

1. Mechanical & Metallurgical Failure

For All Industries

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Graphitization	Causing loss in strength, ductility and/or creep resistance.	427°C to 593 °C	Some grades of CS and 0.5Mo steels	Using Cr containing low alloy steel	Full thickness sample metallography	N/A
Softening (Spheroidization)	May cause a loss in strength and/or creep resistance.	440°C to 760°C	CS and low alloys incl. 1Cr-0.5Mo until 9Cr-1Mo	Minimize exposure to elevated temps	Field metallography or removal of samples	N/A
Strain Aging	Results in an increase in hardness and strength with a reduction in ductility and toughness	Intermediate Temperature	Mostly pre-1980's carbon steels with large grain size and C-0.5 Mo low alloy steel	No issue for newer steels with enough Al for deoxidizer; Apply PWHT to weld repair or "Butter"	None	N/A
Brittle Fracture	Brittle fracture is the sudden rapid fracture under stress (residual or applied) where the material exhibits little or no evidence of ductility or plastic deformation.	Temperatures below ductile-to- brittle transition temp	CS and low alloys esp. prior to 1987; 400 SS also susceptible	Material selection; Minimize pressure at ambient temperatures; PWHT; "Warm" pre-stress hydrotest	None to minimize; Susceptible vessels inspect for pre-existing flaws	Cracks typically straight, non- branching, with no plastic deformation; Limited intergranular cracking
Creep and Stress Rupture	At high temperatures, metal components can slowly deform under load below the yield stress. Deformation may lead to rupture	SEE Table 4-2 for Threshold Temp: C.S. --> 700°F C-1/2 Mo --> 750°F 1.25Cr thru 9Cr --> 800°F 304H --> 900°F 347H --> 1000°F	All metals and alloys	Minimize temperatures; Higher PWHT may help; Minimize hot spots in heaters	Combination of techniques; Tubes bulging, sagging, diametric growth	Noticeable deformation may be observed; May have significant bulging before final fracture occurs

2. Uniform or Localized Loss of Thickness

For All Industries

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Galvanic Corrosion	occur at the junction of dissimilar metals when they are joined together in a suitable electrolyte	N/A	All metals with the exception of most noble metals	Design; Differing alloys not in intimate contact; Coatings	Visual and UT Thickness	More active material can suffer generalized loss in thickness or crevice, groove or pitting corrosion
Atmospheric Corrosion	occurs from moisture associated with atmospheric conditions	Corrosion rates increase with temp up to about 250°F.	CS, low alloys, and copper alloyed Al	Surface prep and proper coating	VT and UT	General or localized; Normally a distinctive iron oxide (red rust) scale forms
Corrosion Under Insulation (CUI)	resulting from water trapped under insulation or fireproofing	More severe 212°F - 250°F for CS	CS, low alloys, 300 SS and duplex SS	Selection of insulation type; Maintain coatings and insulation	Strip insulation; VT, UT, IR, etc.	May be highly localized; Loose, flaky scale covering the corroded component
Cooling Water Corrosion	caused by dissolved salts, gases, organic compounds or microbiological activity.	Process side > 140°F; Brackish and salt water outlet > 115°F	CS, all grades of SS, copper, Al, titanium and Ni base alloys	Design process inlet < 135°F; Operation; Chemical treatment; Maintain water velocities; Avoid ERW tubes	pH; Oxygen content; Outlet temps; EC/IRIS tubes	General corrosion, localized underdeposit, pitting, MIC, SCC, fouling, grooving along ERW tubes
Boiler Water Condensate Corrosion	General corrosion and pitting in the boiler system and condensate return piping.	N/A	Primarily CS; Some low alloy, 300 SS and copper based alloys	Oxygen scavenging treatment; Amine inhibitor treatment	Water analysis; Dearator cracking WFMT	Oxygen: pitting anywhere in the system; CO ₂ : smooth grooving

