

CONSTRUCTION STANDARD
FOR
CORROSION CONSIDERATION
DURING
FABRICATION AND INSTALLATION

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0. INTRODUCTION

Fabrication is the act of process of fabricating material in a form usable for installation and further completion of structures and equipment. The workmanship and finish of material shall be first class in every respect and subject to the closest inspection by the manufacturer's inspector, whether or not the Purchaser waives any part of the inspection. Future stability of materials from corrosion point of view depends on the design, choice of material, fabrication, inspection, installation and final testings.

Choice of material depends on many factors as corrosion resistance, cost, availability, strength, appearance and fabricability.

Fabricability includes the ease of forming, welding, bendings, coating, lining and other mechanical operations.

For design and material selection, reference is made to IPS-E-TP-760 and IPS-E-TP-740.

1. SCOPE

This Construction Standard covers the minimum requirements to be considered in fabrication and installation of vessels, equipment, structures, piping, tanks, etc.; in order to minimize corrosion damage during the service-life of installations and running conditions.

2. REFERENCES

Throughout this Standard the following standards and codes are referred to. The editions of these standards and codes that are in effect at the time of publication of this Standard shall, to the extent specified herein, form a part of this Standard. the applicability of changes in standards and codes that occur after the date of this Standard shall be mutually agreed upon by the Company and the Vendor/Consultant/Contractor.

API (AMERICAN PETROLEUM INSTITUTE)

- RP5 A5 "Recommended Practice for Field Inspection of New Casing, Tubing, and Plain-End Drill Pipe"
- 6 A "Specification for Wellhead and Christmas Tree Equipment"
- 6 D "Specification for Pipeline Valves (Steel Gate, Plug, Ball and Check Valves)"
- 14 D "Specification for Wellhead Surface Valves and Underwater Safety Valves for Offshore Service"
- Std. 1104 "Welding of Pipelines and Related Facilities"

ASME/ANSI (AMERICAN SOCIETY OF MECHANICAL ENGINEERS / AMERICAN NATIONAL STANDARD INSTITUTE)

- B 31.3 "Chemical Plant and Petroleum Refinery Piping", Appendix A, Table A-1
- Sec. IX "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, Welding and Brazing Operators"
- SPPE-1 "Quality Assurance and Certification of Safety and Pollution Prevention, Equipment Used in Offshore Oil and Gas Operations"

ASTM (AMERICAN SOCIETY FOR TESTING AND MATERIALS)

- G 48 "Test Method for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by the Use of Ferric Chloride Solution"
- D 1141 "Specification for Substitute Ocean Water"
- A 262 "Standard Practices for Detecting Susceptibility to Intergranular Corrosion Attack in Austenitic Stainless Steels"
- A 763 "Standard Practices for Detecting Susceptibility to Intergranular Attack in Ferritic Stainless Steel"
- A 380 "Standard Recommended Practices for Cleaning and Descaling Stainless Steel Parts, Equipment and System"

NACE (NATIONAL ASSOCIATION OF CORROSION ENGINEERS)

MR-01-75	"Standard Material Requirements Sulfide Stress Cracking Resistant Metallic Materials for Oil Field Equipment"
TM-01-77	"Testing of Metals for Resistance to Sulfide Stress Cracking at Ambient Temperature"

IPS (IRANIAN PETROLEUM STANDARDS)

IPS-C-TP-102	"Painting (Construction)"
IPS-E-TP-100	"Painting (Engineering)"
IPS-C-TP-274	"Coating (Construction)"
IPS-E-TP-270	"Coating (Engineering)"
IPS-C-TP-352	"Lining (Construction)"
IPS-E-TP-350	"Lining (Engineering)"
IPS-C-TP-701	"Thermal Insulation (Construction)"
IPS-E-TP-700	"Thermal Insulation (Engineering)"
IPS-E-TP-740	"Corrosion Consideration in Material Selection"
IPS-E-TP-760	"Corrosion Consideration in Design"
IPS-C-TP-820	"Cathodic Protection on Construction"
IPS-I-TP-820	"Cathodic Protection on Inspection"

3. DEFINITIONS AND TERMINOLOGY

Automatic welding

Welding in which the welding variables and the mean of making the weld are controlled by machine.

Bead

A single run of weld metal on a surface.

Braze welding

The joining of metals using a technique similar to fusion welding and a filler metal with a lower melting point than the parent metal but neither using capillary action as in brazing nor intentionally melting the parent metal.

Brazing

A process of joining metals in which, during or after heating, molten filler metal is drawn by capillary action into the space between closed adjacent surfaces of the parts to be joined. In general, the melting point of the filler metal is above 500°C, but always below the melting temperature of the parent metal.

Brazing alloy

Filler metal used in brazing.

Butt joint

A connection between the ends or edges of two parts making an angle to one another of 135° to 180° inclusive in the region of the joint.

Carbon dioxide welding

Metal-arc welding in which a bare wire electrode is used, the arc and molten pool being shielded with carbon dioxide gas.

Covered filler rod

A filler rod having a covering of flux.

Deposited metal

Filler metal after it becomes part of a weld or joint.

Edge preparation

Squaring, grooving, chamfering or beveling an edge in preparation for welding.

Electro-slag welding

A welding process in which consumable electrodes are fed into a joint containing flux; the current melts the flux, and the flux in turn melts the faces of the joint and the electrodes, allowing the weld metal to form a continuous cast ingot between the joint faces.

Electron-beam welding

Fusion welding in which the joint is made by fusing the parent metal by the impact of a focused beam of electrons.

Filler metal

Metal added during welding, braze welding, brazing or surfacing.

Filler rod

Filler metal in the form of a rod. It may also take the form of filler wire.

Flux

Material used during welding, brazing or braze welding to clean the surfaces of joint, prevent atmospheric, oxidation and to reduce impurities.

Fusion penetration

Depth to which the parent metal has been fused.

Fusion welding

Welding in which the weld is made between metals in a molten state without the application of pressure.

Fusion zone

The part of the parent metal which is melted into the weld metal.

Heat affected zone (HAZ)

That part of the parent metal which is metallurgically affected by the heat of the joining process, but not melted.

Hydrogen controlled electrode

A covered electrode which when used correctly, produces less than a specified amount of diffusible hydrogen in the weld deposit.

Manual welding

Welding in which the means of making the weld are held in the hand.

Metal-arc welding

Arc welding using a consumable electrode.

MIG-welding

Metal-Inert Gas arc welding using a consumable electrode.

Oxyacetylene welding

Gas welding in which fuel gas is acetylene and which is burnt in an oxygen atmosphere.

Parent metal

Metal to be joined, base metal.

Pressure welding

A welding process in which a weld is made by a sufficient pressure to cause plastic flow of the surfaces, which may or may not be heated.

Resistance welding

Welding in which force is applied to surfaces in contact and in which the heat for welding is produced by the passage of electric current through the electrical resistance at, and adjacent to, these surfaces.

Run

The metal method or deposited during one passage of an electrode, torch or blow-pipe.

Semi-automatic welding

Welding in which some of the variables are automatically controlled, but manual guidance is necessary.

Spatter

Globules of metal expelled during welding onto the surface of parent metal or of a weld.

Spelter

A brazing alloy consisting nominally of 50% Cu and 50% Zn.

Submerged-arc welding

Metal-arc welding in which a bare wire electrode is used; the arc is enveloped in flux; some of which fuses to form a removable covering of slag on the weld.

TIG-welding

Tungsten Inert-Gas arc welding using a non-consumable electrode of pure or activated tungsten.

Thermal cutting

The parting or shaping of materials by the application of heat with or without a stream of cutting oxygen.

Weld

A union between pieces of metal at faces rendered plastic or liquid by heat or by pressure, or by both. A filler metal whose melting temperature is of the same order as that of the parent metal may or may not be used.

Welding

The making of a weld.

Weld metal

All metal melted during the making of a weld and retained in the weld.

Weld zone

The zone containing the weld metal and the heat-affected zone.

4. UNITS

This Standard is based on International System of Units (SI), except where otherwise specified.

5. FACTORS AFFECTING CORROSION

Factors affecting corrosion prevention during the service life of plants and equipment are as follows:

- Design.
- Materials.
- Fabrication.
- Handling, storage and erection.
- Installation.
- Inspection.
- Operation; which is beyond the scope of this Standard.

6. DESIGN

6.1 Where corrosion can interfere the true functional purpose will not be achieved. Thus the designer is responsible for proper design by selective employment of qualified precautions or by optimal adjustment of his functional design.

6.2 The designer shall not concentrate purely on the functional aspects of design, to the total exclusion of other consideration, but he must be aware that there are many ways in which corrosion can ruin even the best creation.

6.3 The design of a structure is frequently as important as the choice of materials of construction. Design should consider mechanical and strength requirements together with an allowance for corrosion. In all cases the mechanical design of a component shall be based on the material of construction. This is important to recognize, since materials of construction used for corrosion resistance vary widely in their mechanical characteristics.

6.4 There are many design rules which shall be followed for best corrosion resistance. Design in a way to lead corrosion out of the system instead of waiting until the equipment fails in service. It costs much less to change some lines on the drawings.

This resulted in close communication between designers and corrosion engineers, and all major projects included funds for utilization of corrosion engineers.

For corrosion consideration in design see IPS-E-TP-760.

6.5 Here are some of the design rules that should be followed, as listed below. It would be helpful if the designer had a good background in corrosion but unfortunately this is usually not the case.

6.5.1 Weld rather than rivet tanks and other containers. Riveted joints provide sites for crevice corrosion.

6.5.2 Design tanks and other containers for easy draining and easy cleaning. Tank bottoms shall be sloped toward drain holes so that liquids cannot collect after the tank is emptied. Concentrated sulfuric acid is only negligibly corrosive toward steel. However, if a steel sulfuric acid tank is incompletely drained and the remaining liquid is exposed to the air, the acid tends to absorb moisture, resulting in dilution, and rapid attack occurs.

6.5.3 Design systems for the easy replacement of components that are expected to fail rapidly in service. Frequently, pumps in chemical plants are designed so that they can be readily removed from a piping system.

6.5.4 Avoid excessive mechanical stresses and stress concentrations in components exposed to corrosive mediums. Mechanical or residual stresses are one of the requirements for stress-corrosion cracking. This rule should be followed especially when using materials susceptible to stress-corrosion cracking.

6.5.5 Avoid electrical contact between dissimilar metals to prevent galvanic corrosion. If possible, use similar materials throughout the entire structure, or insulate different materials from one another.

6.5.6 Avoid sharp bends in piping systems when high velocities and/or solids in suspension are involved (erosion corrosion).

6.5.7 Provide thicker structures to take care of impingement effects.

6.5.8 Make sure materials are properly selected.

6.5.9 List complete specifications for all materials of construction and provide instructions to be sure the specs are followed all the way through to final inspection. Specify quality control procedures if relevant.

6.5.10 Be sure all relevant codes and standards are met.

6.5.11 Set realistic and scheduled dates for delivery of equipment.

6.5.12 Specify procedures for testing and storage of parts and equipment.

For example, after hydraulic testing do not let the equipment sit full or partially full of water for any extended period of time. This could result in microbial corrosion, pitting, and stress corrosion. With regard to storage, spare stainless steel tubing showed stress-corrosion cracking when stored near the seacoast.

- 6.5.13** Specify operating and maintenance procedures (i.e., scheduled shut-downs).
- 6.5.14** Properly design against excessive vibration, not only for rotating parts but also, for example, for heat exchanger tubes.
- 6.5.15** Provide for "blanketing" with dry air or inert gas if vessels "inhale" moist marine atmosphere while being emptied.
- 6.5.16** Select plant site upwind from other "polluting" plants or atmosphere if relevant and/or feasible.
- 6.5.17** Avoid hot spots during heat-transfer operations. Heat exchangers and other heat-transfer devices should be designed to ensure uniform temperature gradients. Uneven temperature distribution leads to local heating and high corrosion rates. Further, hot spots tend to produce stresses that may produce stress-corrosion cracking failures.
- 6.5.18** Design to exclude air. Oxygen reduction is one of the most common cathodic reactions during corrosion, and if oxygen is eliminated, corrosion can often be reduced or prevented. In designing chemical plant equipment, particular attention should be paid to agitators, liquid inlets, and other points where air entrainment is a possibility. Exceptions to this rule are active-passive metals and alloys. Titanium and stainless steels are more resistant to acids containing dissolved air or other oxidizers.
- 6.5.19** The most general rule for design is: avoid heterogeneity. Dissimilar metals, vapor spaces, uneven heat and stress distributions, and other differences between points in the system lead to corrosion damage. Hence, in design, attempt to make all conditions as uniform as possible throughout the entire system.

7. MATERIALS

7.1 Selection of materials to resist deterioration in service is not within the scope of this Standard. However, some corrosion consideration which affect the safety of installations is specified here. Consideration shall be given to allowances made for temperature and pressure effects of process reactions, and for hazards from instability of contained fluids.

7.2 For corrosion consideration in material selection reference is made to IPS-E-TP-740 and information on material performance in corrosive environments can be found in publications, such as "The Corrosion Data Survey" published by the National Association of Corrosion Engineers (NACE).

Note (Informative):

API 6A and 6D present design and material requirements for oil and gas production and pipeline equipment. The API standards usually contain references to ASTM, AISI, ASME, or other general specifications for acceptable materials for these products and always include a reference to NACE MR-01-75 when the products are to be used in H₂S service. The engineer must be aware that in certain cases the NACE standard may overrule API or other standards and that under these conditions design considerations must be addressed.

Recent concern about consistency in quality and product performance prompted API to re-write API 6A. The new standard was issued in April 1986 and it requires manufactures of API equipment to produce and maintain a documented control system that can be audited. This control system must also be capable of providing engineering, manufacturing, and quality guidelines for the consistent production of products meeting the requirements of the revised edition. Before approval, each manufacturer certified will be audited by an independent API-approved auditing team.

The new document also introduces four product specification levels, which can be used to specify the desired quality level. In addition to the quality levels. API has added various environmental conditions. These enable the end user to be very specific in terms of product end use, the expected quality level, and product performance.

7.3 General Considerations

Following are some general considerations which shall be evaluated when selecting and applying materials (see also Paragraph 7.4).

- 7.3.1** The possibility of exposure of the metals to fire and the melting point, degradation temperature, loss of strength at elevated temperature, and combustibility of the structural material under such exposure.
- 7.3.2** The susceptibility to brittle failure or failure from thermal shock of the structural material when exposed to fire or to fire-fighting measures, and possible hazards from fragmentation of the material in the event of failure.
- 7.3.3** The ability of thermal insulation to protect structure such as piping against failure under fire exposure (e.g., its stability, fire resistance, and ability to remain in place during a fire).
- 7.3.4** The susceptibility of the piping material to crevice corrosion under backing rings, in threaded joints, in socket welded joints, and in other stagnant, confined areas.
- 7.3.5** The possibility of adverse electrolytic effects if the metal is subject to contact with a dissimilar metal.
- 7.3.6** The compatibility of lubricants or sealants used on threads with the fluid service.
- 7.3.7** The compatibility of packing, seals, and O-rings with the fluid service.
- 7.3.8** The compatibility of materials, such as cements, solvents, solders, and brazing materials, with the fluid service.
- 7.3.9** The chilling effect of sudden loss of pressure on highly volatile fluids as a factor in determining the lowest expected service temperature.
- 7.3.10** The possibility of pipe support failure resulting from exposure to low temperatures (which may embrittle the supports) or high temperatures (which may weaken them).
- 7.3.11** The compatibility of materials, including sealants, gaskets, lubricants, and insulation, used in strong oxidizer fluid service (e.g., oxygen or fluorine).

7.4 Specific Material Considerations - Metals

Following are some specific considerations which shall be evaluated when applying certain metals in metal structures such as piping.

7.4.1 Irons-Cast, Malleable, and High Silicon (14.5%). Their lack of ductility and their sensitivity to thermal and mechanical shock.

7.4.2 Carbon steel, and low and intermediate alloy steels

7.4.2.1 The possibility of embrittlement when handling alkaline or strong caustic fluids.

7.4.2.2 The possible conversion of carbides to graphite during long time exposure to temperatures above 427°C (800°F) of carbon steels, plain nickel steel, carbon-manganese steel, manganese-vanadium steel, and carbon-silicon steel.

7.4.2.3 The possible conversion of carbides to graphite during long time exposure to temperatures above 468°C (875°F) of carbon-molybdenum steel, manganese-molybdenum-vanadium steel, and chromium-vanadium steel.

7.4.2.4 The advantages of silicon-killed carbon steel (0.1% silicon minimum) for temperatures above 482°C (900°F).

7.4.2.5 The possibility of hydrogen damage to piping material when exposed (under certain temperature-pressure conditions) to hydrogen or aqueous acid solutions.

7.4.2.6 The possibility of stress corrosion cracking when exposed to wet hydrogen sulfide (a maximum hardness limit is usually specified; see API RP 942), and the further possibility of deterioration (sulfidation) in the presence of hydrogen sulfide at elevated temperature.

Notes:

1) NACE MR-01-75 (1978 revision) and all later revisions cover the requirements for metallic materials used in the drilling and completion of oil and gas wells and the production of oil and gas that contain hydrogen sulfide (H_2S). Hydrogen sulfide is highly toxic; concentrations as low as 1000 ppm can cause death. The safe use of H_2S is discussed in NACE TM-01-77.

2) In addition to the necessary safety considerations, oil and gas that contain H_2S can cause materials that are normally strong and ductile to fail in a sudden and brittle manner at very low stress levels. The special metallurgical requirements for metallic materials in this environment are discussed in NACE MR-01-75.

3) In general, all carbon and low-alloy steels that are properly heat treated to a maximum hardness of 22 HRC are acceptable for use in H_2S service with two exceptions: free-machining steels and steels containing more than 1% Ni. Laboratory tests have indicated that these materials can fail at hardnesses below 22 HRC.

As their hardnesses exceed 22 HRC, carbon and low-alloy steels become progressively more susceptible to failure. Laboratory tests have indicated almost instantaneous failures at stresses considerably below yield for hard materials; therefore, all carbon and low-alloy steels can be made susceptible to sulfide stress cracking by improper thermal treatment and/or by mechanical damage (cold work) due to handling problems.

In addition to carbon and low-alloy steels, NACE MR-01-75 discusses stainless and other high-alloy steels. Some of these steels can be used at hardnesses above 22 HRC when additional strength is needed. These materials shall be selected with care.

7.4.2.7 The importance of limiting maximum hardness of metals in applications subject to stress corrosion.

7.4.3 High alloy (stainless) steels

7.4.3.1 The possibility of stress corrosion cracking of austenitic stainless steels exposed to media such as chlorides and other halides either internally or externally; the latter can result from improper selection or application of thermal insulation.

7.4.3.2 The susceptibility to intergranular corrosion of austenitic stainless steels after sufficient exposure to temperatures between 427°C and 871°C (800°F and 1600°F) unless stabilized or low carbon grades are used.

7.4.3.3 The susceptibility to inter crystalline attack of austenitic stainless steels on contact with zinc or lead above their melting points or with many lead and zinc compounds at similarly elevated temperatures.

7.4.3.4 The brittleness of ferritic stainless steels at room temperature after service at temperature above 371°C (700°F).

7.4.4 Nickel and nickel base alloys

7.4.4.1 The susceptibility to grain boundary attack of nickel and nickel base alloys not containing chromium when exposed to small quantities of sulfur at temperatures above 316°C (600°F).

7.4.4.2 The susceptibility to grain boundary attack of nickel base alloys containing chromium at temperatures above 593°C (1100°F) under reducing conditions and above 760°C (1400°F) under oxidizing conditions.

7.4.4.3 The possibility of stress corrosion cracking of nickel-copper alloy (70Ni-30Cu) in hydrofluoric acid vapor if the alloy is highly stressed or contains residual stresses from forming or welding.

7.4.5 Aluminum and aluminum alloys

7.4.5.1 The compatibility with aluminum of thread compounds used in aluminum threaded joints to prevent seizing and galling.

7.4.5.2 The possibility of corrosion from concrete, mortar, lime, plaster, or other alkaline materials used in buildings or structures.

7.4.5.3 The susceptibility of Alloy Nos. 5083, 5086, 5154, and 5456 to exfoliation or intergranular attack; and the upper temperature limit of 66°C (150°F) shown in Appendix A, to avoid such deterioration.

7.4.6 Copper and copper alloys

7.4.6.1 The possibility of dezincification of brass alloys.

7.4.6.2 The susceptibility to stress-corrosion cracking of copper-based alloys exposed to fluids such as ammonia or ammonium compounds.

7.4.6.3 The possibility of unstable acetylide formation when exposed to acetylene.

7.4.7 Titanium and titanium alloys

The possibility of deterioration of titanium and its alloys above 316°C (600°F).

7.4.8 Zirconium and zirconium alloys

The possibility of deterioration of zirconium and zirconium alloys above 316°C (600°F).

7.4.9 Tantalum

Above 299°C (570°F), the possibility of reactivity of tantalum with all gases except the inert gases. Below 299°C the possibility of embrittlement of tantalum by nascent (monatomic) hydrogen (but not molecular hydrogen). Nascent hydrogen is produced by galvanic action, or as a product of corrosion by certain chemicals.

7.4.10 Metals with enhanced properties

The possible loss of strength, in a material whose properties have been enhanced by heat treatment, during long-continued exposure to temperatures above its tempering temperature.

7.4.11 The desirability of specifying some degree of production impact testing, in addition to the weld procedure qualification tests, when using materials with limited low temperature service experience below the minimum temperature stated in Appendix A, Table A.1, B31/3 ASME.

7.5 Material Considerations Nonmetals

Following are some considerations to be evaluated when applying nonmetals in structures such as piping. See also Paragraphs 7.1 and 7.3.

7.5.1 Static charges

Because of the possibility of producing hazardous electrostatic charges in nonmetallic piping and metallic piping lined with nonmetals, consideration should be given to grounding the metallic components of such systems conveying non-conductive fluids.

7.5.2 Thermoplastics

If thermoplastic piping is used above ground for compressed air or other compressed gases, special precautions shall be observed. In determining the needed safeguarding for such services, the energetics and the specific failure mechanism need to be evaluated. Encasement of the plastic piping in shatter-resistant material may be considered.

7.5.3 Borosilicate glass

Take into account its lack of ductility and its sensitivity to thermal and mechanical shock.

8. FABRICATION

8.1 General

8.1.1 The concerned contractor and/or fabricator shall follow the fabrication procedures introduced by the designer precisely and use the specified methods and materials prescribed by him.

8.1.2 In addition the contractor and fabricator shall make consideration to all factors affecting fabrication which in turn facilitate to improve resistance of equipment and structures against corrosion.

8.1.3 When a contractor is responsible for the whole construction, he is also responsible for the performance of first class fabrication.

8.1.4 Due consideration shall be given to special treatment required for different materials to improve resistance to corrosion, e.g. special welding techniques, stress relieving, blast peening, metallizing, sealing of welds, etc.; also to any fabrication or assembly methods which would aggravate any tendency of the material to corrosion failure.

8.1.5 With approval of the designer, alloys in as highly alloyed a condition as necessary should be used when the cost of fabrication is higher than the cost of basic material. Proportional cost of material in some multishaped or complicated component is much less than the simple ones.

8.1.6 Distribute stress with the metals' anisotropic characteristics in mind:

8.1.6.1 Either avoid exposing traverse planes or protect them.

8.1.6.2 Avoid or relieve residual stress from quenching and fitting.

8.1.6.3 Select fabrication with special attention to avoid consequence, of high localized stress pattern.

8.1.7 Select fabrication, machining and assembly operations imparting minimum residual stresses, fillets should be stream-lined if possible.

8.1.8 Protective coating shall be applied after all punching, drilling, machining, forming and after fabrication have been completed paint finishing systems if required may also be applied after metal deposition or over chemical film treatment.

8.1.9 The workmanship and finish shall be first class in every respect and subject to the closest inspection by the manufacturer's inspector, whether or not the Purchaser waives any part of the inspection.

8.1.10 When material requires straightening, the work shall be done by pressing or another noninjurious method prior to any layout or shaping. Heating or hammering is not permissible unless the material is heated to a forging temperature.

8.2 Factors affecting fabrication can be classified as follows:

- Design and materials; both of which have been described before.
- Welding.
- Welding and joining.
- Bending and forming.
- Brazing and soldering.
- Heat treatment.
- Preheating.
- Coating and lining.

8.3 Welding

8.3.1 Corrosion of weldments

8.3.1.1 General

8.3.1.1.1 It is not unusual to find that, although the wrought form of a metal or alloy is resistant to corrosion in a particular environment, the welded counterpart is not. Further, welds can be made with the addition of filler metal or can be made autogenously (without filler metal). However, there are also many instances in which the weld exhibits corrosion resistance superior to that of the unwelded base metal. There also are times when the weld behaves in an erratic manner, displaying both resistance and susceptibility to corrosive attack. Corrosion failures of welds occur in spite of the fact that the proper base metal and filler metal have been selected, industry codes and standards have been followed, and welds have been deposited that possess full weld penetration and have proper shape and contour. It is sometimes difficult to determine why welds corrode; however, one or more of the following factors often are implicated:

- Weldment design.
- Fabrication technique.
- Welding practice.
- Welding sequence.
- Moisture contamination.
- Organic or inorganic chemical species.
- Oxide film and scale.
- Weld slag and spatter.
- Incomplete weld penetration or fusion.
- Porosity.
- Cracks (crevices).
- High residual stresses.
- Improper choice of filler metal.
- Final surface finish.

