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Standard Terminology Relating to Hydrogen Embrittlement Testing[1]

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1. Scope

1.1 This terminology covers the principal terms, abbreviations, and symbols relating to mechanical methods for hydrogen embrittlement testing. These definitions are published to encourage uniformity of terminology in product specifications.

2. Referenced Documents

2.1 *ASTM Standards:*

A 941 Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys[2]

E 6 Terminology Relating to Methods of Mechanical Testing[3]

E 8 Test Methods for Tension Testing of Metallic Materials[3]

E 812 Test Method for Crack Strength of Slow Bend, Precracked Charpy Specimens of High-Strength Metallic Materials[3]

E 1823 Terminology Relating to Fatigue and Fracture Testing[3]

F 1624 Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique[4]

G 15 Terminology Relating to Corrosion and Corrosion Testing[5]

3. Significance and Use

3.1 The terms used in describing hydrogen embrittlement have precise definitions. The terminology and its proper usage must be completely understood to communicate and transfer information adequately within the field.

3.2 Some of the terms are defined in other terminology standards, which are respectively identified in parentheses following the definition.

4. Terminology

4.1 *Definitions:*

baking—heating to a temperature at least 50°F below the tempering or aging temperature of the metal or alloy to remove hydrogen before embrittlement occurs by the formation of microcracks.

DISCUSSION—No metallurgical changes take place as a result of baking. **(A 941)**

brittle—the inability of a material to deform plastically before fracturing.

crack strength—the maximum value of the nominal stress that a cracked specimen is capable of sustaining. **(E 1823)**

ductile—the ability of a material to deform plastically before fracturing. **(E 6)**

embrittle—to make brittle; that is, to lose ductility.

embrittlement—the loss of ductility or toughness of a metal or alloy. **(G 15)**

environmental hydrogen embirttlement (EHE)—generally caused by hydrogen introduced into the steel from the environment after exposure to an externally applied stress.

DISCUSSION—Embrittlement as a result of hydrogen introduced into steel from external sources while under stress. Tests are conducted in an environment. **(STP 962)**

DISCUSSION—Found in plated parts that cathodically protect the metal from corroding. Generates hydrogen at the surface of the metal. Produces a clean, intergranular fracture surface. Not reversible. (The subtle differences between IHE and EHE are detailed in Appendix X1.) **(STP 543)**

environmentally assisted cracking (EAC)—generic, crack growth as a result of exposure to the environment.

fracture strength—the load at the beginning of fracture during a tension test divided by the original cross-sectional area.

gaseous hydrogen embrittlement (GHE)—a distinct form of EHE caused by the presence of external sources of high pressure hydrogen gas; cracking initiates on the outer surface.

heat treatment—heating to a temperature that produces metallurgical changes in the steel that alter the mechanical properties and microstructure of the metal. **(A 941)**

hydrogen-assisted stress cracking (HASC)—crack growth as a result of the presence of hydrogen; it can be either IHE or EHE and sometimes is referred to as hydrogen stress cracking (HSC).

hydrogen embrittlement—a permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either an externally applied or an internal residual stress. **(G 15)**

[1] This terminology standard is under the jurisdiction of ASTM Committee F07 on Aerospace and Aircraft and is the direct responsibility of Subcommittee F07.04 on Hydrogen Embrittlement.

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[2] *Annual Book of ASTM Standards*, Vol 01.01.

[3] *Annual Book of ASTM Standards*, Vol 03.01.

[4] *Annual Book of ASTM Standards*, Vol 15.03.

[5] *Annual Book of ASTM Standards*, Vol 03.02.

hydrogen susceptibility ratio (Hsr)—the ratio of the threshold for the onset of hydrogen assisted cracking to the tensile strength of the material.

internal hydrogen embrittlement (IHE)—hydrogen embrittlement caused by absorbed atomic hydrogen from any chemical process that introduces hydrogen into the steel before exposure to an externally applied stress.

