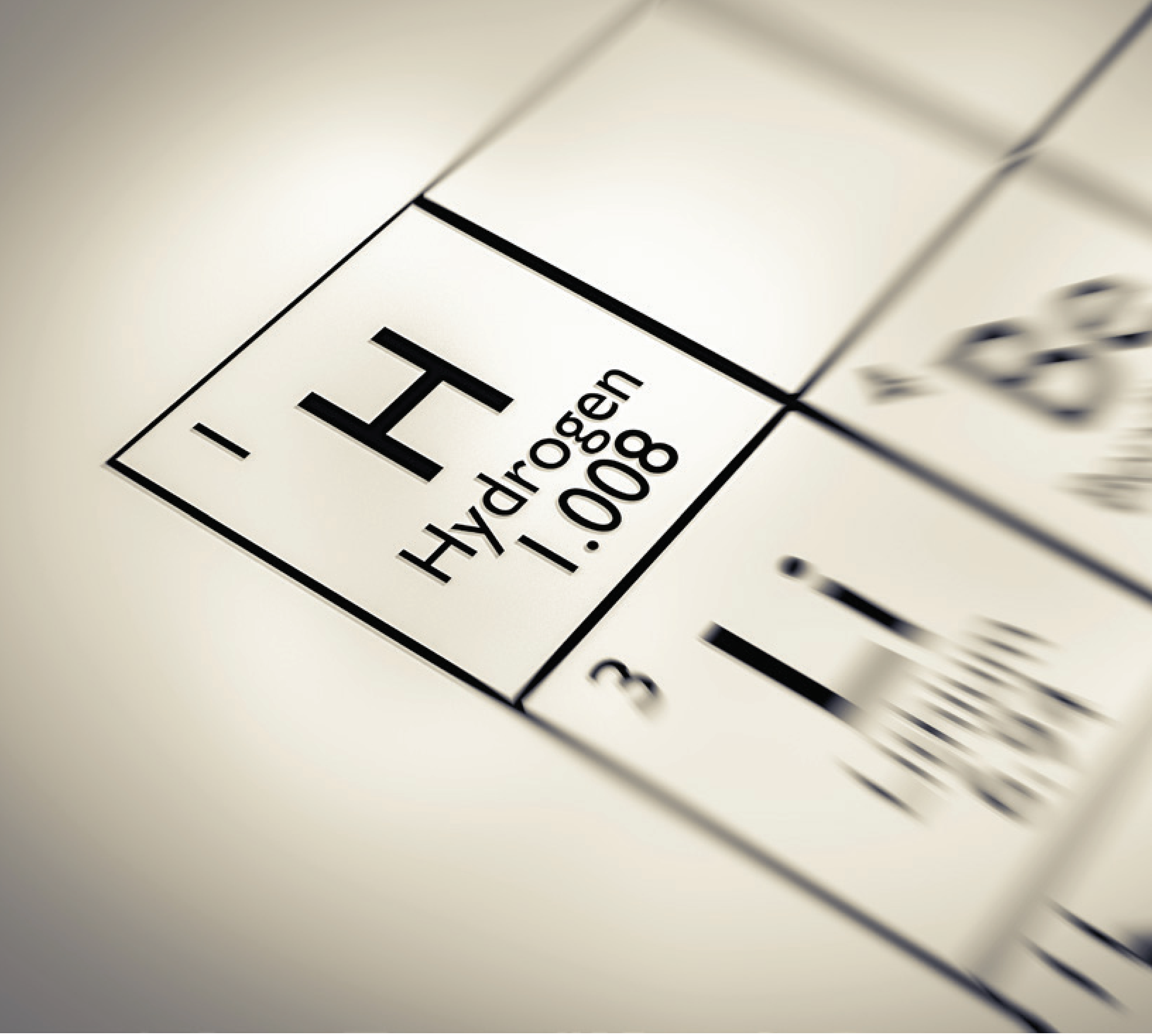

Addressing the Challenge of Hydrogen Embrittlement in Metallurgy

White Paper

ENGINEERING YOUR SUCCESS.

The Impact of Hydrogen

In the quest for a decarbonised society there is no doubt that Hydrogen as an environmentally friendly fuel source is gaining a lot of popularity to become the fuel of the future. And the hydrogen revolution is happening now.

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Driving the ecological transition, hydrogen-based technologies are rapidly evolving, mass entering the market and becoming part of our daily lives. From clean power generation to environmentally friendly cars, the possibilities are endless.

The transportation sector is a prime example of how hydrogen technologies are taking off and making truly sustainable mobility more tangible than ever.

Heavy trucks with hydrogen-powered cells are already hitting the roads, and although developing a global hydrogen refuelling infrastructure might take several years or even decades, the commitment to hydrogen economies from governments all around the world will certainly accelerate its pace.

As a leading manufacturer in motion and control technologies Parker offers a wide range of products orientated to the hydrogen transportation market, from fuel cell powered platforms, for trucks and buses to hydrogen storage.

