

Guide for the Joining of Solid Solution Austenitic Stainless Steels



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An American National Standard

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Guide for the Joining of Solid Solution Austenitic Stainless Steels

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Prepared by the
American Welding Society (AWS) G2 Committee on Joining of Metals and Alloys

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This guide presents a description of solid solution austenitic stainless steels and the processes and procedures that can be used for the joining of these materials. This standard discusses the welding processes and welding parameters, qualifications, inspection and repair methods, cleaning, and safety considerations. Practical information has been included in the form of figures, tables, and graphs that should prove useful in determining capabilities and limitations in the joining of austenitic stainless steels.



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Foreword

This foreword is not part of this standard but is included for informational purposes only.

The American Welding Society formed the G2 Committee on the Joining of Metals and Alloys in 1992 in response to an industry demand for information on welding the metals and alloys that have not been covered by other documents and committees. This document is written by the G2 Committee on the Joining of Metals and Alloys.

NOTE: The user's attention is called to the possibility that compliance with this standard may require use of an invention covered by patent rights.

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A vertical line in the margin or underlined text in clauses, tables, or figures indicates an editorial or technical change from the 2012 edition.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS G2 Committee on Joining of Metals and Alloys, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166.

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Guide for the Joining of Solid Solution Austenitic Stainless Steels

1. General Requirements

1.1 Scope. This guide presents a description of solid solution austenitic stainless steels and the most commonly used welding processes and procedures for joining these materials. The most commonly used welding processes, including shielded metal arc welding (SMAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), submerged arc welding (SAW), and flux cored arc welding (FCAW), are discussed in detail; laser beam, electron beam, plasma arc, resistance, and braze welding are not covered in great detail.

The welding processes discussed in this guide include recommended welding parameters, filler metals, shielding gases, and fluxes. Procedure qualifications, inspection and repair considerations and methods, and cleaning and safety considerations are also discussed. Practical information has been included as figures, tables, and graphs that should prove useful for determining the capabilities and limitations in the joining of austenitic stainless steels. This guide does not address martensitic, ferritic, or duplex stainless steels.

Although this guide is not written with mandatory requirements, mandatory language, such as the use of “shall,” will be found in those portions of the document where failure to follow the instructions or procedures could produce inferior, misleading, or unsafe results.

1.2 Units of Measure. This standard uses both the International System of Units (SI) and U.S. Customary Units. The latter are shown with brackets ([]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system should be used independently.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard; some safety and health information is provided, but such issues are not fully addressed herein.

Safety and health information is available from the following sources:

American Welding Society:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS Safety and Health Fact Sheets
- (3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

- (1) Safety Data Sheets supplied by materials manufacturers
- (2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The standards listed below contain provisions, which through reference in this text, constitute mandatory provisions of this AWS standard. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

American Welding Society (AWS) standards:

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*;

AWS A4.2M:2006 (ISO 8249:2000 MOD), *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal*;

AWS A5.4/A5.4M, *Specification for Stainless Steel Electrodes for Shielded Metal Arc Welding*;

AWS A5.8M/A5.8, *Specification for Filler Metals for Brazing and Braze Welding*;

AWS A5.9/A5.9M, *Specification for Bare Stainless Steel Welding Electrodes and Rods*;

AWS A5.11/A5.11M, *Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding*;

AWS A5.12M/A5.12 (ISO 6848:2004 MOD), *Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting*;

AWS A5.14/A5.14M, *Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods*;

AWS A5.22/A5.22M, *Specification for Stainless Steel Flux Cored and Metal Cored Welding Electrodes and Rods*;

AWS A5.32M/A5.32 (ISO 14175:2008 MOD), *Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes*;

AWS A5.34/A5.34M, *Specification for Nickel-Alloy Electrodes for Flux Cored Arc Welding*; and

AWS C5.3, *Recommended Practices for Air Carbon Arc Gouging and Cutting*.

ASTM International standard:

ASTM A380, *Standard Recommended Practice for Cleaning and Descaling and Passivation of Stainless Steel Parts, Equipment and Systems*.

SAE International standard:

SAE HS-1086, *Metals & Alloys in the Unified Numbering System*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

austenite. A **solid solution** phase with the **face-centered cubic** (FCC) crystal structure. The FCC crystal structure of austenite is nonmagnetic and remains ductile even at cryogenic temperatures. Austenite forms in stainless steels when iron is alloyed with sufficient austenite-promoting elements including nickel, carbon, nitrogen, manganese, or copper.

Charpy Impact Test. A pendulum-type single blow impact test in which a notched specimen is supported at both ends as simple beam and broken by a falling pendulum. The energy absorbed is a measure of impact strength and notch toughness. Toughness of austenitic stainless steels is typically measured in terms of lateral expansion. Toughness may also be measured in terms of energy absorption in Joules [ft·lbf].

cleaning. Cleaning as discussed herein refers to the removal of surface contaminants (lubricants, soil, **free iron**, etc.) using cleaning solutions that range from soapy water to organic solvents to acid-based liquids, or by mechanical means.

creep. The time-dependent strain that occurs under load at elevated temperature.

ductility-dip cracking. A solid-state crack formed at elevated temperatures. Typically occurs in alloys with the austenitic face-centered cubic (FCC) microstructure and is associated with an abrupt drop in ductility. This form of cracking typically occurs with high weld restraint, such as in the thick-section weldments, and when a large austenite grain size is present.

ferrite. An atomic crystal structure of a steel alloy where the atoms are arranged in a body-centered cubic (BCC) crystal structure. In the stainless steels that are primarily austenitic, ferrite can be found in some base materials and weld deposits that have sufficient amounts of ferrite-promoting elements such as Cr, Mo, Nb compared to the amount of elements that promote the formation of austenite such as C, Ni, N, and Cu. Ferrite is characterized as magnetic. Unless otherwise noted, the term “ferrite” as discussed in this document refers to the ferrite that is present after solidification and after metallurgical transformations (if any) have completed.

Ferrite Number (FN). A value assigned to the ferrite content of weld metal according to its magnetic response using a scale defined by the AWS A4.2M standard. At low levels, the FN is sometimes considered to approximate the percent ferrite, but percent ferrite is much more difficult to determine and not very reproducible. Due to ease and reproducibility of measurement, FN is normally preferred as a means of expressing ferrite content.

free iron. Iron particles or iron deposits on the material’s surface not originating from the stainless steel base metal.

heat (of material). A finite quantity of material melted and produced at a mill at one time.

heat-affected zone (HAZ). The portion of base metal that has had its mechanical properties or microstructure altered by the heat of welding, brazing, soldering, or thermal cutting.

heat tint. Discoloration of the surface of metal by formation of an oxide film that occurs when metal is exposed to oxygen-containing atmosphere at an elevated temperature.

hot crack. A crack formed at temperatures near the completion of solidification in weld metal or the partially melted zone. See also **liquation cracking** and **weld metal solidification cracking**.

knifeline attack (KLA). Corrosion that occurs in a very narrow region directly adjacent to the weld fusion line. Stable carbides (niobium or titanium carbides) in that region are dissolved (put into solution) from the heat of welding, but do not reprecipitate with carbon during welding or cooling. Instead, chromium carbides form in that region during high-temperature exposure or when cooling rates after welding are too slow. The precipitation of chromium carbide sensitizes the region making it susceptible to KLA unless a stabilization anneal is performed. The stabilization anneal temperature is sufficient to reprecipitate the niobium or titanium carbides, thus removing the sensitization effect (see Figure 5.4b).

liquation cracking. A form of hot cracking that occurs in the **heat-affected zone (HAZ)** of single pass welds, or in reheated weld metal in multipass welds due to formation of liquid films along grain boundaries in the partially melted zone adjacent to the fusion line. Liquation results from the segregation of impurities to grain boundaries or by constitutional liquation (e.g., partial melting of NbC or TiC). It can be difficult to detect and typically appears as small cracks in the HAZ or “micro fissures” in prior weld passes.

magnetic. As used in this document, the ability of a magnet to be attracted to the material being tested.

passivation. The chemical treatment of a stainless steel with a mild oxidant so as to remove free iron from the surface and speed up the process of forming a protective/passive layer. However, passivation is not effective for the removal of **heat tint** or oxide scale on stainless steel.

phase. A portion of a material that has roughly the same composition, structure and atomic arrangement throughout, and having a distinct boundary between it and any surrounding or adjoining phases.