8.3.1.1.2 ASME Section IX and API 1104 discuss the welding of pressure vessels and line pipe, including the requirements for qualifying welding procedure, welders, and the quality level of the production weldments. These standards also identify the variables that dictate when different procedures are required to cover material thickness, material chemistry, joint design, welding position and thermal treatments. If weldments are to be used in H₂S environments, such factors as additional hardness testing, the type of welding electrode, and the wire/flux combination used should be considered.

The American Petroleum Institute and the National Association of Corrosion Engineers publish documents that indicate whether weldments made with certain wire/flux combinations have experienced failure in H₂S environments under conditions in which failures were unexpected. Weldments with high manganese and silicon contents have been shown to be very susceptible to sulfide stress cracking at hardnesses at or below 22 HRC even after thermal treatments.

If temperature is an environmental consideration, the designer should be aware that the ability of materials and weldments to withstand sudden impact loading decreases significantly with temperature. Materials and weldments that have ductile characteristics at room temperature (20°C, or 70°F) may behave in a brittle manner when exposed to lower temperatures. In addition to the typical mechanical-property testing of materials and weldments, impact testing is required to ensure that the product is properly designed for the anticipated operating temperatures. Standards from ASTM, ASME, and other address these design requirements and generally specify materials that have Charpy V-notch impact test requirements added to the normal mechanical property tests.

In the case of weldments, Charpy V-notch impact testing of the base metal, the heat-affected zone, and the weld metal is also required to ensure that the weldment will function satisfactorily at the design temperature. Welding must be performed with care to ensure that the completed weldment is produced in accordance with standard procedures.

8.3.1.1.3 API 14D establishes requirements for well head Surface Safety Valves (SSV valves), Underwater Safety Valves (USV valves), and their actuators (SSV/USV actuators). The requirements include design, materials quality, performance testing, and functional testing.

Equipment manufactured to this specification is primarily intended for service in outer continental waters (OCS) contiguous to the United States. The equipment is identified with the API 14D monogram. It is also eligible for the OCS monogram when manufactured under a quality program conforming to ANSI/ASME-SPPE-1 specifications. The federal government has mandated that all such equipment installed in federal OCS waters have both monograms.

8.3.1.1.4 The ANSI/ASME-SPP-1 standards establish requirements for quality programs, accreditation of quality programs, and reporting of malfunctions and failures. Manufacturers conforming to these standards are authorized by ASME to apply the OCS monogram to SSVS (valve and actuator).

8.3.1.2 Metallurgical factors

The cycle of heating and cooling that occurs during the welding process affects the micro-structure and surface composition of welds and adjacent base metal. Consequently, the corrosion resistance of autogenous welds and welds made with matching filler metal may be inferior to that of properly annealed base metal because of:

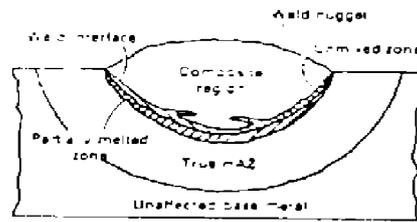
- Microsegregation.
- Precipitation of secondary phases.
- Formation of unmixed zones.
- Recrystallization and grain growth in the weld Heat-Affected Zone (HAZ).
- Volatilization of alloying elements from the molten weld pool.
- Contamination of the solidifying weld pool.

Corrosion resistance can usually be maintained in the welded condition by balancing alloy compositions to inhibit certain precipitation reactions, by shielding molten and hot metal surfaces from reactive gases in the weld environment, by removing chromium-enriched oxides and chromium-depleted base metal from thermally discolored (heat tinted) surfaces, and by choosing the proper welding parameters.

8.3.1.3 Weld solidification

During the welding process, a number of important changes occur that can significantly affect the corrosion behavior of the weldment. Heat input and welder technique obviously play important roles. The way in which the weld solidifies is equally important to understanding how weldments may behave in corrosive environments.

A metallographic study has shown that welds solidify into various regions, as illustrated in Fig. 1. The composite region, or weld nugget, consists of essentially filler metal that has been diluted with material melted from the surrounding base metal. Next to the composite region is the unmixed zone, a zone of base metal that melted and solidified during welding without experiencing mechanical mixing with the filler metal. The weld interface is the surface bounding the region within which complete melting was experienced during welding, and it is evidenced by the presence of a cast structure. Beyond the weld interface is the partially melted zone, which is a region of the base metal within which the proportion melted ranges from 0 to 100%. Lastly, the true HAZ is that portion of the base metal within which microstructural change has occurred in the absence of melting. Although the various regions of a weldment shown in Fig. 1 are for a single-pass weld, similar solidification patterns and compositional differences can be expected to occur in underlying weld beads during multipass applications.



SCHEMATIC OF A WELD CROSS SECTION

Fig. 1

8.3.1.4 Corrosion of carbon steel weldments

The corrosion behavior of carbon steel weldments is dependent on a number of factors. Consideration must be given to the compositional effects of the base metal and welding consumable and to the different welding processes used. Because carbon steels undergo metallurgical transformations across the weld and HAZ, microstructures and morphologies become important. A wide range of microstructures can be developed based on cooling rates, and these microstructures are dependent on energy input, preheat, metal thickness (heat sink effects), weld bead size, and reheating effects due to multipass welding. As a result of their different chemical compositions and weld inclusions (oxides and sulfides), weld metal microstructures are usually significantly different from those of the HAZ and base metal. Similarly, corrosion behavior can also vary.

In addition, hardness levels will be lowest for high heat inputs, such as those produced by submerged-arc weldments, and will be highest for low-energy weldments (with faster cooling rates) made by the shielded metal arc processes. Depending on the welding conditions, weld metal microstructures generally tend to be fine grained with basic flux and somewhat coarser with acid or rutile (TiO_2) flux compositions.

During welding, the base metal, HAZ, and underlying weld passes experience stresses due to thermal expansion and contraction. Upon solidification, rather high levels of residual stress remain as a result of weld shrinkage. Stress concentration effects as a result of geometrical discontinuities, such as weld reinforcement and lack of full weld penetration (dangerous because of the likelihood of crevice corrosion and the possibility of fatigue cracking), are also important because of the possibility of SCC. Achieving full weld penetration, minimizing excessive weld reinforcement through control of the welding process or technique, and grinding (a costly method) can be effective in minimizing these geometric effects. A stress-relieving heat treatment is effective in reducing internal weld shrinkage stress and metal hardness to safe levels in most cases.

8.3.1.4.1 Preferential HAZ corrosion

An example of preferential weld corrosion in the HAZ of a carbon steel weldment is shown in Fig. 2. This phenomenon has been observed in a wide range of aqueous environments, the common link being that the environments are fairly high in conductivity, while attack has usually, but not invariably, occurred at pH values below about 7 to 8.

The reasons for localized weldment attack have not been fully defined. There is clearly a microstructural dependence, and studies on HAZs show corrosion to be appreciably more severe when the material composition and welding are such that hardened structures are formed. It has been known for many years that hardened steel may corrode more rapidly in acid conditions than fully tempered material, apparently because local microcathodes on the metal surface stimulate the cathodic hydrogen evolution reaction. On this basis, water treatments ensuring alkaline conditions should be less likely to induce HAZ corrosion, but even at pHs near 8, hydrogen ion (H^+) reduction can account for about 20% of the total corrosion current; pH values substantially above this level would be needed to suppress the effect completely.



**PREFERENTIAL CORROSION IN THE HAZ OF A CARBON STEEL WELDMENT
AFTER SERVICE IN AN AQUEOUS ENVIRONMENT. 5 x**

Fig. 2

8.3.1.4.2 Preferential weld corrosion

It is probable that similar microstructural considerations also apply to the preferential corrosion of weld metal, but in this case, the situation is further complicated by the presence of deoxidation products, their type and number depending largely on the flux system employed. Consumable type plays a major role in determining weld metal corrosion rate, and the highest rates of metal loss are normally associated with shielded metal arc electrodes using a basic coating. In seawater, for example, the corrosion rate for a weld made using a basic-coated consumable may be three times as high as for weld metal from a rutile-coated consumable. Fewer data are available for submerged-arc weld metals, but it would appear that they are intermediate between basic and rutile shielded metal arc electrodes and that a corrosion rate above that of the base steel can be expected.

8.3.1.4.3 Galvanic-corrosion

Galvanic-corrosion effects have also been observed and have caused unexpected failure of piping tankage and pressure vessels where the welds are anodic to the base metal. The following examples illustrate the point.

In one case, premature weld failures were experienced in a 102-mm (4 inch) ASTM A53 pipe that was used to transfer a mixture of chlorinated hydrocarbons and water. During construction, the pipeline was fabricated with E7010-A1 welding electrodes (see Table 1 for the composition limits for all materials discussed in these examples).

TABLE 1 - COMPOSITIONS OF CARBON STEEL BASE METALS AND SOME FILLER METALS SUBJECT TO GALVANIC CORROSION

See Tables 8 and 9 for corrosion rates of galvanic couples

METAL	COMPOSITION, %						
	C	Mn	Si	Cr	Ni	Fe	OTHERS
BASE METALS							
ASTM A53, Grade B	0.30	1.20	...	...	...	bal.	...
ASTM A285, Grade C	0.22	0.90	...	...	...	bal.	...
FILLER METALS							
E6010	-No specific chemical limits —						
E6013	-No specific chemical limits —						
E7010-Al	0.12	0.60	0.40	...	...	bal.	0.4-0.65Mo
E7010-G	...	1.00(a)	0.80(a)	0.30(a)	0.50(a)	bal.	0.2Mo, 0.1V
E7016	...	1.25(b)	0.90	0.20(b)	0.30(b)	bal.	0.3Mo(b), 0.08V(b)
E7018	...	1.60(c)	0.75	0.20(c)	0.30(c)	bal.	0.3Mo(c), 0.08V(c)
E8018-C2	0.12	1.20	0.80	...	2.0-2.75	bal.	...
ENiCrFe-2 (Inco Weld A)	0.10	1.0-3.5	1.0	13.0-17.0	bal.	12.0	1-3.5Mo, 0.5Cu, 0.5-3(Nb + Ta)
Incoloy welding electrode 135	0.08	1.25-2.50	0.75	26.5-30.5	35.0-40.0	bal.	2.75-4.5Mo, 1-2.5Cu

- a) The weld deposit must contain only the minimum of one of these elements.
- b) The total of these elements shall not exceed 1.50%.
- c) The total of these elements shall not exceed 1.75%.

Initial weld failures and subsequent tests showed the following welding electrodes to be anodic to the A53 Grade B base metal: E7010-Al, E6010, E6013, E7010-G, and E8018-C2. Two nickel-base electrodes — Inco-Weld A (AWS A5,11, Class ENiCrFe-2) and Incoloy welding electrode 135 — were tested; they were found to be cathodic to the base metal and to prevent rapid weld corrosion. The corrosion rates of these various galvanic couples are listed in Table 2.

TABLE 2 - CORROSION RATES OF GALVANIC COUPLES OF ASTM A53, GRADE B, BASE METAL AND VARIOUS FILLER METALS IN A MIXTURE OF CHLORINATED HYDROCARBONS AND WATER

The areas of the base metal and the deposited weld metal were equal

GALVANIC COUPLE	CORROSION RATE	
	mm/yr	mils/yr
Base metal	0.4	15
E6010	0.9	35
Base metal	0.18	7
E6013	0.9	35
Base metal	1.3	50
E7010-Al	4.3	169
Base metal	1.7	68
E7010-G	2.8	112
Base metal	0.36	14
E8018-C2	1.7	66
Base metal	0.48	19
Inco Weld A	0.013	0.5
Base metal	0.36	14
Incoloy welding electrode 135	< 0.0025	<0.1

Another example is the failure of low-carbon steel welds in seawater service at 25°C (75°F). Fabrications involving ASTM A285, Grade C, plate welded with E6013 electrodes usually start to fail in the weld after 6 to 18 months in seawater service at this temperature. Welds made with E7010 electrodes do not fail. Tests were conducted in seawater at 50°C (120°F) using A285, Grade C, plate welded with E6010, E7010-Al, and E7010-G. It was determined that E7010-Al was the best electrode to use in seawater and that E6010 and E7010-G were not acceptable (although they were much better than E6013), because they were both anodic to the base metal. A zero resistance ammeter was used to determine whether the electrodes were anodic or cathodic in behavior.

In another case, welds made from E7010-Al electrodes to join ASTM A285, Grade C, base metal were found to be anodic to the base metal when exposed to raw brine, an alkaline-chloride (pH > 7) stream, and raw river water at 50°C (120°F). When E7010-G was exposed to the same environment, it was anodic to the base metal in raw brine and raw river water and was cathodic to ASTM A285, Grade C, in the alkaline-chloride stream. When the base metal was changed to ASTM A53, Grade B, and A106, Grade B, it was found that E7010-Al weld metal was cathodic to both when exposed to raw brine at 50°C (120°F).

Finally, routine inspection of a column in which a mixture of hydrocarbons was water washed at 90°C (195°F) revealed that E7016 welds used in the original fabrication were corroding more rapidly than the ASTM A285, Grade C, base metal. Corroded welds were ground to sound metal, and E7010-Al was used to replace the metal that was removed. About 3 years later, during another routine inspection, it was discovered that the E7010-Al welds were being selectively attacked. Tests were conducted that showed E7010-Al and E7016 weld metals to be anodic to A285, Grade C, while E7018 and E8018-C2 would be cathodic. Corrosion rates of these various galvanic couples are given in Table 3.

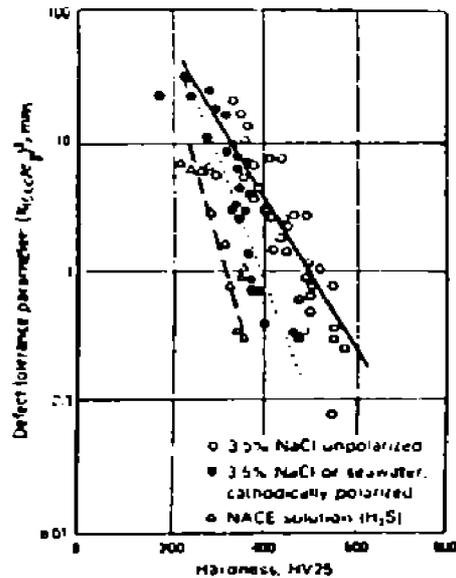
TABLE 3 - CORROSION RATES OF GALVANIC COUPLES OF ASTM A285, GRADE C, BASE METAL AND VARIOUS FILLER METALS AT 90°C (195°F) IN WATER USED TO WASH A HYDROCARBON STREAM

GALVANIC COUPLE	CORROSION RATE	
	mm/yr	mils/yr
Base metal	0.69	27
E7010-Al	0.81	32
Base metal	0.46	18
E7016	0.84	33
Base metal	1.3	50
E7018	1.2	48
Base metal	2.2	85
E8018-C2	1.04	41

These examples demonstrate the necessity for testing each galvanic couple in the environment for which it is intended. Higher-alloy filler metals can sometimes be used to advantage to prevent rapid preferential weld corrosion.

8.3.1.4.4 Stress-corrosion cracking

There is no doubt that residual welding stresses can cause SCC in environments in which such failure represents a hazard. This is the case for failure by both active path and hydrogen embrittlement mechanisms, and in the latter case, failure may be especially likely at low heat input welds because of the enhanced susceptibility of the hardened structures inevitably formed. Most SCC studies of welds in carbon and carbon-manganese steels have evaluated resistance to hydrogen-induced SCC, especially under sour (H₂S) conditions prevalent to the oil and gas industry. Although full definition of the effect of specific microstructural types has not been obtained, an overriding influence of hardness is evident (Fig. 3). The situation regarding active path cracking is less clear, but there are few, if any, cases in which SCC resistance increases at higher strength levels. On this basis, it is probable that soft, transformed microstructures around welds are preferable.



SCC DEFECT TOLERANCE PARAMETER VERSUS HARDNESS FOR CARBON STEEL WELDMENTS IN THREE ENVIRONMENTS. DATA ARE DERIVED FROM PUBLISHED TESTS ON PRECRACKED SPECIMENS OF VARIOUS TYPES OF CARBON STEEL BASE METALS, HAZs, AND WELD METALS. SCC DEFECT TOLERANCE PARAMETER IS DEPENDENT ON CRACK LENGTH

Fig. 3

Carbon and low-alloy steels are also known to fail by SCC when exposed to solutions containing nitrates (NO_3^-). Refrigeration systems using a 30% magnesium nitrate ($\text{Mg}(\text{NO}_3)_2$) brine solution, for example, are commonly contained in carbon steel. In this case, pH adjustment is important, as is temperature. Failures in the HAZ due to SCC have been reported when brine temperatures have exceeded 30°C (90°F) during shutdown periods. To avoid these failures, carbon steel is being replaced with Type 304L stainless. Others have stress relieved welded carbon steel systems and have operated successfully, although elevated-temperature excursions are discouraged.

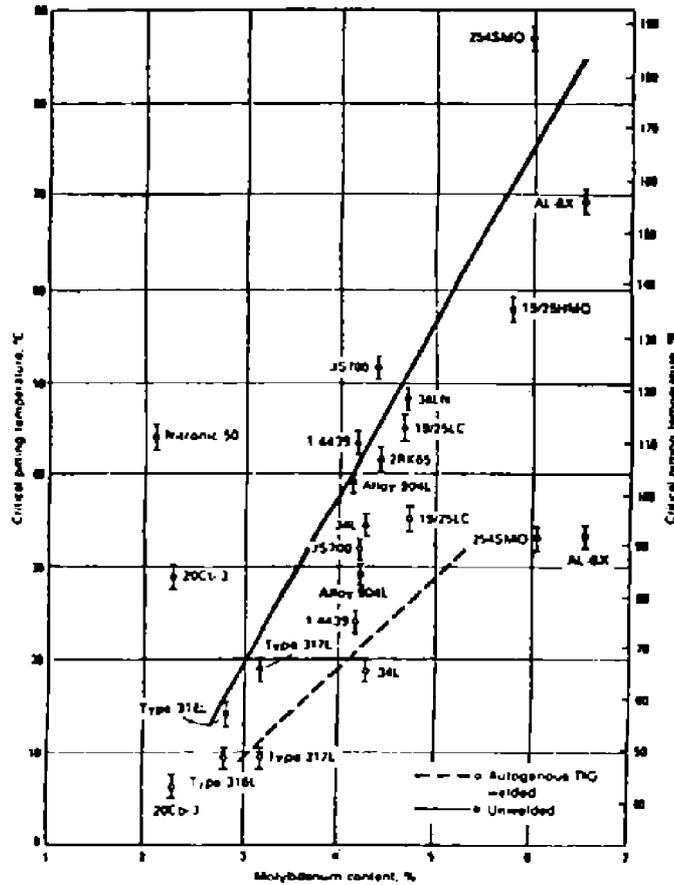
More recently, it has been shown that cracking can occur under certain conditions in carbon dioxide (CO_2) containing environments, sometimes with spectacular and catastrophic results. Processes in the oil, gas, and chemical industries require removal of CO_2 from process streams by a variety of absorbents. In most cases, process equipment is fabricated from plain carbon steel. For corrosion of carbon steel weldments for specific conditions see Appendix A.2.

8.3.1.5 Corrosion of austenitic stainless steel weldments

The corrosion problems commonly associated with welding of austenitic stainless steels are related to precipitation effects and chemical segregation. These problems can be eliminated or minimized through control of base metal metallurgy, control of the welding practice, and selection of the proper filler metal.

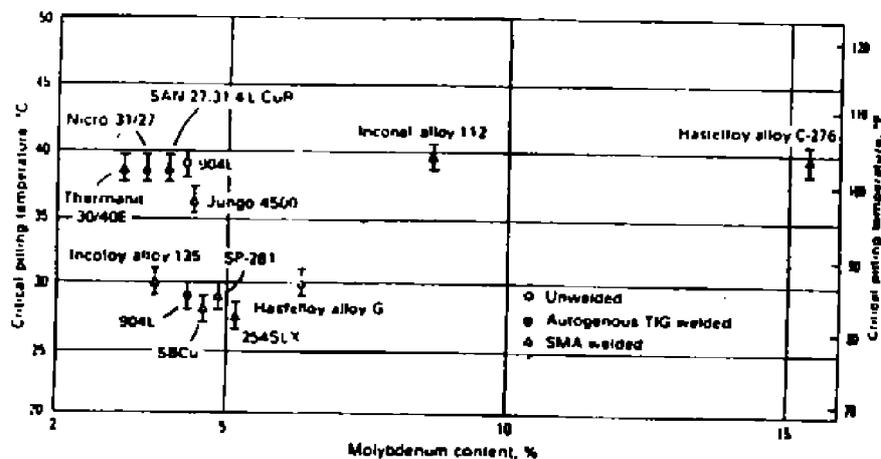
8.3.1.5.1 Pitting corrosion

Under moderately oxidizing conditions, such as a bleach plant, weld metal austenite may suffer preferential pitting in alloy-depleted regions. This attack is independent of any weld metal precipitation and is a consequence of microsegregation or coring in weld metal dendrites. Preferential pitting is more likely in autogenous (no filler) Gas Tungsten Arc (GTA) welds (Fig. 4), in 4 to 6% Mo alloys (Table 4), when the recommended filler metal has the same composition as the base metal (Fig. 5), and when higher heat input welding leaves a coarse microstructure with surface-lying dendrites. Such a micro-structure is avoided by use of a suitably alloyed filler metal (Fig. 5).



CRITICAL PITTING TEMPERATURE VERSUS MOLYBDENUM CONTENT FOR COMMERCIAL AUSTENITIC STAINLESS STEELS TESTED 10% FeCl₃. RESISTANCE TO PITTING, AS MEASURED BY THE CRITICAL PITTING TEMPERATURE, INCREASES WITH MOLYBDENUM CONTENT AND DECREASES AFTER AUTOGENOUS TUNGSTEN INERT GAS (TIG) WELDING

Fig. 4



EFFECTS OF VARIOUS WELDING TECHNIQUES AND FILLER METALS ON THE CRITICAL PITTING TEMPERATURE OF ALLOY 904L. DATA FOR AN UNWELDED SPECIMEN ARE INCLUDED FOR COMPARISON

Fig. 5

TABLE 4 - AMOUNTS OF PRINCIPAL ALLOYING ELEMENTS IN STAINLESS STEELS TESTED FOR PITTING RESISTANCE

ALLOY	COMPOSITION, %			
	Cr	Ni	Mo	N
Base metals				
Type 316L	16	13	2.8	...
Type 317L	18	14	3.2	...
34L	17	1	54.3	...
34LN	18	14	4.7	...
1.4439	18	14	4.3	0.13
Nitronic 50	21	14	2.2	0.20
20Cb-3	20	33	2.4	...
Alloy 904L	20	25	4.2	...
2RK65	20	25	4.5	...
JS700	21	25	4.5	...
19/25LC	20	25	4.8	...
AL-6X	20	24	6.6	...
254SMO	20	18	6.1	...
19/25HMO	21	25	5.9	0.20 0.15
Filler metals				
Type 316L	19	12	2.3	...
Type 317L	19	13	3.8	...
309MoL	23	14	2.5	...
Batox Cu	19	24	4.6	...
254SLX	20	24	5.0	...
SP-281	20	25	4.6	...
Jungo 4500	20	26	4.4	...
Nicro 31/27	28	30	3.5	...
Thermanit 30/40E	28	35	3.4	...
SAN 27.31.4.LCuR	27	31	3.5	...
Incoloy Alloy 135	27	31	3.5	...
Hastelloy Alloy G	22	38	3.7	...
P12	21	61	8.6	...
Inconel Alloy 112	21	61	8.7	...
Hastelloy Alloy C-276	15	58	15.4	...

Filler metals with pitting resistance close to or better than that of corresponding base metals include:

BASE METAL	FILLER METALS
Type 316L	316L, 317L, 309MoL
Type 317	317L, 309MoL
Alloy 904	Sandvik 27.31.4.LCuR Thermanit 30/40 E, Nicro 31/27
Avesta 254 SMO	Fox CN 20 25 M, IN-112, Avesta P12, Hastelloy Alloy C-276 Avesta P12, IN-112, Hastelloy Alloy C-276

Even when suitable fillers are used, preferential pitting attack can still occur in an unmixed zone of weld metal. High heat input welding can leave bands of melted base metal close to the fusion line. The effect of these bands on corrosion resistance can be minimized by welding techniques that bury unmixed zones beneath the surface of the weldment.

When the wrong filler metal is used, pitting corrosion can readily occur in some environments. For example when the Type 316L base metal is welded with a lower-alloy filler metal (Type 308L).

8.3.1.5.2 Crevice corrosion

Defects such as residual welding flux and microfissures create weld metal crevices that are easily corroded, particularly in chloride-containing environments. Some flux formulations on coated shielded metal arc or stick electrodes produce easily detached slags, and others give slags that are difficult to remove completely even after gritblasting. Slags from rutile (titania-base) coatings are easily detached and give good bead shape. In contrast, slags from the basic-coated electrodes for out-of-position welding can be difficult to remove; small particles of slag may remain on the surface, providing an easy initiation site for crevice attack.

Microfissures or their larger counterparts, hot cracks, also provide easy initiation sites for crevice attack, which will drastically reduce the corrosion resistance of a weldment in the bleach plant. Microfissures are caused by thermal contraction stresses during weld solidification and are a problem that plagues austenitic stainless steel fabrications. These weld metal cracks are more likely to form when phosphorus and sulfur levels are higher (that is, more than 0.015% P and 0.015% S), with high heat input welding, and in austenitic weld metal in which the δ -ferrite content is low (<3%).

