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Mechanisms of Material Failure

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Abstract

This report investigates the hydrogen atom and types of hydrogen damage caused to metals such as steels and zirconium. Hydrogen embrittlement and absorption into metals is investigated, whether it is during manufacturing, processing/fabrication or in the components working environment. Hydrogen content was significant after heat treating, especially carburizing. Additional analysis of fracture surfaces of components subjected to longer hydrogen charging detailed hydrogen embrittlement caused: reduced necking, smooth outer layers on fracture surface (brittle fracture), and hydrogen induced cracking on side surfaces. Therefore, mechanical properties see reduced ductility, fatigue resistance, strength and component lifespan.

1 Introduction

Hydrogen damage is a broad and commonly investigated metallurgy topic due to the severity of sudden failures. This document initially investigates the origins, atomic nature and commonly found compounds of hydrogen that lead to these failures under the damage category of hydrogen embrittlement (others are briefly discussed). This report also details the structural changes to metals caused by hydrogen absorption and diffusion which is analysed by using metallurgy examination methods: optical microscopy and scanning electron microscopy for hydrogen embrittlement surface morphology. A final investigation and analysis are conducted on ferrous metals to better understand the effects on mechanical properties.

2 Literature Review

2.1 The Origins of Hydrogen

2.1.1 Hydrogen Isotopes

When an element has a different number of neutrons when compared to its atomic element, it is considered an isotope. As an isotope, the element will have the same chemical characteristics, valence states and electronic configuration (Alexandre, 2020). The difference is relative atomic mass. According to the National Isotope Development Centre (n.d), isotopes of elements are formed either naturally by radioactive decay of a nucleus by energy emission, or “artificially by bombarding a stable nucleus with charged particles via accelerators or neutrons in a nuclear reactor”. Hydrogen is a unique element with hydrogen isotopes each having individual names: ‘Protium’, ‘Deuterium’ and ‘Tritium’ (figure 1). Protium consists of 1 electron, 1 proton and 0 neutrons and is atomic hydrogen, being stable but reactive. Deuterium is a stable hydrogen isotope consisting of 1 proton, 1 electron and 1 neutron; out of 6420 hydrogen atoms on average, only one is deuterium (IAEA, 2023). Finally, tritium is an unstable isotope with 1 proton, 1 electron and 2 neutrons.

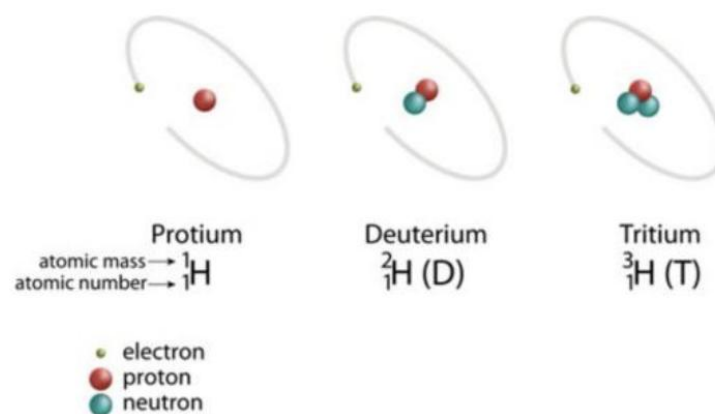


Figure 1: Diagram of Hydrogen Isotopes (Alexandre, 2020).

2.1.2 Diatomic Hydrogen

As protium (atomic hydrogen) is highly reactive due to missing 1 electron from its outer shell, it is one of seven diatomic molecules and is labelled H_2 as a gas at room temperature (figure 2). Diatomic hydrogen is where two hydrogen atoms covalently bond and share electrons (Lefebvre-Brio & Field, 2004). Hydrogen is the second smallest atom and is therefore difficult to store and control in manufacturing.

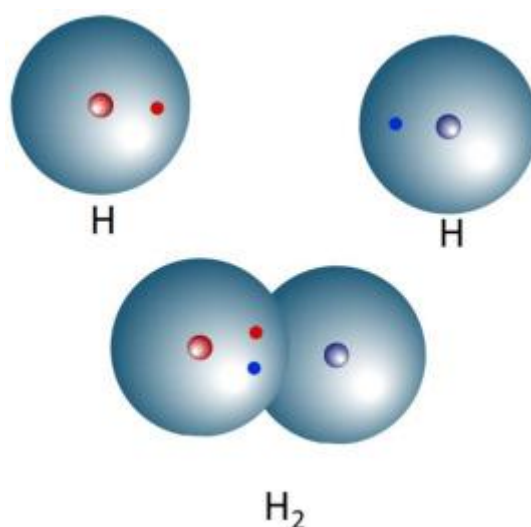


Figure 2: Diatomic Hydrogen Gas Molecular Diagram (Okonkwo, et al., 2023)

Dihydrogen in gaseous form can be produced in numerous different ways; the primary methods are thermochemical, electrolysis, direct solar water splitting process and biological. (US Department of Energy, n.d). Primary sources of hydrogen are organic materials, fossil fuels, water and bacteria.

2.1.3 Hydrogen Compounds

As a reactive element, hydrogen occurs naturally on earth in compound forms of gases, solids and liquids (US Energy Information Administration, 2023). Common compounds that involve hydrogen are water (H_2O), ammonia (NH_3), methane (CH_4) and more (Mendeleev, 1891). Compounds such as water and methane are formed naturally on Earth where water is a result of dihydrogen and oxygen bonding and methane from animals and the breakdown/decay of organic materials.

2.2 Hydrogen Damage and Structural Changes

When hydrogen damage occurs (figure 3), it is usually in one of the following forms (table 1): hydrogen embrittlement (HE), blistering, hydrogen-assisted cracking, metal hydride formation and more (Berto, et al., 2020).

Table 1: Hydrogen Damage Methods (Berto, et al., 2020).

	Hydrogen embrittlement			Hydrogen attack	Blistering	Shatter cracks, flakes, fisheyes	Micro-perforation	Degradation in flow properties	Metal hydride formation
	Hydrogen environment embrittlement	Hydrogen stress cracking	Loss in tensile ductility						
Materials	Steels, Ni-base alloys, metastable stainless steel, Ti alloys	Carbon and low alloy steels	Steels, Ni-base alloys, Be-Cu bronze, Al alloys	Carbon and low alloy steels	Steels, Cu, Al	Steels (forgings and castings)	Steels (compressor)	Fe, steels, Ni-base alloys	V, Nb, Ta, Ti, Zr, U
Source of hydrogen	GH ₂	Thermal processing, electrolysis, corrosion	GH ₂ , internal hydrogen from electrochemical charging	GH ₂	H ₂ S corrosion, electrolytic charging, GH ₂	Water vapor reacting with molten steel	GH ₂	GH ₂ or internal H ₂	Internal H ₂ from melt; corrosion, electrolytic charging, welding
Conditions	10 ⁻¹² ÷ 10 ³ MPa, -100 ÷ 700 °C	0.1 ÷ 10 ppm H ₂ content, -100 ÷ 100 °C	0.1 ÷ 10 ppm H ₂ content, -100 ÷ 700 °C	Up to 10 ² MPa at 200 ÷ 595 °C	H ₂ activity 0.2 ÷ 1 × 10 ³ MPa at 200 ÷ 595 °C	Precipitation of dissolved ingot cooling	2 ÷ 8 × 10 ⁵ MPa at 20 ÷ 100 °C <	1 ÷ 10 ppm H ₂ content, up to 10 ³ MPa	0.1 ÷ 10 ⁴ MPa

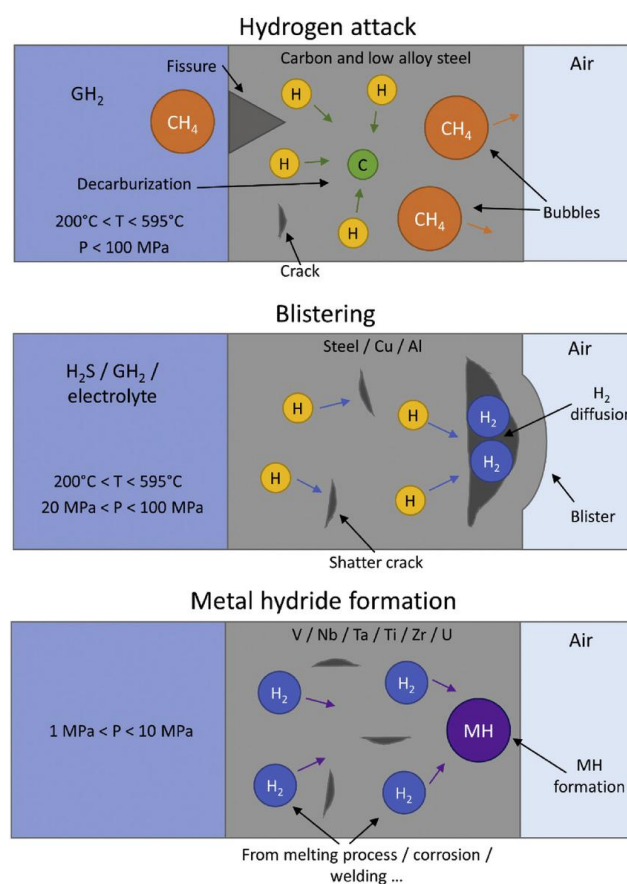


Figure 3: Hydrogen Damage Techniques (Berto, et al., 2020).

2.2.1 Hydrogen Environment Embrittlement (HEE)

HEE (figure 4) is used to classify a material that becomes brittle due to hydrogen when the material is said to be purposefully exposed to a gaseous hydrogen environment and impacted by an applied stress (Lee, 2016). Low hydrogen soluble materials such as metals with a body centred cubic (BCC) or hexagonal close packed (HCP) lattice structure (Berto, et al., 2020) have an increasing impact on HEE, as does increases in pressure (Michler, et al., 2008).