DISCUSSION—Embrittlement results from the formation of microcracks with time and is often referred to as "time-delayed embrittlement." Once microcracks have been formed, ductility cannot be restored. Tests are generally conducted in air. **(STP 543)**

DISCUSSION—This type of embrittlement is referred to as the classic type of hydrogen embrittlement in steel, although IHE has also been observed in a wide variety of other materials including nickel base alloys and austenitic stainless steels provided that they are severely charged with hydrogen. **(STP 543)**

DISCUSSION—For steels, IHE is most severe at room temperature. The problem primarily results from electroplating. Other sources of hydrogen are the processing treatments, such as melting and pickling. **(STP 543)**

notched tensile strength—the maximum nominal (net section) stress that a notched tensile specimen is capable of sustaining. **(E 1823)**

process—a defined event or sequence of events in plating or coating that may include pretreatments and posttreatments.

reaction hydrogen embrittlement (RHE)—hydrogen can react with itself, with the matrix, or with a foreign element in the matrix and form new phases that are usually quite stable, and embrittlement is not reversible.

DISCUSSION—Quite distinct from the other types in that the hydrogen may react near the surface or diffuse a substantial distance before it reacts. **(STP 543)**

sharp-notch strength—the maximum nominal (net section) stress that a sharply notched specimen is capable of sustaining. **(E 1823)**

stress corrosion cracking (SCC)—a cracking process that requires the simultaneous action of a corrodent and sustained tensile stress.

DISCUSSION—This excludes corrosion-reduced sections that fail by fast fracture and intercrystalline or transcrystalline corrosion, which disintegrate an alloy without either applied or residual stress. **(G 15)**

DISCUSSION—Considered to occur while under anodic polarization. Not reversible. Produces an oxidized, intergranular fracture surface. **(STP 543)**

stress–intensity factor, K, K_I, K_{II}, K_{III},—the magnitude of the ideal crack–tip stress field (stress field singularity) for a particular mode in a homogeneous linear–elastic body. **(E 1823)**

susceptibility to hydrogen embrittlement—is a material property that is measured by the threshold stress intensity parameter for hydrogen induced stress cracking, K_{Iscc}, K_{IHE}, or K_{EHE}, which is a function of hardness and microstructure.

threshold (th)—a point separating conditions that will produce a given effect from conditions that will not produce the effect; the lowest load at which subcritical cracking can be detected.

threshold stress (σ_{th})—a stress below which no hydrogen stress cracking will occur and above which time-delayed fracture will occur; in Test Method F 1624, the threshold is identified as the maximum load at the onset of cracking that cuases a 5 % drop in load of $NSF(B)_{F1624}$ under displacement control.

threshold stress intensity (K_{th})—a stress intensity below which no hydrogen stress cracking will occur and above which, time-delayed fracture will occur.

4.2 *Symbols:*

P—applied load

P_c—critical load required to rupture a specimen using a continuous loading rate

P_i—crack initiation load for a given loading and environmental condition using an incrementally increasing load under displacement control

P_{th}—threshold load in which P_i is invariant with respect to loading rate; P_{th} is the basis for calculating the threshold stress or the threshold stress intensity

σ—applied stress

σ_{net}—net stress based on area at minimum diameter of notched round bar

σ_i—stress at crack initiation

$\sigma_{th\text{-}IHE}$—threshold stress—test conducted in air—geometry dependent

$\sigma_{th\text{-}EHE}$—threshold stress—test conducted in a specified environment—geometry dependent

R_{sb}—ratio of specimen crack strength to yield strength in bending

R_{nsb}—ratio of specimen notched strength to yield strength in bending

K_{Iscc}—threshold stress intensity for stress corrosion cracking

K_{IHE}—threshold stress intensity for IHE

K_{EHE}—threshold stress intensity for EHE

4.3 *Abbreviations:*

NFS(B)—notched fracture strength in bending

NFS(T)—notched fracture strength in tension

$NFS(B)_{F1624}$—notched fracture strength in bending of a bare specimen at Test Method F 1624 step-loading rates

ISL—incremental step load

ISL_{th}—threshold from an incremental step-load test

ANNEX

(Mandatory Information)

A1. DEFINITIONS OF SYMBOLIC EXPRESSIONS

A1.1 The following abbreviations and symbols are included as separate sections in this standard because they evolved specifically from tests conducted on fasteners, which inherently have all of the ingredients necessary to create hydrogen embrittlement problems.