Small-scale microfissures are often invisible to the naked eye, and their existence can readily explain the unexpectedly poor pitting performance of one of a group of weldments made with filler metals of apparently similar general composition. The microfissure provides a crevice, which is easily corroded because stainless alloys are more susceptible to crevice corrosion than to pitting. However, microfissure-crevice corrosion is often mistakenly interpreted as self-initiated pitting.

Crevice corrosion sites can also occur at the beginning or end of weld passes, between weld passes, or under weld spatter areas. Weld spatter is most troublesome when it is loose or poorly adherent.

Microfissure corrosion in austenitic stainless steel weldments containing 4 to 6% Mo is best avoided with the nickel-base Inconel 625, Inconel 112, or Avesta P12 filler metals, which are very resistant to crevice attack. Some stainless electrodes are suitable for welding 4% Mo steels, but they should be selected with low phosphorus and sulfur to avoid microfissure problems.

Hot tap water is not thought to be particularly aggressive; however, it can damage a weld that contains a lack-of-fusion defect in the presence of chlorides. In this case, the base metal is Type 304 stainless steel, and the weld metal Type 308.

8.3.1.5.3 Carbide precipitation in the HAZ

The best known weld-related corrosion problem in stainless steels is weld decay (sensitization) caused by carbide precipitation in the weld HAZ. Sensitization occurs in a zone subject to a critical thermal cycle in which chromium-rich carbides precipitate and in which chromium diffusion is much slower than that of carbon. The carbides are precipitated on grain boundaries that are consequently flanked by a thin chromium-depleted layer. This sensitized microstructure is much less corrosion resistant, because the chromium-depleted layer and the precipitate can be subject to preferential attack. Sensitization can be avoided by the use of low-carbon grades such as Type 316L (0.03% C Max.) in place of sensitization-susceptible Type 316 (0.08% C Max.). It is more common to use 0.05% C (Max.) steels, which are still reasonably resistant to sensitization, particularly if they contain molybdenum and nitrogen; these elements appear to raise the tolerable level of carbon and/or heat input. However, low-carbon stainless steels carry a small cost premium; therefore, they are not universally specified.

At higher solution temperatures, sensitized Type 304 and Type 316 are particularly susceptible to SCC—whether caused by chlorides, sulfur compounds or caustic. In many cases cracking occurs after HCl acid cleaning. Although the initial crack path may be intergranular, subsequent propagation can have the characteristic branched appearance of transgranular chloride SCC. Intergranular SCC caused by sulfur compounds can also occur during the acid cleaning of sensitized stainless steels.

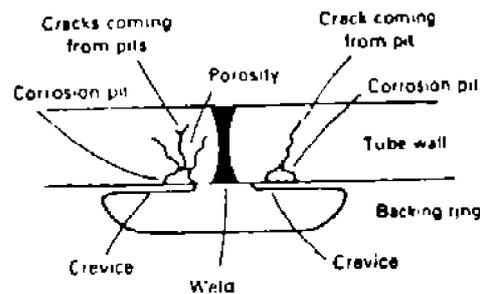
8.3.1.5.4 Corrosion associated with postweld cleaning

Postweld cleaning is often specified to remove the heat-tinted metal formed during welding. Recent work has shown that cleaning by stainless steel wire brushing can lower the corrosion resistance of a stainless steel weldment. This is a particular problem in applications in which the base metal has marginal corrosion resistance. The effect may be caused by inadequate heat-tint removal, by the use of lower-alloy stainless steel brushes such as Type 410 or 304, or by the redeposition of abraded metal or oxides.

Any cleaning method may be impaired by contamination or by lack of control. Results of a study in bleach plants suggest that pickling and glass bead blasting can be more effective than stainless wire brushing and that brushing is more difficult to perform effectively in this case.

8.3.1.5.5 Corrosion associated with weld backing rings

Backing rings are sometimes used when welding pipe. In corrosion applications, it is important that the backing ring insert be consumed during the welding process to avoid a crevice. In the example shown in Fig. 6, the wrong type of backing ring used, could leave a crevice after welding.



SCHEMATIC OF A STAINLESS STEEL NITRATOR COOLING COIL WELD JOINT. FAILURE WAS CAUSED BY IMPROPER DESIGN OF THE BACKING RING, WHICH WAS NOT CONSUMED DURING WELDING AND LEFT A CREVICE

Fig. 6

The best solution to this problem was to eliminate the crevices, that is, not to use backing rings. For more information see A.3 (Appendix).

8.3.1.6 Corrosion of ferritic stainless steel weldments

Conventional 400-series ferritic stainless steels such as AISI Types 430, 434, and 446 are susceptible to intergranular corrosion and to embrittlement in the as-welded condition. Corrosion in the weld area generally encompasses both the weld metal and weld HAZ. Early attempts to avoid some of these problems involved the use of austenitic stainless steel filler metals; however, failure by corrosion of the HAZ usually occurred even when exposure was to rather mild media for relatively short periods of time.

Fig. 7 shows an example of a saturator tank used to manufacture carbonated water at room temperature that failed by leakage through the weld HAZ of the base metal after being in service for only 2 months. This vessel, fabricated by welding with a Type 308 stainless steel welding electrode, was placed in service in the as-welded condition.



AS-WELDED TYPE 430 STAINLESS STEEL SATURATOR TANK USED IN THE MANUFACTURE OF CARBONATED WATER THAT FAILED AFTER 2 MONTHS OF SERVICE. THE TANK WAS SHIELDED METAL ARC WELDED USING TYPE 308 STAINLESS STEEL FILLER METAL

Fig. 7

To overcome some of earlier difficulties and to improve weldability, several of the standard grade ferritic stainless steels have been modified. For example, Type 405, containing nominally 11% Cr, is made with lower carbon and a small aluminum addition of 0.20% to restrict the formation of austenite at high temperature so that hardening is reduced during welding. For maximum ductility and corrosion resistance, however, postweld annealing is necessary. Recommendations for welding include either a 430- or a 309- type filler metal, the latter being used where increased weld ductility is desired.

8.3.1.6.1 A new generation of ferritic stainless steels

In the late 1960s and early 1970s, researchers recognized that the high chromium-molybdenum-iron ferritic stainless steels possessed a desirable combination of good mechanical properties and resistance to general corrosion, pitting, and SCC. These properties made them attractive alternatives to the austenitic stainless steels commonly plagued by chloride SCC.

It was reasoned that by controlling the interstitial element (carbon, oxygen, and nitrogen) content of these new ferritic alloys, either by ultrahigh purity or by stabilization, the formation of martensite (as well as the need for preheat and postweld heat treatment) could be eliminated, with the result that the welds would be corrosion resistant, tough, and ductile in the as-welded condition. To achieve these results, electron beam vacuum refining, vacuum and argon-oxygen decarburization, and vacuum induction melting processes were used. From this beginning, two basic ferritic alloy systems evolved:

- Ultrahigh purity:

The (C + N) interstitial content is less than 150 ppm.

- Intermediate purity:

The (C + N) interstitial content exceeds 150 ppm.

Although not usually mentioned in the alloy chemistry specifications, oxygen and hydrogen are also harmful, and these levels must be carefully restricted. Table 5 lists the compositions of some ultrahigh purity, intermediate purity, and standard-grade ferritic stainless steels.

TABLE 5 - TYPICAL COMPOSITIONS OF SOME FERRITIC STAINLESS STEELS

ALLOY	COMPOSITION, %						
	C(max)	Cr	Fe	Mo	N	Ni	OTHER
Standard grades (AISI 400 series)							
Types 405	0.08	13	bal.	...	...	...	0.2Al
Types 430	0.12	17	bal.	...	...	...	...
Type 430Ti	0.10	17	bal.	...	...	...	Ti 6 × C min
Type 434	0.12	17	bal.	0.75 - 1.25	...	...	...
Type 446	0.20	25	bal.	...	...	...	...
Intermediate purity grades							
26-1 Ti	0.02	26	bal.	1	0.025	0.25	0.5Ti
AISI Type 444	0.02	18	bal.	2	0.02	0.4	0.5Ti
SEA-CURE	0.02	27.5	bal.	3.4	0.025	1.7	0.5Ti
Monit	0.025	25	bal.	4	0.025	4	0.4Ti
Ultrahigh purity grades							
E-Brite 26-1	0.002	26	bal.	1	0.01	0.1	0.1Nb
AL 29-4-2	0.005	29	bal.	4	0.01	2	...
SHOMAC 26-4	0.003	26	bal.	4	0.005	...	...
SHOMAC 30-2	0.003	30	bal.	2	0.007	0.18	...
YUS 190L	0.004	19	bal.	2	0.0085	...	0.15Nb

The unique as-welded properties of the new ferritic stainless steels have been made possible by obtaining very low levels of impurities, including carbon, nitrogen, hydrogen, and oxygen, in the case of the alloys described as ultralow interstitials and by obtaining a careful balance of niobium and/or titanium to match the carbon content in the case of the alloys with intermediate levels of interstitials. For these reasons, every precaution must be taken, and welding procedures that optimize gas shielding and cleanliness must be selected to avoid pickup of carbon, nitrogen, hydrogen and oxygen.

To achieve maximum corrosion resistance, as well as maximum toughness and ductility, the GTA welding process with a matching filler metal is usually specified; however, dissimilar high-alloy weld metals have also been successfully used. In this case, the choice of dissimilar filler metal must ensure the integrity of the ferritic metal system. Regardless of which of the new generation of ferritic stainless steels is to be welded, the following precautions are considered essential.

- First, the joint groove and adjacent surfaces must be thoroughly degreased with a solvent, such as acetone, that does not leave a residue. This will prevent pickup of impurities, especially carbon, before welding. The filler metal must also be handled carefully to prevent it from picking up impurities. Solvent cleaning is also recommended.

Caution:

Under certain conditions, when using solvents, a fire hazard or health hazard may exist.

- Second, a welding torch with a large nozzle inside diameter, such as 19 mm (¾ inch), and a gas lens (inert gas calming screen) is necessary. Pure, welding grade argon with a flow rate of 28 L/min (60 ft³/h) is required for this size nozzle. In addition, the use of a trailing gas shield is beneficial, especially when welding heavy-gage materials. Use of these devices will drastically limit the pickup of nitrogen and oxygen during welding. Back gas shielding with argon is also essential.

Caution:

Procedures for welding austenitic stainless steels often recommend the use of nitrogen backing gas. Nitrogen must not be used when welding ferritic stainless steels. Standard GTA welding procedures used to weld stainless steels are inadequate and therefore must be avoided.

- Third, overheating and embrittlement by excessive grain growth in the weld and HAZ should be avoided by minimizing heat input. In multipass welds, overheating and embrittlement should be avoided by keeping the interpass temperature below 95°C (200°F).

- Lastly, to avoid embrittlement further, pre-heating (except to remove moisture) or postweld heat treating should not be performed. Postweld heat treatment is used only with the conventional ferritic stainless alloys. Appendix A presenting an example illustrates the results of not following proper procedures.

8.3.1.7 Corrosion of duplex stainless steel weldments

In the wrought condition, duplex stainless steels have microstructures consisting of a fairly even balance of austenite and ferrite. The new generation of duplex alloys are now being produced with low carbon and a nitrogen addition. These alloys are useful because of their good resistance to chloride SCC, pitting corrosion, and intergranular corrosion in the as-welded condition. Nominal compositions of some duplex stainless steels are given in Table 6.

TABLE 6 - COMPOSITIONS OF VARIOUS DUPLEX STAINLESS STEELS

UNS No.*	TYPICAL ALLOY	COMPOSITION, % (a)									
		C	Cr	Cu	Fe	Mn	Mo	Ni	N	Si	OTHERS
S31500.....	SAF 3RE60	0.03 Max.	18.5	...	bal.	1.6	2.7	4.9	0.07	1.7	...
S32404.....	Uranus 50	0.04 Max.	21.5	1.5	bal.	2.0 Max.	2.5	7.0	0.1	1.0 Max.	....
S31803.....	Alloy 2205	0.03 Max.	22	...	bal.	2.0 Max.	3.0	5.5	0.15	1.0 Max.	...
S32304.....	SAF 2304	0.03 Max.	23	...	bal.	2.5 Max.	0.5	4.0	0.1	1.0 Max.	....
S32900.....	Type 329 SS	0.2 Max.	25.5	...	bal.	1.0 Max.	1.5	3.75	...	0.75 Max.	....
S31100.....	IN-744	0.05 Max.	26	...	bal.	1.0 Max.	...	6.5	...	0.6 Max.	....
S31200.....	44LN	0.03 Max.	25	...	bal.	2.0 Max.	3.0	6.5	0.17	1.0 Max.	....
S32950.....	7Mo-Plus	0.03 Max.	27.5	...	bal.	2.0 Max.	1.8	4.4	0.25	0.6 Max.	...
S31260.....	DP-3	0.3 Max.	25	0.5	bal.	1.0 Max.	3.0	6.5	0.2	0.75 Max.	0.3 W
S32250.....	Ferralium Alloy 255	0.04 Max.	25.5	1.7	bal.	1.5 Max.	3.0	5.5	0.17	1.0 Max.	...

(a) Nominal unless otherwise indicated.

* UNS : Unified Numbering System.

The distribution of austenite and ferrite in the weld and HAZ is known to affect the corrosion properties and the mechanical properties of duplex stainless steels. To achieve this balance in properties, it is essential that both base metal and weld metal be of the proper composition. For example, without nickel enrichment in the filler rod, welds can be produced with ferrite levels in excess of 80%. Such microstructures have very poor ductility and inferior corrosion resistance. For this reason, autogenous welding (without the addition of filler metal) is not recommended unless postweld solution annealing is performed which is not always practical. To achieve a balanced weld microstructure, a low carbon

content and the addition of nitrogen (with Alloy 2205 at least 0.12% N) shall be specified for the base metal. Low carbon helps to minimize the effects of sensitization, and the nitrogen slows the precipitation kinetics associated with the segregation of chromium and molybdenum during the welding operation. Nitrogen also enhances the reformation of austenite in the HAZ and weld metal during cooling.

These duplex alloys have been used in Europe for many years; therefore, guidelines relating to austenite-ferrite phase distribution are available. It has been shown that to ensure resistance to chloride SCC welds shall contain at least 25% ferrite. To maintain a good phase balance for corrosion resistance and mechanical properties (especially ductility and notch toughness) comparable to the base metal, the average ferrite content of the weld shall not exceed 60%. This means using welding techniques that minimize weld dilution, especially in the root pass. Conditions that encourage mixing of the lower-nickel base metal with the weld metal reduce the overall nickel content. Weld metal with a lower nickel content will have a higher ferrite content, with reduced mechanical and corrosion properties.

Once duplex base metal and welding consumables have been selected, it is then necessary to select joint designs and weld parameters that will produce welding heat inputs and cooling rates so as to produce a favorable balance of austenite and ferrite in the weld and HAZ.

Researchers have shown that the high-ferrite microstructures that develop during welding in lean (low-nickel) base metal and weld metal compositions can be altered by adjusting welding heat input and cooling rate. In these cases, a higher heat input that produces a slower cooling rate can be used to advantage by allowing more time for ferrite to transform to austenite. There are, however, some practical aspects to consider before applying higher heat inputs indiscriminately. For example, as heat input is increased, base metal dilution increases. As the amount of lower-nickel base metal in the weld increases, the overall nickel content of the deposit decreases: this increases the potential for more ferrite, with a resultant loss in impact toughness, ductility, and corrosion resistance. This would be another case for using an enriched filler metal containing more nickel than the base metal. Grain growth and the formation of embrittling phases are two other negative effects of high heat inputs. When there is uncertainty regarding the effect that welding conditions will have on corrosion performance and mechanical properties, a corrosion test is advisable.

The influence of different welding conditions on various material properties of Alloy 2205 has been studied. See Appendix A (A.5).

8.3.1.8 Corrosion of nickel and high-nickel alloy weldments

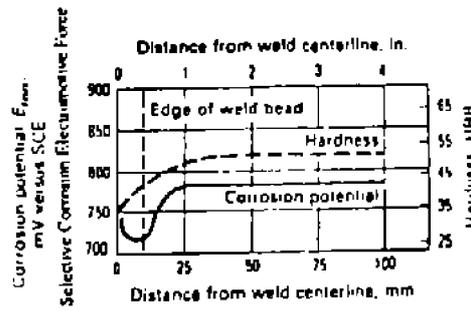
The corrosion resistance of weldments is related to the microstructural and microchemical changes resulting from thermal cycling. The effects of welding on the corrosion resistance of nickel-base alloys are similar to the effects on the corrosion resistance of austenitic stainless steels. For example, sensitization due to carbide precipitation in the HAZ is a potential problem in both classes of alloys. However, in the case of nickel-base alloys, the high content of such alloying elements as chromium, molybdenum, tungsten, and niobium can result in the precipitation of other intermetallic phases, such as μ , σ , and η .

The characteristics of the various nickel-base alloys and the evolution of these alloys are discussed in A.6 (see Appendix). The corrosion resistance of weldments is dictated not only by the HAZ but also by the weld metal itself. The effect of elemental segregation on weld metal corrosion must also be examined. The nickel-base alloys discussed in Appendix A.6 are the solid-solution alloys.

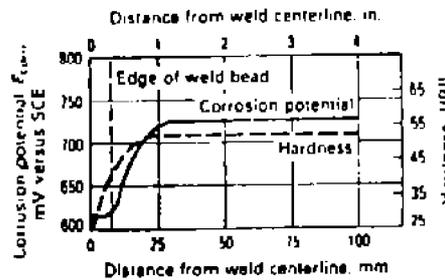
8.3.1.9 Corrosion of aluminum alloy weldments

8.3.1.9.1 Variations in microstructure across the weld and HAZ of aluminum weldments are known to produce susceptibility to corrosion in certain environments. These differences can be measured electrochemically and are an indication of the type of corrosion behavior that might be expected. Although some aluminum alloys can be autogenously welded, the use of a filler metal is preferred to avoid cracking during welding and to optimize corrosion resistance.

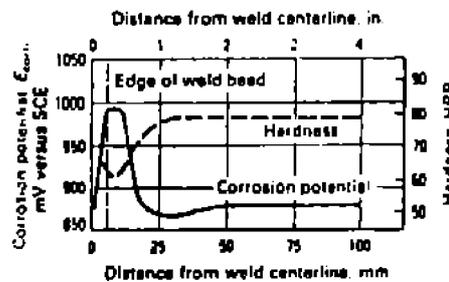
8.3.1.9.2 The variations in corrosion potential (equilibrium potential) across three welds are shown in Fig. 8 for Alloys 5456, 2219 and 7039. These differences can lead to localized corrosion. In general, the welding procedure that puts the least amount of heat into the metal has the least influence on microstructure and the least chance of reducing the corrosion behavior of aluminum weldments.



(a) Alloy 5456-H321 base metal with Alloy 5556 filler; 3-pass metal inert gas weld



(b) Alloy 2219-T87 base metal with Alloy 2319 filler; 2-pass tungsten inert gas weld

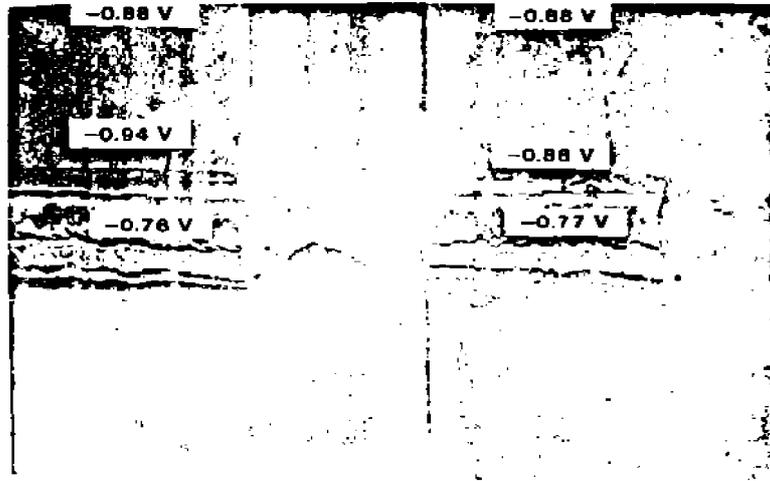


(c) Alloy 7039-T651 base metal with Alloy 5183 filler; 2-pass tungsten inert gas weld

EFFECT OF THE HEAT OF WELDING ON MICROSTRUCTURE, HARDNESS, AND CORROSION POTENTIAL OF WELDED ASSEMBLIES OF THREE ALUMINUM ALLOYS. THE DIFFERENCES IN CORROSION POTENTIAL BETWEEN THE HAZ AND THE BASE METAL CAN LEAD TO SELECTIVE CORROSION

Fig. 8

8.3.1.9.3 Tables are available in American Society for metal, (1984, Page 283) that summarize filler alloy selection recommended for welding various combinations of base metal alloys to obtain maximum properties, including corrosion resistance. Care must be taken not to extrapolate the corrosion performance ratings indiscriminately. Corrosion behavior ratings generally pertain only to the particular environment tested, usually rated in continuous or alternate immersion in fresh or salt water. For example, the highest corrosion rating (A) is listed for use of filler Alloy 4043 to join 3003 Alloy to 6061 alloy. In strong (99%) nitric acid (HNO₃) service, however, a weldment made with 4043 filler alloy would experience more rapid attack than a weldment made using 5556 filler metal. With certain alloys, particularly those of the heat-treatable 7xxx series thermal treatment after welding is sometimes used to obtain maximum corrosion resistance (Fig. 9).



a) As-welded assembly shows severe localized corrosion in the HAZ

b) Specimen showing the beneficial effects of postweld aging. Corrosion potentials of different areas of the weldments are shown where they were measured. Electrochemical measurements performed in 53 g/l NaCl Plus 3 g/l H_2O_2 versus a 0.1 calomel reference electrode and recalculated to a saturated calomel electrode (SCE).

WELDED ASSEMBLIES OF ALUMINUM ALLOY 7005 WITH ALLOY 5356 FILLER METAL AFTER A 1-YEAR EXPOSURE TO SEAWATER

Fig. 9

8.3.1.9.4 As with many other alloy systems, attention must be given to the threat of crevice corrosion under certain conditions. Strong (99%) HNO_3 is particularly aggressive toward weldments that are not made with full weld penetration.

8.3.1.10 Corrosion of tantalum and tantalum alloy weldments

Examination of equipment fabricated from tantalum that has been used in a wide variety of service conditions and environments generally shows that the weld, Haz, and base metal display equal resistance to corrosion. This same resistance has also been demonstrated in laboratory corrosion tests conducted in a number of different acids and other environments. However, in applications for tantalum-lined equipment, contamination of the tantalum with iron from underlying backing material, usually carbon steel, can severely impair the corrosion resistance of tantalum. About the only known reagents that rapidly attack tantalum are fluorine; HF and acidic solutions containing fluoride; fuming sulfuric acid (H_2SO_4) (oleum), which contains free sulfur trioxide (SO_3); and alkaline solutions.

An exception to the generalization that base metal and weldments in tantalum show the same corrosion resistance under aggressive media is discussed in the following example. Because tantalum is a reactive metal, the pickup of interstitial elements, such as oxygen, nitrogen, hydrogen and carbon, during welding can have a damaging effect on a refractory metal such as tantalum.

8.3.1.10.1 Preferential pitting of a tantalum alloy weldment in H_2SO_4 service

A 76-mm (3-inch) diameter tantalum alloy tee removed from the bottom of an H_2SO_4 absorber that visually showed areas of severe etching attack was examined. The absorber had operated over a period of several months, during which time about 11 400 kg (25000 lb) of H_2SO_4 was handled. The absorber was operated at 60°C (140°F) with nominally

98% H₂SO₄. There was a possibility that some of the H₂SO₄ fed into the process stream may have been essentially anhydrous or even in the oleum range. Oleum is known to attack tantalum very laoidly at temperatures only slightly higher than 60°C (140°F). In addition, the H₂SO₄ effluent was found to contain up to 5 ppm of fluoride.

8.3.1.10.2 Oxygen tolerance of tantalum weldments

Tantalum reacts with oxygen, nitrogen, and hydrogen at elevated temperatures. The absorption of these interstitial elements, often called a gettering reaction, produces a sharp reduction in ductility and can cause embrittlement. This impairment in ductility (and also in notch toughness, as manifested by an increase in ductile-to-brittle transition temperature) can be considered a form of corrosion. The other Group Va refractory metals (niobium and vanadium) and the Group IVa reactive metals (titanium, zirconium, and hafnium) can also suffer similar attack.

An investigation was conducted to determine the approximate tolerances of tantalum and Tantaloy "63" weldments for oxygen contamination that may be permitted during fabrication or subsequent service. Weldments of the materials were doped with various amounts of oxygen added either by anodizing or by oxidation in air. This was followed by vacuum annealing treatments to diffuse the oxygen through the sample cross section. The oxygen concentration was monitored principally by hardness tests. Hardness is generally believed to be a better indicator of the extent of interstitial contamination than chemical analysis, which is subject to scatter and inaccuracy because of sampling difficulty. Bend tests (at room and liquid argon temperatures) and room-temperature Olsen cup formability tests were conducted to determine the hardness levels at which the materials embrittled.

The results showed that weldments of both materials remain ductile when hardened by interstitial contamination by oxygen up to Rockwell 30T hardness in the low 80s. Above this hardness, embrittlement may be expected. The hardness level at which embrittlement occurs is substantially above the typical maximum allowable hardness of 65 HR30T specified for Tantaloy "63" or the 50 HR30T for tantalum flat mill products. Thus, if the extent of interstitial contamination by oxygen (and/or nitrogen) is controlled so that these maximum allowable hardness limits are not exceeded, embrittlement of weldments should not occur.