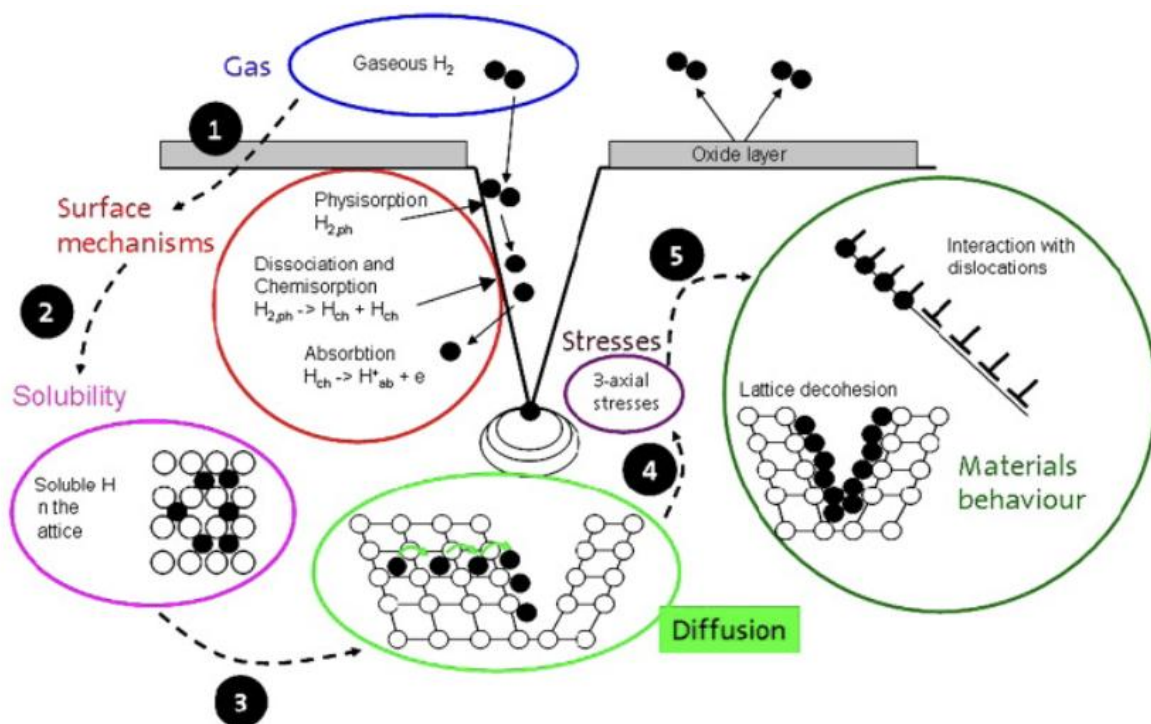


Figure 4: HEE Diagram (Michler & Naumann, 2009).

2.2.2 Internal Hydrogen Embrittlement (IHE)

IHE is where hydrogen is introduced (unintentionally) into a susceptible metal during production or finishing stages (Lee, 2016). The following methods introduce high hydrogen contents: electroplating, thermal processing (heat treatment) and corrosion (Berto, et al., 2020). The chemical properties and thickness of surface coating both impact hydrogen production and absorption. In aluminium's case (figure 5), the oxidation reaction between water vapor and aluminium produces atomic hydrogen. This absorbs into the coating and diffuses into material (Ostwald, et al., 2023).

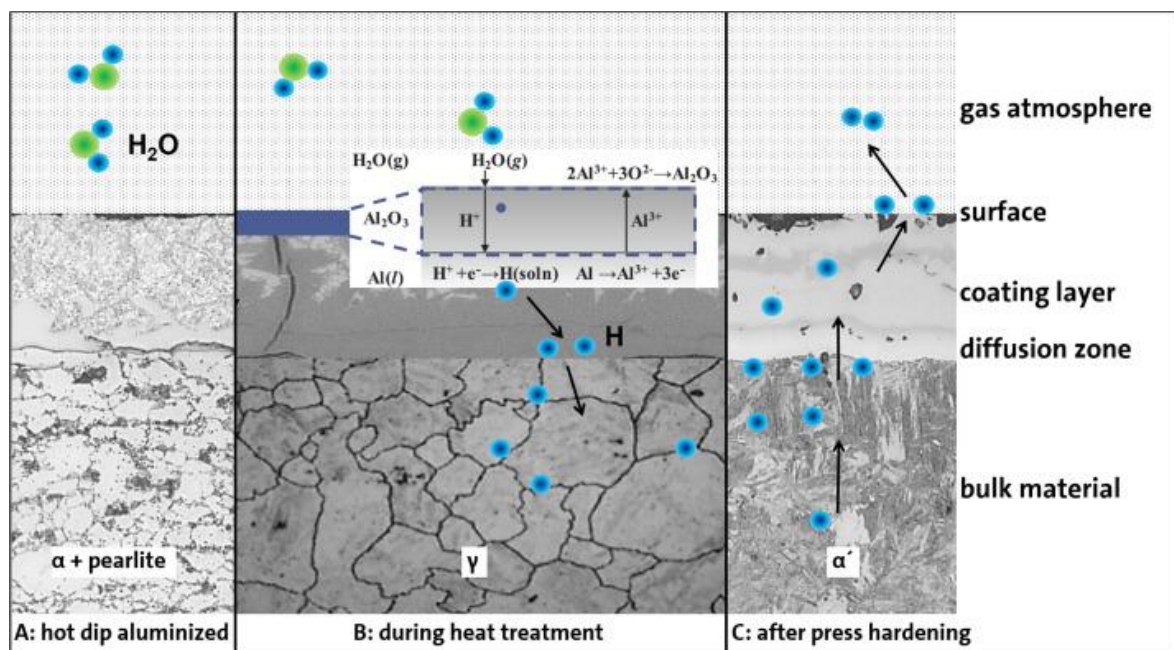


Figure 5: Hydrogen Absorption Through Heat Treatment of Aluminium (Ostwald, et al., 2023).

2.2.3 Hydrogen Reaction Embrittlement (HRE)/Hydrides

When hydrogen bonds with an element it forms an element-hydrogen bond ('hydride'). At relatively low temperatures hydrogen can react with metals within a matrix to form hydrides, this type of embrittlement is described as HRE (Lee, 2016). For hydrides to form, conditions such as a presence of hydrogen and temperature are required. Depending on which element hydrogen bonds to, determines the category of bond: ionic, covalent or metallic (figure 6). When hydrogen bonds with most transition metals (groups 3-5) a metal hydride is formed, remaining transition metals (except chromium) form complex covalent and ionic (saline) hydrides instead (Blackledge, et al., 2013). The type of hydride formed depends on the element and if electrons are shared/donated.

Saline		Metallic										Covalent	
I A	II A											III B	IV B
LiH	(BeH ₂) _n Covalent											Series of Boron Hydrides (See Chap. 12)	
NaH	MgH ₂											(AlH ₃) _n	Series of Si Hydrides (See Chap. 12)
		III A	IV A	V A	VI A	VII A	VIII A	I B	II B				
KH	CaH ₂	ScH ₂	TiH ₂ (cubic and tetrag.)	VH VH ₂	CrH CrH ₂	Mn —	Fe —	Co —	NiH	CuH	(ZnH ₂) _n	(GaH ₃) _n	Series of Ge Hydrides (See Chap. 12)
RbH	SrH ₂	YH ₂ YH ₃	ZrH ₂ (cubic and tetrag.)	NbH NbH ₂	Mo —	Tc —	Ru —	Rh —	PdH	Ag —	(CdH ₂) _n	(InH) _n (InH ₃) _n	SnH ₄ Sn ₂ H ₆
CsH	BaH ₂	See Rare Earth Series	HfH ₂ (cubic and tetrag.)	TaH	W —	Re —	Os —	Ir —	Pt —	Au —	(HgH ₂) _n	(TlH) _n (TlH ₃) _n	PbH ₄

LaH ₂₋₃	CeH ₂₋₃	PrH ₂₋₃	NdH ₂₋₃	Pm ?	SmH ₂ SmH ₃	EuH ₂	GdH ₂ GdH ₃	TbH ₂ TbH ₃	DyH ₂ DyH ₃	HoH ₂ HoH ₃	ErH ₂ ErH ₃	TmH ₂ TmH ₃	YbH ₂ YbH ₃ (?)	LuH ₂ LuH ₃
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AcH ₂	ThH ₂ Th ₄ H ₁₅	PaH ₃	UH ₃	NpH ₂ NpH ₃	PuH ₂ PuH ₃	AmH ₂ AmH ₃ (?)
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Figure 6: Metal Hydride Categories (Blackledge, et al., 2013).

2.3 Hydrogen Absorption into Metals

A metals strength can be significantly impacted by the entrapment of hydrogen within the crystalline structure. Within any gas, solid or liquid above a temperature of absolute zero (0 Kelvin), there is movement/vibration of atoms, depending on arrangement there is variations in energy. Within a solid the movement of atoms is restricted by the crystalline structure, however, according to Campbell, F (2008), “thermal vibrations in solids allow atoms to diffuse” and as temperature increases the vibration of atoms about their positions also increases, a concentration gradient also drives diffusion. Due to hydrogens small size the atoms can interstitially diffuse (figure 7) into a metals crystalline structure (Campbell, 2008), concentration gradient and temperature significantly affect diffusion coefficient.

