

# Technical Report: Hydrogen Embrittlement in High-Strength Steels

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## Executive Summary

Hydrogen embrittlement (HE) represents a critical failure mode affecting high-strength steels and engineering alloys, particularly in aerospace, automotive, and energy sectors[1]. This report provides a comprehensive analysis of hydrogen embrittlement mechanisms, material susceptibility, testing methodologies, and mitigation strategies. The study demonstrates that a multi-faceted approach combining materials selection, process control, protective coatings, and rigorous testing is essential for preventing catastrophic failure in critical applications[2].

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## 1. Introduction

### 1.1 Background

Hydrogen embrittlement is a degradation process where hydrogen atoms interact with susceptible materials, resulting in a dramatic reduction of mechanical properties, particularly ductility and fracture toughness[3]. This phenomenon has plagued the aerospace and high-strength material industries for decades, despite widespread awareness of its existence. The problem intensifies as materials are developed with higher strength levels, as these materials are inherently more susceptible to hydrogen-induced failure[1].

### 1.2 Significance and Scope

High-strength steels, commonly used in safety-critical applications such as landing gears, fasteners, and hydraulic systems, are particularly vulnerable. The material can lose up to 50% of its tensile elongation when exposed to hydrogen sources during manufacturing processes[2]. This report examines:

- Fundamental mechanisms of hydrogen embrittlement
  - Material susceptibility factors
  - Testing and detection methodologies
  - Preventive and mitigation strategies
  - Industry standards and best practices
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## 2. Mechanisms of Hydrogen Embrittlement

### 2.1 Overview

Hydrogen embrittlement is a complex, multifaceted phenomenon that does not operate through a single exclusive mechanism. Current research indicates that multiple contributing micro-mechanisms may operate simultaneously or sequentially, depending on material composition, hydrogen concentration, stress state, and loading conditions[2].

### 2.2 Primary Mechanisms

#### Hydrogen-Enhanced Decohesion (HEDE)

HEDE occurs when hydrogen accumulates at grain boundaries and internal interfaces, reducing the cohesive strength of atomic bonds[3]. This localized weakening allows cracks to propagate more easily under applied stress, with fracture occurring at lower stress levels than expected. The mechanism is particularly prevalent in high-strength ferritic steels.

#### Hydrogen-Enhanced Localized Plasticity (HELP)

HELP represents an alternative mechanism where hydrogen increases dislocation nucleation and mobility at crack tips[1]. Counter-intuitively, while localized plasticity increases near the crack tip, the surrounding material experiences reduced deformation, giving the fracture a brittle appearance despite ductile failure at the crack tip. This mechanism has been extensively studied through molecular dynamics simulations.

#### Hydrogen-Induced Brittle Fracture (HIBF)

Hydrogen suppresses dislocation emission at crack tips, preventing crack tip blunting and promoting sharp crack propagation[2]. This mechanism prevents the natural rounding mechanism that occurs at stress concentrations, leading to pure brittle-cleavage failure with minimal plastic deformation.

#### Hydride Formation

In some susceptible materials (titanium alloys, zirconium alloys), hydrogen combines with the base metal to form brittle hydride phases[1]. These intermetallic compounds are significantly more brittle than the parent material and provide pathways for rapid crack propagation.

### 2.3 Synergistic Mechanisms

Recent research suggests that HEDE and HELP mechanisms operate synergistically rather than exclusively, with dominance contingent on local hydrogen concentration and stress state[2]. The hydrogen-enhanced and plasticity-mediated decohesion model incorporates aspects of both mechanisms, providing a more comprehensive understanding of the embrittlement process.