On the basis of chemical composition, the maximum oxygen tolerance for tantalum weldments appears to be about 400 to 550 ppm; for Tantaloy "63" weldments, it is about 350 to 500 ppm. Although commercially pure tantalum exhibits a somewhat higher tolerance for oxygen (and total interstitial contamination) than Tantaloy "63", the latter material appears to have somewhat better resistance to oxidation; this tends to offset the advantage tantalum has of a higher allowable oxygen pickup before embrittlement occurs. It should be further emphasized that the results are based on the assumption that oxygen was believed to be distributed relatively uniformly throughout the cross section in all parts of the weldment. A locally high concentration, such as a high surface contamination of oxygen or nitrogen, could result in a sever loss in ductility and could possibly even produce embrittlement. Therefore, all handling, cleaning, and fabrication practices on tantalum and its alloys should avoid producing such surface contamination as well as gross contamination. The article "Corrosion of Tantalum" in this Volume gives more detailed information on the corrosion of tantalum and tantalum alloys.

8.3.2 Welding procedure

8.3.2.1 Welding of carbon steels, welding requirements, qualification and repair

All welding works shall be according to appropriate ASME Codes Section IX and/or relevant IPS Standards for fabrication of equipment, vessels, piping, etc.

8.3.2.2 Welding of stainless steels

8.3.2.2.1 General

The main problems encountered in welding stainless steels are the same as those seen in heat treatment. The heat of welding (portions of the base metal adjacent to the weld may be heated to 430 to 870°C, (or 800 to 1600°F) can cause sensitization and formation of intermetallic phases, thus increasing the susceptibility of stainless steel weldments to in-

tergranular corrosion, pitting, crevice corrosion, and SCC. These phenomena often occur in the heat-affected zone of the weld. Sensitization and intermetallic phase precipitation can be corrected by solution annealing after welding. Alternatively, low carbon or stabilized grades may be used.

Another problem in high heat input welds is grain growth, particularly in ferritic stainless steels. Excessive grain growth can increase susceptibility to intergranular attack and reduce toughness. Thus, when welding most stainless steels, it is wise to limit weld heat input as much as possible. For more detailed information on welding of stainless steels and the problems encountered see 8.3.1.

8.3.2.2.2 Cleaning procedures

Before any welding begins, all materials, chill bars, clamps, hold down bars, work tables, electrodes, and wire, as well as the stainless steel, must be cleaned of all foreign matter. Moisture can cause porosity in the weld that would reduce corrosion resistance. Organic materials, such as grease, paint, and oils, may result in carbide precipitation. Copper contamination may cause cracking. Other shop dirt can cause weld porosity and poor welds in general.

8.3.2.2.3 Weld design and procedure

Weld design and procedure are very important in producing a sound corrosion-resistant weld. Good fit and minimal out-of-position welding will minimize crevices and slag entrapment. The design shall not place welds in critical flow areas. When attaching such devices as low-alloy steel supports and ladders on the outside of a stainless steel tank, a stainless steel intermediate pad shall be used. In general, stainless steels with higher alloy content than Type 316 shall be welded with weld metal richer in chromium, nickel, and molybdenum than the base metal. Every attempt shall be made to minimize weld spatter.

After welding, all weld spatter, slag, and oxides shall be removed by brushing blasting, grinding, or chipping. All finishing equipment must be free of iron contamination. It is advisable to follow the mechanical cleaning and finishing with a chemical cleaning. Such a cleaning will remove any foreign particles that may have been embedded in the surface during mechanical cleaning without attacking the weldment. More information on welding of stainless steels is available in Volume 6 of the 9th Edition of Metals Handbook, ASM.

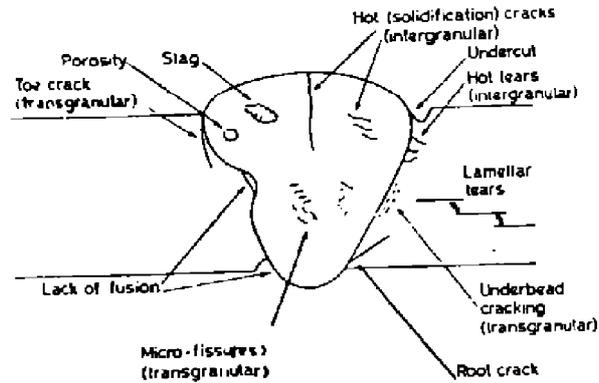
8.3.3 Weld defects

8.3.3.1 There is no guarantee that crack-free joints will automatically be obtained when fabricating 'weldable' metals. This is a result of the fact that weldability is not a specific material property but a combination of the properties of the parent metals, filler metal (if used) and various other factors (see Table 7).

TABLE 7 - FACTORS AFFECTING WELDABILITY

PARENT METAL	FILLER METAL	OTHER FACTORS
Composition	Composition	Degree of fusion
Thickness	Impact strength	(Joint formation)
State of heat treatment	Toughness	Degree of restraint
Toughness	Hydrogen content	Form factor
Temperature	Purity	(Transition)
Purity	Homogeneity	Deposition technique
Homogeneity	Electrode diameter	Skill and reliability of the welder
	(Heat input during welding)	

8.3.3.2 The consequence of the average structural material possessing imperfect weldability is to produce a situation where defects may arise in the weld deposit or heat-affected zone (see Fig. 10 and Table 8).



POSSIBLE WELD DEFECTS

Fig. 10

TABLE 8 - WELDABILITY DEFECTS

DEFECT	CAUSES	REMEDIES
Hot cracks	Large solidification range Segregation Stress	More crack-proof filler Less fusion
Underbead cracks	Hardenable parent plate Hydrogen Stress	Low hydrogen process Planned bead sequence Preheating
Microfissures	Hardenable deposit Hydrogen Stress	Low hydrogen process Pre-and post-heating
Toe cracks	High stress Notches Hardenable parent plate	Planned bead sequence Preheating Avoidance of notches
Hot tears	Segregation Stress	Less fusion Cleaner parent plate
Porosity	Gas absorption	Remove surface scale Remove surface moisture Cleaner gas shield

8.3.3.3 Carbon and low-alloy steels (see also 8.3.1.4)

These usually present little problem since the parent and filler metals are generally of similar composition, although there is some evidence that the precise electrode type in manual metal-arc welding for marine conditions may be important; weld metal deposited from basic-coated rods appears to corrode more rapidly than that deposited from rutile-based coatings.

An environment containing H₂S, cyanides, nitrates or alkalis may produce stress-corrosion cracking in highly stressed structures and these should be first stress relieved by heating to 650°C.

An interesting development in weldable corrosion-resistant steels is the copper-bearing or weathering steels which exhibit enhanced corrosion resistance in industrial atmospheres in the unpainted condition. For optimum corrosion resistance after welding, the filler employed should be suitably alloyed to give a deposit of composition similar to that of the steel plate.

8.3.3.4 Stainless steels

8.3.3.4.1 Since stainless steels are widely used for resisting corrosive environments, it is relevant to consider the welding of these alloys in some detail. There are three groups of stainless steels, each possessing their own characteristic welding problem (see 8.3.1.5):

Ferritic type

Welding produces a brittle deposit and a brittle heat-affected zone caused by the very large grain size that is produced. The problem may be reduced in severity by the use of austenitic filler and/or the application of pre- and post-weld heat treatments: the latter is a serious limitation when large welded structures are involved.

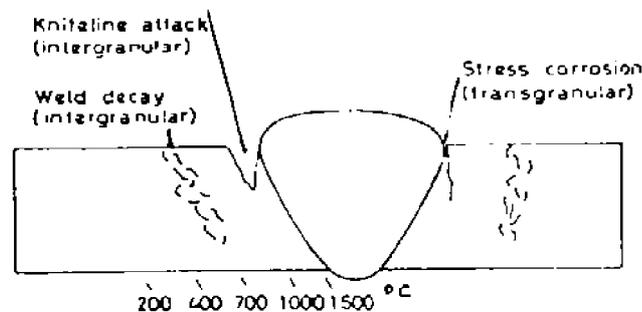
Martensitic type

Heat-affected zone cracking is likely and may be remedied by employing the normal measures required for the control of hydrogen-induced cracking.

Austenitic type

These are susceptible to hot cracking which may be overcome by balancing the weld metal composition to allow the formation of a small amount of δ -Fe (ferrite) in the deposit, optimum crack resistance being achieved with a δ -Fe content of 5-10%. More than this concentration increases the possibility of σ -phase formation if the weldment is used at elevated temperature with a concomitant reduction in both mechanical and corrosion resistance.

The main problems that might be encountered in stainless steel are weld decay, knifeline attack and stress-corrosion cracking (Fig. 11).



CORROSION SITES IN STAINLESS STEEL WELDS. THE TYPICAL PEAK TEMPERATURES ATTAINED DURING WELDING ($^{\circ}\text{C}$) ARE GIVEN AT THE FOOT OF THE DIAGRAM. NOTE THAT KNIFELINE ATTACK HAS THE APPEARANCE OF A SHARPLY DEFINED LINE ADJACENT TO THE FUSION ZONE

Fig. 11

8.3.3.4.2 Weld decay is the result of the intergranular precipitation of chromium carbide in the temperature range of 430-870 $^{\circ}\text{C}$ and material in this condition is referred to as being 'sensitised'. Sensitisation depletes the matrix in the grain-boundary region of chromium and this region may eventually suffer intergranular corrosion. In corrosive environments some zone in the vicinity of the weld area is inevitably raised within the sensitisation temperature range and the degree of severity of sensitization will be dependent on a number of process factors that determine the time in this temperature range, e.g. heat input, thickness of plate. For most commercial grades of stainless steel in thin section (< 10 mm) the loss in corrosion resistance is slight and seldom warrants any special measures. For a high degree of corrosion resistance, or in welded thick plate, it becomes necessary to take one of the following courses of action:

- a) Thermally treat the structures to effect a re-resolution of the chromium carbide; this is often impractical in large structures unless local heat treatment is employed, but is not always satisfactory since a sensitized zone could be produced just outside the local thermally treated region.
- b) Use extra-low-carbon steel.
- c) Use stabilized steels, i.e. austenitic steels containing niobium, tantalum or titanium.

8.3.3.5 Nickel alloys (see also 8.3.1.8)

In the main, welding does not seriously affect the corrosion resistance of the high nickel alloys and stress relief is not generally required since the resistance to stress corrosion is particularly high; this property increases with increase in nickel content and further improvement may be obtained by the addition of silicon. The chromium-containing alloys can be susceptible to weld decay and should be thermally stabilised with titanium or niobium, and where conditions demand exposure to corrosive media at high temperatures a further post-weld heat treatment may be desirable. For the Ni-Cr-Mo-Fe-W type alloys, it suggested that the material should be given a two-stage heat treatment prior to single-pass welding in order to produce a dependable microstructure with a thermally stabilised precipitate.

The Ni-28Mo alloy provides a special case of selective corrosion analogous to the weld-decay type of attack; it may be removed by solution treatment or using an alloy containing 2% Vanadium.

Of the weldability problems, nickel and nickel-based alloys are particularly prone to solidification porosity, especially if nitrogen is present in the arc atmosphere, but this may be controlled by ensuring the presence of titanium as a denitrider in the filler and maintaining a short arc length. The other problem that may be encountered is hot cracking, particularly in alloys containing Cr, Si, Ti, Al, B, Zr, S, Pb and P.

For optimum corrosion resistance it is recommended that similar composition fillers be used wherever possible, and obviously any flux residues that may be present must be removed.

8.3.3.6 Aluminum alloys (see also 8.3.1.9)

These alloys are very susceptible to hot cracking and in order to overcome this problem most alloys have to be welded with a compensating filler of different composition from that of the parent alloy, and this difference in composition may lead to galvanic corrosion. A further problem in the welding of these materials is the high solubility of the molten weld metal for gaseous hydrogen which causes extensive porosity in the seam on solidification; the only effective remedy is to maintain the hydrogen potential of the arc atmosphere at a minimum by using a hydrogen-free gas shield with dry, clean consumables (e.g. welding rods, wire) and parent plate.

In general, the corrosion resistance of many of the alloys is not reduced by welding. Any adverse effects that may be encountered with the high-strength alloys can be largely corrected by post-weld heat treatment; this is particularly true of the copper-bearing alloys. Pure aluminum fillers impart the best corrosion resistance, although the stronger Al-Mg and Al-Mg-Si fillers are normally suitable; the copper-bearing fillers are not particularly suitable for use in a corrosive environment. Resistance welding does not usually affect the corrosion resistance of the aluminum alloys.

The heat-affected zone may become susceptible to stress-corrosion cracking, particularly the high-strength alloys, and expert advice is necessary concerning the suitability of a particular alloy for a certain environment after welding. In this context Al-Zn-Mg type alloys have been extensively studied and it has been shown that maximum sensitivity appears to occur when there is a well-developed precipitation at the heat-affected zone grain boundaries adjacent to the fusion line, a fine precipitate within the grain and a precipitate-free zone immediately adjacent the grain boundaries. The action of stress-corrosion cracking then appears to be a result of local deformation in the precipitate-free zone combined with the anodic character of the precipitate particles.

8.3.3.7 Other materials for welding

Suggestions are made in Table 9. It is sufficient to state that with a knowledge of the general characteristics of welding process and its effects on a metal a reliable joint for a particular problem will normally be the rule and not the exception.

TABLE 9 - POSSIBLE PROBLEMS IN LESS COMMONLY WELDED METALS

METAL	WELDABILITY	CORROSION
Copper alloys	Porosity	De-zincification
	Hot cracking	De-aluminification
	Hot tearing	Stress corrosion
	Steam explosion	
Magnesium alloys	Porosity	
	Hot cracking	Stress corrosion
	Lack of fusion	Pitting
Titanium alloys	Porosity	
	Embrittlement	Stress corrosion

8.3.4 Welding and joining

8.3.4.1 General

A jointed fabrication is one in which two or more components are held in position:

- by means of a mechanical fastener (screw, rivet or bolt);
- by welding, brazing or soldering;
- by an adhesive.

The components of the joint may be metals of similar or dissimilar composition and structure, metals and non-metals or they may be wholly non-metallic. Since the majority of fabrications are joined at some stage of their manufacture, the corrosion behavior of joints is of the utmost importance, and the nature of the metals involved in the joint and the geometry of the joint may lead to situation in which one of the metals is subjected to accelerated and localized attack. Although corrosion at bimetallic contacts involving different metals has been dealt with in IPS-E-TP-760, it is necessary to emphasize the following in relation to corrosion at joints in which the metals involved may be either identical or similar.

8.3.4.1.1 A difference in potential may result from differences in structure or stress brought about during or subsequent to the joining process.

8.3.4.1.2 Large differences in area may exist in certain jointed structures, e.g. when fastening is used.

Furthermore, many joining processes lead to a crevice, with the consequent possibility of crevice corrosion.

Before considering the factors that lead to corrosion it is necessary to examine briefly the basic operations of joint manufacture.

For joining dissimilar metals it is needed to use insulating washers, insulating gaskets and insulating sleeves as required.

8.3.4.2 Mechanical fasteners

These require little description and take the form of boltings, screws, rivets, etc. Mechanical failure may occur as a result of the applied stress in shear or tension exceeding the ultimate strength of the fastener, and can normally be ascribed to poor design, although the possibility of the failure of steel fittings at ambient or sub-zero temperatures by brittle fracture, or at ambient temperatures by hydrogen embrittlement, cannot be ignored. If brittle failure is a problem then it can be overcome by changing the joint design or employing a fastener having a composition with better ductility transition properties.

For soldered joints and brazed joints see 8.3.4.3.2.

8.3.4.3 Joining, brazing and soldering

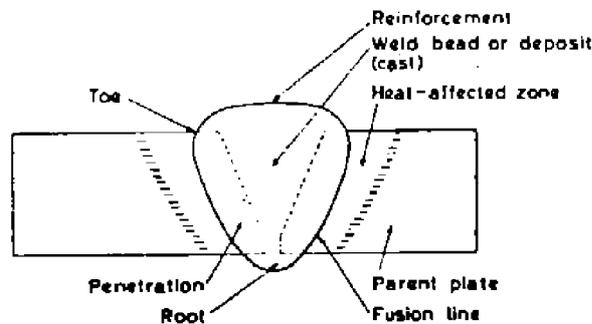
8.3.4.3.1 Joining

The joining differs from all others in that an attempt is made to produce a continuity of homogeneous material which may or may not involve the incorporation of a filler material. There are a large variety of processes by which this may be achieved, most of which depend upon the application of thermal energy to bring about a plastic or molten state of the metal surfaces to be joined. The more common processes of used welding compared with mechanical fasteners, soldering and brazing are classified in Table 10.

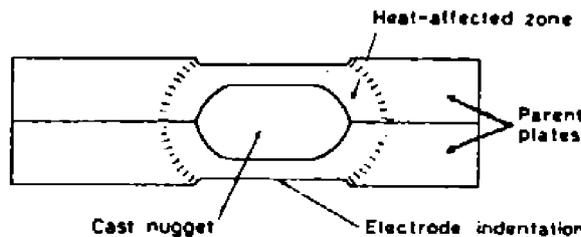
TABLE 10 - TYPICAL JOINING PROCESSES

JOINING PROCESS	TYPES
- Mechanical fasteners	Nuts, bolts, rivets, screws
- Soldering and brazing	Hot iron, torch, furnace, vacuum
- Fusion welding	Oxyacetylene, manual metal arc, tungsten inert gas, metal inert gas, carbon dioxide, pulsed arc, fused arc, submerged arc, electro slag and electron beam
- Resistance welding	Spot, seam, stitch, projection, butt and flash butt
- Solid-phase welding	Pressure, friction, ultrasonic and explosive

The macrographic examination of a welded joint shows two distinct zones, namely the fusion zone with its immediate surroundings and the parent metal (Fig. 12). It is apparent therefore, that such processes produce differences in micro-structure between the cast deposit, the heat-affected zone which has undergone a variety of thermal cycles, and the parent plate.



(a) Fusion weld



(b) Resistance spot weld

WELD DEFINITIONS
Fig. 12

8.3.4.3.1.1 Protection of welded joints

Structural steels are frequently protected from corrosion by means of a paint primer, but these materials can have an adverse effect on the subsequent welding behavior and this is mainly observed as porosity. Hot-dip galvanising for long-term protection can also lead to porosity and intergranular cracking after welding, in which case it may be necessary to remove the zinc coating from the faying edges prior to welding. The presence of zinc can also lead to operator problems due to the toxicity of the fume evolved unless adequate fume extraction is employed.

Prior to painting, all welding residues must be removed and the surface prepared by grinding, grit blasting, wire brushing or chemical treatment. This preparation is of fundamental importance, the method of applying the paint and the smoothness of the bead apparently having little effect on the final result.

8.3.4.3.2 Pressure pipe brazing and soldering

8.3.4.3.2.1 Qualification

a) Brazing qualification

The qualification of brazing procedures, brazers, and brazing operators shall be in accordance with the requirements of the Boilers and Pressure Vessels (BPV) Code, ASME Section IX, Part QB. For Category D Fluid service at design temperature not over 93°C (200°F), such qualification is at the owner's option.

b) Brazing and soldering materials

Filler metal

The brazing alloy or solder shall melt and flow freely within the specified or desired temperature range and, in conjunction with a suitable flux or controlled atmosphere, shall wet and adhere to the surfaces to be joined.

Flux

A flux that is fluid and chemically active at brazing or soldering temperature shall be used when necessary to eliminate oxidation of the filler metal and the surfaces to be joined, and to promote free flow of brazing alloy or solder.

c) Preparation

Surface preparation

The surfaces to be brazed or soldered shall be clean and free from grease, oxides, paint, scale, and dirt of any kind. A suitable chemical or mechanical cleaning method shall be used if necessary to provide a clean wettable surface.

Joint clearance

The clearance between surfaces to be joined by soldering or brazing shall be no larger than necessary to allow complete capillary distribution of the filler metal.

d) Requirements

Soldering procedure

Solderers shall follow the procedure in the Copper Tube Handbook of the Copper Development Association or other approved procedures.

Heating

To minimize oxidation, the joint shall be brought to brazing or soldering temperature in as short a time as possible without localized underheating or overheating.

Flux removal

Residual flux shall be removed if detrimental.

8.3.4.3.2.2 Soldered joints

Soldering and brazing are methods of joining components together with a lower-melting-point alloy so that the parent metal (the metal or metals to be joined) is not melted (Table 10-a). In the case of soft soldering the maximum temperature employed is usually of the order of 250°C and the filler alloys (used for joining) are generally based on the tin-lead system. The components must present a clean surface to the solder to allow efficient wetting and flow of the molten filler and to provide a joint of adequate mechanical strength. To obtain the necessary cleanliness, degreasing and mechanical abrasion may be required followed by the use of a flux to remove any remaining oxide film and to ensure that no tarnish film develops on subsequent heating.

In the case of carbon steels and stainless steels, and many of the non-ferrous alloys, the fluxes are based on acidic inorganic salts, e.g. chlorides, which are highly corrosive to the metal unless they are removed subsequently by washing in hot water. For soldering tinplate, clean copper and brass, it is possible to formulate rosin-based fluxes having non-corrosive residues and these are essential for all electrical and electronic work. Activators are added to the rosin to increase the reaction rate, but these must be such that they are thermally decomposed at the soldering temperature if subsequent corrosion is to be avoided. Corrosion is always a risk with soldered joints in aluminum owing to the difference in electrical potential between the filler alloy and the parent metal and the highly corrosive nature of the flux that is generally used for soldering. However, it is possible to employ ultrasonic soldering to eliminate use of flux. With aluminum soldering it is imperative that the joints be well cleaned both prior and subsequent to the soldering operation, and the design should avoid subsequent trapping of moisture.

TABLE 10-a - SOLDERING AND BRAZING

PROCESS	TEMPERATURE RANGE (°C)	TYPICAL FILLERS	FLUXES	
SOLDERING				
Hot iron	60-300	70 Pb - 30 Sn	Chloride based	
Oven		40 Pb - 60 Sn		
Induction		70 Pb - 27 Sn - 3 Sb	Resin based	
Ultrasonic				
Dip				40 Pb - 58 Sn - 2 Sb
Resistance				Sn - Zn - Pb
Wave and cascade				
BRAZING				
Torch	500-1200	90 Al - 10 Si	Borax based	
Dip		50 Ag - 15 Cu - 17 Zn - 16 Cd	Fluoride based	
Salt bath		Ag - Cu - Ni - In		
Furnace		40 Ag - 30 Cu - 10 Zn	Hydrogen gas	
Induction		50 Cu - 50 Zn	Town's gas	
Resistance		97 Cu - 3 P		
	70 Ni - 17 Cr - 3 B - 10 Fe			
	82 Ni - 7 Cr - 5 Si - 3 Fe			
	68 Pd - 48 Ni	Vacuum		

8.3.4.3.2.3 Brazed joints

When stronger joints are required, brazing may be used. The filler alloys employed generally melt at much higher temperatures (600-1200°C), but the effectiveness of the joining process still depends upon surface cleanliness of the components to ensure adequate wetting and spreading. Metallurgical and mechanical hazards may be encountered in that the filler may show poor spreading or joint filling capacity in a certain situation or may suffer from hot tearing, whilst during furnace brazing in hydrogen-containing atmospheres there is always the possibility that the parent metal may be susceptible to hydrogen embrittlement or steam cracking. Furthermore, brittle diffusion products may be produced at the filler base-metal interface as a result of the reaction of a component of the filler alloy with a base-metal component, e.g. phosphorus-bearing fillers used for steel in which the phosphorus diffuses into the steel.

Serious damage can be caused by:

- a) diffusion into the parent metal of the molten brazing alloy itself when either one or both of the parent metal(s) is in a stressed condition induced by previous heat treatment or cold working, and;
- b) by an externally applied load which need only be the weight of the workpiece.

Nickel and nickel-rich alloys are particularly prone to liquid-braze-filler attack especially when using silver-based braze fillers at temperatures well below the annealing temperature of the base metal, since under these conditions there is then no adequate stress relief of the parent metal at the brazing temperature. The problem may be avoided by annealing prior to brazing and ensuring the maintenance of stress-free conditions throughout the brazing cycle. There is a whole range of silver-nickel and palladium-based braze fillers of high oxidation and corrosion resistance that have been developed for joining the nickel-rich alloys; however, the presence of sulphur, lead or phosphorus in the base-metal surface or in the filler can be harmful, since quite small amounts can lead to interface embrittlement. In the case of the Monels, the corrosion resistance of the joint is generally less than that of the parent metal and the design must be such that as little as possible of the joint is exposed to the corrosive media.

When, in an engineering structure, the aluminum-bronzes are used for their corrosion resistance, the selection of braze filler becomes important and although the copper-zinc brazing alloys are widely used, the corrosion resistance of the joint will be that of the equivalent brass rather than that of the bronze. With the carbon and low-alloy steels, the braze fillers are invariably noble to the steel so that there is little likelihood of trouble (small cathode/large anode system), but for stainless steels a high-silver braze filler alloy is desirable for retaining the corrosion resistance of the joint, although stress-corrosion cracking of the filler is always a possibility if the latter contains any zinc, cadmium or tin.

An interesting example of judicious choice of braze filler is to be found in the selection of silver alloys for the brazing of stainless steels to be subsequently used in a tap-water environment. Although the brazed joint may appear to be quite satisfactory, after a relatively short exposure period failure of the joint occurs by a mechanism which appears to be due to the break-down of the bond between the filler and the braze metal. Dezincification is a prominent feature of the phenomenon and zinc-free braze alloys based on the Ag-Cu system with the addition of nickel and tin have been found to inhibit this form of attack. A similar result is obtained by electroplating 0.007 mm of nickel over the joint area prior to brazing with a more conventional Ag-Cu-Zn-Cd alloy.