pickling. The removal of highly adherent oxides using aggressive acid-based solutions. These oxides include **heat tint** formed adjacent to welds as well as thicker oxide layers formed during longer term, high-temperature exposure (e.g., furnace heat treatments performed without protective atmospheres, mill scales from rolling and forging operations, and high-temperature service exposure). Pickling is also effective for removing free iron.

precipitate \pri-'si-pə-'tāt\ *vb.* The process of forming small, discrete particles (**phases**) (usually formed at elevated temperatures) within a material’s structure.

precipitate \pri-'si-pə-tət\ *n.* Small, discrete particles (**phases**) usually formed at elevated temperatures within a material’s structure. Depending on the alloy, their presence can either be intentional and beneficial, or, undesired and potentially detrimental.

sensitization. The formation of chromium-depleted regions adjacent to chromium-rich carbides that nucleate and grow on **austenite** grain boundaries during exposure to temperatures of about 480°C to 850°C [900°F to 1560°F]. Regions depleted of chromium are susceptible to preferential attack by a corroding medium.

sigma phase. A hard, brittle, nonmagnetic phase with a tetragonal crystal structure containing large amounts of chromium and iron. It can form after extended time in the temperature range of about 600°C to 925°C [1100°F to 1700°F] and can significantly reduce corrosion resistance and produces a marked reduction in room temperature ductility. It forms most readily from weld-metal delta ferrite.

solid solution. A solid solution alloy is a homogeneous mixture of two or more elements. The type and proportions of alloying elements are such that the final alloy mixture is formulated to be homogenous without separating into multiple different structure types or chemical compounds.

solution annealing. Heating austenitic stainless steels and holding at a temperature (typically 1040°C [1900°F] minimum) long enough to redissolve constituents to enter into **solid solution**. Cooling must be sufficiently rapid to hold constituents into solution.

stress-relief anneal. A heat treatment performed to reduce residual stresses. See 10.2.

superaustenitic stainless steel. A series of solution strengthened austenitic stainless steels typically containing high alloying levels of chromium, nickel, nitrogen, and molybdenum. These alloying additions provide superior resistance to pitting corrosion and stress corrosion cracking relative to standard austenitic stainless steel grades.

Waveform controlled power sources. Terminology used to describe GMAW welding equipment that has the capability to simultaneously adjust various electrical parameters such as voltage, wave shape, or pulsing frequency when the operator adjusts wire feed speed.

weld metal solidification cracking. A form of intergranular cracking occurring as the cooling weld metal transitions from liquid to solid in the simultaneous presence of low melting points compounds and shrinkage stresses. This form typically appears as either centerline or crater cracks.

whiskers. Short pieces of unmelted GMAW electrode attached to the material being welded. Whiskers are occasionally found on the interior surface of pipe welds when the GMAW electrode passes through the root opening then shorts out and welds itself to the weld joint root face.

worm tracks. A linear depression in the surface of a weld as a result of insufficient outgassing of the weld puddle.

4. General Information

4.1 History. Austenitic stainless steels were first researched by Leon Guillet in France in 1904. In 1906, Guillet published a detailed study of the iron-nickel-chromium alloys; this study established the basic metallurgical characteristics of austenitic steels. Between 1908 and 1912, E. Maurer of the research department at Germany's F. Krupp steel plant developed the first commercial austenitic stainless steel.

From the late 1920s, different forms of austenitic stainless steels were produced. The most notable is the use of Type 302 on the roof of the Chrysler Building in New York.

Until 1968, stainless steels were produced by melting the charge in an electric furnace and refining it by certain slag practices. Carbon contents were lowered by blowing the melt with oxygen; however, they were limited to about 0.05%. To produce very low levels of carbon (under 0.03% is ideal for welding), special charges were required and the resultant alloys were designated with the letter "L." After 1968, the use of argon-oxygen decarburization refining practices began in conjunction with the electric melt furnace, producing very low levels of carbon as a matter of course. Many of today's alloys may be dual certified to both standard and low-carbon compositions and mechanical properties.

4.1.1 Alloy Description. Austenitic stainless steels are iron-based alloys with primary alloying elements of chromium and nickel (see Table 4.1). Chromium contributes to the well-known corrosion resistance of the alloys, while nickel is one of the primary elements that contribute to its austenitic microstructure. Alloying variations of common alloys are shown in Figure 4.1.

Table 4.1
The Chemical Composition Limits of Common
Wrought Austenitic Stainless Steel Base Materials

Base Metal Type	UNS Number ^a	C	Cr	Ni	Mo	Mn	Si	N	Other
201	S20100	0.15	16.0–18.0	3.5–5.5	—	5.5–7.5	1.0	0.25	—
202	S20200	0.15	17.0–19.0	4.0–6.0	—	7.5–10.0	1.0	0.25	—
205	S20500	0.12–0.25	16.0–18.0	1.0–1.75	—	14.0–15.5	1.0	0.32–0.40	—
209	S20910	0.06	20.5–23.5	11.5–13.5	1.5–3.0	4.0–6.0	1.0	0.20–0.40	Nb 0.10–0.30, V 0.10–0.30
216	S21600	0.08	17.5–22.0	5.0–7.0	2.0–3.0	7.5–9.0	1.0	0.25–0.50	—
218	S21800	0.10	16.0–18.0	8.0–9.0	—	7.0–9.0	3.5–4.5	0.08–0.18	—
219	S21904	0.04	19.0–21.5	5.5–7.5	—	8.0–10.0	1.0	0.15–0.40	—
240	S24000	0.08	17.0–19.0	2.5–3.75	—	11.5–14.5	1.0	0.20–0.40	—
241	S24100	0.15	16.5–19.5	0.5–2.5	—	11.0–14.0	1.0	0.20–0.45	—
301	S30100	0.15	16.0–18.0	6.0–8.0	—	2.0	1.0	—	—
302	S30200	0.15	17.0–19.0	8.0–10.0	—	2.0	1.0	—	—
302B	S30215	0.15	17.0–19.0	8.0–10.0	—	2.0	2.0–3.0	—	—
303	S30300	0.15	17.0–19.0	8.0–10.0	—	2.0	1.0	—	S 0.15 min.
304	S30400	0.08	18.0–20.0	8.0–10.5	—	2.0	1.0	—	—
304L	S30403	0.03	18.0–20.0	8.0–12.0	—	2.0	1.0	—	—
304LN	S30453	0.03	18.0–20.0	8.0–12.0	—	2.0	1.0	0.10–0.16	—
304H	S30409	0.04–0.10	18.0–20.0	8.0–11.0	—	2.0	1.0	—	—
304HN	S30452	0.08	18.0–20.0	8.0–10.5	—	2.0	1.0	0.10–0.16	—
305	S30500	0.12	17.0–19.0	10.0–13.0	—	2.0	1.0	—	—
309	S30900	0.20	22.0–24.0	12.0–15.0	—	2.0	1.0	—	—
309Cb	S30940	0.08	22.0–24.0	12.0–15.0	—	2.0	1.0	—	Nb 10 × C min. –1.0
309H	S30909	0.04–0.10	22.0–24.0	12.0–16.0	—	2.0	0.75	—	—
309S	S30908	0.08	22.0–24.0	12.0–15.0	—	2.0	1.0	—	—
310	S31000	0.25	24.0–26.0	19.0–22.0	—	2.0	1.5	—	—
310H	S31009	0.04–0.10	24.0–26.0	19.0–22.0	—	2.0	0.75	—	—
310S	S31008	0.08	24.0–26.0	19.0–22.0	—	2.0	1.5	—	—
310MoLN	S31050	0.03	24.0–26.0	20.5–23.5	1.6–3.0	2.0	0.4	0.09–0.16	—
314	S31400	0.25	23.0–26.0	19.0–22.0	—	2.0	1.5–3.0	—	—
316	S31600	0.08	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	—	—
316H	S31609	0.04–0.10	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	—	—
316L	S31603	0.03	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	—	—
316LN	S31653	0.03	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	0.10–0.16	—
316N	S31651	0.08	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	0.10–0.16	—
316Ti	S31635	0.08	16.0–18.0	10.0–14.0	2.0–3.0	2.0	1.0	0.10	Ti 5 × (C+N) min. –0.7
317	S31700	0.08	18.0–20.0	11.0–15.0	3.0–4.0	2.0	1.0	—	—
317L	S31703	0.03	18.0–20.0	11.0–15.0	3.0–4.0	2.0	1.0	—	—
317LM	S31725	0.03	18.0–20.0	13.0–17.0	4.0–5.0	2.0	0.75	0.10	—
317LMN	S31726	0.03	17.0–20.0	13.5–17.5	4.0–5.0	2.0	0.75	0.10–0.20	Cu 0.75