A1.2 Fasteners are generally (*1*) a notched, high-strength structural element that in service is always torqued to a high percentage of the fracture strength, (*2*) chemically cleaned, (*3*) coated with a sacrificial anodic coating that is generally electrochemically deposited producing a hydrogen charging condition, and (*4*) placed in service under cathodic charging conditions when exposed to an aqueous environment—all of the conditions necessary to cause classical hydrogen embrittlement (IHE) or environmentally induced hydrogen embrittlement (EHE).

A1.3 *Test Methods E 8 Loading Rates*—These results are independent of any residual hydrogen concentration because the tests are performed at a rate that does not allow sufficient time for the diffusion of hydrogen to occur.

A1.3.1 *Tensile Test Symbols:*

TS(T) = tensile strength (tension), ksi; calculated from the minimum specified tensile strength (mst) and minor diameter of the fastener = $4 \cdot P_{mst}/\pi \cdot d_{minor^2}$; Ex: SAE J1237/M10 = TS(T) = $4 \cdot (P_{mst} = 12\,120)/\pi \cdot (d_{minor} = 0.3285)^2$ = 143 ksi

FS(T) = fracture strength (tension), ksi; calculated from the measured fracture or ultimate tensile load of the fastener, or notched or precracked test sample = P_{ult}/net area FS(T) = $4 \cdot P_{ult}/\pi \cdot d_{minor^2} \geq$ TS(T)

R_{nst} = notched strength ratio in tension; calculated from FS(T)/TS(T) = $R_{nst} \leq 1.5$

A1.3.2 *Bend Test Symbols:*

YS(B) = TS(T), which for M10 = 143 ksi; and

P_{ys} *(B)* = $[\mathrm{TS(T)} \cdot \pi\, d^3]/256 = [143 \cdot \pi\, (0.3285^3)]/256$ = 62 lbs, or $d \cdot P_{TS(T)}/64 = (0.3285) \cdot (12\,120$ lbs$)/64$ = 62 lbs; or

FS(B) = fracture strength (bend), ksi; calculated from the measured fracture or ultimate bend of the fastener, or notched or precracked test sample; that is, FS(B) = $256 \cdot P_{measured\ bend}/(\pi \cdot d_{minor^3})$

R_{nsb} = notched strength ratio in bending: Ref: Test Method E 812; calculated from FS(B)/TS(T) = $R_{nsb} \leq 2.3$

A1.4 *Test Method F 1624 Loading Rates*—These abbreviations are used for the terms for results that are dependent on the residual hydrogen concentration. The tests are performed at a rate that allows sufficient time for the diffusion of hydrogen to occur.

A1.4.1 *ISL*—incremental step-load test to measure the threshold stress per Test Method F 1624, which is slow enough to allow for the diffusion of hydrogen to occur

A1.4.2 $\sigma_{th\text{-}air(T/B)}$—the threshold stress at a given loading rate measured in air per Test Method F 1624 in either tension or bend

A1.4.3 $\sigma_{th\text{-}@V(T/B)}$—the threshold stress at a given loading rate measured at a given cathodic potential per Test Method F 1624 in either tension or bend

A1.4.4 $\sigma_{th\text{-}H^+(T/B)}$—the lower limit of the threshold stress at an invariant loading rate measured in the most aggressive hydrogen charging environment of -1.2V versus SCE per Test Method F 1624 in either tension or bend