Brazing is generally considered unsuitable for equipment exposed to ammonia and various ammoniacal solutions because of the aggressiveness of ammonia to copper-and nickel-base alloys, but recently an alloy based on Fe-3.25B-4.40Si-50.25Ni has been shown to be suitable for such applications.

Studying of the marine corrosion behavior of a number of braze alloy-parent metal combinations has shown that compatibility is a function of the compositions of the filler and parent metals, their microstructures and chance factors such as over heating during the brazing operation.

8.4 Pipe Bending and Forming

8.4.1 General

Pipe may be bent and components may be formed by any hot or cold method which is suitable for the material, the fluid service, and the severity of the bending or forming process. The finished surface shall be free of cracks and substantially free from buckling. Thickness after bending or forming shall be not less than that required by the design.

8.4.2 Bending

8.4.2.1 Bend flattening

Flattening of a bend, the difference between maximum and minimum diameters at any cross section, shall not exceed 8% of nominal outside diameter for internal pressure and 3% for external pressure.

8.4.2.2 Bending temperature

8.4.2.2.1 Cold bending of ferritic materials shall be done at a temperature below the transformation range.

8.4.2.2.2 Hot bending shall be done at a temperature above the transformation range and in any case within a temperature range consistent with the material and the intended service.

8.4.2.3 Corrugated and other bends

Dimensions and configuration shall conform to the design.

8.4.3 Forming

The temperature range for forming shall be consistent with material, intended service, and specified heat treatment.

8.4.4 Required heat treatment for bending and forming

Heat treatment shall be performed in accordance with Paragraph 8.3.4.3.2.1 when required by the following:

8.4.4.1 Hot bending and forming

After hot bending and forming, heat treatment is required for P-Nos. 4, 5, 6 and 10A materials in all thicknesses. Times and temperatures shall be in accordance with 8.5.2.

8.4.4.2 Cold bending and forming

After cold bending and forming, heat treatment is required (for all thicknesses, and with temperature and duration as given in Table 11 when any of the following conditions exist:

8.4.4.2.1 For P-Nos. 1 through 6 materials see Note 1 on Table 11, where the maximum calculated fiber elongation after bending or forming exceeds 50% of specified basic minimum elongation (in the direction of severest forming) for the applicable specification, grade, and thickness. This requirement may be waived if it can be demonstrated that the selection of pipe and the choice of bending or forming process provide assurance that, in the finished condition, the most severely strained material retains at least 10% elongation.

8.4.4.2.2 For any material requiring impact testing, where the maximum calculated fiber elongation after bending or forming will exceed 5%.

8.4.4.2.3 When specified in the engineering design.

TABLE 11 - REQUIREMENTS FOR HEAT TREATMENT AFTER WELDING

BASE METAL P-NUMBER [NOTE (1)]	WELD METAL ANALYSIS A-NUMBER [NOTE (2)]	BASE METAL GROUP	NOMINAL WALL THICKNESS		SPECIFIED min. TENSILE STRENGTH, BASE METAL		METAL TEMPERATURE RANGE		HOLDING TIME		BRINELL HARDNESS [NOTE (3)] min. max.
			mm	inch	MPa	Ksi	°C	°F	hr/25mm	NOMINAL WALL TIME	
									hr.		
1	1	Carbon steel	≤ 19 > 19	≤ 3/4 > 3/4	All All	All All	None 593-649	None 1100-1200	... 1	... 1	......
3	2,11	Alloy steels, Cr ≤ 1/2%	≤ 19 > 19 All	≤ 3/4 > 3/4 All	≤ 490 All > 490	≤ 71 All > 71	None 593-718 593-718	None 1100-1325 1100-1325	... 1 1	... 1 1	... 215 225
4	3	Alloy steels, 2/2% < Cr ≤ 2%	≤ 12.7 > 12.7 All	≤ 1/2 > 1/2 All	≤ 490 All > 490	≤ 71 All > 71	None 704-746 704-746	None 1300-1375 1300-1375	... 1 1	... 1 1	... 225 225
5	4,5	Alloy steels, 2 1/4% ≤ Cr ≤ 10% (53% Cr, 50.15% C) (≥ 3% Cr or ≥ 0.15% C or)	≤ 12.7 > 12.7	≤ 1/2 > 1/2	All All	All All	None 704-760	None 1300-1400	... 1	... 1	... 241
6	6	High alloy steels martensitic A 240 Cr-429	All	All	All	All	732-788	1350-1450	1	1	241
7	7	High alloy steels ferritic	All	All	All	All	621-663	1150-1225	1	1	241
8	8,9	High alloy steels austenitic	All	All	All	All	None	None	...	...	...
9A, 9B	10	Nickel alloy steels	≤ 19 > 19	≤ 3/4 > 3/4	All All	All All	None 593-635	None 1100-1175	... 1/2	... 1	......
10	...	Cr-Cu steel	All	All	All	All	760-816 ⁴	1400-1500 ⁴	1/2	1/2	...
10A	...	Min-V steel	≤ 19 > 19 All	≤ 3/4 > 3/4 All	≤ 490 All > 490	≤ 71 All > 71	None 593-704 593-704	None 1100-1300 1100-1300	... 1 1	... 1 1	... 215 215
10E	...	27 Cr steel	All	All	All	All	663-704 ⁵	1225-1300 ⁵	1	1	...
10H	...	Cr-Ni-Mn steel	All	All	All	All	Note (6)	Note (6)	1/2	1/2	...
11A, 5G 1	...	8Ni, 9Ni steel	≤ 51 > 51	≤ 2 > 2	All All	All All	None 552-595 ⁴	None 1025-1085 ³	... 1	... 1	......
11A, 5G 2	...	5Ni steel	> 51	> 2	All	All	552-595 ⁴	1025-1085 ³	1	1	...

(to be continued)

TABLE 11 (continued)

Notes:

1) P-Number from ASME, BPV Code, (Boilers and pressure vessels code) Section IX, Table QW-422. Special P-Numbers (SP-1, SP-2, SP-3, SP-4, and SP-5) require special consideration.

The required thermal treatment for Special P-Numbers shall be established by the engineering design and demonstrated by the welding procedure qualification.

2) A-Number from BPV Code, Section IX, Table QW-442.

3) See Paragraph 8.5.2.8.

4) Cool as rapidly as possible after the hold period.

5) Cooling rate to 649°C (1200°F) shall be less than 56°C (100°F)/hr, thereafter, the cooling rate shall be fast enough to prevent embrittlement.

6) Postweld heat treatment is neither required nor prohibited, but any heat treatment applied shall be performed at 982°C-1038°C (1800°F-1900°F) followed by rapid cooling.

7) Cooling rate shall be > 167°C (300°F)/hr to 316°C (600°F)/h.

8.5 Effect of Heat Treatment

8.5.1 General

8.5.1.1 Many of the mechanical properties of materials are improved by various heat treatments. Unfortunately, such properties as hardness and strength are often achieved at the expense of corrosion resistance. For example, the hardness and strength of martensitic steels are counterbalanced by a lower corrosion resistance than for the ferritic and austenitic steels. The very high strengths achieved for precipitation-hardened steels are due to the secondary precipitates formed during the solution heat treating and aging process. As discussed above, precipitates with electrochemical properties distinctly different from those of the matrix have a deleterious effect on corrosion.

8.5.1.2 Processes such as cold working, in which the material is plastically deformed into some desired shape, lead to the formation of elongated and highly deformed grains and a decrease in corrosion resistance. Cold working can also introduce residual stresses that make the material susceptible to stress-corrosion cracking. An improvement in corrosion resistance can be achieved by subsequently annealing at a temperature at which grain recrystallization can occur. A partial anneal leads to stress relief without a major effect on the overall strength of the material.

8.5.1.3 From the corrosion viewpoint, welding is a particularly troublesome treatment. Because welding involves the local heating of a material, it can lead to phase transformations and the formation of secondary precipitates. It can also induce stress in and around the weld. Such changes can lead to significant local differences in electro-chemical properties as well as the onset of such processes as intergranular corrosion. Therefore, the weld filler metal should be as close in electro-chemical properties to the base metal as technically feasible, and the weld should be subsequently stress relieved. Detailed information on the corrosion problems associated with welded joints can be found in the article "corrosion of weldment" in Vol. 13 Corrosion Handbook (see Clause 8.3.1).

8.5.1.4 Heat treatment shall be used to avert or relieve the detrimental effects of high temperature and severe temperature gradients inherent in welding, and to relieve residual stresses created by bending and forming. Provisions in 8.5.2 are basic practices which are suitable for most welding, bending, and forming operations, but not necessarily appropriate for all service conditions.

8.5.2 General Heat treatment requirements

8.5.2.1 Heat treatment shall be in accordance with the material groupings and thickness ranges in Table 11 except as provided in Paragraphs 8.5.3.1 and 8.5.3.2.

8.5.2.2 Heat treatment to be used after production welding shall be specified in the Welding Procedure Specification (WPS) and shall be used in qualifying the welding procedure.

8.5.2.3 The engineering design shall specify the examination and/or other production quality control (not less than the requirements of this Standard) to ensure that the final welds are of adequate quality.

8.5.2.4 Heat treatment for bending and forming shall be in accordance with 8.4.4.

8.5.2.5 Governing thickness

When components are joined by welding, the thickness to be used in applying the heat treatment provisions of Table 11 shall be that of the thicker component measured at the joint, except as follows.

8.5.2.5.1 In the case of branch connections, metal (other than weld metal) added as reinforcement, whether an integral part of a branch fitting or attached as a reinforcing pad or saddle, shall not be considered in determining heat treatment requirements. Heat treatment is required, however, when the thickness through the weld in any plane through the branch is greater than twice the minimum material thickness requiring heat treatment, even though the thickness of the components at the joint is less than the minimum thickness. Thickness through the weld for the details shown in Fig. 23D shall be computed using the following formulas:

$$\text{Sketch (1)} = T_b + t_c$$

$$\text{Sketch (2)} = T_h + t_c$$

$$\text{Sketch (3)} = \text{greater of } T_b + t_c \text{ or } T_h + t_c$$

Where:

T_b = nominal thickness of branch pipe

T_h = nominal thickness of header

t_c = check (ok) of $0.7 T_b$

T_r = nominal thickness of reinforcing pad or saddle

t_{\min} = lesser of T_b or T_r

$$\text{Sketch (4)} = T_h + T_r + t_c$$

$$\text{Sketch (5)} = T_b + t_c$$

8.5.2.5.2 In the case of fillet welds at slip-on and socket welding flanges and piping connections NPS 2 and smaller, for seal welding of threaded joints in piping NPS 2 and smaller, and for attachment of external non-pressure parts such as lugs or other pipe supporting elements in all pipe sizes, heat treatment is required when the thickness through the weld in any plane is more than twice the minimum material thickness requiring heat treatment (even though the thickness of the components at the joint is less than that minimum thickness) except as follows:

a) not required for P-No. 1 materials when weld throat thickness is 16 mm ($\frac{5}{8}$ inch) or less, regardless of base metal thickness;

b) not required for P-No. 3, 4, 5, or 10A materials (see Table 11) when weld throat thickness is 13 mm ($\frac{1}{2}$ inch) or less, regardless of base metal thickness, provided that not less than the recommended preheat is applied, and the specified minimum tensile strength of the base metal is less than 490 MPa (71 ksi);

c) not required for ferritic materials when welds are made with filler metal which does not air harden. Austenitic welding materials may be used for welds to ferritic materials when the effects of service conditions, such as differential thermal expansion due to elevated temperature, or corrosion, will not adversely affect the weldment.

8.5.2.6 Heating and cooling

The heating method shall provide the required metal temperature, metal temperature uniformity, and temperature control, and may include an enclosed furnace, local flame heating, electric resistance, electric induction, or exothermic chemical reaction. The cooling method shall provide the required or desired cooling rate and may include cooling in a furnace, in air, by application of local heat or insulation, or by other suitable means.

8.5.2.7 Temperature verification

Heat treatment temperature shall be checked by thermocouple pyrometers or other suitable methods to ensure that the Welding Procedure Specification (WPS) requirements are met. See Paragraph 8.6.4.2 for attachment of thermocouples by the capacitor discharge method of welding.

8.5.2.8 Hardness tests

Hardness tests of production welds and of hot bent and hot formed piping are intended to verify satisfactory heat treatment. The hardness limit applies to the weld and to the Heat Affected Zone (HAZ) tested as close as practicable to the edge of the weld:

- a) Where a hardness limit is specified in Table 11 at least 10% of welds, hot bends, and hot formed components in each furnace heat treated batch and 100% of those locally heat treated shall be tested.
- b) When dissimilar metals are joined by welding, the hardness limits specified for the base and welding materials in Table 11 shall be met for each material.

8.5.3 Specific requirements of heat treatment

Where warranted by experience or knowledge of service conditions, alternative methods of heat treatment or exceptions to the basic heat treatment provisions of Paragraph 8.5.2 may be adopted as provided in 8.5.3.1 and 8.5.3.2.

8.5.3.1 Alternative heat treatment

Normalizing, or normalizing and tempering, or annealing may be applied in lieu of the required heat treatment after welding, bending, or forming, provided that the mechanical properties of any affected weld and base metal meet specification requirements after such treatment and that the substitution is approved by the designer.

8.5.3.2 Exceptions to basic requirements

The basic practices therein may require modification to suit service conditions in some cases. In such cases, the designer may specify more stringent requirements in the engineering design, including heat treatment and hardness limitations for lesser thickness, or may specify less stringent heat treatment and hardness requirements, including none.

8.5.3.2.1 When provisions less stringent than those in Table 11 are specified, the designer must demonstrate to the owner's satisfaction the adequacy of those provisions by comparable service experience, considering service temperature and its effects, frequency and intensity of thermal cycling, flexibility stress levels, probability of brittle failure, and other pertinent factors. In addition, appropriate tests shall be conducted, including Welding Procedure Specification (WPS) qualification tests.

8.5.3.3 Dissimilar materials

8.5.3.3.1 Heat treatment of welded joints between dissimilar ferritic metals or between ferritic metals using dissimilar ferritic filler metal shall be at the higher of the temperature ranges in Table 11 for the materials in the joint.

8.5.3.3.2 Heat treatment of welded joints including both ferritic and austenitic components and filler metals shall be as required for the ferritic material or materials unless otherwise specified in the engineering design.

8.5.3.4 Delayed heat treatment

If a weldment is allowed to cool prior to heat treatment, the rate of cooling shall be controlled or other means shall be used to prevent detrimental effects.

8.5.3.5 Partial heat treatment

When an entire structure assembly to be heat treated cannot be fitted into the furnace, it is permissible to heat treat in more than one heat, provided there is at least (0.3 m) 1 ft overlap between successive heats, and that parts of the assembly outside the furnace are protected from harmful temperature gradients.

8.5.3.6 Local heat treatment

When heat treatment is applied locally, a circumferential band of the run structure, and of the branch where applicable, shall be heated until the specified temperature range exists over the entire section(s), gradually diminishing beyond the ends of a band which includes the weldment or the bent or formed section and at least 25 mm (1 inch) beyond the edges thereof.

8.5.4 Heat treatment of casing and tubing

8.5.4.1 General

Pipe furnished to this specification shall be made by the seamless or electric weld process as shown in Table 12 and as specified on the purchase order. Pup joints and connectors may be made from standard casing or tubing or by machining heavy wall casing, tubing or bar stock. Couplings shall be manufactured by one of the processes listed in Paragraph 8.1 of API, 5CT. Cold drawn tubular products without appropriate heat treatment are not acceptable:

- a) Seamless pipe is defined as a wrought steel tubular product made without a welded seam. It is manufactured by hot working steel, or if necessary, by subsequently cold finishing the hot-worked tubular product to produce the desired shape, dimensions, and properties.
- b) Electric-welded pipe is defined as pipe having one longitudinal seam formed by electric-flash welding or electric-resistance welding, without the addition of extraneous metal. The weld seam of electric-welded pipe shall be heat treated after welding to a minimum temperature of 538°C (1000°F) or processed in such a manner that no untempered martensite remains.

8.5.4.2 Heat treatment

Process of manufacture of pipe for prevention of stress corrosion pipe shall be heat treated as stipulated in Table 12 for the particular grade and type specified by the Purchaser. Heat treated upset pipe shall be heat treated full length after upsetting. When requested by the Purchaser, the manufacturer/processor shall produce evidence to show that the tempering practice for Group 2 pipe will result in the pipe attaining the minimum tempering temperature. Pipe and coupling stock shall be heat treated the full length.

TABLE 12 - PROCESS OF MANUFACTURE AND HEAT TREATMENT

	Grade	Type	Process of Manufacture	Heat Treatment	Tempering Temp., Min.		
					*F	*C	
Group 1	H40	—	S or EW	None	—	—	
	J55	—	S or EW	None.	—	—	
	K55	—	S or EW	None.	Note 1	—	—
					Note 1	—	—
					Note 1	—	—
N80 (Casing)	—	S or EW	None.	—	—		
N80 (Piping)	—	S or EW	Note 1	—	—		
Group 2	C75	1	S or EW	N&T	1150	621	
	C75	2	S or EW	Q&T	1150	621	
	C75	3	S or EW	N&T	1150	621	
	C75	9 Cr	S	Q&T*	1100	593	
	C75	13 Cr	S	Q&T*	1100	593	
	C90	1	S	Q&T	1150	621	
	C90	2	S	Q&T	1150	621	
	C95	—	S or EW	Q&T	1000	538	
	L80	1	S or EW	Q&T	1050	566	
	L80	9 Cr	S	Q&T*	1100	593	
L80	13 Cr	S	Q&T*	593	1100		
Group 3	P105	—	S	Q&T or N&T†	—	—	
	P110	—	S	Q&T or N&T†	—	—	
Group 4	Q125	1	S or EW*	Q&T	—	—	
	Q125	2	S or EW*	Q&T	—	—	
	Q125	3	S or EW*	Q&T	—	—	
	Q125	4	S or EW*	Q&T	—	—	

Note:

1) Full length normalized, normalized and tempered (N & T), or quenched and tempered (Q & T), at the manufacturer’s option or if so specified on the purchase order.

* Type 9 Cr and 13 Cr grades may be air quenched.

♣ Unless otherwise agreed on between purchaser and manufacturer/processor.

• Special requirements unique to electric welded Q-125 casing are specified in SR11. (Supplementary requirements No. 11, API, 5CT) when electric welded Q-125 casing is furnished, the provisions of SR11 are automatically in effect.

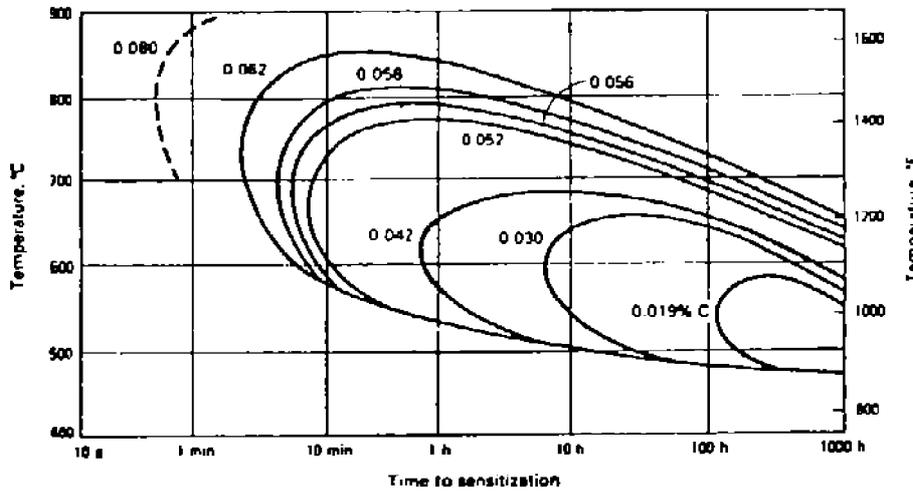
8.5.5 Heat treatment of stainless steel

Improper heat treatment can produce deleterious changes in the microstructure of stainless steels. The most troublesome problems are carbide precipitation (sensitization) and precipitation of various intermetallic phases, such as σ , χ , and laves (η).

8.5.5.1 Sensitization

Sensitization, or carbide precipitation at grain boundaries, can occur when austenitic stainless steels are heated for a period of time in the range of about 425 to 870°C (800 to 1600°F). Time at temperature will determine the amount of carbide precipitation. When the chromium carbides precipitate in grain boundaries, the area immediately adjacent is depleted of chromium. When the precipitation is relatively continuous, the depletion renders the stainless steel susceptible to intergranular corrosion, which is the dissolution of the low-chromium layer or envelope surrounding each grain. Sensitization also lowers resistance to other forms of corrosion, such as pitting, crevice corrosion, and SCC.

Time-temperature-sensitization curves are available that provide guidance for avoiding sensitization and illustrate the effect of carbon content on this phenomenon Fig. 14. The curves shown in Fig. 14 indicate that a Type 304 stainless steel with 0.062% C would have to cool below 595°C (1100°F) within about 5 min to avoid sensitization, but a Type 304L with 0.030% C could take about 20 h to cool below 480°C (900°F) without becoming sensitized. These curves are general guidelines and should be verified before they are applied to various types of stainless steels.



TIME-TEMPERATURE-SENSITIZATION CURVES FOR TYPE 304 STAINLESS STEEL IN A MIXTURE OF CuSO_4 AND H_2SO_4 CONTAINING FREE COPPER. CURVES SHOW THE TIMES REQUIRED FOR CARBIDE PRECIPITATION IN STEELS WITH VARIOUS CARBON CONTENTS. CARBIDES PRECIPITATE IN THE AREAS TO THE RIGHT OF THE VARIOUS CARBON CONTENT CURVES

Fig. 14

Another method of avoiding sensitization is to use stabilized steels. Such stainless steels contain titanium and/or niobium. These elements have an affinity for carbon and form carbides readily; this allows the chromium to remain in solution even for extremely long exposures to temperatures in the sensitizing range. Type 304L can avoid sensitization during the relatively brief exposure of welding, but it will be sensitized by long exposures.

Annealing is the only way to correct a sensitized stainless steel. Because different stainless steels require different temperatures, times, and quenching procedures, the user shall contact the material supplier for such information. A number of tests can detect sensitization resulting from carbide precipitation in austenitic and ferritic stainless steels. The most widely used tests are described in ASTM Standards A 262 and A 763. More detailed information on sensitization of stainless steels can be found in the article "Metallurgically Influenced Corrosion" in this Volume.

8.5.5.2 Precipitation of intermetallic phases

Sigma-phase precipitation and precipitation of other intermetallic phases also increase susceptibility to corrosion. Sigma phase is a chromium-molybdenum-rich phase that can render stainless steels susceptible to intergranular corrosion, pitting, and crevice corrosion. It generally occurs in higher-alloyed stainless steels (high-chromium high-molybdenum stainless steels). Sigma phase can occur at a temperature range between 540 and 900°C (1000 and 1650°F). Like sensitization, it can be corrected by solution annealing. Precipitation of intermetallic phases in stainless steels is also covered in detail in the article "Metallurgically Influenced Corrosion".

8.5.5.3 Cleaning procedures

Any heat treatment of stainless steel shall be preceded and followed by cleaning. Steel shall be cleaned before heat treating to remove any foreign material that may be incorporated into the surface during the high-temperature exposure. Carbonaceous materials on the surface could result in an increase in the carbon content on the surface, causing carbide precipitation. Salts could cause excessive intergranular oxidation. Therefore, the stainless steel must be clean before it is heat treated.

After heat treatment, unless an inert atmosphere was used during the process, the stainless steel surface will be covered with an oxide film. Such films are not very corrosion resistant and must be removed to allow the stainless steel to form its passive film and provide the corrosion resistance for which it was designed. There are numerous cleaning methods that may be used before and after heat treating. An excellent guide is ASTM A 380.

8.6 Preheating of Metals

8.6.1 General

Preheating is used, along with heat treatment, to minimize the detrimental effects of high temperature and severe thermal gradients inherent in welding. The necessity for preheating and the temperature to be used shall be specified in the engineering design and demonstrated by procedure qualification. The requirements and recommendations herein apply to all types of welding including tack welds, repair welds, and seal welds of threaded joints.

8.6.2 Requirements and recommendations

Required and recommended minimum preheat temperatures for materials of various P-Numbers are given in Table 13. If the ambient temperature is below 0°C (32°F), the recommendations in Table 13 become requirements. The thickness intended in Table 13 is that of the thicker component measured at the joint.