3. High Temperature Corrosion

For All Industries

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Oxidation	Oxygen in air reacts with carbon steel and other alloys at high temperature	Oxidation of CS significant > 1000°F; 300 Series SS susceptible to scaling > 1500°F.	CS and low alloys; All 300 SS, 400 SS and Ni base alloys oxidize to varying degrees	Upgrade alloy; Addition of Cr primary element for oxidation resistance	Monitor process conditions and temperatures; UT for thickness loss	General thinning; Usually covered on the outside surface with an oxide scale
Sulfidation	Corrosion of carbon steel and other alloys resulting from their reaction with sulfur compounds in high-T	> 500°F	CS, low alloys, 300 SS and 400 SS; Ni base alloys; Copper base alloys	Upgrade to higher Cr; Al diffusion treatment of low alloys	Monitor process conditions and temperatures; UT for thickness loss; Proactive and retroactive PMI	Most often uniform thinning but may be localized; Sulfide scale will usually cover the surface
Carburization	Carbon is absorbed into a material at elevated temperature while in contact with a carbonaceous material	> 1100°F	CS and low alloys, 300 SS and 400 SS, cast SS, Ni base alloys with significant Fe content and HK/HP alloys	Alloy selection (Si & Al oxidizers); Lower temperatures and higher oxygen/sulfur partial pressures.	Hardness/Field metallography if process side accessible; RT, UT, MT for cracking in advanced stages	In advanced stage may be a volumetric increase
Decarburization	A condition where steel loses strength due the removal of carbon and carbides leaving only an iron matrix.	Elevated temperatures	CS and low alloys	Control chemistry of gas phase; Cr and Mo form more stable carbides	Field metallography; Hardness tests for softening	N/A
Metal Dusting	is form of carburization resulting in accelerated localized pitting	900°F - 1500°F	All; No known alloy immune under all conditions	Protective layer of sulfur (usually as H ₂ S); Material selection; Al diffusion treatment	Compression wave UT for heater tubes; RT for pitting/thinning; VT if ID is accessible	Low alloys can be uniform but usually small pits filled with crumbly residue;

4. Environment Assisted Cracking

For All Industries

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Chloride Stress Corrosion Cracking (Cl-SCC)	Due aqueous chloride environment. The presence of dissolved oxygen increases propensity for cracking.	> 140°F	300 SS; Ni 8% - 12% most susceptible; Ni > 35% highly resistant, Ni > 45% nearly immune	Material selection; Low chloride water for hydro test; Coatings under insulation;	VT in some cases, PT (surface prep may be necessary), ECT, UT	"spider web"; Branched, transgranular, and may have "crazecracked" appearance
Corrosion Fatigue	cracks develop under the combined effects of cyclic loading and corrosion	N/A	All metals and alloys	inhibitors, material selection, coatings, BFW chemical control, etc.); PWHT;	UT, MT	"rabbit ears"; Transgranular but not branched, often multiple parallel cracks
Caustic Stress Corrosion Cracking (Caustic Embrittlement)	surface-initiated cracks that occur in piping and equipment exposed to caustic, primarily adjacent to non-PWHT'd welds.	Increasing temps increase likelihood and severity	CS, low alloys and 300 SS; Ni base alloys more resistant.	PWHT at 1150°F for CS; Alloy upgrade to Ni based alloys; Design/operation of injection system;	WFMT, EC, RT, ACFM for crack detection; PT not effective (tight, scale-filled cracks); SWUT for crack depth	"spider web"; Predominantly intergranular, parallel to weld in adjacent base metal but can occur in the weld or HAZ
Ammonia Stress Corrosion Cracking	Due to aqueous streams containing ammonia	Any temperature	Copper alloys with aqueous ammonia and/or ammonium compounds; CS in anhydrous ammonia	Copper - prevent ingress of air, upgrade to 300 SS or Ni alloys; CS - PWHT	Copper - monitor pH, ECT or VT on tubes for cracking; CS - WFMT, AET, or External SWUT	Cu: bluish corrosion products at surface cracks, single or highly branched, either trans or intergranular
Hydrogen Embrittlement (HE)	A loss in ductility due to the penetration of atomic hydrogen can lead to brittle cracking	Ambient - 300°F;	CS, low alloys, 400 SS, Precipitation Hardenable SS, some high strength Ni base alloys.	Use lower strength steels; PWHT; Low hydrogen, dry electrodes, and preheat for welding; Bake out at 400°F or higher;	MT or PT for surface cracks; UT may be helpful; RT not sensitive enough	Can initiate sub-surface, but in most cases is surface breaking; Higher strength steels cracking is often intergranular

