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Fasteners — Fundamentals of hydrogen embrittlement in steel fasteners

Fixations — Principes de la fragilisation par l'hydrogène pour les fixations en acier

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Foreword

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This document was prepared by Technical Committee ISO/TC 2 *Fasteners*, Subcommittee SC 14, *Surface coatings*.

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Introduction

High strength mechanical steel fasteners are broadly characterized by tensile strengths (R_m) above 1 000 MPa and are often used in critical applications such as in bridges, engines, aircraft, where a fastener failure can have catastrophic consequences. Preventing failures and managing the risk of hydrogen embrittlement (HE) is a fundamental consideration implicating the entire fastener supply chain, including: the steel mill, the fastener manufacturer, the coater, the application engineer, the joint designer, all the way to the end user. Hydrogen embrittlement has been studied for decades, yet the complex nature of HE phenomena and the many variables make the occurrence of fastener failures unpredictable. Researches are typically conducted under simplified and/or idealized conditions that cannot be effectively translated into *know-how* prescribed in fastener industry standards and practices. Circumstances are further complicated by specifications or standards that are sometimes inadequate and/or unnecessarily alarmist. Inconsistencies and even contradictions in fastener industry standards have led to much confusion and many preventable fastener failures. The fact that HE is very often mistakenly determined to be the *root cause* of failure as opposed to a *mechanism* of failure reflects the confusion.

Fasteners — Fundamentals of hydrogen embrittlement in steel fasteners

1 Scope

This document presents the latest knowledge related to hydrogen embrittlement, translated into *know-how* in a manner that is complete yet simple, and directly applicable to steel fasteners.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
hardness
resistance of a metal to plastic deformation, usually by indentation or penetration by a solid object (at the surface or in the core)

3.2
work hardening
increase of mechanical strength and *hardness* (3.1) when a metal is plastically deformed at ambient temperature (by rolling, drawing, stretching, sinking, heading, extrusion, etc.) also resulting in a decrease of ductility

3.3
heat treatment
process cycle (controlled heating, soaking and cooling) of a solid metal or alloy product, to obtain a controlled and homogeneous transformation of the material structure and/or to achieve desired physical or mechanical properties

Note 1 to entry: Quenching and tempering, annealing, case-hardening and stress relief are examples of heat treatment for fasteners.

3.4
quenching and tempering
QT
heat treatment (3.3) process of quench hardening comprising austenitizing and fast cooling, under conditions such that the austenite transforms more or less completely into martensite (and possibly into bainite), followed by a reheat to a specific temperature for a controlled period, then cooling, in order to achieve the required level of physical or mechanical properties

3.5

case-hardening

thermochemical treatment process consisting of carburizing or carbonitriding followed by quenching which induces an increase of *hardness* (3.1) in the surface of the fastener steel

Note 1 to entry: This process is used for tapping screws, thread forming screws, self-drilling screws, etc.

3.6

stress relief

heat treatment (3.3) process by which fasteners are heated to a predetermined and controlled temperature followed by a slow cooling, for the purpose of reducing residual stresses induced by *work hardening* (3.2)

3.7

baking

process of heating fasteners for a specified duration at a given temperature in order to minimize the risk of *internal hydrogen embrittlement* (3.15)

[SOURCE: ISO 1891-2:2014, 3.4.11, modified — "time" was replaced with "duration"]

3.8

crack

beginning of *fracture* (3.10) without complete separation

[SOURCE: ASTM F2078-15, modified — "line" was replaced with "beginning"]

3.9

failure

loss of the ability of a fastener to perform a specified function, which in some cases can lead to complete *fracture* (3.10)

3.10

fracture

break occurring when the plastic deformation in a fastener increases locally above its resistance limit, resulting in the separation of the fastener into two or more pieces, during testing or in service

3.11

fracture morphology

structure and aspect of the fractured surface

3.12

ductile

exhibiting a large amount of plastic deformation before *fracture* (3.10) with a resulting non-flat fracture surface showing fibrous ductile dimple morphology that is typically dull or matte

3.13

brittle

exhibiting little or no plastic deformation before *fracture* (3.10) with a resulting flat fracture surface showing brittle morphology that is typically shiny

Note 1 to entry: Brittle fracture along cleavage planes is known as transgranular fracture.