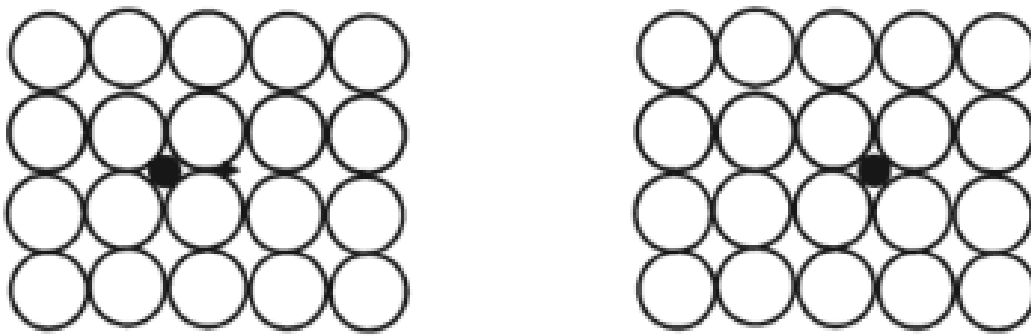


Figure 7: Interstitial Diffusion of Solute Atoms in Crystalline Structure (Campbell, 2008).

Hydrogens primary method into metals is through surface absorption, due to lack of equilibrium leading to surface energy on the metal. The three primary principles of hydrogen diffusion into a metal are: physical absorption which is influenced by environmental conditions (temperature and pressure), chemical absorption is formation of covalent chemical bonds between atoms, and hydrogen (uptake) diffuses into metal through desorption and becomes integrated into metal lattice (Alam, et al., 2024). Once hydrogen has diffused into the metal lattice there are two methods for how hydrogen diffuses within the metal, these being ‘interstitial’ (figure 8) and ‘quantum’ mechanical tunnel diffusion. Quantum is prominent at lower temperatures and interstitial at higher (Alam, et al., 2024).

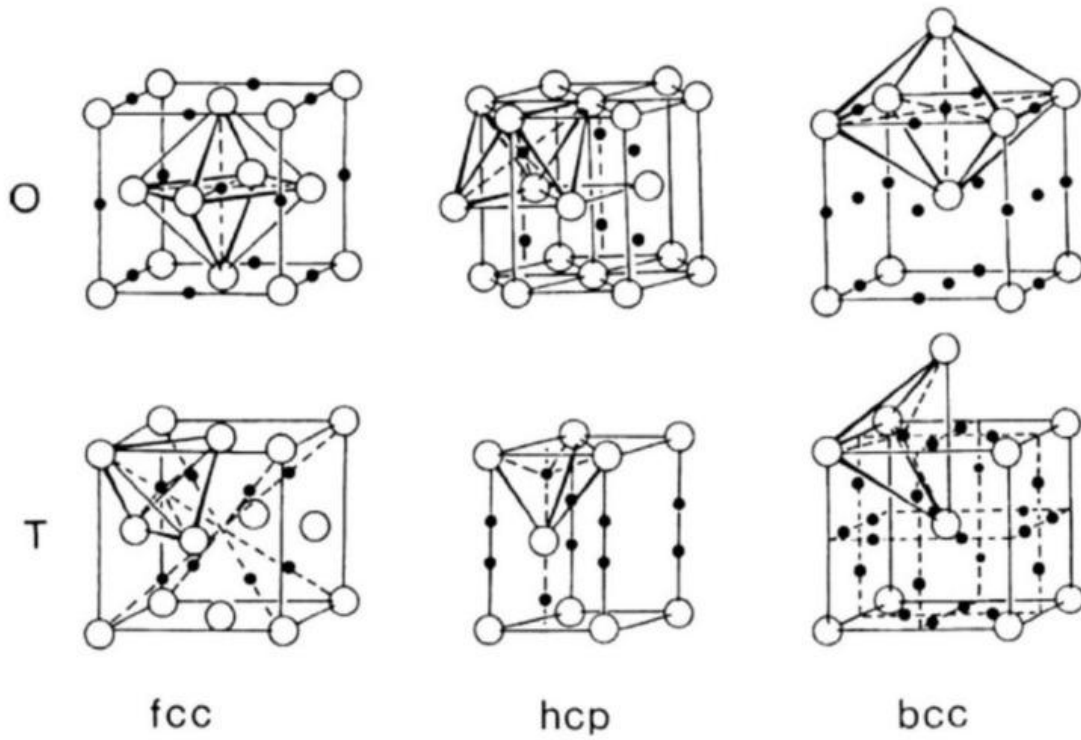


Figure 8: Octahedral (O) and Tetrahedral (T) Interstitial Sites for Crystalline Structures (Alam, et al., 2024).

As a true metal contains many point, line and volumetric defects the ability for hydrogen to become trapped and accumulate is high (figure 9). When these hydrogen atoms become trapped in vacancies and at grain boundaries the formation and accumulation of hydrogen gas reduces component ductility, leading to embrittlement (Carter & Cornish, 2001) and ‘hydrogen induced cracking’ (figure 10).

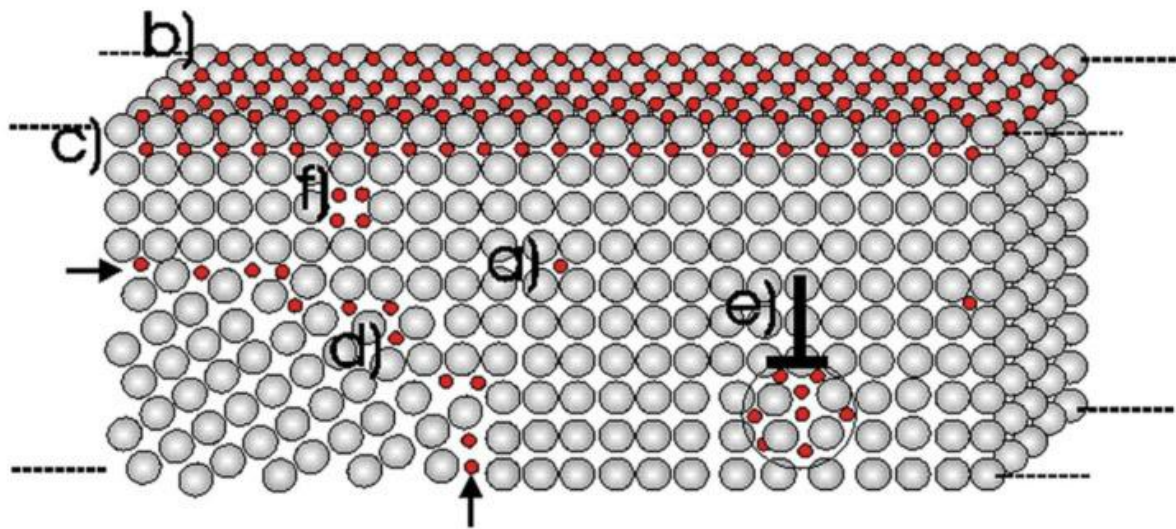


Figure 9: Hydrogen Trapping Types: “a) Interstitial Sites, b) Surface, c) Subsurface, d) Boundaries, e) Edge Dislocations, f) Vacancies” (Alam, et al., 2024).

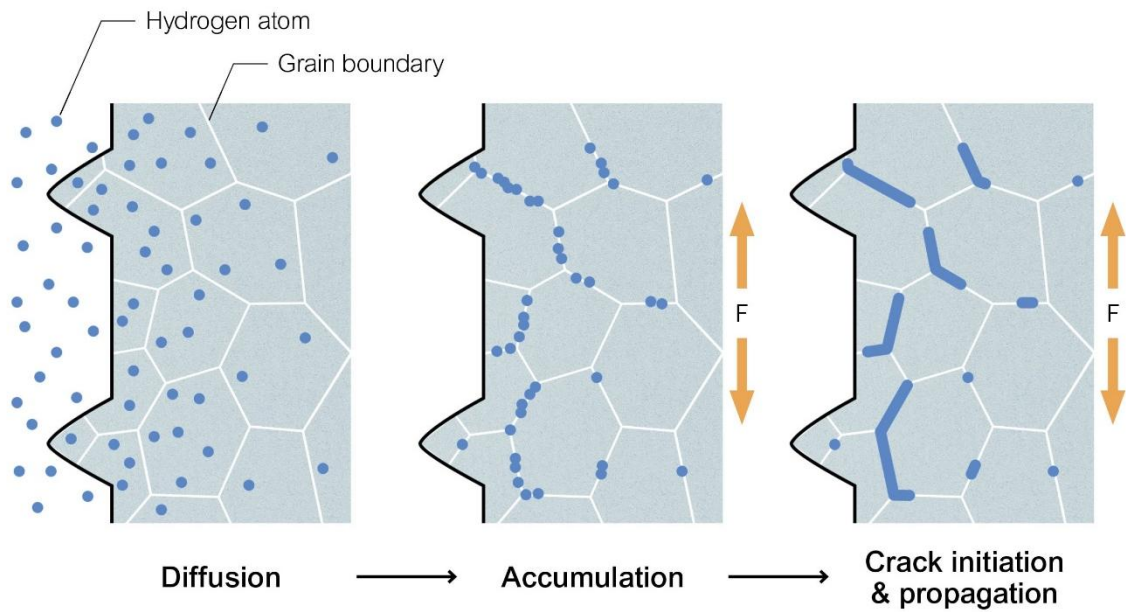


Figure 10: Hydrogen Embrittlement Diagram (MTC Solutions, 2024).

Figure 11 demonstrates a Venn diagram detailing three factors that can induce cracking caused by hydrogen embrittlement, dependant on HE. From this diagram, there are three factors that cause cracking: presence of hydrogen, a tensile stress and a crack susceptible microstructure/material (Da Silva, et al., 2013). By removing or reducing one aspect below a specific threshold, hydrogen embrittlement can be prevented.