TABLE 13 - PREHEAT TEMPERATURES

Base Metal P-No. [Note (1)]	Weld Metal Analysis A-No. [Note (2)]	Base Metal Group	Nominal Wall Thickness		Specified Min. Tensile Strength, Base Metal		Min. Temperature			
							Required		Recommended	
			mm	in.	MPa	ksi (5)	°C	°F	°C	°F
1	1	Carbon steel	< 25.4	< 1	≤ 490	≤ 71	...	...	10	50
			≥ 25.4	≥ 1	All	All	...	...	79	175
			All	All	> 490	> 71	...	...	79	175
3	2, 11	Alloy steels, Cr ≤ 1/2%	< 12.7	< 1/2	≤ 490	≤ 71	...	...	10	50
			≥ 12.7	≥ 1/2	All	All	...	...	79	175
			All	All	> 490	> 71	...	...	79	175
4	3	Alloy steels 1/2% < Cr ≤ 2%	All	All	All	All	149	300	...	...
5	4, 5	Alloy steels, 2 1/4% ≤ Cr ≤ 10%	All	All	All	All	177	350	...	...
	6	High alloy steels martensitic	All	All	All	All	...	...	149 ^a	300 ^a
7	7	High alloy steels ferritic	All	All	All	All	...	...	10	50
8	8, 9	High alloy steels austenitic	All	All	All	All	...	...	10	50
9A, 9B	10	Nickel alloy steels	All	All	All	All	...	...	93	200
10	...	Cr-Cu steel	All	All	All	All	149-204	300-400	...	...
10A	...	Mn-V steel	All	All	All	All	...	...	79	175
10E	...	27Cr steel	All	All	All	All	149 ^a	300 ^a	...	...
11A SG 1	...	8Ni, 9Ni steel	All	All	All	All	...	...	10	50
11A SG 2	...	5Ni steel	All	All	All	All	10	50	...	...
21-52	...	...	All	All	All	All	...	...	10	50

Notes:

- 1) P-Number from Boiler and Pressure Vessel Code (BPV) Section IX, Table QW-422 of ASME. Special P-Numbers (SP-1, SP-2, SP-3, SP-4, and SP-5) require special consideration. The required thermal treatment for Special P-Numbers shall be established by the engineering design and demonstrated by the welding procedure qualification.
- 2) A-Number from BPV Code, Section IX, QW-442.
- 3) Maximum Interpass Temperature 316°C (600°F).
- 4) Maintain interpass Temperature 177°C-232°C (350°F-470°F).
- 5) Ksi is Kips per square inch (1000 lb. per square inch).

8.6.3 Unlisted materials

Preheat requirements for an unlisted material shall be specified in the Welding Procedure Specification (WPS).

8.6.4 Temperature verification

8.6.4.1 Preheat temperature shall be checked by use of temperature indicating crayons, thermocouple pyrometers, or other suitable means to ensure that the temperature specified in the WPS is obtained prior to and maintained during welding.

8.6.4.2 Thermocouples may be temporarily attached directly to pressure containing parts using the capacitor discharge method of welding without welding procedure and performance qualifications. After thermocouples are removed, the areas shall be visually examined for evidence of defects to be repaired.

8.6.5 Preheat zone

The preheat zone shall extend at least 25 mm (1 inch) beyond each edge of the weld.

8.6.6 Heat treatment specific requirements

8.6.6.1 Dissimilar materials

When materials having different preheat requirements are welded together, it is recommended that the higher temperature shown in Table 13 be used.

8.6.6.2 Interrupted welding

If welding is interrupted, the rate of cooling shall be controlled or other means shall be used to prevent detrimental effects in the piping. The preheat specified in the WPS shall be applied before welding is resumed.

8.6.6.3 For Cr-Mo steels, preheating in accordance with Appendix R of ASME Code Section VIII and irrespective of wall thickness, shall be carried out during the time of welding. This applies also for welding of nozzles, attachments, temporary brackets and miscellaneous supports, temperatures shall be checked and monitored.

8.6.6.4 A preheating as above shall be performed also for carbon steel of large thickness (such as above 40 mm), for high-strength steel of mean thickness (such as above 25 mm).

8.6.6.5 When the required preheat temperature is 144°C or higher, the postal temperature shall be maintained at preheat temperature until the weld is completed.

8.7 Surface Treatment of Stainless Steel

8.7.1 Surface condition

To ensure satisfactory service life, the surface condition of stainless steels must be given careful attention. Smooth surfaces, as well as freedom from surface imperfections, blemishes, and traces of scale and other foreign material, reduce the probability of corrosion. In general, a smooth, highly polished, reflective surface has greater resistance to corrosion. Rough surfaces are more likely to catch dust, salts, and moisture, which tend to initiate localized corrosive attack.

Oil and grease can be removed by using hydrocarbon solvents or alkaline cleaners, but these cleaners must be removed before heat treatment. Hydrochloric acid (HCl) formed from residual amounts of trichloroethylene, which is used for degreasing, has caused severe attack of stainless steels. Surface contamination may be caused by machining, shearing, and drawing operations. Small particles of metal from tools become embedded in the steel surface and, unless removed, may cause localized galvanic corrosion. These particles are best removed by the passivation treatments described below. Additional information on cleaning and descaling of stainless steel is available in Volume 5 of the 9th Edition of Metals Handbook.

Shotblasting or sandblasting should be avoided unless iron-free silica is used; metal shot, in particular, will contaminate the stainless steel surface. If shotblasting or shotpeening with metal grit is unavoidable, the parts must be cleaned after blasting or peening by immersing them in an HNO_3 solution, as noted above.

8.7.2 Passivation techniques

During handling and processing operations, such as machining, forming, tumbling, and lapping, particles of iron, tool steel, or shop dirt may be embedded in or smeared on the surfaces of stainless steel components. These contaminants may reduce the effectiveness of the natural oxide (passive) film that forms on stainless steels exposed to oxygen at low temperatures. If allowed to remain, these particles may corrode and produce rustlike spots on the stainless steel. To prevent this condition, semifinished or finished parts are given a passivation treatment. This treatment consists of cleaning and then immersing stainless steel parts in a solution of HNO_3 or of HNO_3 plus oxidizing salts. The treatment dissolves the embedded or smeared iron, restores the original corrosion-resistant surface, and maximizes the inherent corrosion resistance of the stainless steel.

8.7.2.1 Cleaning

Each workpiece to be passivated must be cleaned thoroughly to remove grease, coolant, or other shop debris. A worker will sometimes eliminate the cleaning step based on the reasoning that the cleaning and passivation of a grease-laden part will occur simultaneously by immersing it in an HNO_3 bath. This assumption is mistaken. The grease will react with the HNO_3 to form gas bubbles, which collect on the surface of the workpiece and interfere with passivation. Also, contamination of the passivating solution (particularly with high levels of chlorides) can cause flash attack, which results in a gray or black appearance and deterioration of the surface.

To avoid such problems, each part should be wiped clean of any large machining chips or other debris. More tenacious deposits should be removed by brushing with a stainless steel wire brush, grinding, polishing with an iron-free abrasive, or sandblasting. Tools and materials used for these processes should be clean and used only for stainless steels. Machining, forming, or grinding oils must be removed in order for passivation to be effective. Cleaning should begin with solvent cleaning, which may be followed by alkaline soak cleaning and thorough water rinsing. Optimum results are obtained in passivation when the parts to be treated are as clean as they would have to be for plating. When large parts or bulky vessels are to be cleaned, it may be necessary to apply cleaning liquids by means of pressure spray; exterior surfaces may be cleaned by immersion or swabbing.

8.7.2.2 Passivating

After cleaning, the workpiece can be immersed in the passivating acid bath. As shown in Table 14, the composition of the acid bath depends on the grade of stainless steel. The 300-series stainless steels can be passivated in 20 vol% HNO_3 . A sodium dichromate ($\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$) addition or an increased concentration of HNO_3 is used for less corrosion-resistant stainless steels to reduce the potential for flash attack.

The procedure suggested for passivating free-machining stainless steels is somewhat different from that used for nonfree-machining grades. This is because sulfides of sulfur-bearing free-machining grades, which are totally or partially removed during passivation, create microscopic discontinuities in the surface of the machined part. Even normally efficient water rinses can leave residual acid trapped in these discontinuities after passivation. This acid can then attack the surface of the part unless it is neutralized or removed. For this reason, a special passivation process, referred to as the alkaline-acid-alkaline method, is suggested for freemachining grades.

**TABLE 14 - PASSIVATING SOLUTIONS FOR STAINLESS STEELS
(NONFREE-MACHINING GRADES)**

Grade	Passivation treatment
Austenitic 300-series grades Grades with $\geq 17\%$ Cr (except 440 series)	20 vol% HNO ₃ at 50-60°C (120-140°F) for 30 min
Straight chromium grades (12-14% Cr)	20 vol% HNO ₃ plus 22 g/L (3 oz/gal)
High-carbon/high-chromium grades (440 series)	Na ₂ Cr ₂ O ₇ ·2H ₂ O at 50-60°C (120-140°F) for 30 min or
Precipitation-hardening grades	50 vol% HNO ₃ at 50-60°C (120-140°F) for 30 min

The following steps should be followed when passivating free-machining stainless steels with the alkaline-acid-alkaline technique:

8.7.2.2.1 After degreasing, soak the parts for 30 min in 5 wt% sodium hydroxide (NaOH) at 70 to 80°C (160 to 180°F).

8.7.2.2.2 Water rinse.

8.7.2.2.3 Immerse the part for 30 min in 20 vol% HNO₃ plus 22 g/L (3 oz/gal) Na₂Cr₂O₇·2H₂O at 50 to 60°C (120 to 140 °F).

8.7.2.2.4 Water rinse.

8.7.2.2.5 Immerse for 30 min in 5 wt% NaOH at 70 to 80°C (160 to 180°F).

8.7.2.2.6 Water rinse and dry.

8.7.2.3 Testing

Testing is often performed to evaluate the passivated surface. For example, 400-series, precipitation-hardening, and free-machining stainless steels are often tested in a cabinet capable of maintaining 100% humidity at 35°C (95°F) for 24 h. Material that is properly passivated will be virtually free of rust, although light staining may occur. Austenitic 300-series grades can be evaluated using a technique given in ASTM Standard Method A 380. This test consists of swabbing the part with a copper sulfate (CuSO₄·5H₂O)/sulfuric acid (H₂SO₄) solution; wetness should be maintained for 6 min. Free iron, if present, plates out the copper from the solution, and the surface develops a copper cast or color. Information on passivation treatments for corrosion-resistant steels is also available in US Federal Specification QQ-P-35B.

8.8 Painting, Coating and Lining

8.8.1 Painting

Painting shall be in accordance with IPS-C-TP-102, with respect to Engineering Standard IPS-E-TP-100.

8.8.2 Coating

Coating when specified shall be in accordance with IPS-C-TP-274, with respect to relevant Engineering Standard IPS-E-TP-270.

8.8.3 Lining

Lining shall be referred in accordance with IPS-C-TP-352, with respect to relevant Engineering Standard IPS-E-TP-350.

8.9 Installation, Assembly and Erection

8.9.1 Metallic structures, steelworks and components are prepared for assembly and erection by one or more of the fabrication processes covered in this Standard. When any of these processes is used in assembly and erection, considerations are the same as for fabrication.

8.9.2 Thermal insulating of pipe and equipment shall be in accordance with IPS-C-TP-701, with respect to the engineering standard of IPS-E-TP-700.

8.9.3 Painting, coating and lining and their repairs after assembly shall be in accordance with 8.8.

8.9.4 Cathodic and anodic protection installations shall be in accordance with IPS-C-TP-820, with respect to engineering standard for cathodic protection IPS-E-TP-820.

8.10 Handling, Transport, Storage and Erection of Coated Metalworks

8.10.1 Selection of coating systems

One of the factors which shall be taken into account when selecting a coating system for a particular item is its resistance to mechanical damage during service. When works-coated steelwork is involved, the risk of damage to coatings during handling, transport, storage and erection is greatly increased and the coating's resistance to mechanical damage assumes prime importance.

In addition to the risks of mechanical damage, coatings applied at works may also be subjected to many different adverse environments during transport and storage of steelwork before erection. Marine and other contaminating environments of various types, high humidity, and prolonged exposure for a variety of reasons may have to be allowed for. In some cases covers and other forms of protection may be provided prior to erection but in most cases, the coating system shall take these requirements into account in addition to fulfilling its role when in normal service.

Mechanical damage to coatings is of less consequence when only part of the system has been applied, because the making-good of damage to a full coating system is more difficult and costly, and may even be impossible where patch-painting of a final coat is not permitted. However, the adoption of a policy of partial coating at works and completion of the system at a later stage may lead to problems of intercoat contamination, and the resistance of the coating to the effects of adverse environments during transport and storage is reduced.

8.10.2 Methods of preventing damage

Care in the selection of coating systems will help to minimize damage to coatings before erection. Features which can be incorporated in the design of the fabrication and other measures which can be adopted to reduce further the effects of mechanical damage are as follows:

- a) The design shall include lifting lugs or brackets where practicable.
- b) The provision of a special lifting harness, nylon slings, rubber protected chains and chocks, etc.
- c) An adequate drying/curing period for each coat and for the complete system before handling.
- d) Methods of loading that will reduce site handling to the minimum.
- e) Order and timing of loading to reduce site storage to the minimum.
- f) Special supports, packings and lashings on the vehicles and trucks, and stacking in holds and on decks, to avoid chafing.
- g) Special wrapping of coated pipes and packaging of smaller items.

8.10.3 Storage of coated steelwork

The degradation of coatings on stored steelwork can be minimized (especially in poor environments) by the adoption of the following precautions.

8.10.3.1 Separators

Coated surfaces should preferably not be in contact. Wrapping, packaging or crates used to reduce damage whilst items are in transit may perform this function. For large items, timber packings should be specified.

8.10.3.2 Stacking

Components shall be stacked in such a manner that there can be no pending where cover is not provided. It may be necessary to limit the number of layers in a stack. The bottom layer shall be laid on packings raised above the ground and the rain splash zone. Timber, usually of a softwood variety, provides a good surface on which coated steelwork may be stored with minimum damage to the coatings. Timber packing may be set on top of concrete or other more rigid supports. The area of the timber in contact with the members should be sufficiently large to avoid damage to the coatings, taking into account the dead weight of the steelwork stacked on the packing. The number of positions of the packing shall ensure that steelwork is not distorted. Packings shall be reasonably clean and free from any contaminating agents which may adversely affect coatings.

8.10.4 Responsibilities for preventing damage

The responsibilities for care of the coatings should be given careful consideration, since the benefits of careful coating work and handling whilst the items are at the works can be lost by rough treatment during transport to, or storage on, the site. The possible variations in the methods of transport and handling whilst steelwork is being moved and erected and also in storage environments, and other considerations are limitless. It is not possible to give firm recommendations and the requirements for each project should be considered individually. It is essential, however, that the responsibilities at the design and erection stage are clearly defined and that decisions on coating systems, design requirements, methods of transport and handling, equipment used and other special measures, are taken with a clear understanding of all requirements.

8.10.5 Transportation, handling, and storage of coated pipes

8.10.5.1 General

API RP5CI tubular goods in general, and threads in particular, are made with such precision that they require careful handling, and whether new, used, or reconditioned, they should always be handled with thread protectors in place.

8.10.5.2 Transportation

8.10.5.2.1 Water transportation

Suppliers or their agents should provide proper supervision at the time of loading and unloading of water carriers to guard against improper or insufficient dunnage, inadequate bracing to prevent shifting during lurching of the ship, stowing in or adjacent to bilge water, injurious chemicals or other corrosive material, dragging pipe along the pile and permitting couplings or thread protectors to hook together or strike the edge of hatch opening or bump against the ship rail.

8.10.5.2.2 Railroad transportation

When loading pipe on freight cars in addition to ICC (International Chamber of Commerce) requirements, wooden stringers shall be provided across the bottom of the car to provide suitable support for pipe and to allow space for lifting, and also to keep pipe away from dirt. If the bottom of the car is uneven, the stringers shall be rigidly shimmed so that their tops will be in the same plane. Stringers shall not be placed under couplings or the upset part of pipe. The load shall be tied down and properly bulkheaded to keep it from shifting.

8.10.5.2.3 Truck transportation

The following precautions shall be taken for truck transportation:

- a) Load pipe on bolsters and tie down with suitable chain at the bolsters. In hauling long pipe, an additional chain shall be provided in the middle.
- b) Load pipe with all couplings on the same end of truck.
- c) Care shall be taken to prevent chafing of tool-joint shoulders on adjacent joints.
- d) Do not overload truck to the point where there is any danger that load cannot be delivered to its destination without unloading.
- e) After load has been hauled a short distance retighten load binding chains loosened as a result of the load settling.

8.10.5.3 Handling

The following precautions shall be observed in handling pipe:

- a) Before unloading, make sure that the thread protectors are tightly in place. The use of a spreader-bar with a choker-sling at each end is the recommended method of handling long pipe.
- b) Avoid rough handling which might ding or dent the body of pipe. Out-of-roundness will reduce collapse strength greatly.
- c) Do not unload pipe by dropping. Unload one, two, or three lengths at a time, depending upon the number that can be fully controlled. When unloading by hand use rope slings. When rolling down skids roll pipe parallel to the stack and do not allow pipe to gather momentum or to strike the ends because, even with protectors in place, there is danger of damaging the threads.
- d) Stop each length before it reaches the preceding length, then push into place by hand.

8.10.5.4 Storage

The following precautions are recommended for pipe storage:

- a) Do not pile pipe directly on ground, rails, steel or concrete floors. The first tier of pipe shall be no less than 18 inch from the ground to keep moisture and dirt away from pipe.
- b) Pipe shall rest on supports properly spaced to prevent bending of the pipe or damage to the threads. The stringers shall lie in the same plane and be reasonably level, and shall be supported by piers adequate to carry the full stack load without settling.
- c) Provide wooden strips as separators between successive layers of pipe so that no weight rests on the couplings. Use at least three spacing strips.
- d) Place spacing strips at right angles to pipe and directly above the lower strips and supports to prevent bending of the pipe.

- e) Stagger adjoining lengths of pipe in the tiers an amount approximating the length of the coupling.
- f) Block pipe by nailing 1 by 2 or 2 by 2 blocks at both ends of the spacing strips.
- g) For purposes of safety, ease of inspection, and handling, pipe shall not be stacked higher than 3m (10 ft.) Pipe shall not be stacked higher than five tiers at the rig.
- h) Pipe in storage shall be inspected periodically and protective coatings applied when necessary to arrest corrosion.

8.10.6 Handling and storage of aluminum

8.10.6.1 Because of the excellent corrosion resistance of the 1xxx, 3xxx, 4xxx, 5xxx, and 6xxx series alloys, users occasionally have not employed good practice in the handling and storage of these alloys. This can result in water stains or in pitting. Methods to avoid these unsightly surface effects are described in the article "Cleaning and Finishing of Aluminum and Aluminum Alloys" in Volume 5 of the 9th Edition of Metals Handbook.

8.10.6.2 Water stain is superficial corrosion that occurs when sheets of bare metal are stacked or nested in the presence of moisture. The source of moisture may be condensation from the atmosphere that forms on the edges of the stack and is drawn between the sheets by capillary action. Aluminum should not be stored at temperatures or under atmospheric conditions conducive to condensation. When such conditions cannot be avoided, the metal sheets or parts should be separated and coated with oil or a suitable corrosion inhibitor. Once formed, water stain can be removed by either mechanical or chemical means, but the original surface brightness may be altered.

8.10.6.3 Outdoor storage of aluminum, even under a tarpaulin, is generally not desirable for long periods of time; this varies with the alloy, the end product, and the local environment. Moisture can collect on the surface, sometimes at relative humidities below the dew point, because of the hygroscopic nature of the dust or particles that deposit on the metal from the atmosphere. The resulting staining or localized pitting, although of little structural consequence in the 1xxx, 3xxx, 4xxx, 5xxx, and 6xxx alloys, is undesirable if the aluminum will be used for an end product for which surface finish is critical. The 2xxx and 7xxx bare alloys are susceptible to intergranular attack under these conditions, and for these alloys, use of strippable coatings, protective wrappers, papers, or inhibited organic films is advisable when adverse conditions can not be avoided.

8.10.6.4 Mechanical damage can be easily avoided by good housekeeping practices, proper equipment, and proper protection during transportation. When transporting flat sheets or plates, the aluminum should be oiled or interleaved with approved paper to prevent traffic marks, where fretting action at points of contact causes surface abrasion.

8.11 Inspection

8.11.1 Important of inspection

Excellent materials selection, design, and detailed specification for construction of a plant or a piece of equipment may be set forth, but they can be essentially meaningless if they are not followed. Proper inspection is a must-particularly for critical components operating under hazardous conditions. Inspectors shall scrutinize critically during fabrication and construction - not limiting inspection to the final product only. In addition to being capable and well qualified, inspectors should have substantial authority. Inspectional aspects are as important as design and material selection.

8.11.2 Results of lack of good inspection

Many examples of premature and sometimes catastrophic failures are known as follows:

- A section of welded 254 mm (10 inch) pipe failed because the weld penetration at the joint was only 1.6 mm ($\frac{1}{16}$ inch) (merely an overlay) incomplete weld penetration is not uncommon.

- Tube hangers in an oil refinery furnace failed because these castings were extremely porous (over 50% of the cross section at the point of fracture consisted of voids).
- Un-satisfactory performances obtained because cleaning procedures were not followed.
- Cladding metal did not bond to the substrate steel because paper labels on the inner surface of the cladding were not removed.
- Rapid corrosion of heat exchanger tubing resulted because Type 304 stainless steel was used instead of the specified 316 stainless steel.
- Stress corrosion and/or fatigue failures because the radii at fillets were sharp instead of rounded as called for on the drawings.
- Pressure tests must be properly executed.
- Many cases of improper heat treatment exist.
- Improper assembly such as cold or hot bending of pipe to proper alignment induces high stresses and other undesirable factors.
- The wrong welding rod is sometimes used.
- Poor surface preparation results in failure of coatings.
- It was found that adequate inspection translates into good quality control.

APPENDICES

APPENDIX A

A.1 General

This Appendix is prepared as a supplementary to Clause 8.3.1 to give some more details about the corrosion of weldments of metal and alloys used in Petroleum, Gas and Petrochemical Industries.

A.2 Corrosion of Carbon Steel Weldments

A.2.1 SCC in oil refineries

Monoethanolamine (MEA) is an absorbent used to remove acid gases containing H_2S and CO_2 in oil refining operations. Recent failures in several refineries have shown that cracks can be parallel or normal to welds, depending on the orientation of principal tensile stresses. Cracking has been reported to be both transgranular and intergranular.

Before 1978, postweld stress relief of carbon steel weldments in MEA systems was performed only when the metal temperature of the equipment was expected to exceed $65^\circ C$ ($150^\circ F$) and the acid gas contained more than 80% CO_2 or when temperatures were expected to exceed $95^\circ C$ ($200^\circ F$) in any acid gas concentration.

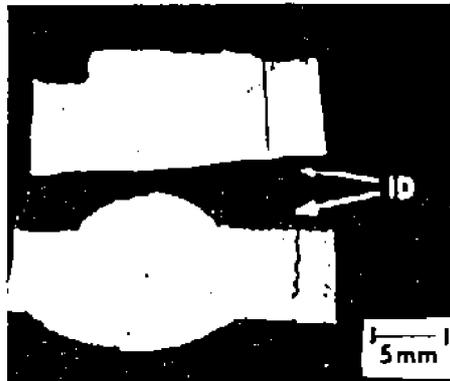
Currently, any equipment containing MEA at any temperature and at any acid gas concentration is being postweld stress relieved. This is the result of surveys conducted by several refineries to define the extent of the SCC problem in this environment. These inspection programs showed that leaks were widespread and were found in vessels that ranged in age from 2 to 25 years. However, there were no reports of cracking in vessels that had been postweld stress relieved. In addition, it was found that all concentrations of MEA were involved and that MEA solutions were usually at relatively low temperatures (below $55^\circ C$, or $130^\circ F$). Equipment found to suffer from cracking included tanks, absorbers, carbon treater drums, skimming drums, and piping. The following example of a metallurgical investigation conducted by one oil refinery illustrates the problem of SCC of carbon steel in amine service.

A.2.2 Leaking carbon steel weldments in a sulfur recovery unit

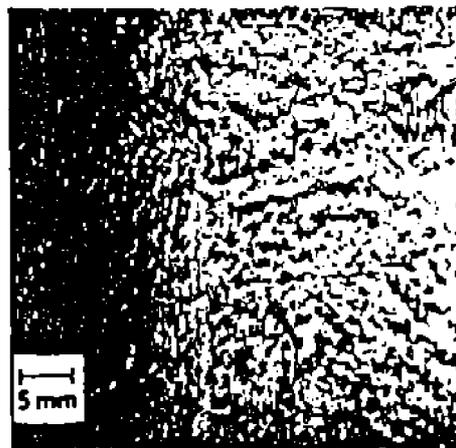
In December 1983, two leaks were discovered at a sulfur recovery unit. More specifically, the leaks were at pipe-to-elbow welds in a 152-mm (6 inch) diam line operating in lean amine service at $50^\circ C$ ($120^\circ F$) and 2.9 Mpa (425 psig). Thickness measurements indicated negligible loss of metal in the affected areas, and the leaks were clamped. In March 1984, 15 additional leaks were discovered, again at pipe-to-elbow welds of lean amine lines leading to two major refining units. The piping had been in service for about 8 years.

A.2.2.1 Investigation

Metallurgical examination of several of the welds revealed that leaking occurred at what appeared to be stress-corrosion cracks originating from the inside surface. Cracks were present in weld metal and base metal approximately 5 mm (0.2 inch) away from the weld, and they passed through the HAZ, as shown in Fig. A.2.1. In other cases, stress-corrosion cracks also originated in the HAZ. The cracks typically ran parallel to the weld (Fig. A.2.2).



**CROSS SECTIONS OF PIPE-TO-ELBOW WELDS SHOWING STRESS-CORROSION
CRACKS ORIGINATING FROM THE INSIDE SURFACE OF THE WELD METAL
AND THE BASE METAL**
Fig. A.2.1



**PHOTOGRAPH OF INSIDE SURFACE OF A PIPE SHOWING 38-mm (1.5 INCH) STRESS-
CORROSION CRACK (A) NEXT TO AND PARALLEL TO A CIRCUMFERENTIAL
WELD. ALSO SHOWN ARE SHALLOW CORROSION PITS (B)**
Fig. A.2.2

Brinell hardness values, obtained by conversion of Knoop microhardness readings, were 133 to 160 (pipe base metal), 160 to 230 (weld metal), 182 to 227 (HAZs), and 117 to 198 (elbow base metal). The pipe base metal had an equiaxed fine-grain microstructure typical of low-carbon steel, and the elbow base metal had a nonequiaxed microstructure typical of hot-finished fittings. Carbon contents ranged from 0.25 to 0.30% by weight. Cracking was intergranular.