Note 2 to entry: Brittle fracture by separation at prior austenite grain boundaries is known as intergranular fracture.

3.14

hydrogen embrittlement

HE

permanent loss of ductility in a metal or alloy caused by atomic hydrogen in combination with load induced and/or residual tensile stress that can lead to *brittle* (3.13) *fracture* (3.10) after certain time[1]

Note 1 to entry: In the context of describing hydrogen embrittlement of high strength steel fasteners, the term “hydrogen” refers to atomic hydrogen and not molecular H_2 gas.

[SOURCE: ISO 1891-2:2014, 3.4.9, modified — Note 1 to entry has been added.]

3.15

internal hydrogen embrittlement

IHE

embrittlement caused by residual hydrogen from manufacturing processes, resulting in delayed brittle *failure* (3.9) of fasteners under load induced and/or residual tensile stress

[SOURCE: ISO 1891-2:2014, 3.4.10]

3.16

environmental hydrogen embrittlement

EHE

embrittlement caused by hydrogen absorbed as atomic hydrogen from a service environment, resulting in delayed brittle *failure* (3.9) of fasteners under tensile stress (i.e. load induced and/or residual tensile stress)

[SOURCE: ISO 1891-2:2014, 3.4.13]

3.17

hydrogen embrittlement threshold stress

critical stress below which *hydrogen embrittlement* (3.14) does not occur, which represents the degree of susceptibility of a steel for a given quantity of available hydrogen

3.18

stress corrosion cracking

SCC

category of *environmental hydrogen embrittlement* (3.16) where *failure* (3.9) occurs during service by cracking under the combined action of corrosion generated hydrogen and load induced tensile stress

[SOURCE: ISO 1891-2:2014, 3.4.14]

3.19

hydrogen diffusion

propagation of hydrogen and interaction with metallurgical features within the steel microstructure (microcracks, dislocations, precipitates, inclusions, grain boundaries, etc.) which constitute areas of traps into the fastener material: *non-reversible traps* (characterized by high bonding energies and low probability of hydrogen being released) and *reversible traps* (characterized by low bonding energies and hydrogen being released more readily)

3.20

hydrogen effusion

outward migration of hydrogen from the fastener material, occurring naturally at ambient temperature due to concentration gradient or as the result of a thermal driving force [e.g. *baking* (3.7)]

4 Symbols and abbreviated terms

EHE	environmental hydrogen embrittlement
HAC	hydrogen assisted cracking
HE	hydrogen embrittlement
HELP	hydrogen enhanced local plasticity
HIC	hydrogen induced cracking
IHE	internal hydrogen embrittlement
SCC	stress corrosion cracking

5 General description of hydrogen embrittlement

Generally, hydrogen embrittlement is classified under two broad categories based on the source of hydrogen: internal hydrogen embrittlement (IHE) and environmental hydrogen embrittlement (EHE). IHE is caused by residual hydrogen from steelmaking and/or from processing steps such as pickling and electroplating. EHE is caused by hydrogen introduced into the metal from external sources while it is under stress, such as in-service fastener.

The term “stress corrosion cracking” (SCC) is used in relation to EHE that occurs when hydrogen is produced as a by-product of surface corrosion and is absorbed by the steel fastener. Cathodic hydrogen absorption is a subset of SCC. Cathodic hydrogen absorption occurs in the presence of metallic coatings such as zinc or cadmium that are designed to sacrificially corrode to protect a steel fastener from rusting. If the underlying steel becomes exposed, a reduction process on the exposed steel surface simultaneously results in the evolution of hydrogen in quantities that are significantly greater than in the case of uncoated steel.

The terms “de-embrittlement” and “re-embrittlement” are also used in the aerospace field but are technically incorrect because embrittlement is not reversible. De-embrittlement is misused to describe the effect of baking, and re-embrittlement is misused to describe the effect of hydrogen absorption during service or by use of maintenance cleaning fluids.