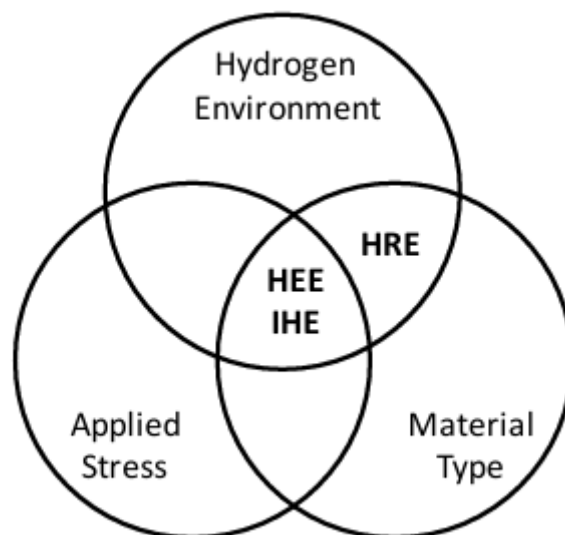


Figure 11: Hydrogen Embrittlement Venn Diagram (Da Silva, et al., 2013).

3 Metallographic Examination

3.1 Optical Microscopy

Optical microscopy (OM) can examine absorption and hydrides formation. Components made from zirconium alloys undergo exothermic retention of hydrogen in which metal hydrides are formed, this is accelerated in nuclear reactors for example, when exposed to water and high temperatures (Puls, 2012). Throughout the hydride region material properties such as density and strength change in a negative manor when compared to metal matrix. Zirconium alloy (Zr-2.5Nb) hydride formations are irregular and according to Puls (2012), “are generally not single solid hydrides but consist of a dense agglomeration of smaller hydride precipitates”. The formation of hydrides is seen to be affected by crack tip type, noticeable when comparing figure 12 with 13. Hydride regions throughout materials are generally non-uniformly distributed and when the collective volume of these hydride regions cause the materials strength and fracture toughness to fall below the required threshold, the component becomes brittle and susceptible to rapid and unpredictable crack propagation and failure.

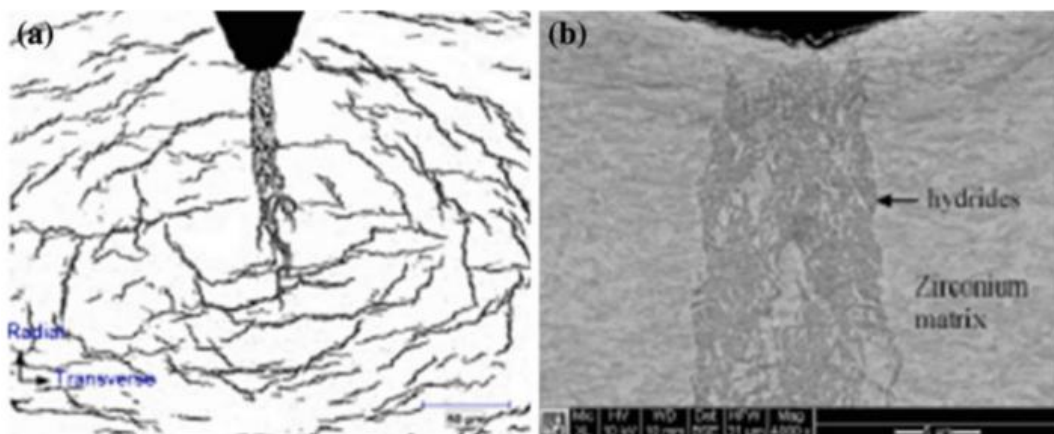


Figure 12: Sharp Crack Tip Hydride Region in Zr-2.5Nb *a)* OM, *b)* SEM (Puls, 2012).

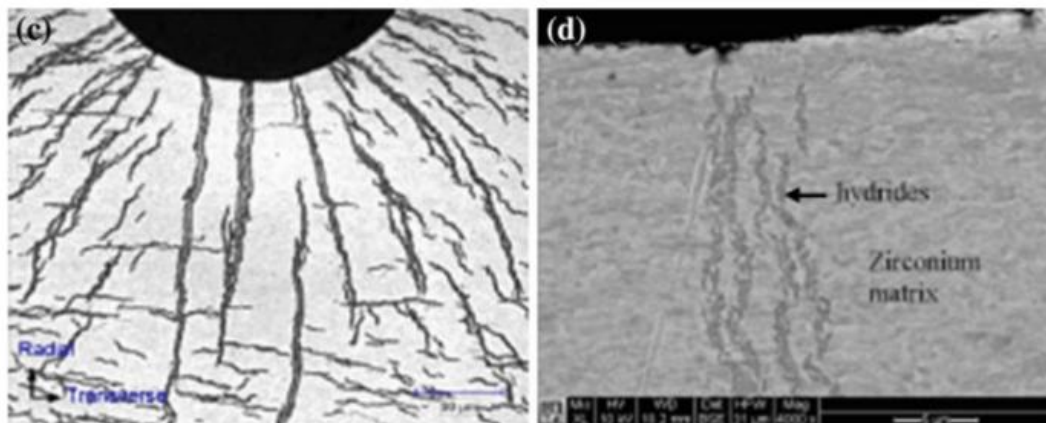


Figure 13: Blunt Crack Tip Hydride Region in Zr-2.5Nb *c)* OM, *d)* SEM (Puls, 2012).

Treatment methods electroplating and pickling (in particular) are prone to hydrogen absorption. Due to the submersion of a component in a substrate, water molecules break down into constituent elements. Hydrogen is therefore exposed and absorbed into metal surface, free to then diffuse within the metal. Chen, *et al.*, (2021) investigated the changes in hot stamped steel (B1500HS) mechanical properties when exposed to different charging times and currents in an electrochemical hydrogen charging system. Using OM to inspect surface morphology, effects of increasing charging time can irreversibly impact absorption rates. Hydrogen blistering in figure 14 (b) has significantly more blisters and of larger, more random sizing and distribution when compared to (a). Further examination of cross-sections (figure 15) demonstrates a positive correlation between hydrogen blisters and crack sizing.

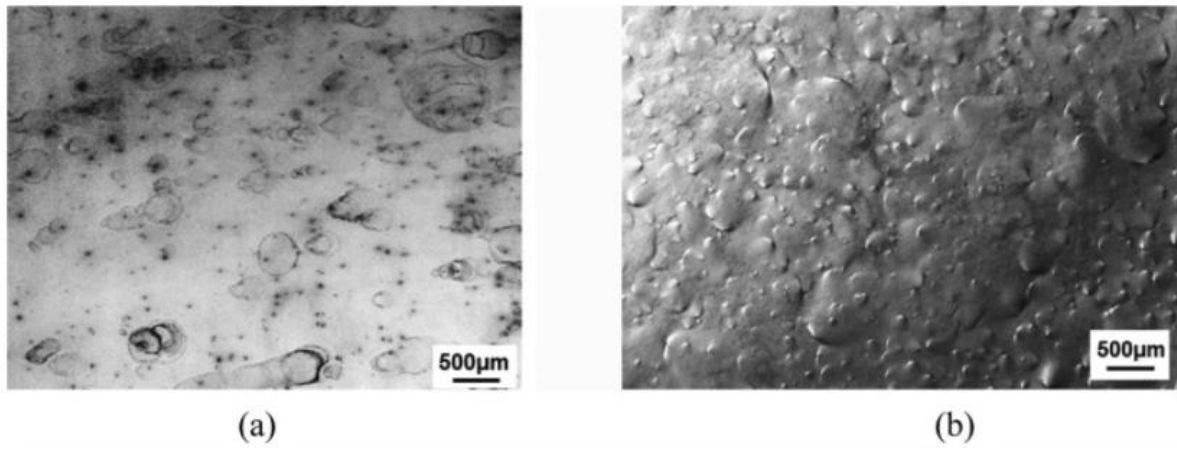


Figure 14: OM Hot Stamped Steel (B1500HS) Surface Morphology After Electrochemical Hydrogen Charging: (a) 0.001A for 2 Hours (b) 0.1A for 24 Hours (Chen, *et al.*, 2021).