1. Uniform or Localized Loss of Thickness

For Refinery Industry

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Amine Corrosion	occurs principally on carbon steel in amine treating processes due to amine & dissolved acid gases (CO ₂ and H ₂ S)	Increases with increasing temps; Above 220°F can result in acid gas flashing and severe localized corrosion	Primarily CS; 300 SS highly resistant	Proper operation; Avoid buildup of HSAS; Design should control local pressure drop to minimize flashing;	VT and UT thickness internal; UT scans or profile RT for external; Corrosion coupons	General uniform thinning, localized corrosion or localized underdeposit attack
Ammonium Bisulfide Corrosion (Alkaline Sour Water)	corrosion occurring in hydroprocessing reactor effluent streams and in units handling alkaline sour water.	< 150°F	CS; 300 SS, duplex SS, Al alloys and Ni base alloys more resistant	Symmetrical/balanced flow in and out of air cooled exchangers; Maintain velocities 10 to 20 fps for CS, resistant materials > 20 fps;	Frequent UT and RT profile thickness; IRIS and ECT tubes; Monitor water injection	General loss in thickness with potential for high localized rates;
Ammonium Chloride Corrosion	occurring under ammonium chloride or amine salt deposits	< 300°F; May corrode well above water dewpoint of 300°F	All commonly used materials;	Pitting resistant alloys more have improved resistance; Limit chlorides; Water wash; Filming inhibitors	RT or UT Thickness; Monitor feed streams; Corrosion coupons may be helpful if salts deposit on the element	Possible fouling or corrosion
Hydrochloric Acid (HCl) Corrosion	Caused by aqueous HCl	Increases with increasing temp up to point where water vaporizes	All common materials of construction	Upgrade CS to Ni base can help; Remove chlorides (neutralize, water wash, absorb, etc.);	AUT or RT for thickness; Corrosion coupons; Check pH	General uniform thinning, localized corrosion or underdeposit attack
High Temp H₂/H₂S Corrosion	presence of hydrogen in H ₂ S-containing hydrocarbon streams caused in a uniform loss in thickness	> 500°F	Order of increasing resistance: CS, low alloys, 400 SS, and 300 SS	Use alloys with high chromium content; 300 SS are highly resistant at service temps	UT, VT and RT for thickness; Verify operating temps;	Uniform loss in thickness from the process side with an iron sulfide scale

2. Environment Assisted Cracking

For Refinery Industry

Damage Mechanisms	Description of Damage	Temperature Range	Affected Materials	Prevention	Inspection & monitoring	Appearance
Polythionic Acid Stress Corrosion Cracking (PASCC)	normally occurring during shutdowns, startups or during operation when sulfur acid, air and moisture are present	Sensitization occurs 750°F - 1500°F	Sensitized austenitic SS; 300 SS, Alloy 600/600H, and Alloy 800/800H	Material selection; Flush with alkaline or soda ash to neutralize or purge with nitrogen or nitrogen/ammonia;	Flapper disc sanding to remove deposits and PT	Intergranular; Quite localized; Typically next to welds, but may be in base metal
Amine Stress Corrosion Cracking	Occurs in aqueous alkanolamine systems used to remove/absorb H ₂ S and/or CO ₂	N/A	CS and low alloys	PWHT all CS welds; Material selection (clad or solid);	Crack detection best with WFMT or ACFM; PT usually not effective; SWUT crack depths; AET	Surface cracking on ID primarily in HAZ, but also in weld or adjacent to HAZ;
Wet H₂S Damage	Four type of damages can occurs: - Blistering - HIC - SOHIC - SSC	Blistering, HIC, and SOHIC ambient to 300°F or higher; SSC < 180°F	CS and low alloys	Coatings or alloy cladding; Water wash to dilute HCN	Monitor free water phase; Crack detection best with WFMT, EC, RT or ACFM; SWUT for crack sizing; AET	Blistering, HIC "stepwise cracking", SOHIC stacked arrays, SSC through thickness potentially
Hydrogen Stress Cracking - HF	Cracking as a result of exposure to aqueous HF acid environments	Aqueous HF environments	CS and low alloys	PWHT; Weld hardness < 200 HB and no localized zones > 237 HB; CS with Carbon Equivalent < 0.43; B7M Bolts;	WFMT for cracks; Hardness testing	Surface breaking intergranular cracks
Carbonate Stress Corrosion Cracking	occur adjacent to carbon steel welds under the combined action of tensile stress in systems containing a free water phase with carbonate	Generally no temperature ranges; However, > 200°F if CO ₂ > 2% in gas scrubbing units	CS and low alloys	PWHT at 1150°F; Material selection; Coatings or alloy cladding;	Monitoring of pH and CO ₃ ⁻² concentration; WFMT or ACFM for crack detection; SWUT for crack depth; AET	"spider web"; Parallel to weld in adjacent base, but also in weld or HAZ; Predominantly intergranular