6 Hydrogen damage mechanism

High strength steel is broadly defined as having a tensile strength (R_{m}) above 1 000 MPa. When high strength steel is tensile stressed, as is the case with a high strength fastener that is under tensile load from tightening, the stress causes atomic hydrogen within the steel to diffuse (i.e. move) to the location of *greatest stress* (e.g. at the first engaged thread or at the fillet radius under the head of a bolt). As increasingly higher concentrations of hydrogen collect at this location, steel that is normally ductile gradually becomes brittle. Eventually, the concentration of stress and hydrogen in one location causes a hydrogen assisted (brittle) microcrack. The brittle microcrack continues to grow as hydrogen moves to follow the tip of the propagating crack, until the fastener is overloaded and finally fractures. This phenomenon is often called hydrogen assisted cracking (HAC) [or hydrogen induced cracking (HIC)]. The hydrogen damage mechanism as described causes the fastener to fail at stresses that are significantly lower than the basic strength of the fastener as determined by a standard tensile test[1][2].

Theoretical models that describe hydrogen damage mechanisms under idealized conditions have been proposed since the 1960s[2]. In the case of high strength steel, these models are based primarily on two complementary theories of *decohesion*[3] and *hydrogen enhanced local plasticity (HELP)*[4][5][6]. Given the complexity of HE phenomena, hydrogen damage models continue to evolve and be refined[7]. An in-depth review of the theories of hydrogen damage is outside the scope of this technical report. However, detailed information is given in the references listed in the Bibliography.

Hydrogen "traps" refer to metallurgical features within the steel microstructure such as grain boundaries, dislocations, precipitates, inclusions, etc., to which hydrogen atoms can become bonded[8]. Hydrogen thus “trapped” is no longer free to diffuse (i.e. move) to areas of high stress where it can participate in the mechanism of HAC. Traps are typically classified as *reversible* or *non-reversible* based on their bonding energies. Reversible traps are characterized by low bonding energies: in other words, hydrogen is more easily released from the trap. Non-reversible traps are characterized by high bonding energies: in other words, hydrogen requires a great deal of energy (e.g. from heat or stress field) to be released from the trap. Non-trapped hydrogen which is free to move in the metal lattice is called *mobile* hydrogen; it is also known as *interstitial* or *diffusible* hydrogen[9][10][11].

7 Fracture morphology

With quenched and tempered high strength steel fasteners, the fracture surface resulting from hydrogen assisted cracking (HAC) is typically characterized by *brittle intergranular* morphology which is caused by a crack growth path that follows the grain boundaries (see Figure 1). The morphology of a fracture surface varies based on the susceptibility of the material and the degree of embrittlement. Clearly defined grain facets (i.e. sharp and angular features) and/or a high proportion of brittle versus ductile features are indicative of high degree of embrittlement[12]. Figure 1 illustrates a fracture surface that is 100 % intergranular with very well-defined grain facets. Less susceptible materials can present fracture surfaces that contain a mix of intergranular and cleavage (i.e. trans-granular) morphologies.

With a tensile loaded fastener, a brittle hydrogen assisted crack typically grows up to a point where the reduced cross section of the fastener can no longer withstand the applied load. At this point, the fastener fractures rapidly (i.e. *fast fracture*). A normal fracture morphology corresponding to fast fracture is ductile, characterized by *ductile dimples*. Figure 2 illustrates a fracture surface where the brittle hydrogen assisted crack propagation ended (i.e. final crack tip) prior to final ductile fast fracture of the fastener.

Other forms of embrittlement failure are caused by phenomena not related to the presence of hydrogen such as temper embrittlement, quench embrittlement, quench crack, etc., that must be distinguished from hydrogen embrittlement failures. These other types of embrittlement can exhibit similar intergranular fracture surfaces but are principally distinguished from hydrogen embrittlement by the fact that they are *not time dependent*.