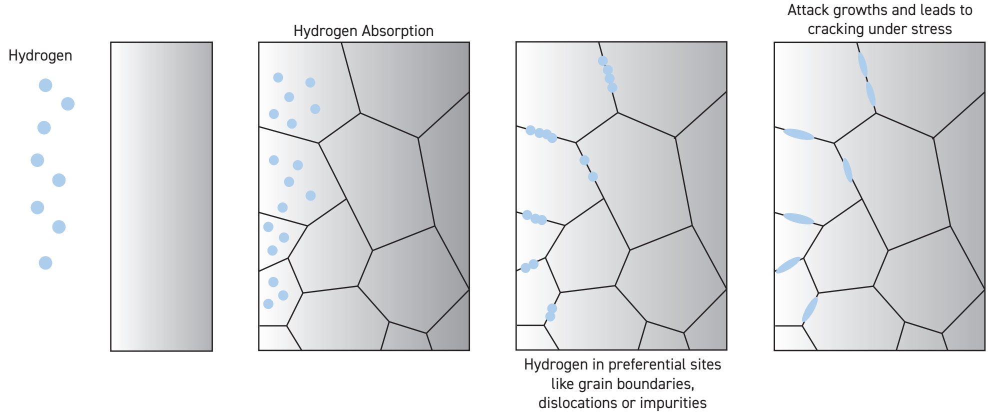
Our comprehensive product portfolio covers a wide variety of pressures to help our customers overcome some of the technical challenges of such critical and demanding applications.

The Hydrogen Challenge
Hydrogen is the most abundant element in nature and its versatility can offer compelling advantages as an accessible, sustainable and efficient alternative source of energy.

However, hydrogen can be very damaging for most metallic materials, causing what is known as hydrogen damage or hydrogen attack. Hydrogen, being an extremely small particle, hydrogen degradation is directly connected to its capability to be easily absorbed by metals coupled with the high mobility those particles have at microstructural level.

Nearly every metallic material can be susceptible to hydrogen damage, and there are several forms of hydrogen degradation. Hydrogen embrittlement cracking is the most common and affects the three main areas of industries that use hydrogen:

- **Production**
- **Transportation**
- **Storage**



Embrittlement occurs when a material loses ductility and becomesffinsi brittle as a result of the diffusion of hydrogen into the material. The hydrogen atoms find preferential places in the structure of the material, modifying its physical properties and its mechanical behaviour.

The result is a loss of ductility which makes the material more brittle and more susceptible to cracking.
Hydrogen can be a silent assassin, weakening the material slowly and without any clear signs of damage, often leading to critical failure.

The effect of Hydrogen embrittlement is determined by three main challenges:

- The Environment
- The Mechanics of the material
- The Microstructure characteristics of the material.

1. Environment

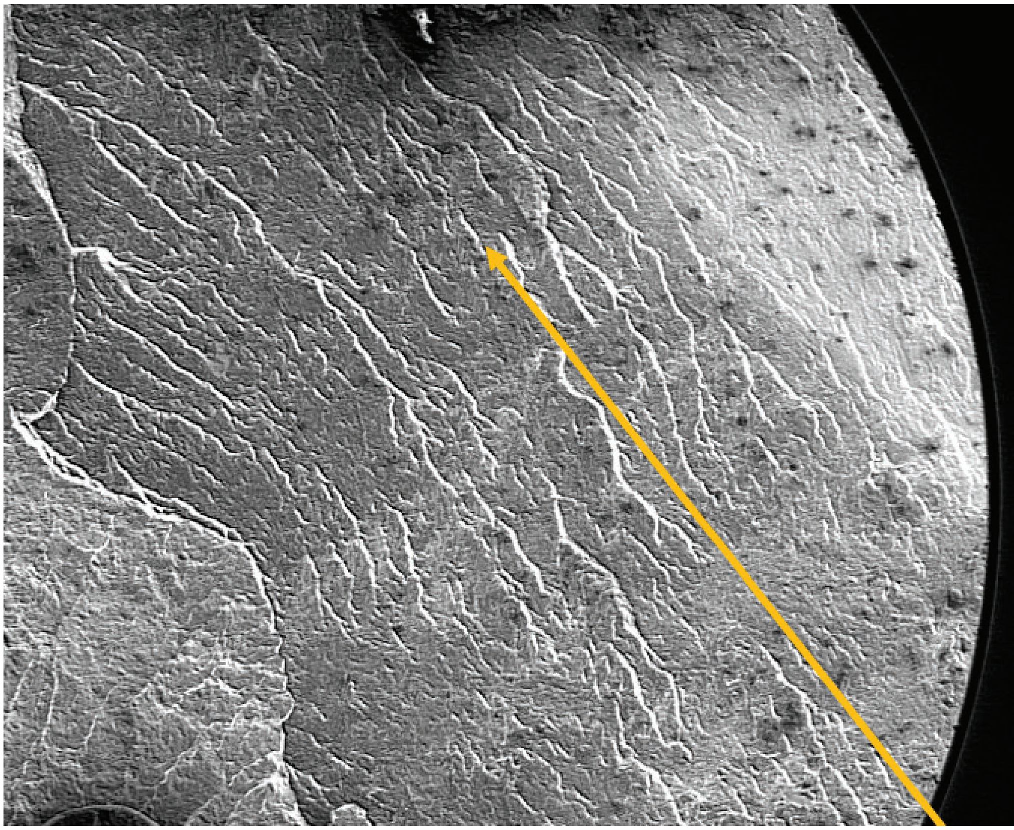
- Internal and external hydrogen
- State of hydrogen (gas)

2. Mechanics (Internal and external factors)

- Cyclic service
- Vibrations
- Over-loading (poor design, low quality equipment, low safety factor)
- Internal stresses due to manufacturing and material processing.