The refinery operators immediately embarked on a program of visual inspection of all amine lines. As of June 1985, a total of 35 leaks in lean amine piping had been discovered. All leaks were at cracks in or around pipe-to-elbow welds, except for two leaks at welds that connected a tee and reducer, respectively. Piping size ranged from 76 to 305 mm (3 to 12 inch). Service temperature ranged from 40 to 60°C (100 to 140°F), with most leaks having occurred in lines carrying lean amine at 55°C (130°F). Pressures ranged from atmospheric to 2.9 Mpa (425 psig), with most leaks having occurred between 2.8 and 2.9 Mpa (400 and 425 psig). All piping had been in service for about 8 years, except two leaks at piping welds that had been in service for only 4 years.

As had been generally accepted industry practice, the specifications called for stress relieving or postweld heat treatment of piping and vessels in amine service at temperatures above 95°C (200°F). Therefore it was highly unlikely that any of the leaking welds had received postweld heat treatment. Further metallurgical examination of leaking welds from various lines conclusively confirmed that the leaking originated at stress corrosion cracks. No leaks were found in rich amine piping. The characteristics of the mode of fracture suggested that the failure mechanism was a form of caustic SCC.

It is interesting to note that other researchers also have metallographically examined numerous samples of similar cracks; their results can be summarized as follows:

- Cracks were essentially intergranular and were filled with gray oxide scale.
- Hardness of welds and HAZ's was less than 200 HB.
- Cause of fracture was believed to be a form of caustic SCC.
- Cracking occurs whether or not MEA solutions contain corrosion inhibitors.

A.2.2.2 Preventive measures

As a result of this particular investigation and others, all welds in equipment in MEA service are being inspected. Wet fluorescent magnetic-particle inspection after sandblasting to remove oxides and scale appears to be the most effective technique. Shear-Wave Ultrasonic (SWU) inspection has also been used for piping, but it does not always distinguish SCC and other defect indications, such as shrinkage cracks, slag inclusions, lack of fusion, or fatigue cracks. Nevertheless, SWU is considered helpful, because these other types of defects also can pose a threat to the structural integrity of the system in question. Inspection frequency is dependent on the critical nature of the particular equipment in question, and most important, all welds in these systems are not being postweld stress relieved.

A.2.3 Corrosion of welds in carbon steel deaerator tanks

Deaerator tanks, the vessels that control free oxygen and other dissolved gases to acceptable levels in boiler feedwater, are subject to a great deal of corrosion and cracking. Several years ago, there were numerous incidences of deaerator tank failures that resulted in injury to personnel and property damage losses. Since that time, organizations such as the National Board of Boiler and Pressure Vessel Inspectors and the Technical Association of the Pulp and Paper Industry have issued warnings to plant operators, and these warnings have resulted in the formation of inspection programs for evaluating the integrity of deaerator tanks. As a result, many operators have discovered serious cracking problems. The following example illustrates the problem.

A.2.4 Weld cracking in oil refinery deaerator vessels

Two deaerator vessels with associated boiler feedwater storage tanks operated in similar service at a refinery. The vertical deaerator vessels were constructed of carbon steel (shell and dished heads), with trays, spray nozzles, and other internal components fabricated of Type 410 stainless steel. Boiler feedwater was treated by sand filtration using pressure filters, followed by ion-exchange water softening. Hardness was controlled at less than 0.5 ppm calcium carbonate (CaCO_3). A strong cationic primary coagulant (amine) was used to aid the filtering of colloidal material. Treated water was blended with condensate containing 5 ppm of a filming amine corrosion inhibitor. Final chemistry of the feedwater was controlled to the limits given in Table A.2.1. Oxygen scavenging was ensured by the addition of catalyzed sodium bisulfite (NaHSO_3) to the storage tanks. Treated water entered the top of the tray section of the deaerators through five or six spray nozzles and was stored in the horizontal tanks below the deaerators.

TABLE A.2.1 - CHEMISTRY LIMITS ON DEAERATOR FEEDWATER

CONTROL PARAMETER	LIMIT
Total hardness	< 0.5 ppm as CaCO ₃
Phenolphthalien alkalinity	Trace (max.)
Methyl orange alkalinity	14-18 ppm as CaCO ₃
Chloride	7.6-8.8 ppm
Total dissolved solids	70-125 ppm

A.2.4.1 Inspection results

Deaerator vessel and storage Tank A were inspected. All tray sections were removed from the deaerator. With the exception of the top head to shell weld in the deaerator, all internal welds were ground smooth and magnetic particle inspected. No cracks were found. Corrosion damage was limited to minor pitting of the bottom head in the deaerator vessel.

Inspection of deaerator vessel B revealed cracking at one weld. Tray sections were removed from the deaerator vessel, and shell welds were gritblasted. Except for the top head to shell weld in the deaerator, all internal welds in both B units were then ground smooth and magnetic particle inspected. Three transverse cracks were found at the bottom circumferential weld in the deaerator vessel. These were removed by grinding to a depth of 1.5 mm (0.06 inch).

Inspection of storage tank B revealed numerous cracks transverse to welds. With the shell constructed from three rings of plate, the longitudinal ring welds were located just below the water level. These longitudinal welds exhibited no detectable cracking. One circumferential crack was found above the working water level in the vessel. The remaining cracks were located at circumferential welds below the working water level. Numerous cracks transverse to circumferential welds were detected, but only one longitudinal crack was detected. All cracks were removed by grinding to a depth of 2 mm (0.08 inch).

Unlike deaerator vessel A, it was noted that none of the spray nozzles in deaerator vessel B was operational at the time of inspection. In addition, two valves had fallen to the bottom of the deaerator vessel. The bottom section of trays in deaerator vessel B had fallen to the bottom of the storage vessel. Corrosion damage in deaerator vessel B was limited to underdeposit pitting attack at circumferential welds in the bottom.

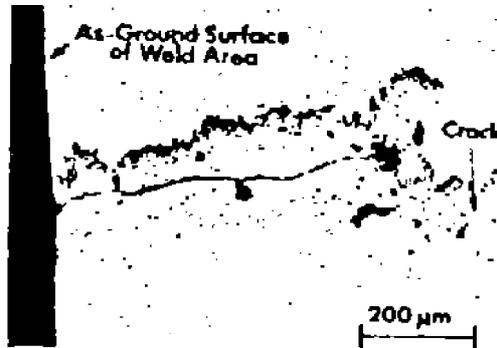
A.2.4.2 Metallurgical analysis

A section was cut from a circumferential weld region in storage tank B. The cracking was predominantly transverse to the weld. Chemical analysis was performed on samples cut from weld metal and base metal; the results are given in Table A.2.2. The results show that the steel plate was not aluminum-or silicon-killed, but was most likely a rimmed grade. Cross sections were cut perpendicular to both transverse and longitudinal cracks and were examined metallographically.

TABLE A.2.2 - CHEMICAL ANALYSES OF STEELS AND WELD DEPOSIT

SAMPLE	ANALYSIS, %									
	C	Mn	Si	P	S	Ni	Cr	Mo	Al	Fe
Plate 1	0.25	0.88	< 0.05	0.029	0.036	< 0.05	< 0.05	< 0.03	< 0.01	bal.
Plate 2	0.21	0.83	< 0.05	0.03	0.024	< 0.05	< 0.05	< 0.03	< 0.01	bal.
Weld deposit	0.14	0.53	0.14	0.035	0.031	< 0.05	< 0.05	< 0.03	< 0.01	bal.

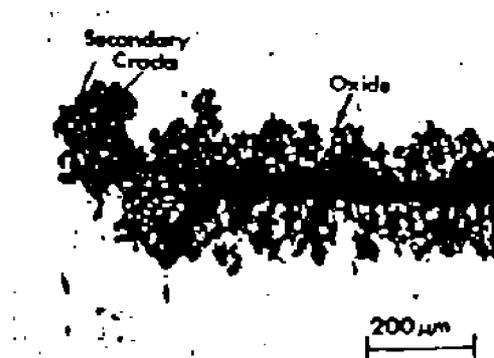
Metallographic examination of the base metal structures revealed ferrite and lamellar pearlite phases with a nearly equiaxed grain structure. The approximate grain size was ASTM 6 to 7. Fig. A.2.3 shows a longitudinal crack in a weld HAZ, with associated grain refinement. Cracking initiated from the bottom of a pit. The oxide associated with the major crack was extensive and contained numerous secondary cracks. Analysis of the oxide deposit within the crack by wavelength-dispersive spectroscopy revealed slightly less oxygen than an Fe₂O₃ standard. Therefore, it was assumed that the oxide deposit was a mixture of Fe₃O₄ and Fe₂O₃.



MICROGRAPH OF A LONGITUDINAL CRACK IN THE HAZ OF A WELD FROM STORAGE VESSEL B. ETCHED WITH NITAL

Fig. A.2.3

Fig. A.2.4 (a,b,c) shows a crack extending into base metal, transverse to the weld, with secondary cracking to the periphery of the oxidized region. It was clear that the oxide exhibited extensive internal cracking. Fig. A.2.4 (a,b,c) also shows the entrainment of lamellar pearlite phase (dark) within the oxide corrosion product. In addition, the crack tips are blunt.



a) Crack extending into base metal. As-polished



b) Lamellar pearlite phase (dark) entrained in the oxide corrosion product



c) Microcracks and entrained pearlite phase in the oxide corrosion product

MICROGRAPHS OF A TRANSVERSE CRACK IN STORAGE VESSEL
Fig. A.2.4 (a, b, c)

A.2.4.3 Discussion

The cracks described in this example are very similar to those found in many other investigations, despite a variety of deaerator vessel designs and operating conditions. Cracks typically display the following characteristics:

- Cracks occur most often in welds and HAZs, but can also occur in the base metal.
- Cracks are generally transverse to the weld HAZ, and occur both parallel and perpendicular to the hoop stress direction.
- The worst cracks appear to be located in circumferential and head-to-shell welds in horizontal vessel designs.
- Cracks are concentrated at, but not solely located within, the working water level in the vessel.
- Cracks are perpendicular to the vessel plate surface.
- Cracks are predominantly transgranular with minor amounts of branching.
- Cracks are filled with iron oxide. Cracking of the oxide corrosion product is followed by progressive corrosion. The ferrite phase is selectively attacked, with retention of the pearlite phase within the oxide corrosion product.
- Cracks initiate from corrosion pits. Weld defects, however, can also become active sites for crack initiation.
- Crack tips are blunt.

A.2.4.4 Conclusions

These findings suggest that the failure mechanism is a combination of low-cycle corrosion fatigue and stress-induced corrosion. Extensive oxide formation relative to the depth of cracking is a key feature. The formation of oxide was associated with corrosion attack of the ferrite phase. The lamellar pearlite phase remained relatively intact and was contained within the oxide product. The oxide itself exhibited numerous cracks, allowing aqueous corrosion of fresh metal to occur at the oxide/metal interface. Mechanical or thermal stresses are most likely responsible for this network of cracks within the oxide product. The mechanism appears to be stress-assisted localized corrosion. Sharp, tight cracks were not found in fresh metal beyond the periphery of the oxide corrosion product. It therefore appears reasonable that cracking could have occurred subsequent to corrosion and within the brittle oxide.

Cracking at welds and HAZs suggests that residual weld shrinkage stresses play a major role. Welds in deaerator vessels typically have not been postweld stress relieved. It is not unusual to find residual welding stresses of yield strength magnitude. This problem can be aggravated by vessel design (high localized bending stresses around saddle supports that fluctuate with water level and are accelerated by operational upsets).

No fault was found with the steel plate chemical composition or with welding consumables. There was no evidence of embrittlement or caustic SCC (that is, no branched intergranular cracks).

A.2.4.5 Recommendations

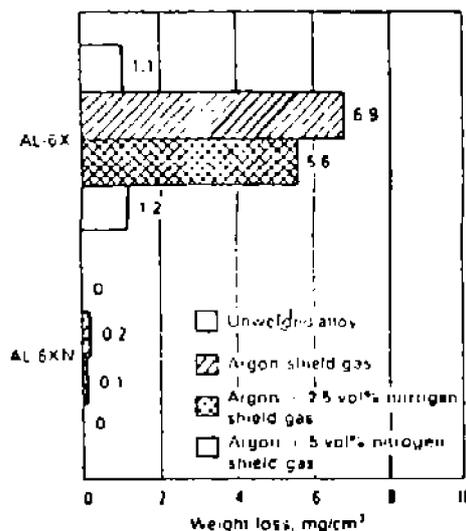
All welds in deaerator vessels shall be postweld stress relieved. Operational upsets should be avoided, and water chemistry must be maintained with acceptable limits. This is especially true with regard to water oxygen levels, which should be kept low to minimize pitting corrosion.

A.3 Corrosion of Austenitic Stainless Steel Weldments

A.3.1 Effects of GTA weld shielding gas composition

The chromium in a stainless steel has a strong chemical affinity for oxygen and carbon. Weld pools formed by electric arc processes must be shielded from the atmosphere to prevent slag formation and oxidation, to maintain a stable arc, and to reduce contamination of the molten metal by the weld environment. Argon or argon plus helium gas mixtures are commonly used in GTA welding processes to create a barrier between the solidifying weld and the atmosphere. In other cases, nitrogen is commonly used as a backing gas to protect the backside of the root pass.

The composition of a shielding gas can be modified to improve the microstructure and properties of GTA welds in austenitic stainless steels. More specifically, the use of argon mixed with small volumes of nitrogen (10 vol% N₂ or less) in a GTA welding process enhances the corrosion resistance of iron-chromium-nickel-molybdenum-nitrogen stainless alloys in oxidizing acid chloride solutions (Fig. A.3.1). In certain nonoxidizing solutions, argon-nitrogen shielding gas reduces the (-ferrite content of weld metal, and influences weld metal solidification behavior.



EFFECT OF GTA WELD SHIELDING GAS COMPOSITION ON THE CORROSION RESISTANCE OF TWO-AUSTENITIC STAINLESS STEELS. WELDED STRIP SAMPLES WERE TESTED, (BY ASTM, G48) THE TEST TEMPERATURE WAS 35°C (95°F)

Fig. A.3.1

The nitrogen content of weld metal increases with the partial pressure of nitrogen in the GTA weld shielding gas. The increase in weld metal nitrogen content is greater when nitrogen is mixed with an oxidizing gas, such as CO₂, than with either a reducing (hydrogen) or a neutral (argon) gas. Porosity and concavity are observed in austenitic stainless steel weld metals when more than 10 vol% nitrogen is added to an argon shielding gas. Although solid-solution additions of nitrogen are not detrimental to the SCC resistance of unwelded molybdenum-containing austenitic stainless steels, an increased weld metal nitrogen content tends to increase susceptibility to SCC.

A.3.2 Effects of heat-tint oxides on the corrosion resistance of austenitic stainless steels

Under certain laboratory conditions, a mechanically stable chromium-enriched oxide layer can be formed on a stainless steel surface that enhances corrosion resistance. In contrast, the conditions created by arc-welding operations produce a scale composed of elements that have been selectively oxidized from the base metal. The region near the surface of an oxidized stainless steel is depleted in one or more of the elements that have reacted with the surrounding atmosphere to form the scale. The rate of oxidation for a stainless steel, and consequently the degree of depletion in the base metal, is independent of the alloy composition and is controlled by diffusion through the oxide. The oxidized, or heat-tinted, surface of a welded stainless steel consists of a heterogeneous oxide composed primarily of iron and chromium above a chromium-depleted layer of base metal. The properties of such a surface depend on:

- The time and temperature of the thermal exposure.
- The composition of the atmosphere in contact with the hot metal surface.
- The chemical composition of the base metal beneath the heat-tint oxide.
- The physical condition of the surface (contamination, roughness, thermomechanical history) prior to heat tinting.
- The adherence of the heat-tint oxide to the base metal.

The defects, internal stresses, and composition of the heat-tint oxide make it a poor barrier to any corrosive media that might initiate localized corrosion in the chromium-depleted layer of base metal.

The severity of localized corrosion at heat-tinted regions exposed to oxidizing chloride solutions is directly related to the temperature of the hot metal surface during welding. A heat-tint oxide on an austenitic stainless steel exposed in air first becomes obvious at approximately 400°C (750°F). As the surface temperature is increased, differently colored oxides develop that appear to be superimposed upon the oxides formed at lower temperatures (Table A.3.1). Dark blue heat-tint oxides are the most susceptible to localized corrosion. It should be noted that gas-shielded surfaces do not form the same distinctly colored oxides as surfaces exposed to air during welding, but gas-shielded surfaces can also be susceptible to preferential corrosion.

TABLE A.3.1 - WELDING CONDITIONS AND CORROSION RESISTANCE OF HEAT-TINTED UNS 531726 STAINLESS STEEL PLATE

WELDING CONDITIONS(a)				CORROSION TEST RESULTS(b)			
HEAT INPUT		WELDING CURRENT, A	CENTERLINE HEAT-TINT COLOR	MAXIMUM PIT DEPTH, mm	PIT DEPTH, mils	NUMBER OF PITS ON HEAT-TINTED SURFACE	
kJ/mm	kJ/in.						
0.3	7.525	50	None	0.1	4	2	
0.59	15.050	100	Straw	0.7	28	10	
0.89	22.576	150	Rose	0.8	31	50	
1.19	30.101	200	Blue	0.7	28	>70	
1.48	37.626	250	White	0.9	35	>70	

a) Single-pass autogenous bead-on-plate GTA welds were made to heat tint the root surface of 6.4-mm (¼ inch) thick plate samples.

b) Duplicate coupons, each one with 25 × 51 mm (1 × 2 inch) heat-tinted surface, were exposed to 10% FeCl₃ solutions at 50°C (120°F). The weld face and edges of each coupon were covered with a protective coating.

Whether a weld heat tint should be removed prior to service depends on the corrosion behavior of the given alloy when exposed to the particular environment in question. Preferential corrosion at heat-tinted regions is most likely to occur on an alloy that performs near the limit of its corrosion resistance in service, but certain solutions do not affect heat-tinted regions. Even when heat-tinted regions are suspected of being susceptible to accelerated corrosion in a particular environment, the following factors should be considered:

- The rate at which pits, once initiated in the chromium-depleted surface layer, will propagate through sound base metal.
- The hazards associated with the penetration, due to localized corrosion, of a process unit.
- The cost and effectiveness of an operation intended to repair a heat-tinted stainless steel surface.

The corrosion resistance of heat-tinted regions can be restored in three stages. First, the heat-tint oxide and chromium-depleted layer are removed by grinding or wire brushing. Second, the abraded surface is cleaned with an acid solution or a pickling paste (a mixture of HNO_3 and HF suspended in an inert paste or gel) to remove any surface contamination and to promote the reformation of a passive film. Third, after a sufficient contact time, the acid cleaning solution or pickling paste is thoroughly rinsed with water, preferably demineralized or with a low chloride ion (Cl^-) content.

Grinding or wire brushing may not be sufficient to repair a heat-tinted region. Such abrading operations may only smear the heat-tint oxide and embed the residual scale into the surface, expose the chromium-depleted layer beneath the heat-tint oxide, and contaminate the surface with ferrous particles that were picked up by the grinding wheel or wire brush. A stainless steel surface should never be abraded with a wheel or brush that has been used on a carbon or low-alloy steel; wire brushes with bristles that are not made of a stainless steel of similar composition should also be avoided. Conversely, attempting to repair a heat-tinted region with only a pickling paste or acid solution may stain or even corrode the base metal if the solution is overly aggressive or is allowed to contact the surface for an extended time. If the acid is too weak, a chromium-depleted scale residue may remain on a surface. Even if the chromium-depleted layer were completely removed by a grinding operation, mechanically ground surfaces generally have inferior corrosion resistance compared to properly acid-pickled surfaces.

A.3.3 Unmixed zones

All methods of welding stainless steel with a filler metal produce a weld fusion boundary consisting of base metal that has been melted but not mechanically mixed with filler metal and a partially melted zone in the base metal. The weld fusion boundary lies between a weld composite consisting of filler metal diluted by base metal and an HAZ in the base metal (Fig. 1). The width of the unmixed zone depends on the local thermal conditions along the weld fusion line. For a GTA welding process, the zone is most narrow at the weld face and is broadest near the middle of the weld thickness.

An unmixed zone has the composition of base metal but the microstructure of an autogenous weld. The microsegregation and precipitation phenomena characteristic of autogenous weldments decrease the corrosion resistance of an unmixed zone relative to the parent metal. Unmixed zones bordering welds made from overalloyed filler metals can be preferentially attacked when exposed on the weldment surface.

The potential for preferential attack of unmixed zones can be reduced by minimizing the heat input to the weld and/or by flowing molten filler metal over the surface of the unmixed zone to form a barrier to the service environment. Care must be taken in this latter operation to avoid cold laps and lack-of-fusion defects. In both cases, preferential attack is avoided as long as the surface of the unmixed zone lies beneath the exposed surface of the weldment.

A.3.4 Chloride SCC

Welds in the 300-series austenitic stainless steels, with the exception of types 310 and 310Mo, contain a small amount of (-ferrite (usually less than 10%) to prevent hot cracking during weld solidification. In hot aqueous chloride environments, these duplex weldments generally show a marked resistance to cracking, while their counterparts crack readily.

The generally accepted explanation for this behavior is that the ferrite phase is resistant to chloride SCC and impedes crack propagation through the austenite phase. Electrochemical effects may also play a part; however, under sufficient tensile stress, temperature, and chloride concentration, these duplex weldments will readily crack. An example is shown in Fig. A.3.2.



CHLORIDE SCC OF TYPE 304 STAINLESS STEEL BASE METAL AND TYPE 308 WELD METAL IN AN AQUEOUS CHLORIDE ENVIRONMENT AT 95°C (200°F). CRACKS ARE BRANCHING AND TRANSGRANULAR

Fig. A.3.2

A.3.5 Caustic embrittlement (caustic SCC)

Susceptibility of austenitic stainless steels to this form of corrosion usually becomes a problem when the caustic concentration exceeds approximately 25% and temperatures are above 100°C (212°F). Because welding is involved in most fabrications, the weld joint becomes the focus of attention because of potential stress raiser effects and because of high residual shrinkage stresses. Cracking occurs most often in the weld HAZ.

In one case, a Type 316L reactor vessel failed repeatedly by caustic SCC in which the process fluids contained 50% sodium hydroxide (NaOH) at 105°C (220°F). Failure was restricted to the weld HAZ adjacent to bracket attachment welds used to hold a steam coil. The stresses caused by the thermal expansion of the Nickel 200 steam coil at 1034 kPa (150 psig) aggravated the problem. Fig. A.3.3 shows the cracks in the weld HAZ to be branching and intergranular. Because it was not practical to reduce the operating temperature below the threshold temperature at which caustic SCC occurs, it was recommended that the vessel be weld overlayed with nickel or that the existing vessel be scrapped and a replacement fabricated from Nickel 200.



CAUSTIC SCC IN THE HAZ OF A TYPE 316L STAINLESS STEEL NaOH REACTOR VESSEL. CRACKS ARE BRANCHING AND INTERGRANULAR
Fig. A.3.3

A.3.6 Microbiologically induced corrosion (MIC)

Microbiological corrosion in the process industries is most often found in three areas: cooling water systems, aqueous waste treatment, and groundwater left in new equipment or piping systems after testing. Nearly all confirmed cases of MIC have been accompanied by characteristic deposits. These are usually discrete mounds. Deposit color can also be an indication of the types of microorganisms that are active in the system. For example, iron bacteria deposits on stainless steel, such as those produced by *Gallionella* are often reddish.

Investigators have shown that in almost all cases the environment causing the damage was a natural, essentially untreated water containing one or more culprit species of microbiological organisms. In the case of austenitic stainless steel weldments, corrosion generated by bacteria takes a distinctive form, that is, subsurface cavities with only minute pinhole penetration at the surface.

A.4 Corrosion of Ferritic Stainless Steel Weldments

A.4.1 Leaking welds in a ferritic stainless steel wastewater vaporizer

A nozzle in a wastewater vaporizer began leaking after approximately 3 years of service with acetic and formic acid wastewaters at 105°C (225°F) and 414 kPa (60 psig):

a) Investigation

The shell of the vessel was weld fabricated in 1972 from 6.4 mm (¼ inch) E-Brite stainless steel plate. The shell measured 1.5 m (58 inch) in diameter and 8.5 m (28 ft) in length. Nondestructive examination included 100% radiography, dye-penetrant inspection, and hydrostatic testing of all E-Brite welds.

An internal inspection of the vessel revealed that portions of the circumferential and longitudinal seam welds, in addition to the leaking nozzle weld, displayed intergranular corrosion. At the point of leakage, there was a small intergranular crack.