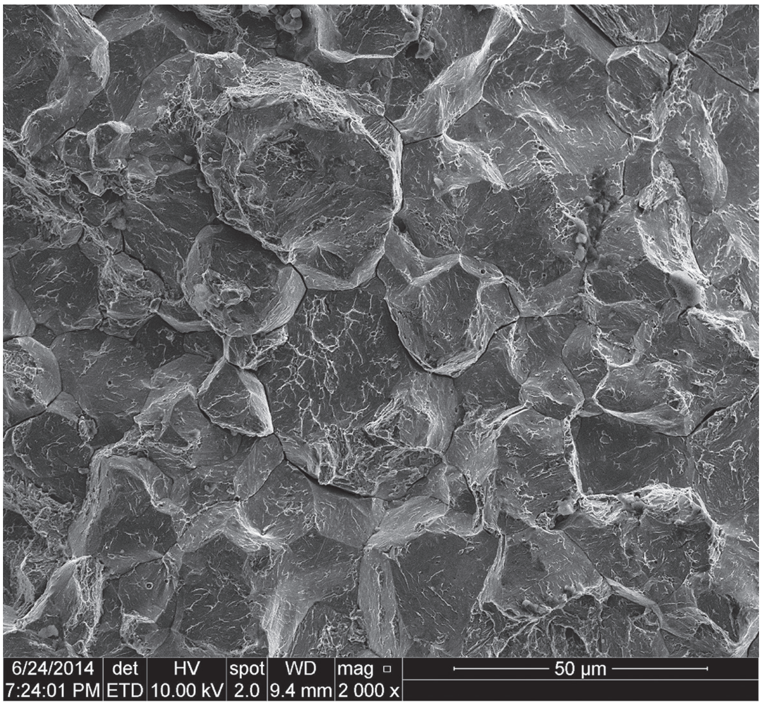

Figure 1 — Fracture surface showing 100 % well defined brittle intergranular morphology — Cr-Mo alloy steel (AISI 4135), quenched and tempered to 530 HV, zinc electroplated

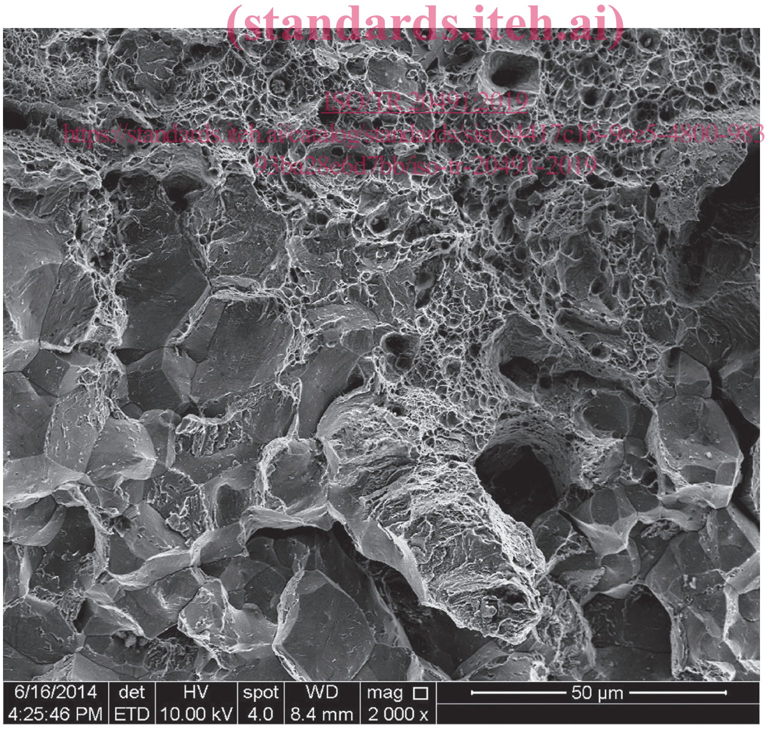

Figure 2 — Fracture surface showing both brittle intergranular morphology resulting from HAC and ductile dimple morphology indicative of final fracture — Cr-Mo alloy steel (AISI 4135) at 530 HV, zinc electroplated