(Continued)

Table 4.1 (Continued)
The Chemical Composition Limits of Common
Wrought Austenitic Stainless Steel Base Materials

Base Metal Type	UNS Number ^a	C	Cr	Ni	Mo	Mn	Si	N	Other
317LN	S31753	0.03	18.0–20.0	11.0–15.0	3.0–4.0	2.0	1.0	0.10–0.22	—
321	S32100	0.08	17.0–19.0	9.0–12.0	—	2.0	1.0	—	Ti 5 × C min.
321H	S32109	0.04–0.10	17.0–20.0	9.0–12.0	—	2.0	1.0	—	Ti 4 × C min. –0.60
347	S34700	0.08	17.0–19.0	9.0–13.0	—	2.0	1.0	—	Nb 10 × C min.
347H	S34709	0.04–0.10	17.0–20.0	9.0–13.0	—	2.0	1.0	—	Nb 8 × C min. –1.0
348	S34800	0.08	17.0–19.0	9.0–13.0	—	2.0	1.0	—	Nb 10 × C min. Ta 0.10 Co 0.20
348H	S34809	0.04–0.10	17.0–20.0	9.0–13.0	—	2.0	1.0	—	Nb 8 × C min. –1.0 Ta 0.10 Co 0.20
28	N08028	0.03	26.0–28.0	30.0–34.0	3.0–4.0	2.5	1.0	—	—
1925 hMo [®] , b (926)	N08925	0.02	19.0–21.0	24.0–26.0	6.0–7.0	1.0	0.5	0.10–0.20	—
20Cb3	N08020	0.07	19.0–21.0	32.0–38.0	2.0–3.0	2.0	1.0	—	Cu 3.0–4.0 Nb 8 × C min. –1.0
20Mo-4 [®] , c	N08024	0.03	22.5–25.0	35.0–40.0	3.5–5.0	1.0	0.5	—	Cu 0.5–1.5 Nb 0.15–0.35
20Mo-6 [®] , c	N08026	0.03	22.0–26.0	33.0–37.2	5.0–6.7	1.0	0.5	0.10–0.16	Cu 2.0–4.0
25-6MO [®] , d	N08926	0.02	19.0–21.0	24.0–26.0	6.0–7.0	2.0	0.5	0.15–0.25	Cu 0.5–1.5
27-7MO [®] , d	S31277	0.02	20.5–23.0	26.0–28.0	6.5–8.0	3.0	0.5	0.30–0.40	Cu 0.5–1.5
253 MA [®] , e	S30815	0.10	20.0–22.0	10.0–12.0	—	0.8	1.4–2.0	0.14–0.20	Ce 0.03–0.08
254 SMO [®] , f	S31254	0.02	19.5–20.5	17.5–18.5	6.0–6.5	1.0	0.8	0.18–0.22	Cu 0.5–1.0
654 SMO [®] , f	S32654	0.02	24.0–25.0	21.0–23.0	7.0–8.0	2.0–4.0	0.5	0.45–0.55	Cu 0.30–0.60
31	N08031	0.015	26.0–28.0	30.0–32.0	6.0–7.0	2.0	0.3	0.15–0.25	Cu 1.0–1.4
RA-330 [®] , e	N08330	0.08	17.0–20.0	34.0–37.0	—	2.0	0.75–1.5	—	Cu 1.0 Pb 0.005 Sn 0.025
AL-6XN [®] , g	N08367	0.03	20.0–22.0	23.5–25.5	6.0–7.0	2.0	1.0	0.18–0.25	—
800	N08800	0.10	19.0–23.0	30.0–35.0	—	1.5	1.0	—	Al 0.15–0.60 Ti 0.15–0.60
825	N08825	0.05	19.5–23.5	38.0–46.0	2.5–3.5	1.0	0.5	—	Al 0.2 Ti 0.60–1.2
904L	N08904	0.02	19.0–23.0	23.0–28.0	4.0–5.0	2.0	1.0	—	Cu 1.0–2.0

^a SAE HS-1086, *Metals & Alloys in the Unified Numbering System*.

^b 1925 hMO is a registered trademark of ThyssenKrupp VDM GmbH.

^c 20Mo-4 and 20Mo-6 are registered trademarks of Carpenter Technology Corporation.

^d 25-6MO and 27-7MO are registered trademarks of Special Metals.

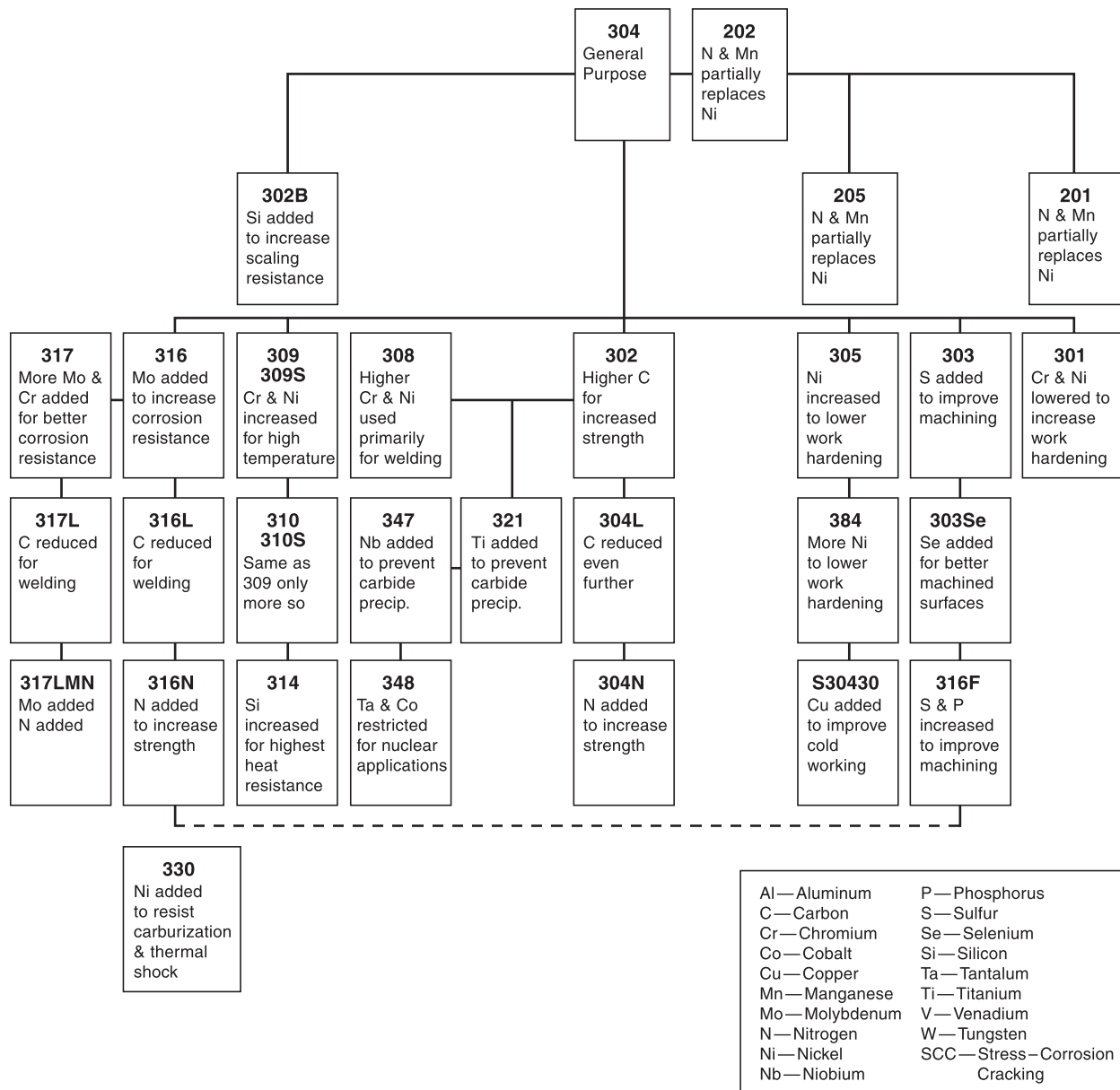
^e RA-330, 253 MA are registered trademarks of Rolled Alloys, Inc.

^f 254 SMO and 654 SMO are registered trademarks of Outokumpu.

^g AL-6XN[®] is a registered trademark of Alleghany Ludlum Corporation.