A1.5 *Evaluation Parameter:*

A1.5.1 *%FS(T/B)*—degradation factor = % fracture strength calculated from %FS(T/B) = $H_{sr(T/B)}/R_{ns(t/b)} \times 100\,\% = \sigma_{th\text{-}H^+(T/B)}$/FS(T/B) or the percentage degradation in strength as measured by the ratio of the worst case or minimum threshold value divided by the maximum attainable strength in air

A1.5.2 $H_{sr(T/B)}$—hydrogen susceptibility ratio = $\sigma_{th\text{-}H^+(T/B)}$/TS(T); a material property that is a function of composition, melting practice, thermomechanical processing, heat treatment, and much more sensitive to microstructure than Test Methods E 8 mechanical properties

A1.5.3 $H_{sr(t/b)\text{-}IHE}$—the threshold notched hydrogen susceptibility ratio in either tension or bend for internal hydrogen embrittlement, IHE, which is given by $H_{sr(t/b)\text{-}IHE} = \sigma_{th\text{-}air(T/B)}$ + TS(T)

A1.5.4 $H_{sr(t/b)\text{-}EHE}$—the threshold notched hydrogen susceptibility ratio in either tension or bend at a given cathodic potential for external or environmental hydrogen embrittlement, EHE, which is given by $H_{sr(t/b)\text{-}EHE} = \sigma_{th\text{-}@V(T/B)}$ + TS(T)

A1.5.5 $H_{sr(t/b)@\text{-}1.2V}$—the lower limit threshold notched hydrogen susceptibility ratio in either tension or bend for hydrogen-induced stress cracking in the most aggressive hydrogen charging environment of -1.2V versus SCE, which is given by

A1.5.6 $H_{sr(T/B)}$—$H_{sr(t/b)\ @\text{-}1.2V} = \sigma_{th\text{-}H^+(T/B)}$ + TS(T) = $H_{sr(T/B)}$

APPENDIX

(Nonmandatory Information)

X1. IHE/EHE COMPARISON CHART

TABLE X1.1 Similarities/Differences Between Internal (IHE) and Environmental (EHE) Hydrogen Embrittlement[A]

IHE	EHE
Time delay fracture when stressed in air after exposure to environment	Time delay fracture in environment after exposure to stress in air
Requires $[H]^+$ critical from processing (plating, acid cleaning) for a given stress above hydrogen stress cracking threshold	Requires $[H]^+$ critical from environment (cathodic corrosion reaction) for a given stress above hydrogen stress cracking threshold
Plating, acid cleaning, and so forth, considered environment in which "corrosion reaction" takes place to generate $[H]^+$, while stress is below threshold	"Corrosion reaction" takes place in environment to generate $[H]^+$, or other environmental sources of $[H]^+$, while stress is above threshold
The only difference between IHE and EHE is the sequence of applying the stress and exposure to hydrogen	
Phenomenon is the same! Mechanism is the same! Principle difference is sequence of stress and introduction of $[H]^+$ into the part!	
IHE: $[H]^+$+ Stress $\rightarrow$ Rupture EHE: Stress + $[H]^+\rightarrow$ Rupture	

[A] If part was bent or plastically deformed to introduce residual stress before being put into a plating bath, and would have cracked during the plating process, it would have been identified as internal hydrogen embrittlement although having all the ingredients of environmental hydrogen embrittlement.

BIBLIOGRAPHY

The following documents and publications may provide additional definitions or terminology in the field of hydrogen embrittlement.

(**1**) Raymond, L., Ed., *Hydrogen Embrittlement Testing, ASTM STP 543*, ASTM, West Conshohocken, PA, 1972.

(**2**) Raymond, L., Ed., *Hydrogen Embrittlement: Prevention and Control, ASTM STP 962*, ASTM, West Conshohocken, PA, 1988.

(**3**) "The Susceptibility of Fasteners to Hydrogen Embrittlement and Stress Corrosion Cracking," *Handbook of Bolts and Bolted Joints*, Marcel Decker, Inc., New York, 1998, Chap. 39, p. 723.