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### 3. Classification and Categories

#### 3.1 External Hydrogen Embrittlement (EHE)

EHE occurs when hydrogen enters the material from external sources during service. Common environmental sources include:

- Aqueous corrosion in marine or humid environments
- Cathodic protection systems
- High-pressure hydrogen gas exposure
- Hydrogen-rich industrial atmospheres

Source	Hydrogen Pressure (MPa)	Risk Level
Marine environments	0.001-0.1	Moderate
Oil and gas wells	10-100	High
High-pressure hydrogen (industrial)	>50	Extreme
Acidic media	0.1-1.0	High

Table 1: External Hydrogen Embrittlement Sources and Risk Levels

#### 3.2 Internal Hydrogen Embrittlement (IHE)

IHE results from unintentional hydrogen introduction during manufacturing processes. Primary sources include:

- Electroplating operations (nickel, cadmium, zinc)
- Welding processes (particularly high heat input)
- Pickling and surface preparation
- Thermal processing in hydrogen-containing atmospheres
- Carburizing operations

#### 3.3 Hydrogen-Resistance Evaluation (HRE)

HRE represents irreversible hydrogen damage due to chemical reactions with hydrogen, which can occur without external applied stress. This category is particularly relevant for materials used in hydrogen storage and high-pressure applications.

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### 4. Material Susceptibility

#### 4.1 Susceptibility Factors

Material susceptibility to hydrogen embrittlement depends on several interrelated factors:

1. **Yield Strength:** Materials with yield strength exceeding 1000 MPa exhibit dramatically increased susceptibility[1]. The relationship is non-linear, with risk increasing exponentially above 1400 MPa.

2. **Microstructure:** Coarse grain structures, martensitic phases, and high dislocation densities promote hydrogen embrittlement. Austenitic stainless steels and duplex stainless steels exhibit superior hydrogen resistance[2].
3. **Chemical Composition:** Carbon content, alloy elements, and impurities significantly influence susceptibility. High-carbon steels are more susceptible than low-carbon variants.
4. **Manufacturing History:** Prior cold work, thermal treatment, and processing routes establish the dislocation density and grain structure that predispose materials to HE.
5. **Environmental Conditions:** Hydrogen partial pressure, temperature, and electrochemical potential all influence hydrogen absorption rates and material response.

## 4.2 Material Screening

Material Category	HE Index	Risk Level
Austenitic Stainless Steel	<0.3	Low
Duplex Stainless Steel	0.3-0.5	Low to Moderate
Ferritic Stainless Steel	0.5-1.0	Moderate
Low-Carbon Steel (<900 MPa)	1.0-1.5	Moderate
High-Strength Steel (1000-1400 MPa)	1.5-3.0	High
Ultra-High-Strength Steel (>1400 MPa)	>3.0	Extreme

Table 2: Hydrogen Embrittlement Susceptibility Index by Material

## 4.3 Recommended Materials

For applications requiring hydrogen resistance:

- Austenitic stainless steels (316L, 317L) - excellent hydrogen resistance
- Nickel-based alloys (Inconel, Monel) - superior performance in extreme environments
- Duplex stainless steels - good balance of strength and hydrogen resistance
- Non-ferrous alloys (aluminum-copper, certain titanium grades) - moderate susceptibility
- Low-carbon structural steels - acceptable for non-critical applications

## 5. Testing and Detection Methodologies

### 5.1 ASTM F519 Standard Test Method

ASTM F519-18 is the primary standard for mechanical hydrogen embrittlement evaluation of steel parts during manufacture[3]. The standard provides two testing procedures:

### **Sustained Load Test (SLT) - 200-Hour Protocol**

The 200-hour sustained load test applies a constant uniaxial tensile load to notched specimens for the full duration. Parameters include:

- Applied stress: typically 90% of the specimen yield strength
- Temperature:  $23^{\circ}\text{C} \pm 5^{\circ}\text{C}$  (room temperature)
- Duration: 200 hours continuous
- Specimen geometry: notched ( $K_t \approx 3.0$ )

Success criterion: No fracture or significant deformation occurs during the 200-hour period.

### **Rising Step Load (RSL) Test - 20-Hour Protocol**

The 20-hour rising step load test provides an accelerated evaluation by incrementally increasing load:

- Initial load: 50% of expected yield strength
- Load increments: applied at 1-hour intervals
- Total duration: 20 hours
- Specimen geometry: notched tensile specimens

This method provides faster results while maintaining correlation with service experience.

## **5.2 Additional Testing Methods**

### **Cathodic Charged Tensile Testing**

Specimens are cathodically charged with hydrogen prior to tensile testing, creating controlled hydrogen saturation[2]. Loss of elongation compared to uncharged specimens quantifies hydrogen sensitivity.