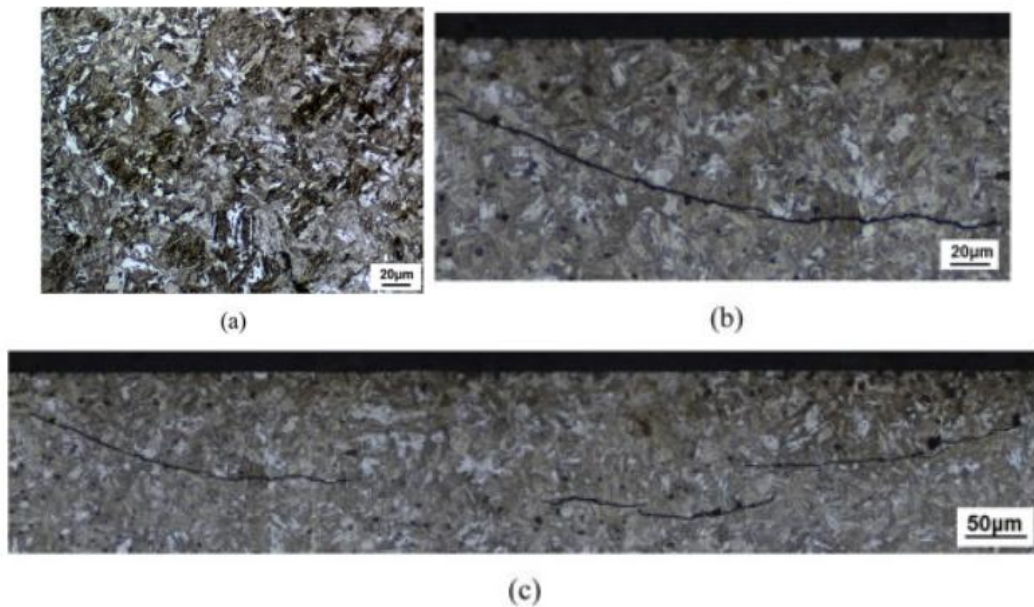
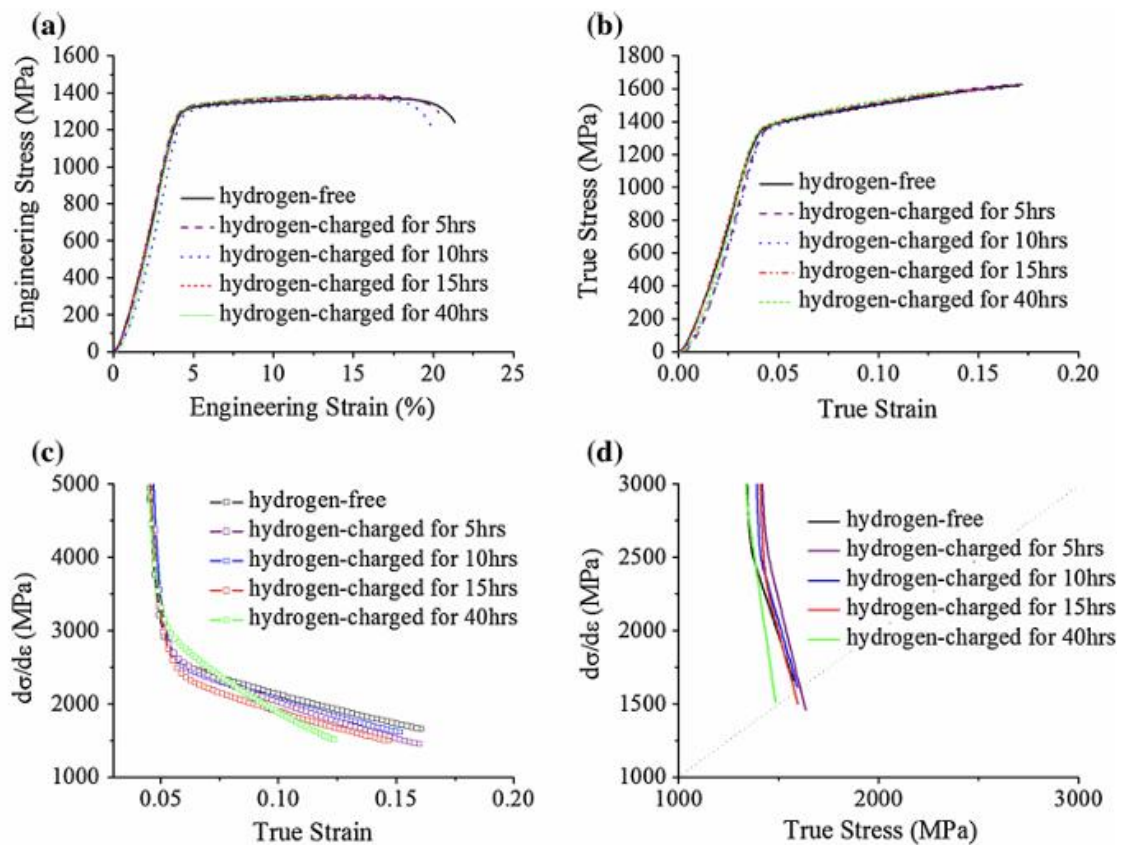


Figure 15: OM Cross-Sectional Morphology of Hot Stamped Steel (B1500HS) After Electrochemical Hydrogen Charging: (a) 0.001A (b and c) 0.1A (Chen, *et al.*, 2021).

3.2 Electron Microscopy

Scanning electron microscopy (SEM) is used to inspect surface morphology of a component, capable of higher resolutions than OM, depth of field can also be obtained when a SEM with energy dispersive x-ray spectroscopy (SEM/EDX) is used (Western University, 2024). Testing and results data from Astafurova, et al., (2017) demonstrate hydrogen fracture mechanics of high-nitrogen chrome-manganese (17Cr–24Mn–1.3V–0.2C–1.3N) steel under varying hydrogen saturation periods. The material preparation was as follows: hot rolling into 1mm sheets at 1150°C, followed by air cooling, mechanical grinding and electrochemical polishing. Components were then stored in liquid nitrogen, and tested at room temperature. To summarise the engineering properties (graphs 1 and table 2), as hydrogen embrittlement index increases, the ductility of a material reduces and embrittlement (due to hydrogen) increases. The common cause of this is reduction in materials ability to plastically deform (material necking decreases with increase in hydrogen charging time, figures 16-19) demonstrated by percentage elongation and (uniform) strain decreasing.



Graph 1: Engineering Data of High-Nitrogen Austenitic Steel Exposed to Varying Hydrogen Charged Durations: (a) Tensile Parameters, (b) True, (c) Work Hardening and True Strain, and (d) Work Hardening and True Stress (Astafurova, et al., 2017).

Table 2: Engineering Properties of High-Nitrogen Austenitic Steel Exposed to Varying Hydrogen Charging Durations (Astafurova, et al., 2017).

Condition	YS (MPa)	UTS (MPa)	Uniform true strain	EL (%)	I_H (EL) (%)
Initial	1270	1580	0.13	17	0
Hydrogenated for 5 h	1270	1640	0.13	16	6
Hydrogenated for 10 h	1250	1600	0.12	16	6
Hydrogenated for 15 h	1210	1600	0.12	13	24
Hydrogenated for 40 h	1190	1490	0.10	11	35

YS yield stress, UTS ultimate tensile stress, EL elongation, I_H hydrogen embrittlement index

As charging duration increases, side surface morphology demonstrates increasing amounts of surface cracking (figures 16 and 17) and crack size (Bembenek, et al., 2020). The most significant side surface damage is when charging time reaches and exceeds 15 hours.

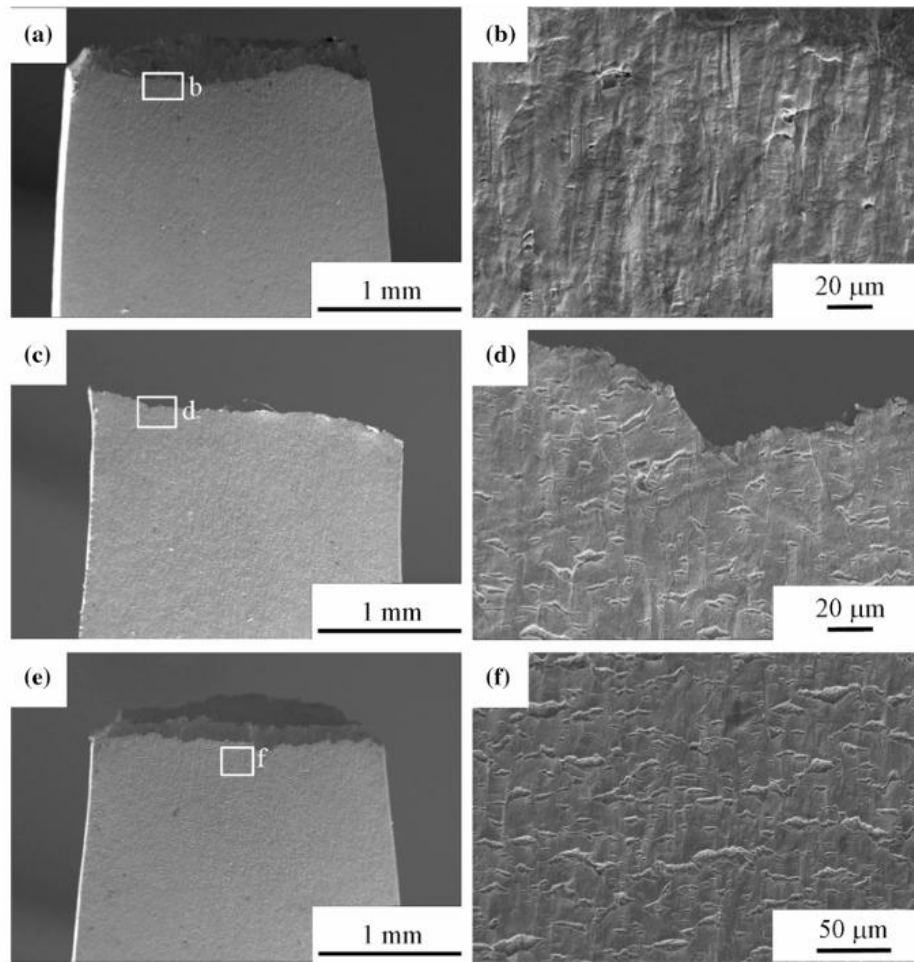


Figure 16: SEM Side Surface Morphology: (a, b) Hydrogen Free, (c, d) 5 Hours Charging, (e, f) 10 Hours Charging. Right Images are Enlargements of Rectangles in Left Images (Astafurova, et al., 2017).