Notes:

- Composition limits are shown in wt %. Specific product material standards should be referred to for the exact composition limits. A single value denotes a maximum limit except where “min.” (minimum) is indicated. Composition maximum limits for the impurities phosphorous and sulfur are not listed in this table.
- Columbium (Cb) = Niobium (Nb).



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Figure 4.1—Alloying Variations of Common Austenitic Stainless Steels

Steel alloys are termed "stainless" when the chromium content exceeds 10.5% to 12%. The presence of at least 10.5% chromium provides for the development of a "passive" chromium-enriched film on the surface that resists oxidation and corrosion. This film is just a few angstroms thick and will spontaneously regenerate, if disrupted, as long as oxygen is present.

The austenitic alloys derive their name because of their predominantly "austenitic" microstructure. The term "stainless" was adopted because the alloy could not be etched using the common etchants that were used for carbon steels. In early years, etching was termed "staining"; hence, the new alloys were then termed "austenitic stainless steels."

The different alloys in the solid solution austenitic family have different compositions and properties, but many common characteristics. They can be hardened by cold working, but not by heat treatment. In the annealed condition, wrought base materials are essentially nonmagnetic, although some might exhibit a slight magnetic attraction because of variations in chemical composition or the extent of cold working after annealing. Cast alloys, depending on the alloy type and the specific composition of the casting, can range from nonmagnetic to strongly magnetic, depending on the casting's ferrite content. Weld metals can also exhibit varying levels of magnetic attraction depending on weld metal ferrite content. The austenitics are readily formed, fabricated, and welded. They generally have a good combination of corrosion resistance, toughness even at cryogenic temperatures, and strength. Some stainless alloys such as Types 304H, 316H, 321, and 347 are used often in high-temperature applications because of their improved creep strength.

Wrought alloys were identified in the old American Iron and Steel Institute (AISI) system as Type 300 series. Today the Unified Numbering System for Metals and Alloys (UNS) is widely used, and stainless steel is identified by a letter followed by a five-digit number (e.g., Type 304 is S30400). Alloys containing over 2% manganese as a minimum requirement, along with deliberate nitrogen addition, are often identified as 200 series alloys.

Type 304 (UNS S30400), sometimes referred to as 18-8 stainless, is the most widely used alloy of the austenitic group. It has a nominal composition of 18% chromium and 8% nickel. Type 304 has excellent corrosion resistance in general aqueous or atmospheric service environments and has good mechanical properties. Molybdenum is added to various alloys, including Types 316 and 317, for improved pitting and crevice corrosion resistance compared to Type 304. Type 317 has improved resistance in increasing chloride environments. Table 4.1 lists the chemical composition limits of some commonly used wrought austenitic grades.

Cast alloy designations were originally established by the Alloy Casting Institute and have since been adopted by ASTM International. Alloy designations beginning with the letter C are most commonly used for their corrosion-resistant characteristics in aqueous environments and in vapors below 650°C [1200°F]. Alloy designations beginning with the letter H are most commonly used above 650°C [1200°F]. The higher carbon content of the H-alloys makes them stronger at elevated temperatures than the corrosion resistant types. Table 4.2 lists the chemical composition limits of some commonly used cast austenitic grades.

4.2 Properties. Since different grades of austenitic stainless steels have different allowable chemical compositions, the austenitic stainless steels can exhibit a wide range of mechanical properties. At room temperature in the annealed condition, the wrought austenitic stainless steels typically exhibit Charpy V-notch energy absorption values well in excess of 135 J [100 ft-lbf]. These alloys also exhibit good ductility and toughness even at high strengths and at cryogenic temperatures.

The mechanical properties of some common wrought, annealed austenitic stainless steels are listed in Table 4.3. The mechanical properties of some common annealed, cast austenitic stainless steels are listed in Table 4.4.

At room temperature, they exhibit yield strengths between 210 MPa to 1380 MPa [30 ksi to 200 ksi], depending on composition and amount of cold work. Note: The heat of welding anneals and removes the strengthening effect of any cold working in the heat-affected zone (HAZ) with the result that strength will be reduced in the HAZ.

When cold worked materials have been selected because of their elevated tensile strength properties, welding should be avoided, or, the reduced strength of the HAZ and the strength of the weld deposit (compared to the base material) should be considered in the welded design.

4.3 Product Forms. Wrought austenitic stainless steels are produced under a wide variety of industry standards including the American Iron and Steel Institute (AISI), Aerospace Materials Specifications (AMS), the American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM), Military Standards (MIL), and SAE International standards.

International standards include AS (Australia), CSA (Canada), GB (China), EN (Europe), AFNOR (France), DIN EN (Germany), MSZ (Hungary), IS (India), ISO (International), UNI (Italy), JIS (Japan), PNH (Poland), STAS (Romania), GOST (Russia), UNE (Spain), SIS (Sweden), BS (UK), as well as others.

Various references for finding information on materials produced according to international standards can be found in Annex B.

4.4 Specifications. For a list of common ASTM standards applicable to wrought and cast austenitic stainless steels, refer to Annex C.

Table 4.2
The Chemical Composition Limits of Common Cast Austenitic Stainless Steel Base Materials

Grade ^a	UNS Number ^b	Typical Microstructure & Other ^c	ASTM Designation Reference ^d	Reference Wrought Grade	C	Cr	Ni	Mo	Mn	Si	Other
CE20N	J92802	—	A351 A451	—	0.20	23.0–26.0	8.0–11.0	0.50	1.50	1.50	N: 0.08–0.20
CF3 CF3A	J92500	4	A351 A451 A743 A744	304L	0.03	17.0–21.0	8.0–12.0	0.50	1.50	2.00	—
CF3M CF3MA	J92800	4	A351 A451 A743 A744	316L	0.03	17.0–21.0	9.0–13.0	2.0–3.0	1.50	1.50	—
CF8 CF8A	J92600	4	A351 A451 A743 A744	304	0.08	18.0–21.0	8.0–11.0	0.50	1.50	2.00	—
CF8C	J92710	4	A351 A451 A743 A744	347	0.08	18.0–21.0	9.0–12.0	0.50	1.50	2.00	Nb: 8 × C min. –1.0
CF8M	J92900	4	A351 A451 A743 A744	316	0.08	18.0–21.0	9.0–12.0	2.0–3.0	1.50	1.50	—
CF10	J92590	4	A351	304H	0.04–0.10	18.0–21.0	8.0–11.0	0.50	1.50	2.00	—
CF10M	J92901	4	A351	316H	0.04–0.10	18.0–21.0	9.0–12.0	2.0–3.0	1.50	1.50	—
CF10MC	J92971		A351	—	0.10	15.0–18.0	13.0–16.0	1.75–2.25	1.50	1.50	Nb: 10 × C min. –1.20
CF20	J92602	4	A743	302	0.20	18.0–21.0	8.0–11.0	—	1.50	2.00	—
CF10SMnN	J92972	4	A351 A743	Nitronic 60	0.10	16.0–18.0	8.0–9.0	—	7.0–9.0	3.5–4.5	N: 0.08–0.18
CG6MMN	J93790		A351 A743	Nitronic 50	0.06	20.5–23.5	11.5–13.5	1.5–3.0	4.0–6.0	1.0	N: 0.20–0.40 Nb: 0.10–0.30 V: 0.10–0.30

(Continued)

Table 4.2 (Continued)
The Chemical Composition Limits of Common Cast Austenitic Stainless Steel Base Materials