### **Thermal Desorption Analysis (TDA)**

Thermal desorption measures hydrogen content and distribution within material samples by heating specimens and measuring released hydrogen gas[1]. This technique provides quantitative hydrogen content data but does not directly measure mechanical property degradation.

### **Fractography and Microscopy**

Scanning electron microscopy (SEM) analysis of fractured specimens reveals characteristic brittle fracture morphology, including intergranular or transgranular crack paths, helping identify dominant HE mechanisms[2].

### **Non-Destructive Testing (NDT)**

Ultrasonic testing and other NDT methods detect early micro-cracking stages before catastrophic failure:

- Ultrasonic testing - detects internal discontinuities
- Eddy current inspection - surface and near-surface defects
- Acoustic emission - crack initiation and propagation monitoring
- Radiography - internal crack detection in critical components

## 6. Prevention and Mitigation Strategies

### 6.1 Design-Phase Mitigation

#### Material Selection

The most effective mitigation begins at the design phase by selecting materials with inherent hydrogen resistance[1]:

1. Lower strength grades when performance permits (reducing HE susceptibility)
2. Austenitic stainless steels and nickel-based alloys
3. Dual-phase and duplex stainless steels
4. Precipitation-hardened alloys with lower susceptibility

#### Stress Management

Design modifications to reduce stress concentration:

- Eliminate sharp corners and notches
- Increase fillet radii to reduce stress concentration factors
- Minimize cross-sectional changes
- Incorporate design redundancy in critical load-bearing components

### 6.2 Manufacturing Process Control

#### Welding Practices

Low-hydrogen welding processes minimize hydrogen introduction[2]:

- Use low-hydrogen electrodes (E7018, E8018 series)
- Implement controlled preheat (typically 100-200°C depending on steel grade)
- Perform post-weld heat treatment (PWHT) to diffuse hydrogen
- Limit heat input to reduce cooling rates
- Use multi-pass techniques to manage hydrogen

#### Electroplating and Coating Processes

Surface protection prevents hydrogen absorption from corrosive environments[1]:

Coating Type	Effectiveness and Applications
Nickel plating	High effectiveness, aerospace standard
Zinc plating	Moderate effectiveness, general industrial
Cadmium plating	High effectiveness, phased out due to toxicity
Organic coatings	Variable, requires intact surface
PVD coatings	Emerging technology, excellent barrier properties

Table 3: Protective Coatings for Hydrogen Embrittlement Prevention

## Hydrogen Removal (Baking)

Post-process thermal treatment removes absorbed hydrogen:

- **Temperature range:** 150-200°C depending on material
- **Duration:** 3-24 hours depending on section thickness
- **Timing:** Applied within 24 hours of plating to minimize hydrogen trapping
- **Effectiveness:** Can reduce hydrogen content by 80-95%

## 6.3 Environmental Control

### Limiting Hydrogen Source

- Avoiding exposure to high-pressure hydrogen environments
- Preventing aqueous corrosion through environmental control
- Using oxygen-hydrogen mixtures (small oxygen additions passivate surfaces)[2]
- Implementing cathodic protection in marine environments (when appropriate)
- Applying barrier coatings to prevent hydrogen ingress

### Operational Parameters

- Control temperature to minimize hydrogen diffusion rates
- Manage applied stress to keep below critical threshold values
- Minimize electrochemical potential in aqueous environments
- Implement regular inspection protocols

## 6.4 Advanced Mitigation Technologies

### Barrier Coatings

Development of advanced barrier coating systems provides multi-level protection:

- Duplex coating systems (mechanical + chemical barriers)
- Nanostructured coatings with enhanced diffusion barriers
- Self-healing coating technologies
- Diamond-like carbon (DLC) coatings with exceptional barrier properties

### Alloy Development

Research into hydrogen-resistant alloys includes:

- High-entropy alloys with superior hydrogen resistance
- Grain-refined microstructures reducing HE susceptibility
- Advanced precipitation-hardened alloys
- Compositionally complex alloys with tuned hydrogen trapping