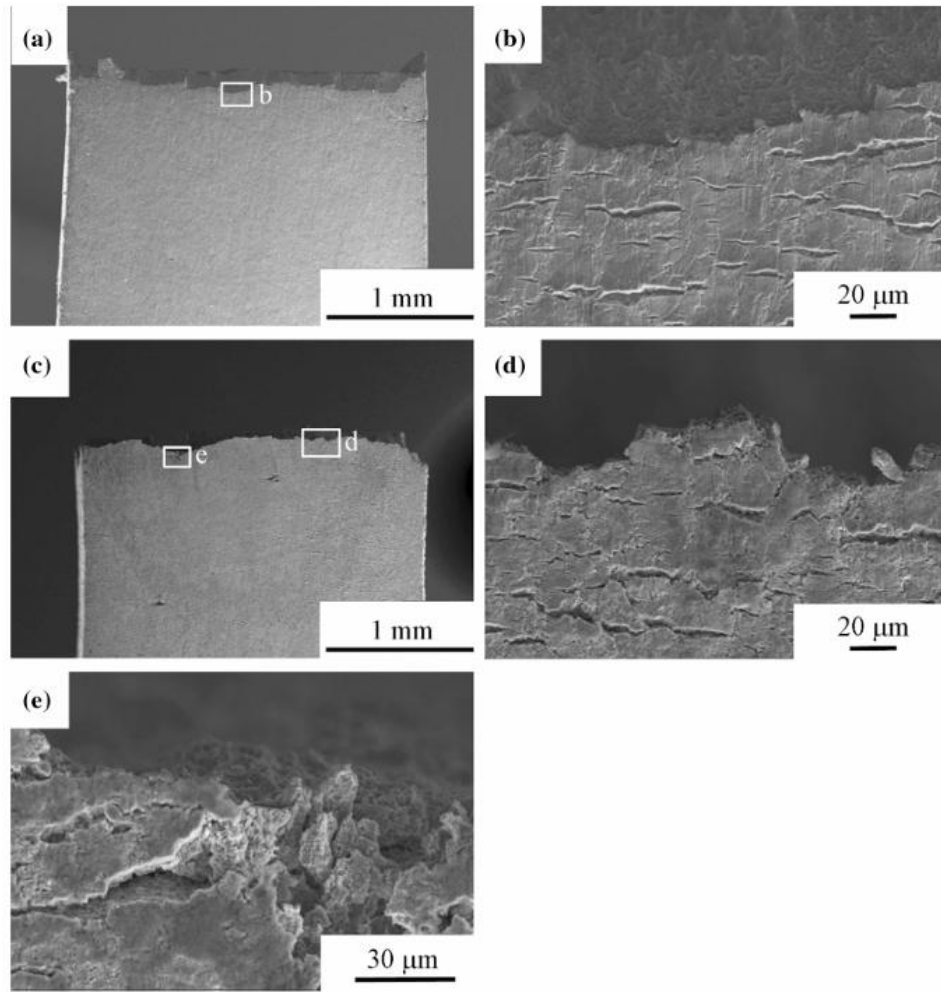


Figure 17: SEM Side Surface Morphology: (a, b) 15 Hours Charging, (c, d, e) 40 Hours Charging. (b, d, e) are Enlargements of Rectangles in (a, c) (Astafurova, et al., 2017).

Surface morphology of figures 18 and 19, contain flat smooth edges where hydrogen has accumulated and caused embrittlement in saturated components, whilst jagged surfaces at centre demonstrate a moderately ductile fracture region. Embrittlement is more pronounced at higher charging durations where microcracks (figure 18, labels G and H) become larger, more common and appear on the surface and subsurface (Bembenek, et al., 2020).

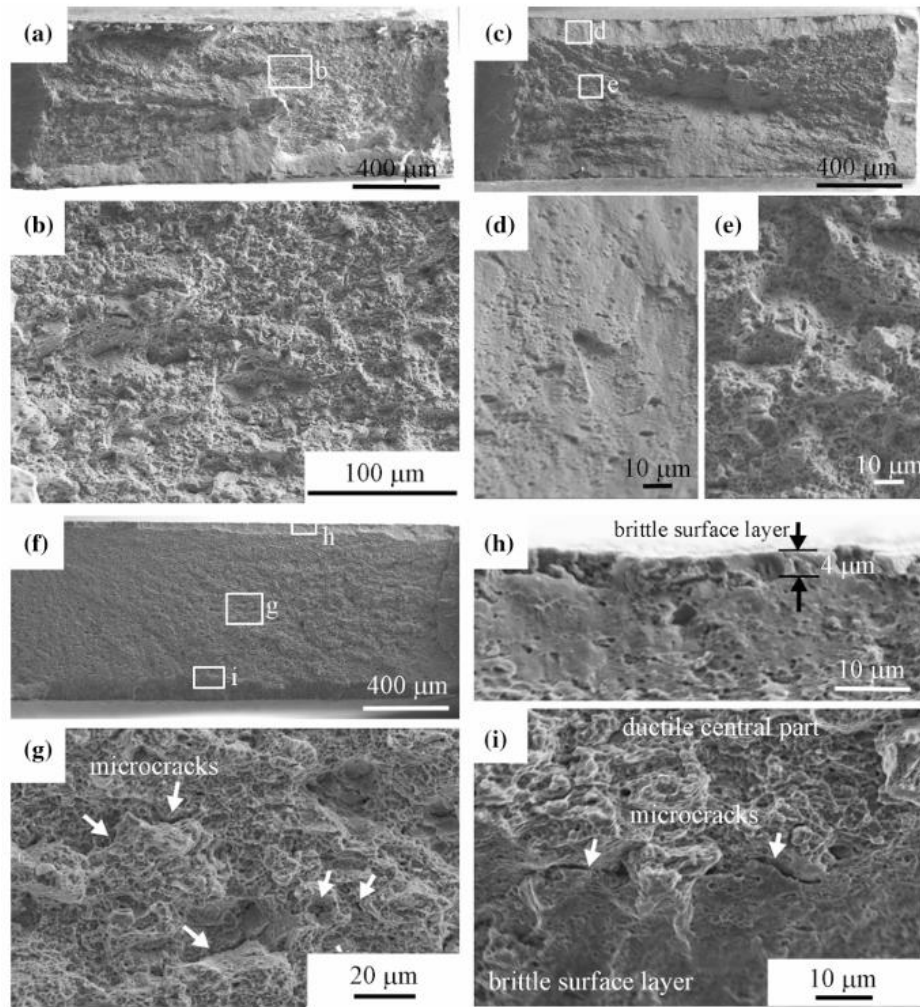


Figure 18: SEM Fracture Surface Morphology: (a, b) Hydrogen Free, (c, d, e) 10 Hours Charging, (f, g, h, i) 15 Hours Charging. (b, d, e, h, g, i) are Enlargements of Rectangles (Astafurova, et al., 2017).

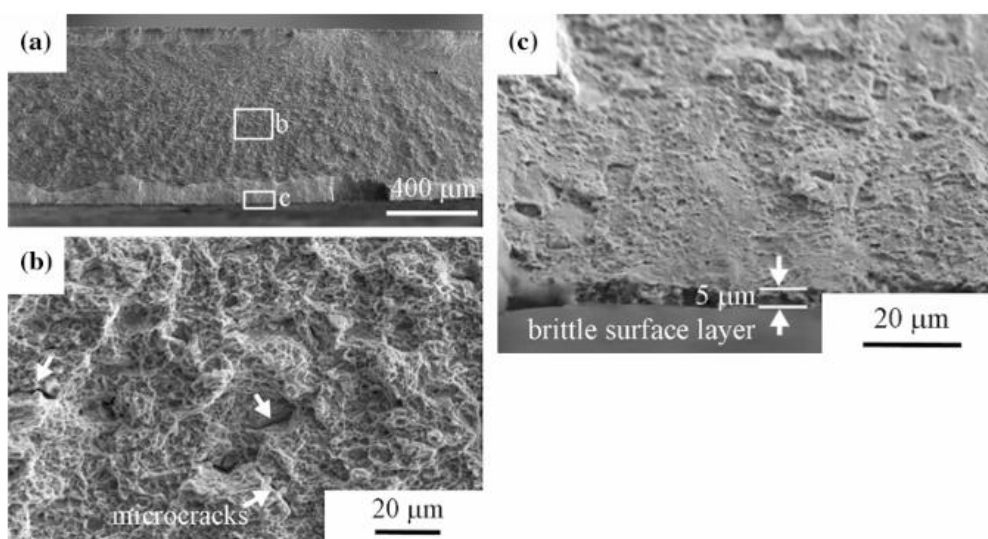
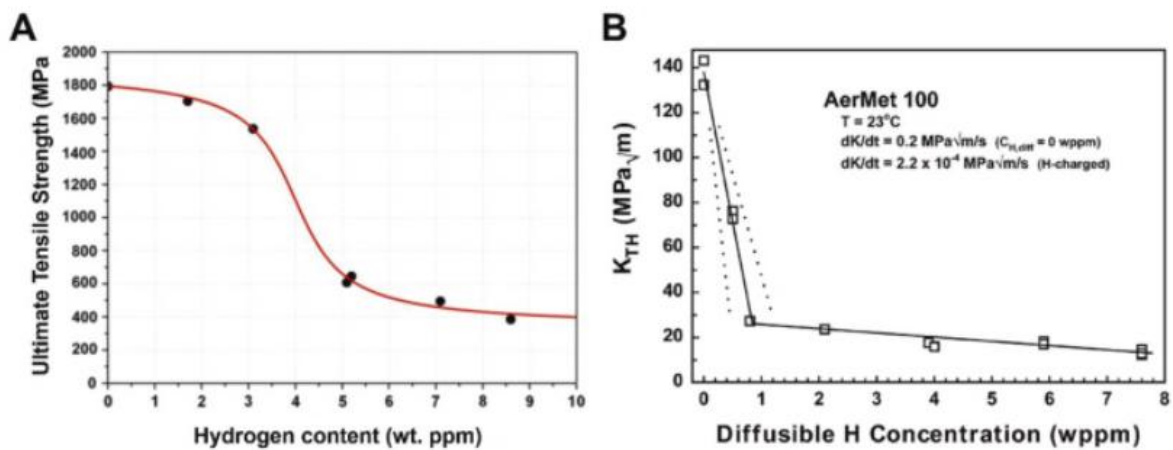


Figure 19: SEM Fracture Surface Morphology where: (a) 40 Hours Charging. (b, c) are Enlargements of Rectangles (Astafurova, et al., 2017).

