Head of Digital Strategy at BASF AG in Ludwigshafen. Since 2020 he has been a Full Professor at Bayreuth's Department of Polymer Engineering. Since 2022 he is also CEO of Neue Materialien Bayreuth GmbH, a non-academic research institute with 60 people focusing on new materials and technology transfer. His research topics and interests are based on sustainable material concepts, application-oriented research, and digitalisation of polymer research and plastics industry, with a focus on cellular polymers and foams, polymer composites, functionalised polymers and blends, bio-based and biodegradable polymers, additive manufacturing, and material testing and fatigue.

Fabian Hübner, MSc
Fabian Hübner studied materials science and engineering at the University of Bayreuth. The focus of his master's studies was polymer materials and composites, which he finished with his master thesis, 'Influence of silane-based coupling agents on the thermal and mechanical properties of highly filled CFRP'. Since 2018, Hübner has been a member of the Thermosets and Composites Group at the Department of Polymer Engineering. His doctoral studies deal with the investigation of low-temperature cryogenic performance of carbon-fibre-reinforced composite materials and winding of vessel structures for hydrogen storage.

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Collaborators
- Universität der Bundeswehr/Institute Aeronautical Engineering/Professorship Composites and Mechanics
- University Paris-Est Créteil/Institute of Chemistry and Materials

Research Objectives

Developing super-strong materials capable of withstanding the high pressure and low temperatures needed for hydrogen storage.

References

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Personal Response

How close are you to scaling up the production of the specially designed storage tank, enabling the widespread use of everyday hydrogen-fuelled transportation?

" We work closely with various development partners from research and industry to meet a wide range of requirements for this key technology. In the upscaling process, it is important to meet both technical and legal requirements.

What were the main challenges you faced when creating the new composite materials?

The greatest challenge during the development process arises from the wide variety of potential applications for this technology. For example, the requirements in the aerospace industry are quite different from those in ground-based transportation. Above all, the price–performance ratio requirements face us with challenges during the development process. "