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## 7. Industry Standards and Best Practices

## 7.1 Applicable Standards

Standard	Scope and Applicability
ASTM F519-18	Mechanical hydrogen embrittlement testing for coated steels
ISO 11014-1	Guidelines for hydrogen embrittlement prevention
SAE J2030	Hydrogen embrittlement prevention requirements
ASME BPVC Section VIII	Pressure vessel design with HE considerations
AWS D1.1	Structural welding code addressing hydrogen control

Table 4: Key Standards Addressing Hydrogen Embrittlement

## 7.2 Industry Best Practices

### Aerospace Sector

The aerospace industry maintains stringent protocols:

- Monthly qualification testing per ASTM F519 for all plating operations
- Mandatory hydrogen removal procedures post-plating
- Comprehensive material and process specifications
- Flight-critical component redundancy and monitoring
- Regular non-destructive inspection programs[3]

### Oil and Gas Industry

High-pressure hydrogen environments demand rigorous control:

- Material selection restricted to proven low-susceptibility grades
- Environmental control through corrosion inhibitors
- Coating integrity verification before service
- In-service monitoring through ultrasonic and eddy current inspection
- Stress management through design optimization

### Automotive Sector

Emerging hydrogen fuel cell technology requires new protocols:

- Development of hydrogen storage tank specifications
  - Advanced material qualification for high-pressure vessels
  - Periodic inspection and maintenance programs
  - Research into long-term hydrogen exposure effects
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## 8. Case Study: Hydrogen Embrittlement in Landing Gear Components

### 8.1 Background

High-strength steel fasteners in aircraft landing gears have historically been susceptible to hydrogen embrittlement failures. These components experience cyclic loading and must function reliably under extreme conditions[1].

### 8.2 Problem Statement

Previous manufacturing processes incorporated electroplating operations that introduced hydrogen into the material. Field failures occurred in fasteners following thousands of flight hours, despite passing initial tension tests[2].

### 8.3 Solution and Outcome

Implementation of comprehensive mitigation:

1. **Material upgrade** to lower-strength, hydrogen-resistant austenitic stainless steel
2. **Process change** to low-hydrogen electroplating with immediate hydrogen baking
3. **Inspection protocol** addition of ultrasonic testing to detect early cracking
4. **Redundancy** incorporation of backup fasteners in critical load paths
5. **Testing program** monthly ASTM F519 qualification tests on production samples

Result: Zero service failures over 10-year period following implementation, with 99.97% fastener reliability[3].

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## 9. Conclusions and Recommendations

### 9.1 Key Findings

1. Hydrogen embrittlement represents a critical failure mode for high-strength engineering materials, particularly above 1000 MPa yield strength[1].
2. Multiple mechanisms operate simultaneously, requiring a sophisticated understanding of the interplay between hydrogen concentration, material microstructure, and applied stress[2].
3. Prevention requires a comprehensive, multi-faceted approach combining material selection, process control, protective coatings, and rigorous testing[3].
4. Existing standards (particularly ASTM F519) provide effective framework for quality assurance, though emerging applications (hydrogen fuel systems) require new protocols[1].
5. Recent advances in barrier coatings and alloy development show promise for extending hydrogen resistance to new material systems[2].

## 9.2 Recommendations

### For Design Engineers:

- Specify materials with yield strength <1000 MPa when performance permits
- Incorporate design features that minimize stress concentration
- Require protective coatings for high-strength components
- Specify hydrogen removal (baking) requirements in material specifications

### For Manufacturing:

- Implement monthly ASTM F519 qualification testing
- Use low-hydrogen welding processes and electroplating
- Perform immediate post-process hydrogen baking
- Establish environmental control protocols
- Maintain comprehensive process documentation

### For Quality Assurance:

- Develop in-service inspection protocols using non-destructive testing
- Establish failure analysis procedures for field returns
- Implement trending and statistical process control
- Maintain traceability from raw material through service

### For Research and Development:

- Continue investigation of hydrogen trapping mechanisms in advanced alloys
- Develop accelerated testing methods for emerging applications
- Advance barrier coating technology
- Investigate synergistic mitigation approaches

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