Grade ^a	UNS Number ^b	Typical Microstructure & Other ^c	ASTM Designation Reference ^d	Reference Wrought Grade	C	Cr	Ni	Mo	Mn	Si	Other
CG8M	J93000	4	A351 A743 A744	317	0.08	18.0–21.0	9.0–13.0	3.0–4.0	1.5	1.5	—
CG12	J93001	—	A743	309	0.12	20.0–23.0	10.0–13.0	—	1.50	2.00	—
CH8	J93400	—	A351 A451	—	0.08	22.0–26.0	12.0–15.0	0.50	1.50	1.50	—
CH10	J93401	8	A351 A451 A743	309	0.04–0.10	22.0–26.0	12.0–15.0	0.50	1.50	2.00	—
CH20	J93402	8	A351 A451 A743	309	0.04–0.20	22.0–26.0	12.0–15.0	0.50	1.50	2.00	—
CK20	J94202	5	A351 A451 A743	310	0.04–0.20	23.0–27.0	19.0–22.0	0.50	1.50	1.75	—
CK3MCuN	J93254	6	A351 A743 A744	254 SMO	0.025	19.5–20.5	17.5–19.5	6.0–7.0	1.20	1.00	N: 0.18–0.24 Cu: 0.50–1.0
CN3M	J94652	6	A351 A743	—	0.03	20.0–22.0	23.0–27.0	4.5–5.5	2.00	1.00	—
CN3MN	J94651	6	A743 A744	AL6XN [®] , e	0.03	20.0–22.0	23.5–25.5	6.0–7.0	2.00	1.00	N: 0.18–0.26 Cu: 0.75
CN3MCu	J80020		A744 A990	20Cb-3	0.03	19.0–22.00	27.5–30.5	2.0–3.0	1.50	1.00	Cu: 3.0–3.5
CN7M	N08007	6	A351 A743 A744	20Cb-3	0.07	19.0–22.0	27.5–30.5	2.0–3.0	1.5	1.5	Cu: 3.0–4.0
CT15C	N08151	7	A351	—	0.05–0.15	19.0–21.0	31.0–34.0	—	0.15–1.50	0.50–1.50	Nb 0.50–1.50
CU5MCuC	N08826	6	A494	Inconel 825	0.05	19.5–23.5	38.0–44.0	2.5–3.5	1.0	1.0	Cu: 1.50–3.50 Nb 0.10–0.30
HE	J93403	4, 3	A297	312/CE30	0.20–0.50	26.0–30.0	8.0–11.0	0.50	2.00	2.00	—

(Continued)

Table 4.2 (Continued)
The Chemical Composition Limits of Common Cast Austenitic Stainless Steel Base Materials

Grade ^a	UNS Number ^b	Typical Microstructure & Other ^c	ASTM Designation Reference ^d	Reference Wrought Grade	C	Cr	Ni	Mo	Mn	Si	Other
HF	J92603	7, 3	A297	302	0.20–0.40	18.0–23	8.0–12.0	0.50	2.00	2.00	—
HH	J93503	7, 8, 3	A297	309/CH20	0.20–0.50	24.0–28.0	11.0–14.0	0.50	2.00	2.00	—
HK	J94224	7	A297	310/CK20	0.20–0.60	24.0–28.0	18.0–22.0	0.50	2.00	2.00	—
HK30	J94203	7	A351 A608	—	0.25–0.35	23.0–27.0	19.0–22.0	0.50	1.50	1.75	—
HK40	J94204	7	A351 A608	—	0.35–0.45	23.0–27.0	19.0–22.0	0.50	1.50	1.75	—
HL	J94604	7, 3	A297	—	0.20–0.60	28.0–32.0	18.0–22.0	0.50	2.00	2.00	—
HN	J94213	6, 3	A297	—	0.20–0.50	19.0–23.0	23.0–27.0	0.50	2.00	2.00	—
HP	J95705	6	A297	—	0.35–0.75	24–28	33–37	0.50	2.00	2.50	—
HT	J94605	6, 3	A297	330 (15–35)	0.35–0.75	15.0–19.0	33.0–37.0	0.50	2.00	2.50	—
HU	J95405	6	A297	(19–39)	0.35–0.75	17.0–21.0	37.0–41.0	0.50	2.00	2.50	—

^a For brevity, grades listed under ASTM A451 do not show the “P” after the “C.” For example, ASTM A451 grade CPF3 is listed in this table simply as CF3.

^b SAE HS-1086, *Metals & Alloys in the Unified Numbering System*.

^c Ferrite content of stainless steel cast alloys can be estimated using the Schoefer diagram (see Annex D).

^d ASTM A297/A297M, *Standard Specification for Steel Castings, Iron-Chromium and Iron-Chromium-Nickel, Heat Resistant for General Application*.

ASTM A351/A351M, *Standard Specification for Castings, Austenitic, for Pressure-Containing Parts*.

ASTM A451/A451M, *Standard Specification for Centrifugally Cast Austenitic Steel Pipe for High-Temperature Service*.

ASTM A608/A608M, *Standard Specification for Centrifugally Cast Iron-Chromium-Nickel High-Alloy Tubing for Pressure Application at High Temperatures*.

ASTM A743/A743M, *Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant for General Application*.

ASTM A744/A744M, *Standard Specification for Castings, Iron-Chromium-Nickel, Corrosion Resistant for Severe Service*.

^e AL-6XN[®] is a registered trademark of Alleghany Ludlum Corporation.

Notes:

- Composition limits were excerpted from the referenced ASTM Specifications. Limits are shown in wt %. Specific product material standards should be referred to for the exact composition limits. A single value denotes a maximum limit except where “min.” (minimum) is indicated. Composition limits for P and S are not listed in this table. P and S limits typically do not exceed 0.040 wt % with some exceptions.
- Niobium (Nb) = Columbium (Cb).
- Similar alloys are listed in ASTM A608: HE35, HF30, HH33, HL30, HL40, HN40, and HT50.
- Depending on the chemical composition of the casting, the structure may range from fully austenitic-to-austenite with up to 40% ferrite. Most commonly the grades contain from 5% to 40% ferrite.
- Predominately austenitic microstructure (with minor amounts of ferrite).
- Completely austenitic.
- Carbides in an austenitic matrix.
- Carbides in an austenitic matrix with minor amounts of ferrite.
- Ferrite content of stainless steel cast alloys can be estimated using the Schoefer diagram (see Annex D).
- HN, HT, and HU alloys do not form sigma phase under any conditions. A ratio of 2 silicon to 1 part carbon in matching type filler metal provides the best weld properties for these grades.

Table 4.3
Mechanical Properties of Wrought Annealed Stainless Steel Alloys

Type	UNS No.	Tensile Strength, min.		Yield Strength, min.		Elongation in 50 mm [2 in] Min. %	Hardness, Maximum	
		MPa	ksi	MPa	ksi		Brinell	Rockwell B
201-1	S20100	515	75	260	38	40	217	95
201-2	S20100	655	95	310	45	40	241	100
202	S20200	620	90	260	38	40	241	—
209	S20910	725	105	415	60	30	241	100
216	S21600	690	100	415	60	40	241	100
218	S21800	655	95	345	50	35	241	100
219 (XM-11) sheet	S21904	690	100	415	60	40	—	—
240	S24000	690	100	415	60	40	241	100
301	S30100	515	75	205	30	40	217	95
302	S30200	515	75	205	30	40	201	92
304	S30400	515	75	205	30	40	201	92
304L	S30403	485	70	170	25	40	201	92
304LN	S30453	515	75	205	30	40	217	95
304H	S30409	515	75	205	30	40	201	92
304N	S30451	550	80	240	35	30	217	95
304HN	S30452	620	90	345	50	30	241	100
305	S30500	485	70	170	25	40	183	88
309H	S30909	515	75	205	30	40	217	95
309S	S30908	515	75	205	30	40	217	95
310Cb	S31040	515	75	205	30	40	217	95
310H	S31009	515	75	205	30	40	217	95
310HCb	S31041	515	75	205	30	40	217	95
310S	S31008	515	75	205	30	40	217	95
310MoLN sheet	S31050	580	84	270	39	25	217	95
254SMo	S31254	690	100	310	45	35	223	96
316	S31600	515	75	205	30	40	217	95
316H	S31609	515	75	205	30	40	217	95
316L	S31603	485	70	170	25	40	217	95
316LN	S31653	515	75	205	30	40	217	95
316N	S31651	550	80	240	35	35	217	95

(Continued)

Table 4.3 (Continued)
Mechanical Properties of Wrought Annealed Stainless Steel Alloys

Type	UNS No.	Tensile Strength, min.		Yield Strength, min.		Elongation in 50 mm [2 in] Min. %	Hardness, Maximum	
		MPa	ksi	MPa	ksi		Brinell	Rockwell B
316Ti	S31635	515	75	205	30	40	217	95
317	S31700	515	75	205	30	35	217	95
317L	S31703	515	75	205	30	40	217	95
317LM	S31725	515	75	205	30	40	217	95
317LMN	S31726	550	80	240	35	40	223	96
317LN	S31753	550	80	240	35	40	217	95
321	S32100	515	75	205	30	40	217	95
321H	S32109	515	75	205	30	40	217	95
347	S34700	515	75	205	30	40	201	92
347H	S34709	515	75	205	30	40	201	92
348	S34800	515	75	205	30	40	201	92
348H	S34809	515	75	205	30	40	201	92
28	N08028	500	73	214	31	40	—	70–90
1925 hMo	N08925	600	87	295	43	40	—	—
20Cb3	N08020	550	80	240	35	30	217	95
20Mo-4	N08024	550	80	240	35	30	—	—
20Mo-6	N08026	550	80	240	35	30	—	—
25-6MO	N08926	650	94	295	43	35	—	—
27-7MO	S31277	770	112	360	52	40	—	—
253 MA	S30815	600	87	310	45	40	217	95
254 SMO	S31254	690	100	310	45	35	223	96
654 SMO	S32654	750	109	430	62	40	250	—
31	N08031	650	94	276	40	40	—	—
RA 330	N08330	483	70	207	30	—	—	70–90
AL-6XN ^a	N08367	690	100	310	45	30	—	100
800	N08800	520	75	205	30	30	—	—
825	N08825	586	85	241	35	30	—	—
904L	N08904	490	71	220	31	35	—	90
18-18-2	S38100	515	75	205	30	40	217	95

^a AL-6XN[®] is a registered trademark of Alleghany Ludlum Corporation.