3. Characteristics of the microstructure

- Mechanical properties
- Quality of the microstructure
- Density of defects and inclusions
- Heat treatment
- Chemistry
- Steel making
- Manufacturing processes
- Surface finish

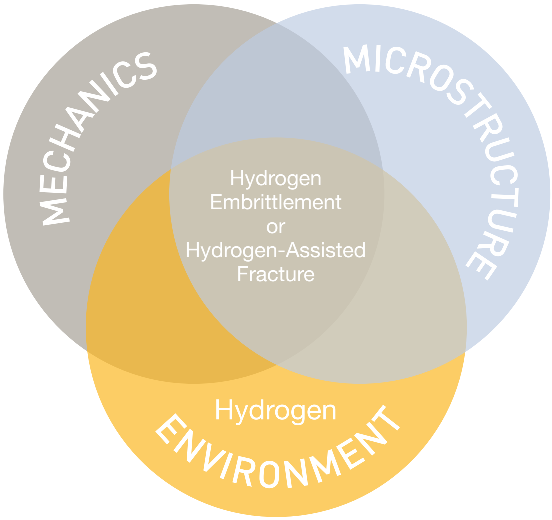


Crack Propagation Detail on A Brittle Fracture Surface due to Hydrogen

Hydrogen and stress need to be present on a susceptible material for hydrogen-assisted fracture to happen.

Firstly, hydrogen absorption can happen at both production and service stages. Processes such as uncontrolled melting, electroplating or welding can promote the pre-charge of hydrogen into a given metal.

In terms of microstructure, and as a rule of thumb, materials that bestow high mechanical strength or show a great number of defects and inclusions are likely to be more susceptible to this type of failure.



The severity of hydrogen embrittlement is also a function of the operating temperature, with low temperatures being the worst case scenario in terms of material ductility and higher temperatures in terms of hydrogen absorption rate.

The factors that can affect the quality of the microstructure are numerous and have been widely documented by the materials society.

Due to the complexity of the subject, the effect of microstructure as a major contributing factor to hydrogen behaviour, cannot be evaluated in simplistic terms. Taking one variable in isolation is not enough to guarantee the quality or performance of a given component and can be misleading.
For example, a material grade with a 'perfect chemistry' or with high levels of a particular ingredient can still result in a very low quality product.

The common consequences of improper and non-controlled material processing, heat treatment and / or manufacturing operations are high densities of undesirable phases and inclusions in the raw material. These will inevitably lead to fatal and premature hydrogen assisted cracking during service in demanding H2 environments. Material processing is key.

Also, the mechanics of the application play a major role. Stress states in components can be caused by the presence of residual stresses associated with certain fabrication techniques as well as stresses applied during service. Improper product design and improper installation can cause overloading of stress onto the material.
All of these factors can cause premature failure of components in Hydrogen Service.

How Parker is at the Front End of Innovation for the Hydrogen Market

When it comes to handling hydrogen, material and equipment selection becomes, more than ever, an essential ingredient for success.

According to the International Industry Standard ISO 15916-2015, due to the fact that most metals are susceptible to different levels of H2 embrittlement, materials of construction and suitable equipment must be carefully selected to avoid failure when hydrogen exposure is anticipated. The positive news is that hydrogen embrittlement can be prevented. End users need to pay special attention to the materials of construction and the quality of the equipment that goes into their assets.

As a manufacturer of pressure containing equipment, Parker has decades of experience in serving hydrogen applications. Parker products are designed to minimise the risk associated with corrosion and hydrogen attack, providing safe and reliable components, minimising leak paths and ultimately delivering successful performance in the field.

The raw materials that we use are fully traceable and closely controlled from melting stage to the finished product.

In addition, our manufacturing processes are selected to ensure minimum operating risk in hydrogen environments. As well as Stainless Steels (the prime material of choice for the H2 transportation sector), we can offer a variety of nickel alloys for a wide range of other applications.

Parker's portfolio also includes EC-79 approved products. The EC-79 approval (the Regulation of the European parliament and the Council of 14th January 2009 on type-approval of hydrogen powered motors) is an EU normative for components and systems which are installed on hydrogen-driven vehicles.

Product ranges certified to this regulation are extensively tested to guarantee the safety and performance of H2 equipment under different pressures, electric, mechanical, thermal or chemical conditions.

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