The evidence indicated weldment contamination; therefore, effort was directed at finding the levels of carbon, nitrogen, and oxygen in the various components present before and after welding. The averaged results were as follows:

E-Brite, stainless steel plate

Base plate

C = 6 ppm

N = 108 ppm (C + N = 114 ppm)

O = 57 ppm

Corroded longitudinal weld

C = 133 ppm

N = 328 ppm (C + N = 461 ppm)

O = 262 ppm

Corroded circumferential weld

C = 34 ppm

N = 169 ppm (C + N = 203 ppm)

O = 225 ppm

E-Brite

Weld wire

C = 3 ppm

N = 53 ppm (C + N = 56 ppm)

O = 55 ppm

Sound longitudinal weld

C = 10 ppm

N = 124 ppm (C + N = 134 ppm)

O = 188 ppm

Sound circumferential weld

C = 20 ppm

N = 106 ppm (C + N = 126 ppm)

O = 85 ppm

These results confirmed suspicions that failure was due to excessive amounts of nitrogen, carbon, and oxygen. To characterize the condition of the vessel further, Charpy V-notch impact tests were run on the unaffected base metal, the HAZ, and the uncorroded (sound) weld metal. These tests showed the following ductile-to-brittle transition temperatures:

SPECIMEN	DUCTILE-TO-BRITTLE TRANSITION	
	TEMPERATURE	
	°C	°F
Base metal	40 ±3	105 ±5
HAZ	85 ±3	180 ±5
Weld	5 ±3	40 ±5

Comparison of the interstitial levels of the corroded welds, sound welds, base metal, and filler wire suggested that insufficient joint preparation (carbon pickup) and faulty gas shielding were probably the main contributing factors that caused this weld corrosion failure. Discussions with the Vendor uncovered two discrepancies. First, the welder was using a large, 19 mm ($\frac{3}{4}$ inch) inside diameter ceramic nozzle with a gas lens, but was flowing only 19 L/min (40 ft³/h) of argon; this was the flow rate previously used with a 13-mm ($\frac{1}{2}$ inch) inside diameter gas lens nozzle. Second, a manifold system was used to distribute pure argon welding gas from a large liquid argon tank to various satellite welding stations in the welding shop. The exact cause for the carbon pickup was not determined.

b) Conclusions

Failure of the nozzle weld was the result of intergranular corrosion caused by the pickup of interstitial elements and subsequent precipitation of chromium carbides and nitrides. Carbon pickup was believed to have been caused by inadequate joint cleaning prior to welding. The increase in the weld nitrogen level was a direct result of inadequate argon gas shielding of the molten weld puddle. Two areas of inadequate shielding were identified:

- Improper gas flow rate for a 19 mm ($\frac{3}{4}$ inch) diam gas lens nozzle.
- Contamination of the manifold gas system.

In order to preserve the structural integrity and corrosion performance of the new generation of ferritic stainless steels, it is important to avoid the pickup of the interstitial elements carbon, nitrogen, oxygen, and hydrogen. In this particular case, the Vendor used a flow rate intended for a smaller welding torch nozzle. The metal supplier recommended a flow rate of 23 to 28 L/min (50 to 60 ft³/min) of argon for a 19 mm ($\frac{3}{4}$ inch) gas lens nozzle. The gas lens collect body is an important and necessary part of the torch used to weld these alloys. Failure to use a gas lens will result in a flow condition that is turbulent enough to aspirate air into the gas stream, thus contaminating the weld and destroying its mechanical and corrosion properties.

The manifold gas system also contributed to this failure. When this system is first used, it is necessary to purge the contents of the manifold of any air to avoid oxidation and contamination. When that is done, the system functions satisfactorily; however, when it is shut down overnight or for repairs, air infiltrates back in, and a source of contamination is re-established. Manifold systems are never fully purged, and leaks are common.

The contaminated welds were removed, and the vessels were rewelded and put back into service. Some rework involved the use of covered electrodes of dissimilar composition. No problems have been reported to date.

c) Recommendations

- First, to ensure proper joint cleaning, solvent washing and wiping with a clean lint-free cloth shall be performed immediately before welding. The filler wire shall be wiped with a clean cloth just prior to welding. Also, a word of caution: Solvents are generally flammable and can be toxic. Ventilation shall be adequate. Cleaning shall continue until cloths are free of any residues.
- Second, when GTA welding, a 19 mm ($\frac{3}{4}$ inch) diameter ceramic nozzle with gas lens collect body is recommended, an argon gas flow rate of 28 L/min (60 ft³/h) is optimum. Smaller nozzles are not recommended. Argon back gas shielding is mandatory at a slight positive pressure to avoid disrupting the flow of the welding torch.
- Third, the tip of the filler wire shall be kept within the torch shielding gas envelope to avoid contamination and pickup of nitrogen and oxygen (they embrittle the weld). If the tip becomes contaminated, welding shall be stopped, the contaminated weld area ground out, and the tip of the filler wire that has been oxidized shall be snipped off before proceeding with welding.
- Fourth, a manifold gas system shall not be used to supply shielding and backing gas. Individual argon gas cylinders have been found to provide optimum performance. A weld button spot test shall be performed to confirm the integrity of the argon cylinder and all hose connections. In this test, the weld button sample shall be absolutely bright and shiny. Any cloudiness is an indication of contamination. It is necessary to check for leaks or replace the cylinder.

- Fifth, it is important to remember that corrosion resistance is not the only criterion when evaluating these new ferritic stainless steels. Welds must also be tough and ductile, and these factors must be considered when fabricating welds.
- Lastly, dissimilar weld filler metals can be successfully used. To avoid premature failure the dissimilar combination shall be corrosion tested to ensure suitability for the intended service.

A.5 Corrosion of Duplex Stainless Steel Weldments

The influence of different welding conditions on various material properties of Alloy 2205 is studied as follows:

Chemical compositions of test materials are given in Table A.5.1, and the results of the investigation are detailed in the following sections.

TABLE A.5.1 - CHEMICAL COMPOSITIONS OF ALLOY 2205 SPECIMENS TESTED AND FILLER METALS USED IN UNS, S 31803

SPECIMEN SIZE AND CONFIGURATION	ELEMENT, %									
	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
PARENT METALS										
48.1-mm (1.89 inch) OD, 3.8-mm (0.149 inch) wall tube...	0.015	0.37	1.54	0.024	0.003	21.84	5.63	2.95	0.09	0.15
88.9-mm (3.5 inch) OD, 3.6-mm (0.142 inch) wall tube...	0.017	0.28	1.51	0.025	0.003	21.90	5.17	2.97	0.09	0.15
110- mm (4.3 inch) OD, 8-mm (0.31 inch) wall tube.....	0.027	0.34	1.57	0.027	0.003	21.96	5.62	2.98	0.09	0.13
213- mm (8.4 inch) OD, 18-mm (0.7 inch) wall tube.....	0.017	0.28	1.50	0.026	0.003	21.85	5.77	2.98	0.10	0.15
20- mm (¾ inch) plate.....	0.019	0.39	1.80	0.032	0.003	22.62	5.81	2.84	...	0.13
FILLER METALS										
1.2 mm (0.047 inch) diam wire										
1.6 mm (0.063 inch) diam rod.....	0.011	0.48	1.61	0.016	0.003	22.50	8.00	2.95	0.07	0.13
3.2 mm (0.125 inch) diam wire										
3.25 mm (0.127 inch) diam covered electrode.....	0.020	1.01	0.82	0.024	0.011	23.1	10.4	3.06	...	0.13
4.0 mm (0.16 inch) diam covered electrode.....	0.016	0.94	0.78	0.015	0.011	23.0	10.5	3.13	...	0.11

A.5.1 Intergranular corrosion

Despite the use of very high arc energies (0.5 to 6 kJ/mm, or 13 to 152 kJ/inch) in combination with multipass welding, the Strauss test (ASTM A 262, Practice E) failed to uncover any signs of sensitization after bending through 180°. The results of Huey tests (ASTM A 262, Practice C) on submerged-arc welds showed that the corrosion rate increased slightly with arc energy in the studied range of 0.5 to 6.0 kJ/mm (13 to 152 kJ/inch). For comparison, the corrosion rate for parent metal typically varies between 0.15 and 1.0 mm/yr (6 and 40 mils/yr), depending on surface finish and heat treatment cycle.

Similar results were obtained in Huey tests of specimens from bead-on-tube welds produced by GTA welding. In this case, the corrosion rate had a tendency to increase slightly with arc energy up to 3 kJ/mm (76 kJ/inch).

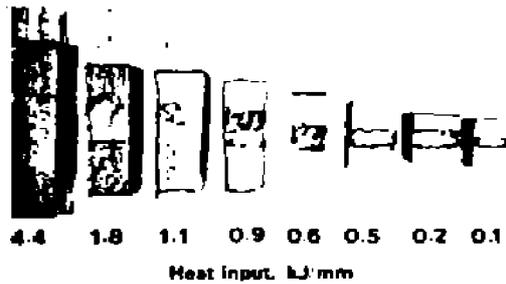
A.5.2 Pitting tests

Pitting tests were conducted in 10% ferric chloride (FeCl₃) at 25 and 30°C (75 and 85°F) in accordance with ASTM G 48. Results of tests on submerged-arc test welds did not indicate any significant change in pitting resistance when the arc energy was increased from 1.5 to 6 kJ/mm (38 to 152 kJ/inch). Pitting occurred along the boundary between two adjacent weld beads. Attack was caused by slag entrapment in the weld; therefore, removal of slag is important.

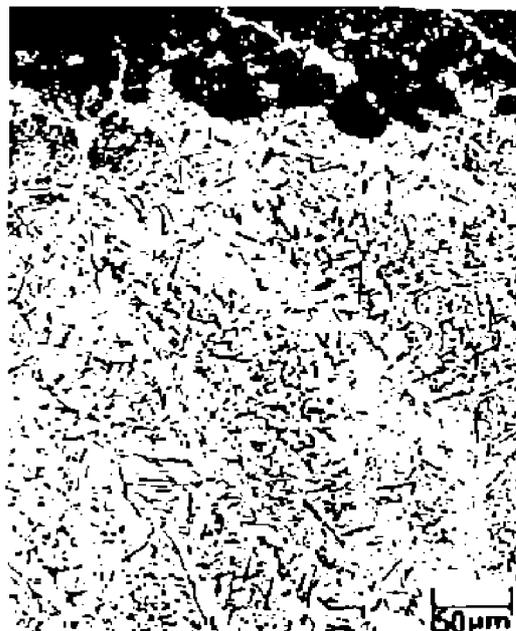
Gas tungsten arc weld test specimens (arc energies from 0.5 to 3 kJ/mm, or 13 to 76 kJ/inch) showed a marked improvement in pitting resistance with increasing arc energy. In order for duplicate specimens to pass the FeCl₃ test at 30°C

(85°F), 3 kJ/mm (76 kJ/inch) of arc energy was required. At 25°C (75°F), at least 2 kJ/mm (51 kJ/inch) was required to achieve immunity. Welds made autogenously (no nickel enrichment) were somewhat inferior, but improvements were achieved by using higher arc energies.

For comparison with a different alloy, Fig. A.5.1 shows the effect of heat input on the corrosion resistance of Ferralium Alloy 255 welds made autogenously and tested in FeCl₃ at 15°C (60°F). Preferential corrosion of the ferrite phase is shown in Fig. A.5.2. In a different test, Ferralium Alloy 255 was welded autogenously and tested in a neutral chloride solution according to ASTM D 1141 (Ref. 4) at 60 to 100°C (140 to 212°F). In this case, preferential attack of the austenite phase was observed. An example is shown in Fig. A.5.3. Similar results would be expected for Alloy 2205.



EFFECT OF WELDING HEAT INPUT ON THE CORROSION RESISTANCE OF AUTOGENOUS GTA (GAS TUNGSTEN ARC) WELDS IN FERRALIUM ALLOY 255 IN 10% FeCl₃ AT 10°C (40°F). THE BASE METAL WAS 25.4 mm (1 INCH) THICK
Fig. A.5.1



PREFERENTIAL CORROSION OF THE FERRITE PHASE IN THE WELD METAL OF FERRALIUM ALLOY 255 GTA WELDS IN 10% FeCl₃ AT ROOM TEMPERATURE. BASE METAL WAS 3.2 mm (1/8 INCH) THICK
Fig. A.5.2



PREFERENTIAL ATTACK OF THE CONTINUOUS AUSTENITE PHASE IN AN AUTOGENOUS GTA WELD IN FERRALIUM ALLOY 255. CREVICE CORROSION TEST WAS PERFORMED IN SYNTHETIC SEAWATER ACCORDING TO ASTM D 1141 AT 100°C (212°F). ETCHED WITH 50% HNO₃. 100 ×
Fig. A.5.3

A study of the Alloy 2205 weld microstructures revealed why high arc energies were found to be beneficial to pitting resistance. Many investigations have indicated that the presence of chromium nitrides in the ferrite phase lowers the resistance to pitting of the weld metal and the HAZ in duplex stainless steels. In this study, both weld metal and HAZ produced by low arc energies contained an appreciable amount of Chromium Nitride (Cr₂N) Fig. A.5.4. The nitride precipitation vanished when an arc energy of 3 kJ/mm (76 kJ/inch) was used (Fig. A.5.5).



MICROSTRUCTURE OF BEAD-ON-TUBE WELD MADE BY AUTOGENOUS GTA WELDING WITH AN ARC ENERGY OF 0.5 kJ/mm (13 kJ/inch). NOTE THE ABUNDANCE OF CHROMIUM NITRIDES IN THE FERRITE PHASE. SEE ALSO FIG. 21 200 ×
Fig. A.5.4



MICROSTRUCTURE OF BEAD-ON-TUBE WELD MADE BY AUTOGENOUS GTA WELDING WITH AN ARC ENERGY OF 3 kJ/mm (76 kJ/inch). VIRTUALLY NO CHROMIUM NITRIDES ARE PRESENT, WHICH RESULTS IN ADEQUATE PITTING RESISTANCE. 200 ×

Fig. A.5.5

The results of FeCl_3 tests on Submerged-Arc Welds (SAW) showed that all top weld surfaces passed the test at 30°C (85°F) without pitting attack, irrespective of arc energy in the range of 2 to 6 kJ/mm (51 to 152 kJ/inch). Surprisingly, the weld metal on the root side, which was the first to be deposited, did not pass the same test temperature.

The deteriorating effect of high arc energies on the pitting resistance of the weld metal on the root side was unexpected. Potentiostatic tests carried out in 3% NaCl at 400 mV versus SCE confirmed these findings. The higher the arc energy, the more austenite of this kind was present in the first two weld beads. Thus, nitrides give rise to negative effects on the pitting resistance, as do fine austenite precipitates that were presumably reformed at as low a temperature as approximately 800°C (1470°F).

Therefore, the resistance of Alloy 2205 to pitting corrosion is dependent on several factors. First, Cr_2N precipitation in the coarse ferrite grains upon rapid cooling from temperatures above about 1200°C (2190°F) caused the most severe impairment to pitting resistance. This statement is supported by a great number of FeCl_3 tests as well as by potentiostatic pitting tests. Generally, it seems difficult to avoid Cr_2N precipitation in welded joints completely, particularly in the HAZ, the structure of which can be controlled only by the weld thermal cycle. From this point of view, it appears advisable to employ as high an arc energy as practical in each weld pass. In this way, the cooling rate will be slower (but not slow enough to encounter 475°C (885°F) embrittlement), and the re-formation of austenite will clearly dominate over the precipitation of Cr_2N .

In addition, if there were no restriction on maximum interpass temperature, the heat produced by previous weld passes could be used to decrease the cooling rate further in the critical temperature range above about 1000°C (1830°F). Preliminary tests with preheated workpieces have shown the significance of temperature in suppressing Cr_2N precipitation. Currently, the maximum recommended interpass temperature for Alloy 2205 is 150°C (300°F). This temperature limit does not appear to be critical, and it is suggested that this limit could be increased to 300°C (570°F). The maximum recommended interpass temperature for Ferralium Alloy 255 is 200°C (390°F). Excessive grain growth as a result of too much heat input must also be considered to avoid loss of ductility and impact toughness.

Second, the fine austenite precipitates found in the reheated ferrite when high arc energies and multipass welding were combined are commonly referred to as γ_2 in the literature. The harmful influence of γ_2 on the pitting resistance has been noted with isothermally aged specimens, but as far as is known, it has never been observed in connection with welding. It is felt, however, that γ_2 is less detrimental to pitting than Cr_2N . Moreover, γ_2 formation is believed to be beneficial to mechanical properties, such as impact strength and ductility.

A third factor that lowers pitting resistance is oxide scale. Where possible, all surface oxides shall be removed by mechanical means or, preferably, by pickling. Root surfaces (in pipe), however, are generally inaccessible, and pitting resistance must rely on the protection from the backing gas during GTA welding. It is therefore advisable to follow the current recommendation for stainless steels, which is a maximum of 25 ppm oxygen in the root backing gas.

A.5.3 Stress-corrosion cracking

The SCC resistance of Alloy 2205 in aerated, concentrated chloride solutions is very good. The effect of welding on the SCC resistance is negligible from a practical point of view. The threshold stress for various welds, as well as for unwelded parent metal in the CaCl₂ test, is as 90% of the tensile strength at the testing temperature. This is far above all conceivable design limits.

Also, in environments containing both hydrogen sulfide (H₂S) and chlorides, the resistance of welds is almost as high as for the parent metal. In this type of environment, however, it is important to avoid too high a ferrite content in weld metal and HAZ. For normal welding of joints, the resulting ferrite contents shall not cause any problems. For weld repair situations, however, care shall be taken so that extremely high ferrite contents (> 75%) are avoided. To preserve the high degree of resistance to SCC, the ferrite content shall not be less than 25%.

Another reason to avoid coarse weld microstructures (generated by excessive welding heat) is the resultant nonuniform plastic flow, which can locally increase stresses and induce preferential corrosion and cracking effects.

A.5.4 Use of high-alloy filler metals

In critical pitting or crevice corrosion applications, the pitting resistance of the weld metal can be enhanced by the use of high nickel-chromium-molybdenum alloy filler metals. The corrosion resistance of such weldments in Ferralium Alloy 255 is shown in Table A.5.2. For the same weld technique, it can be seen that using highalloy fillers does improve corrosion resistance. If high-alloy fillers are used, the weld metal will have better corrosion resistance than the HAZ and the fusion line. Therefore, again, proper selection of welding technique can improve the corrosion resistance of the weldments.

TABLE A.5.2 - CORROSION RESISTANCE OF FERRALIUM ALLOY 255 WELDMENTS USING VARIOUS NICKEL-BASE ALLOY FILLERS AND WELD TECHNIQUES 3.2 mm (0.125 inch) plates tested in 10% FeCl₃ for 120 h

FILLER METAL	CRITICAL PITTING TEMPERATURE					
	GAS TUNGSTEN ARC		AS METAL ARC		SUBMERGED ARC	
	°C	°F	°C	°F	°C	°F
Hastelloy alloy G-3.....	30-35	85-95(a)	30	85(a)	30-35	85-95(b)
IN-112.....	30	85(a)	...	...	35-40	95-105(b)
Hastelloy alloy C-276.....	...	...	...	...	25-30	75-85(a)
Hastelloy alloy C-22.....	30	85(a)	...	...	35-40	95-105(a)

(a) HAZ

(b) HAZ plus weld metal

A.6 Corrosion of Nickel-Base Alloys

A.6.1 The nickel-molybdenum alloys

Represented by Hastelloy Alloys B and B-2, have been primarily used for their resistance to corrosion in nonoxidizing environments such as HCl. Hastelloy Alloy B has been used since about 1929 and has suffered from one significant limitation: weld decay. The welded structure has shown high susceptibility to knife-line attack adjacent to the weld-metal and to HAZ attack at some distance from the weld. The former has been attributed to the precipitation of molyb-

denum carbide (Mo_2C); the latter, to the formation of M_6C -type carbides. This necessitated postweld annealing, a serious shortcoming when large structures are involved. Many approaches to this problem were attempted, including the addition of carbide-stabilizing elements, such as vanadium, titanium, zirconium, and tantalum, as well as the lowering of carbon.

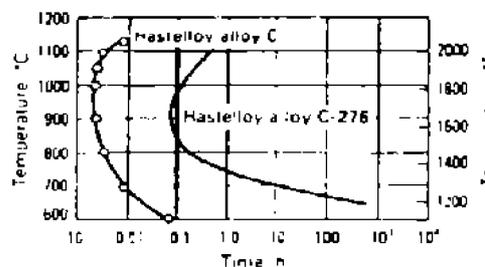
The addition of 1% V to an Alloy B-type composition was first patented in 1959. The resultant commercial alloys — Corronel 220 and Hastelloy Alloy B-282 (were found to be superior to Alloy B in resisting knife-line attack but were not immune to it. In fact, it was demonstrated that the addition of 2% V decreased the corrosion resistance of the base metal in HCl solutions. During this time, improvements in melting techniques led to the development of a low-carbon low-iron version of Alloy B called Alloy B-2. This alloy did not exhibit any propensity to knife-line attack.

Segregation of molybdenum in weld metal can be detrimental to corrosion resistance in some environments. In the case of boiling HCl solutions, the weld metal does not corrode preferentially. However, in $\text{H}_2\text{SO}_4 + \text{HCl}$ and $\text{H}_2\text{SO}_4 + \text{H}_3\text{PO}_4$ acid mixtures, preferential corrosion of as-welded Alloy B-2 has been observed. No knifeline or HAZ attack was noted in these tests. During solidification, the initial solid is poorer in molybdenum and therefore can corrode preferentially. In such cases, postweld annealing at 1120°C (2050°F) will be beneficial.

A.6.2 The nickel-chromium-molybdenum alloys

Represented by the Hastelloy C family of alloys and by Inconel 625 have also undergone evolution because of the need to improve the corrosion resistance of weldments. Hastelloy Alloy C (UNS N10002) containing nominally 16% Cr, 16% Mo, 4% W, 0.04% C and 0.5% Si had been in use for some time but had required the use of postweld annealing to prevent preferential weld and HAZ attack. Many investigations were carried out on the nature of precipitates formed in Alloy C, and two main types of precipitates were identified. The first is a Ni_7Mo_6 intermetallic phase called μ , and the second consists of carbides of the Mo_6C type. Other carbides of the M_{23}C_6 and M_2C were also reported. Another type, an ordered Ni_2Cr -type precipitate, occurs mainly at lower temperatures and after a long aging time; it is not of great concern from a welding viewpoint.

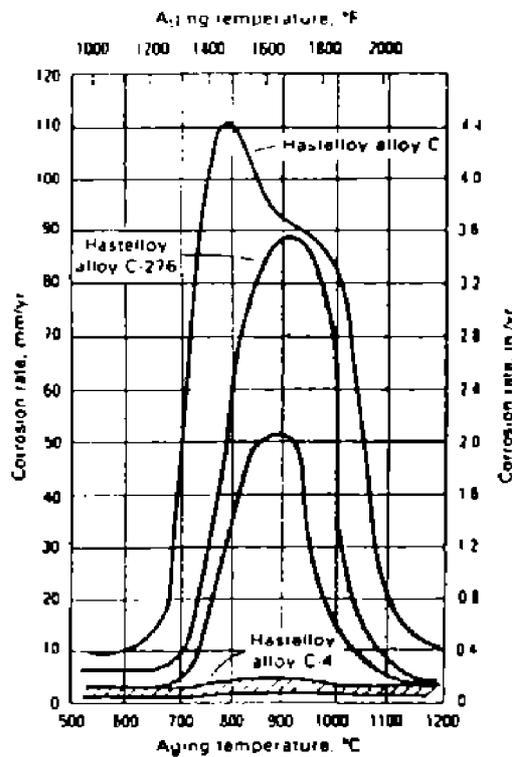
Both the intermetallic phases and the carbides are rich in molybdenum, tungsten, and chromium and therefore create adjacent areas of alloy depletion that can be selectively attacked. Carbide precipitation can be retarded considerably by lowering carbon and silicon; this is the principle behind Hastelloy Alloy C-276. The time-temperature behaviors of Alloys C and C-276 are compared in Fig. A.6.1, which shows much slower precipitation kinetics in Alloy C-276. Therefore, the evolution of Alloy C-276 from Alloy C enabled the use of this alloy system in the as-welded condition. However, because only carbon and silicon were controlled in C-276, there remained the problem of intermetallic μ -phase precipitation, which occurred at longer times of aging. Alloy C-4 was developed with lower iron, cobalt, and tungsten levels to prevent precipitation of μ - μ -phases.



TIME-TEMPERATURE TRANSFORMATION CURVES FOR HASTELLOY ALLOYS C AND C-276. INTERMETALLICS AND CARBIDE PHASES PRECIPITATE IN THE REGIONS TO THE RIGHT OF THE CURVES

Fig. A.6.1

The effect of aging on sensitization of Alloys C, C-276, and C-4 is shown in Fig. A.6.2. For Alloy C, sensitization occurs in two temperature ranges (700 to 800°C, or 1290 to 1470°F, and 900 to 1100°C, or 1650 to 2010°F) corresponding to carbide and æ-phase precipitation, respectively. For Alloy C-276, sensitization occurs essentially in the higher-temperature region because of µ-phase precipitation. Also, the æ-phase precipitation kinetics in Alloy C-276 are slow enough not to cause sensitization problems in many high heat input weldments; however, precipitation can occur in the HAZ of Alloy C-276 welds. Because C-4 has lower tungsten than C-276, it has lower pitting and crevice corrosion resistance, for which tungsten is beneficial. Therefore, an alternate solution to Alloy C-4 was needed in which both corrosion resistance and thermal stability are preserved. Hastelloy Alloy C-22 has demonstrated improved corrosion resistance and thermal stability.



EFFECT OF 1-h AGING TREATMENT ON CORROSION RESISTANCE OF THREE HASTELLOY ALLOYS IN 50% H₂SO₄ + 42 g/L Fe₂(SO₄)₃
Fig. A.6.2

Because of the low carbon content of Alloy C-22, the precipitation kinetics of carbides were slowed. Because Alloy C-22 has lower molybdenum and tungsten levels than Alloy C-276, µ-phase precipitation was also retarded.

From a weld HAZ point of view, this difference is reflected in lower grain-boundary precipitation even in a high heat input weld. The HAZ microstructure of Alloy C-4 was similar to this.