Source: Extracted from various applicable ASTM specifications for sheet and plate product forms in the solution annealed condition. Minimum specified mechanical properties may vary slightly—depending on the product specification.

Table 4.4
Minimum Mechanical Properties of Common Cast Austenitic Stainless Steel Base Materials^a

Grade	UNS Number ^b	UTS, min.		YS, min.		% Elong. min. in 50 mm [2 in]
		MPa	ksi	MPa	ksi	
CE20N	J92802	485	70	195	28	35
CF3	J92500	485	70	205	30	35
CF3A	J92500	530	77	240	35	35
CF3M	J92800	485	70	205	30	30
CF3MA	J92800	559	80	255	37	30
CF8	J92600	485	70	205	30	35
CF8A	J92600	530	77	240	35	35
CF8C	J92710	485	70	205	30	30
CF8M	J92900	485	70	205	30	30
CF10	J92590	485	70	205	30	35
CF10M	J92901	485	70	205	30	30
CF10MC	J92971	485	70	205	30	20
CF20	J92602	485	70	205	30	30
CF10SMnN	J92972	585	85	290	42	30
CG6MMN	J93790	585	85	290	42	30
CG8M	J93000	520	75	240	35	25
CG12	J93001	485	70	195	28	35
CH8	J93400	450	65	195	28	30
CH10	J93401	485	70	205	30	30
CH20	J93402	485	70	205	30	30
CK20	J94202	450	65	195	28	30
CK3MCuN	J93254	550	80	260	38	35
CN3M	J94652	435	63	170	25	30
CN3MN	J94651	550	80	260	38	35
CN7M	N08007	425	62	170	25	35
CT15C	N08151	435	63	170	25	20
CU5MCuC	N08826	520	75	240	35	20
HE	J93403	585	85	275	40	9
HF	J92603	485	70	240	35	25
HH	J93503	515	75	240	35	10
HK	J94224	450	65	240	35	10
HK30	J94203	450	65	240	35	10
HK40	J94204	425	62	240	35	10
HL	J94604	450	65	240	35	10
HN	J94213	435	63	—	—	8
HP	J95705	430	62.5	235	34	4.5
HT	J94605	450	65	—	—	4
HU	J95405	450	65	—	—	4

^a Source: Mechanical properties were adapted from ASTM specifications listed in Table 4.2 for the annealed condition.

^b SAE HS-1086, *Metals & Alloys in the Unified Numbering System*.

Note: Grades produced under some ASTM standards require tensile testing only when specified in a purchase order.

5. Metallurgy

5.1 Ferrite Discussion

5.1.1 Austenite- and Ferrite-Forming Elements. Many of the nominally austenitic stainless steel base metals and weld metals solidify with some ferrite in their microstructure. This ferrite, which will usually transform to austenite during hot working and extensive heat treatment, is beneficial during solidification by imparting resistance to solidification cracking. In the base metal, this ferrite can reappear in the HAZ and in an autogenous weld fusion zone when the base metal is fused during welding.

Elements that promote the formation of ferrite include chromium (Cr), molybdenum (Mo), silicon (Si), niobium (Nb), titanium (Ti), aluminum (Al), vanadium (V), and tungsten (W).

Elements that promote the formation of austenite include nickel (Ni), carbon (C), nitrogen (N), manganese (Mn), and copper (Cu).

Base materials and filler metals are produced to provide the desired chemical composition, microstructure, properties, and corrosion resistance. Changing the quantity and ratio of one or more specific elements in austenitic alloys can significantly alter the alloy's microstructure and properties. Base and filler metal producers can alter the proportions of austenite and ferrite by altering the amounts and the ratio of ferrite-forming elements to austenite-forming elements.

Cast "austenitic" alloys, depending on the alloy type and the specific composition of the casting, can range from fully austenitic to containing up to 40% ferrite. Table 4.2 provides information on the typical microstructures found in cast alloys. The presence of ferrite in castings generally increases strength, decreases toughness, and improves the material's weldability. Depending on the service environment, the presence of ferrite can either improve or decrease the alloy's relative corrosion resistance characteristics. The estimation of the ferrite content of cast base materials using the Schoefer diagram is discussed in Annex D.

5.1.2 Constitution (Ferrite) Diagrams. The amount of weld metal ferrite can be estimated by using the actual filler metal chemical composition and a constitution diagram (i.e., a ferrite diagram). Ferrite diagrams can also be used to predict whether a wrought base material has the potential to contain ferrite, even though in wrought products, ferrite can be eliminated by hot-working (rolling and forging) and also by heat treatment.

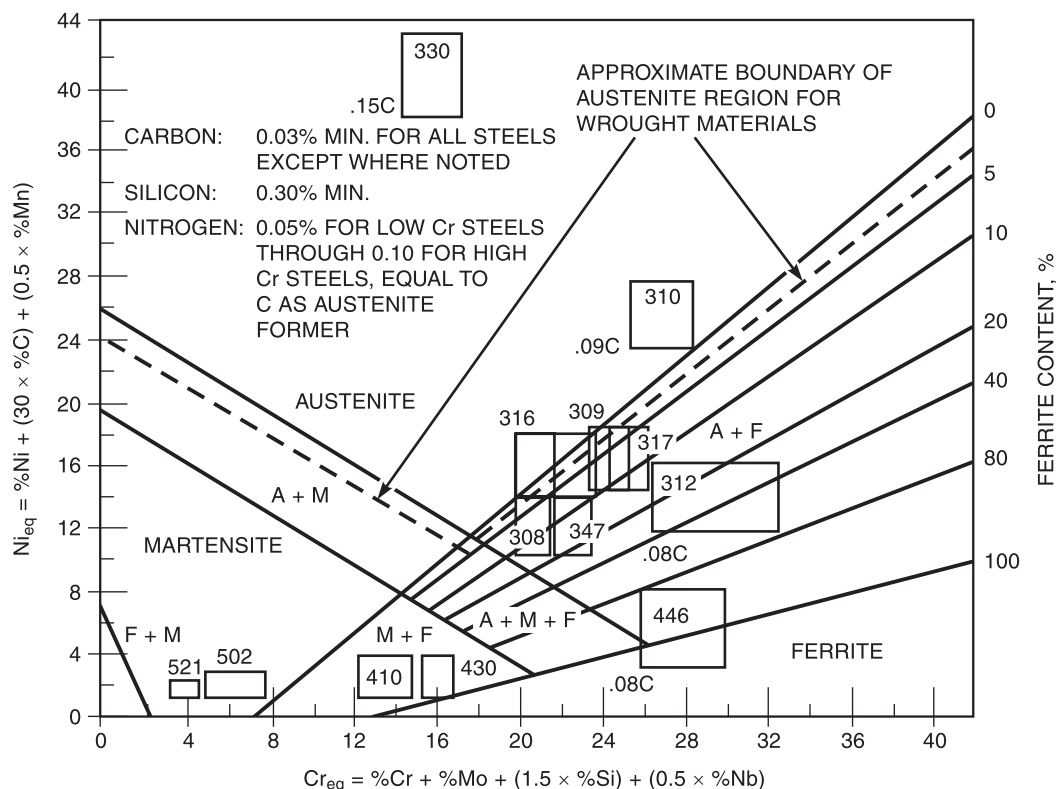
A ferrite diagram plots the austenite-promoting elements (called Ni-equivalents) and the ferrite-promoting elements (called Cr-equivalents); both equivalents are computed from the composition of the material.