4 Analysis of Absorption Effects

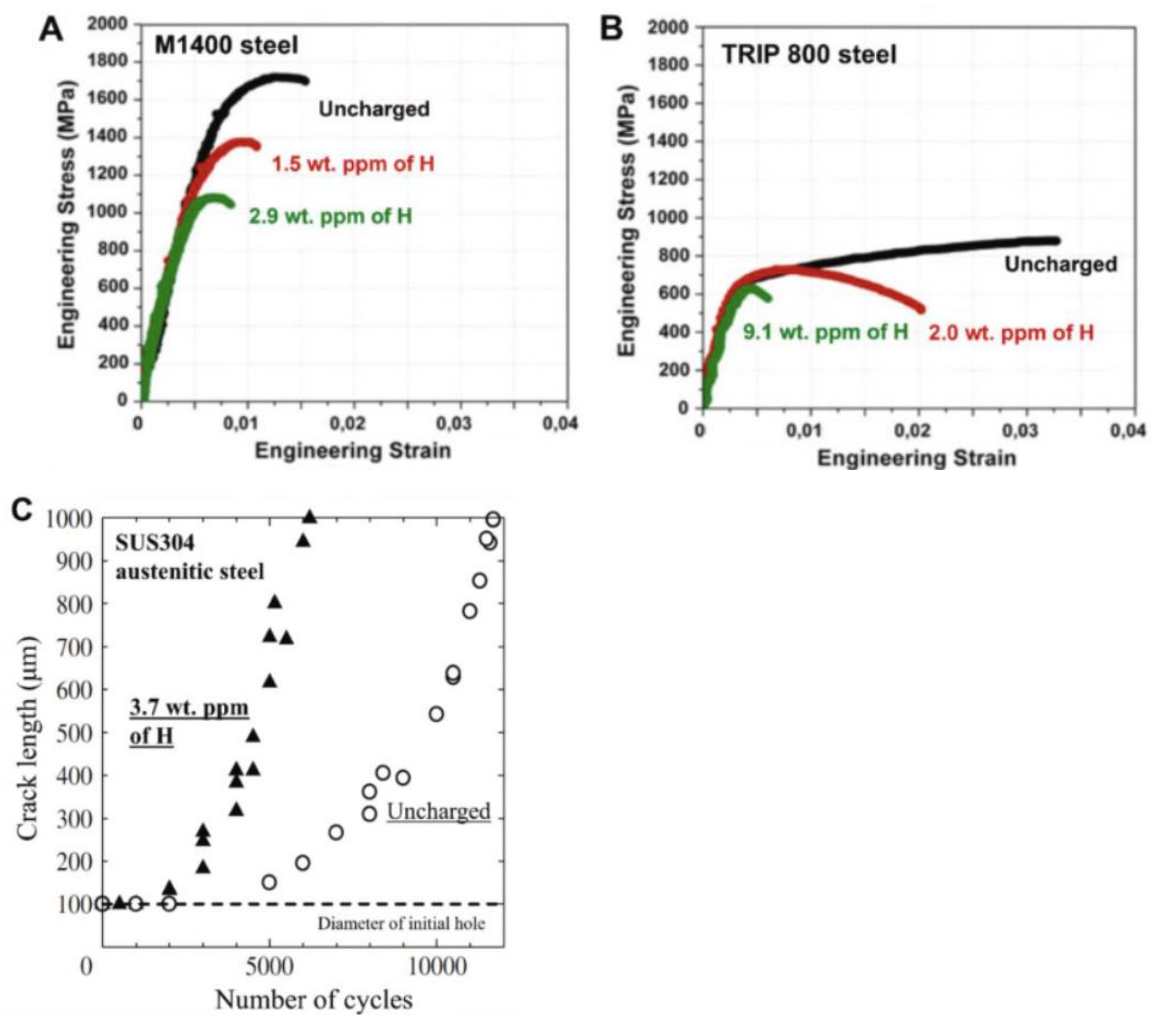
4.1 Mechanical Effects of Hydrogen Absorption

For many steel components subjected to hydrogen absorption, mechanical properties are impacted negatively. HE tends to reduce fracture toughness, fatigue resistance and ductility of the material (Chen, et al., 2024). Referring to table 2 the reduction in materials ductility is clearly seen with the elongation percentage and strain rate decreasing from 0.13 to 0.1 and 17% to 11%. A review of the impact hydrogen content in parts per million (ppm) has on ultimate tensile strength (UTS) graph 2(a) and threshold stress intensity factor (K_{TH}) graph 2(b) of AerMet 100 martensitic steel was conducted by Chen, *et al.*, 2024. The results from graph 2(a) demonstrate for this material that an increase in hydrogen content reduces UTS. The most significant impact is noticeable when hydrogen content is between 3-5 parts per million in weight (wt. ppm), reducing the UTS to approximately 40% (600 MPa) of its UTS when at 3wt. ppm and 27% of its nominal UTS (1765MPa). For graph 2(b), critical (threshold) stress intensity factor is shown to decrease rapidly at lower diffusible concentrations (between 0.2-1 wt. ppm) for this material. Hydrogen absorption can cause HE and with the addition of an applied stress or cyclic loading (fatigue), a rapid and unexpected brittle fracture can occur, leading to component failure (Park & Seo, 2011). The principle behind this is reduced stress intensity factor of component due to absorbed hydrogen.



Graph 2: Mechanical Properties of Steels Exposed to Increased Hydrogen (a) UTS of Untempered Martensitic Steel, (b) Threshold Stress Intensity Factor of AerMet 100 Martensitic Steel (Chen, et al., 2024).

Impacts of hydrogen absorption vary for each material, graph 3(a) details effects of uncharged, 1.5 and 2.9 wt.ppm of hydrogen when using a stress against strain plot. For a material that is originally strong and has a high UTS, HE reduces the strength and strain capabilities of this material. As for a more ductile material such as transformation induced plasticity (TRIP) 800 steel (graph 3(b)), effects of hydrogen embrittlement prove to reduce component ductility where strain decreases, and fracture occurs sooner. Results from a fatigue test on SUS304 austenitic steel graph 3(c) demonstrate a reduction in number of cycles a component can withstand by over half. This shorter lifespan means more regular service intervals are required to prevent fracture as crack length grows quicker.



Graph 3: HE Effects on Different Steels Stresses and Strains (a) M1400 martensitic steel, and (b) TRIP 800 Ferritic Steel, and Fatigue Factors for (c) SUS304 Austenitic Steel (Chen, et al., 2024).

4.2 Hydrogen Absorption in Processing

Hydrogen can impact processing methods such as pickling, heat treatment, electroplating, steel making and welding as detailed below (Pohl & Jurgensen, 2023). To ‘remove’ hydrogen after production methods, hydrogen bake-out is used; by elevating temperatures for prolonged time periods hydrogen is able to effuse out (Cheung, et al., 2022).

4.2.1 Steel Making

When manufacturing pig iron or steel the following are causes to hydrogen’s presence in steel and iron making process: moist additives, alloying elements and residual moisture in furnace linings (Pohl & Jurgensen, 2023). Early stages of steel making are not usually the cause of HE due to hydrogen effusing during later heat treatment methods, at this melt stage though, it is estimated hydrogen solubility is at 30 ppm (Kieselbach & Woodtli, 2000). However, with casting equipment and multiple furnaces used during the steel making process (figure 20), the susceptibility to moisture lining and extreme temperatures can cause hydrogen damage such as flaking or fisheye defects instead (table 1).

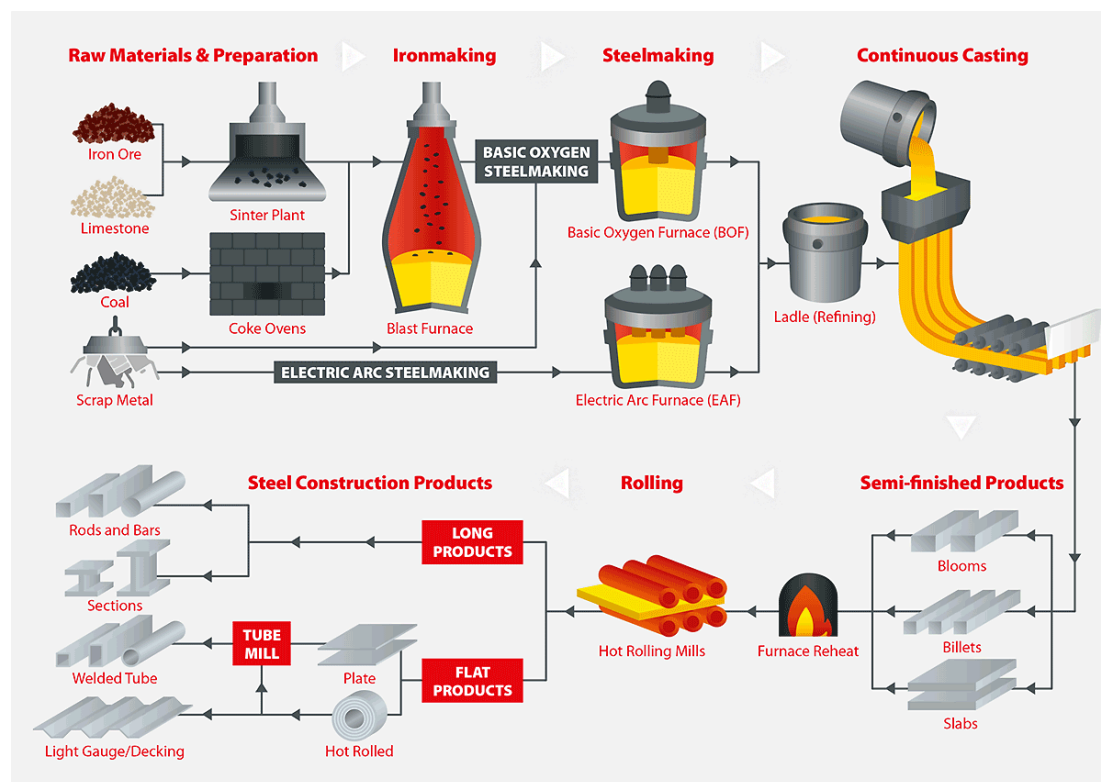
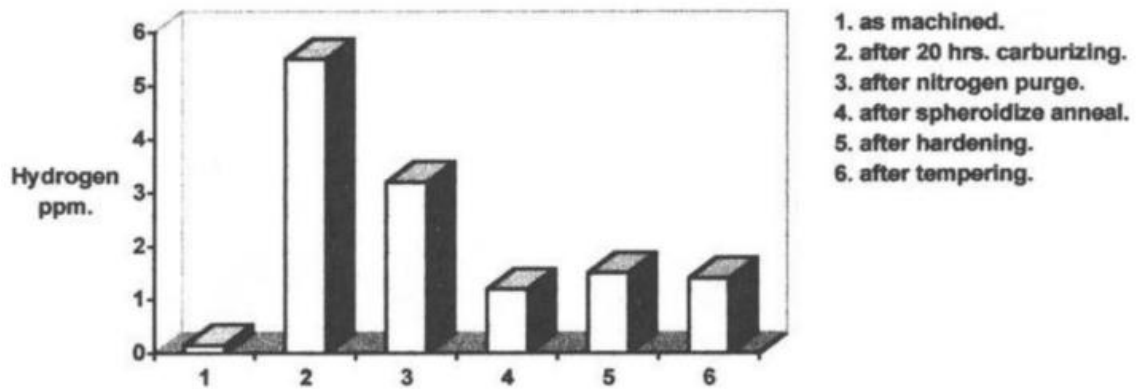


Figure 20: Pig Iron and Steel Manufacturing (NSC, 2017).

4.2.2 Heat Treatment

Components that require wear and abrasion resistance such as gears and engine components are often heat treated to increase lifespan. Several techniques can be used to achieve this: carburizing, annealing, quenching, tempering, hardening and normalizing. Each method works differently where technique, cooling and heating rates/temperatures differ for each material and its desired outcome. In the case of hydrogen damage, case hardening using hydrocarbons such as methane for carbon source leave the component vulnerable to high amounts of hydrogen uptake (Pohl & Jurgensen, 2023). Atomic hydrogen is also a threat during carburizing where diffusion can easily occur (figure 21 intergranular fracture). A comparison in graph 4 demonstrates the different amounts of hydrogen content during processing steps, where carburizing is the main contributor to hydrogen content (Midea, 2000).



Graph 4: Hydrogen Content During Manufacturing Processes (Midea, 2000).

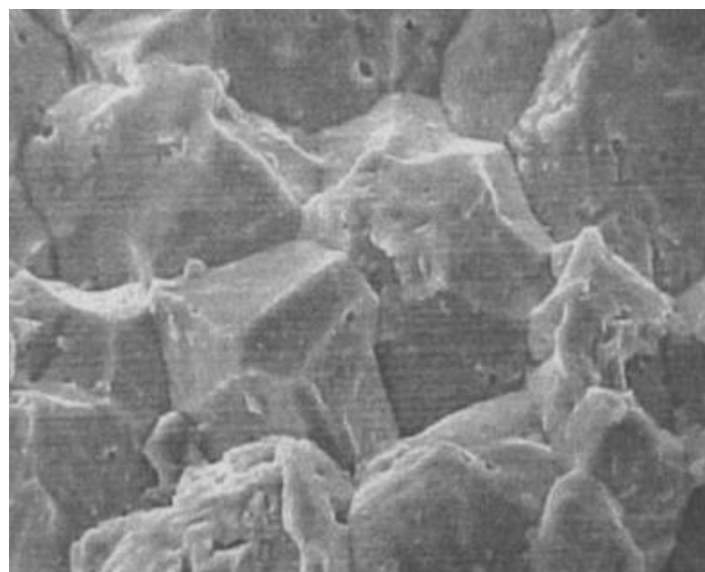


Figure 21: SEM Intergranular Fracture Caused by Hydrogen Diffusion During Carburization (Midea, 2000).

4.2.3 Welding

Hydrogen uptake can be significant in welding, originating from moisture and contaminated joining components. As arc temperatures are extremely high, hydrocarbon compounds break down, causing hydrogen absorption into weld seams (Pohl & Jurgensen, 2023). Modern manufacturing has generally overcome moisture in electrodes, but if damp, electrodes can result in hydrogen absorption or trapping within weld pools. Trapped hydrogen is another problem associated with welding, during the cooling process potentially leading to hydrogen-induced cold cracking (figure 22). When carrying out high strength steel welding the most common problem is hydrogen build up at stress intensifiers. It is common practice for welders to use a multi-pass technique to overcome this, however, every pass causes hydrogen to accumulate (figure 23) at these stress intensifiers (Maroef, et al., 2002).

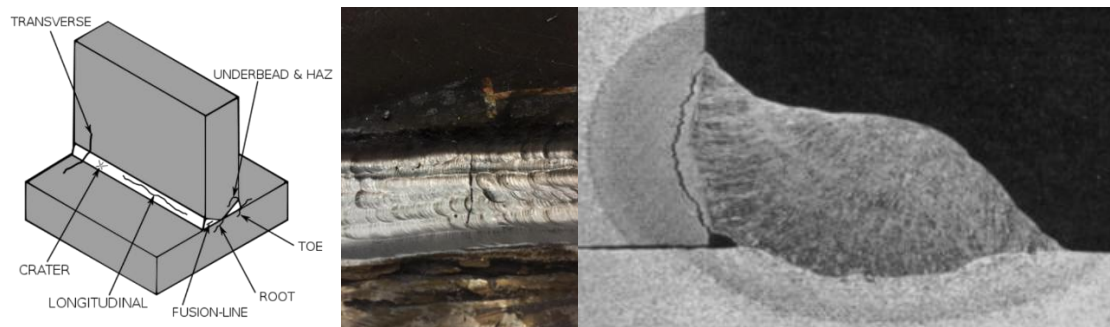


Figure 22: (Left) Hydrogen Induced Cold Cracking Types, (Middle) Transverse Cracking, (Right) Root Cracking (BanCroft, n.d.).

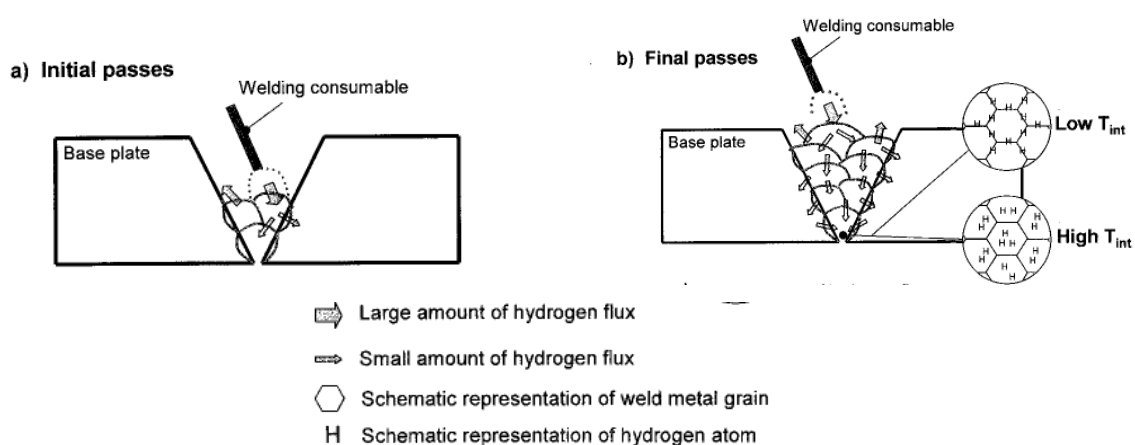


Figure 23: Hydrogen Accumulation During Multi-Pass Welds (Maroef, et al., 2002).

5 Conclusion

In conclusion, hydrogen's small size permits easy absorption into metal surfaces (under given conditions) and diffusion into crystalline structures of zirconium, steel and more, causing in many cases unknown and irreversible hydrogen damage. HE is a common form of hydrogen damage in which hydrogen exposure can be during manufacturing or component working environment. HE increases brittleness and reduces: ductility, fatigue resistance, stress intensity factor, UTS and more. Once hydrogen has entered a material, numerous damage methods can occur, formation of hydrides are particularly harmful to zirconium components whilst atomic hydrogen easily and readily diffuses and accumulates at defects in steels and steel alloys. Manufacturing processes and fabrication such as metal production, heat treating, electroplating, pickling and welding are also responsible for hydrogen damage such as embrittlement and flaking due to the presence of hydrogen in treating compounds, additives, moisture and other. Further work could see investigation into hydrogen attack, micro-perforations, conducting hydrogen charging and HE experiments for microscopy examination and mechanical properties testing (tensile, fatigue and more). Additionally, investigating effects hydrogen isotopes have on HE.

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