Each specific ferrite-forming or austenite-forming element has its own relative "potency" that contributes to the formation of ferrite or austenite. For example, both carbon and nitrogen are "strong" austenite promoters. Very small changes in the amounts of carbon and nitrogen can result in significant changes to the proportions of austenite and ferrite. Nickel is the principal element added to the austenitic alloys that ensures the alloy will be primarily austenitic, but nickel does not have the same "potency" as carbon or nitrogen. For example, changes as small as 0.05 wt % of nitrogen or carbon content have as great of an effect as a 1% change in nickel in determining the final austenite and ferrite content of the base material or weld metal.

To use any of the ferrite/constitution diagrams, the actual chemical composition of the alloy heat analysis is used to determine both the chromium-equivalent (Cr_{eq}) number and the nickel-equivalent (Ni_{eq}) number. The Cr_{eq} number is calculated using a simple mathematical formula with the actual wt % of all ferrite-promoting elements. Since chromium is the principal ferrite-promoting element added to austenitic alloys, the formula used to determine the total effect of the ferrite-promoting elements is termed as a "chromium-equivalent." Similarly, all austenite-promoting elements are used to calculate the "nickel-equivalent."

The Ni_{eq} is plotted on the vertical axis of the diagram, and the Cr_{eq} is plotted on the horizontal axis. The FN may be estimated by drawing a horizontal line across the diagram from the Ni_{eq} and a vertical line from the Cr_{eq} . The FN is indicated by the diagonal line that passes through the intersection of the horizontal and vertical lines.

Of the numerous ferrite diagrams that have been developed, the Schaeffler diagram, developed in the 1940s, is still widely used. The Schaeffler diagram (Figure 5.1) is reasonably accurate for conventional 300 series stainless steel weld deposits using the SMAW process but is less accurate when less conventional compositions are used and when a high level of nitrogen (a powerful austenite former) is present. The diagram predicts ferrite as a percentage (e.g., % ferrite).



Note: The boxes illustrate where the composition of some filler metals lie but are not part of the original Schaeffler diagram.

Source: Reproduced from AWS *The Professional's Advisor on Welding of Stainless Steels*, 1999, Figure 8-7, Miami: American Welding Society.

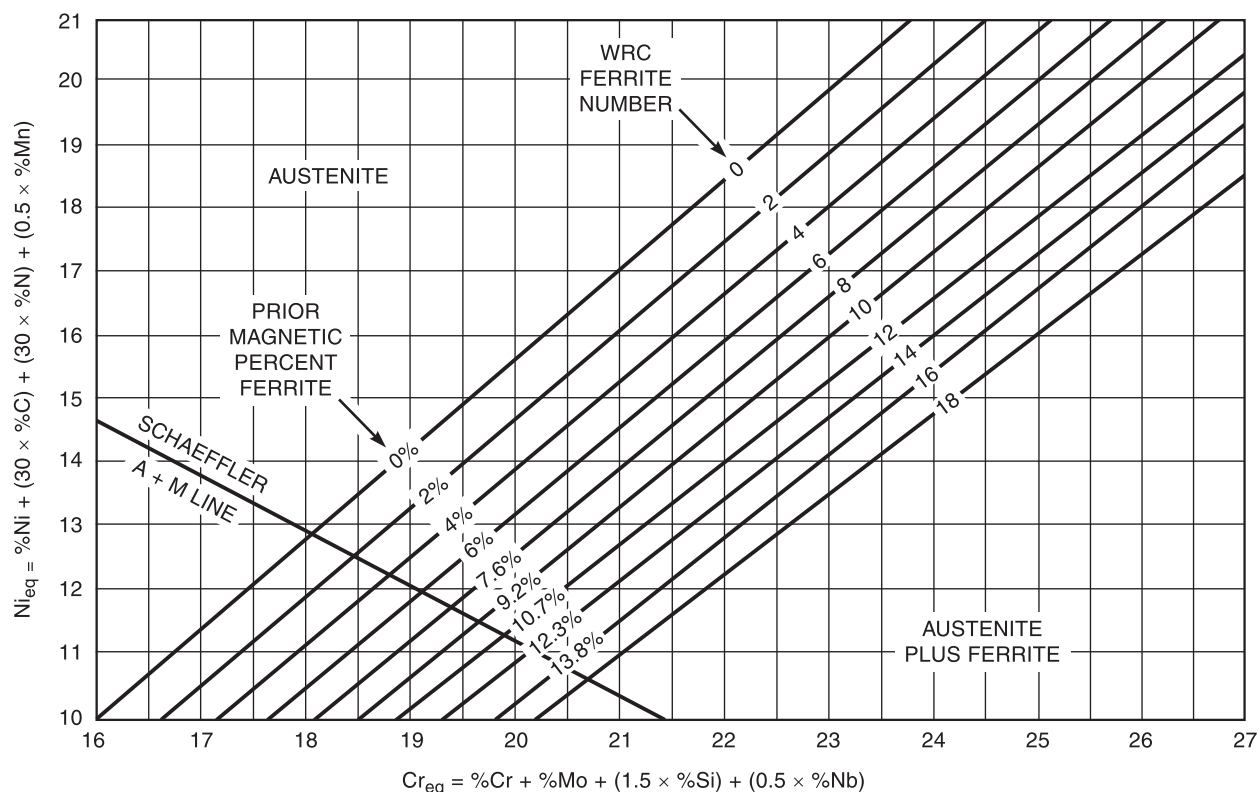
Figure 5.1—The Schaeffler Diagram

The ferrite diagrams developed since the Schaeffler diagram use Ferrite Number (FN) values instead of % ferrite. Originally, the ferrite content of weld metal was expressed as a percentage which presented a problem in reproducibility among testing sources. This problem was reduced by using the FN system which relied on a set of magnetic standards that could be used as universally accepted values. The FN values below 10 are believed to be very close to the % ferrite values previously used, but they are not necessarily the true absolute ferrite percentage of the weld. FNs above 10 exceed the true volume percent of ferrite in the weld, but the FNs established for the higher ferrite content welds have been developed by extensive magnetic testing and comparisons and have been universally accepted as standard values.

The DeLong Diagram, Figure 5.2, was developed in the 1970s. It includes the effects of nitrogen, provides estimates for nitrogen when actual values are unknown. It also provides better correlation with GTAW and GMAW weld deposits than the Schaeffler Diagram because it includes nitrogen analysis to predict ferrite. It uses FN instead of % ferrite.

This diagram allows the use of typical nitrogen levels to be used if the actual nitrogen content is unknown, albeit with the risk that the estimated nitrogen content may not closely reflect the actual content.

In the late 1980s, the Welding Research Council (WRC) funded the development of an improved ferrite diagram termed the WRC-1988 Diagram (not shown). It covers a broader range of compositions than the DeLong Diagram and is considered to be more accurate for predicting ferrite content of the 300 series stainless steel weld metals. The WRC-1988 Diagram was revised and improved several years later, and the WRC-1992 Diagram took its place (see Figure 5.3).



Note: Calculate the nickel and chromium equivalents from the weld metal analysis. If nitrogen analysis of the weld metal is not available, assume 0.06% for GTA and covered electrode, or 0.08% for GMA weld metals. If the chemistry is accurate, the diagram predicts the WRC Ferrite Number within ± 3 in approximately 90% of the tests for the 308, 309, 316, and 317 families.

Source: Reproduced from AWS *The Professional's Advisor on Welding of Stainless Steels*, 1999, Figure 8-6, Miami: American Welding Society.

Figure 5.2—The DeLong Diagram

The WRC Diagram uses an FN scale instead of defining ferrite as a volume percent as in the Schaeffler Diagram. Using volume percent to characterize ferrite turned out to be relatively nonreproducible, while defining ferrite content based on the FN scale is much more reproducible.¹ The FN scale is defined by a set of National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) coating thickness standards. Each standard specimen in a set has a unique thickness of nonmagnetic plating over a magnetic substrate. Each specimen is assigned an FN value, and a series of these standards is used to develop a calibration procedure. The basic test instrument used for the WRC FN system is a Magne-Gage®.^{2,3,4} Other instruments can also be calibrated according to this system using secondary standards also available from NIST. The calibration procedure is completely defined in AWS A4.2M:2006 (ISO 8249:2000 MOD), *Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal*. A further refinement of the WRC-1992 Diagram incorporating the effects of 1%, 4%, and 10% manganese on martensite formation has also been published.⁵

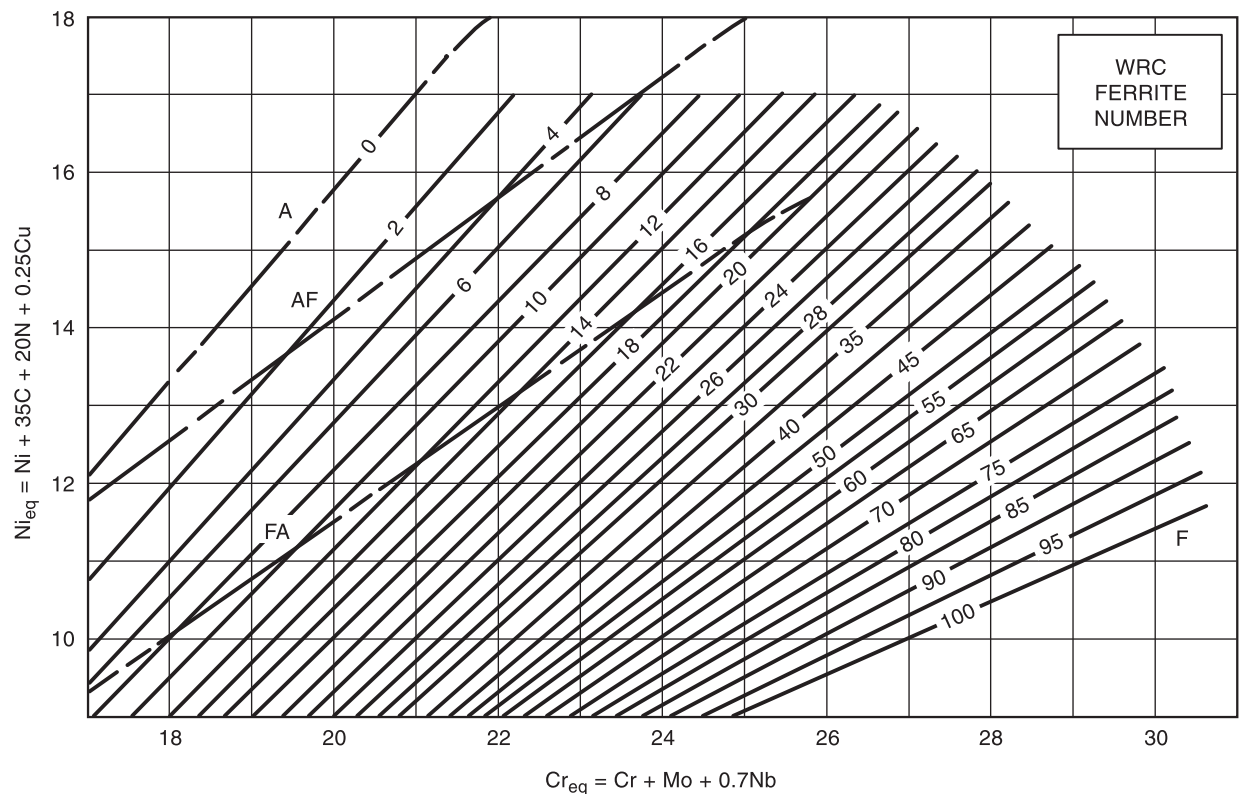
¹ Kotecki, D., 2000, Stainless Q & A, *Welding Journal* 79(12): 64–65.

² Magne-Gage® is a registered trademark of Magne-Gage Sales & Service Co., Inc.

³ McKay Welding Technical Bulletin SS-300-F, *Welding Stainless Steels*.

⁴ Kotecki, D., 1997, Ferrite Determination in Stainless Steel Welds—Advances Since 1974, *Welding Journal* 76(1): 24-s.

⁵ Kotecki, D., 2000, A Martensite Boundary on the WRC-1992 Diagram—Part 2: The Effect of Manganese, *Welding Journal* 79(12): 346-s–354-s.



Source: Kotecki, D. J. and T. A. Siewert, 1992, WRC-1992 Constitution Diagram for Stainless Steel Weld Metals: A Modification of the WRC-1988 Diagram, *Welding Journal* 71(5): 171-s–178-s.

Figure 5.3—WRC-1992 Diagram for Stainless Steel Weld Metal

Table 5.1 offers a comparison of the aforementioned ferrite diagrams.

5.1.3 Measuring Ferrite Number. The FN can be easily determined by measurements made directly on weld deposits. Several instruments are available commercially to make this measurement, such as the Magne-Gage®, Severn Gage®,⁶ and FERITSCOPE®.⁷ All the instruments are portable except the Magne-Gage® which is used primarily in laboratory conditions. Consequently, the test specimen size is limited when the Magne-Gage® is used. Manufacturer's literature should be consulted for operating instructions.

Buyers of fabricated products frequently specify restrictions for deposited weld metal ferrite content. Fabricators should be aware that the deposited ferrite content can vary from the predicted value and that purchasing welding consumables at either the extreme upper or lower limit of the allowed range (defined in the buyer or designers purchase specification) can carry some risk.

Many FN determinations are based on filler metals deposited on a welded pad.⁸ To determine FN in as-deposited weld joints, dilution of the filler metal from the base metal should be considered. The procedure described by Kotecki and Siewert can be used.⁹

⁶The Severn Gage® is a registered trademark of the Severn Engineering Company.

⁷FERITSCOPE® is a registered trademark of Helmut Fischer GmbH Institut für Elektronik und Messtechnik, Sindelfingen, Germany.

⁸Consult references: Annex A6 of AWS A5.4/A5.4M, Annex A7 of AWS A5.9/A5.9M, and Annex A6 of AWS A5.22/A5.22M.

⁹D. J. Kotecki and T. A. Siewert, WRC-1992 Constitution Diagram for Stainless Steel Metals: A Modification of the WRC 1988 Diagram, *Welding Journal Research Supplement*, Vol. 71(5): 171-s–178-s.

Table 5.1
Ferrite Diagram Comparisons of Chrome and Nickel Equivalencies

Ferrite Predictor	Cr _{eq}	Ni _{eq}	Comments
Schaeffler	%Cr + %Mo	%Ni + (30 × %C)	— Original method of calculating Ferrite in 300 series Stainless Steels
	+ (1.5 × %Si)	+ (0.5 × %Mn)	— Range of Ferrite 0%–100%
	+ (0.5 × %Nb)		
DeLong	%Cr + %Mo	%Ni + (30 × %C)	— Modification of the Schaeffler Diagram
	+ (1.5 × %Si)	+ (30 × %N)	— Improved correlation between predicted and measured ferrite
	+ (0.5 × %Nb)	+ (0.5 × %Mn)	— Allows standard Nitrogen values for various welding processes
			— Range of Ferrite 0 FN–18 FN
WRC-1992	%Cr + %Mo	%Ni + (35 × %C)	— Method with the closest agreement between predicted and measured ferrite
	+ (0.7 × %Nb)	+ (20 × %N)	— Range of Ferrite 0 FN–100 FN
		+ (0.25 × %Cu)	— Suitable for Duplex Stainless Steel

Note: Manganese and silicon are not used to calculate the Ni_{eq} and Cr_{eq} equivalents for the WRC-1992 Diagram because their effects were found to be statistically insignificant at levels up to at least 10% Mn and 1% Si.

5.1.4 Welding Variables and Effect on Ferrite. Welding variables can cause a significant change in deposited ferrite content compared to the predicted deposited ferrite content. For example, carbon pickup from contaminated weld joints (e.g., inadequate cleaning of poorly arc-gouged surfaces or from residual oils and greases) and excessive nitrogen pickup from the atmosphere can cause a dramatic decrease of deposited ferrite content. The use of nitrogen in the shielding gas can also affect the resultant ferrite content. Not all filler metal manufacturers analyze consumables for nitrogen content since nitrogen is not an element required to be controlled or reported for most filler metals. Nitrogen content is essential, however, for accurately predicting weld metal ferrite. Consequently, when it is essential to control ferrite of weld deposits, requiring analysis for nitrogen of welding consumables can help the user more accurately predict the FN of the final weld deposit. This requirement, however, has the potential of reducing the availability of consumables.

The typical nitrogen content of weld deposits for a specific welding process can be established by analysis, and these typical nitrogen values may be used to help estimate ferrite contents in other instances when nitrogen content is unknown. Any of the following factors may result in excessive nitrogen pickup:

- (1) Maintaining an excessive arc length;
- (2) Excessively low gas shielding flow rate (which is incapable of providing adequate shielding);
- (3) Excessively high gas shielding flow rate (which results in aspiration of air); and
- (4) Loss of shielding gas coverage, e.g., from drafts (fans, wind, fume exhaust systems), or when welding certain joint configurations such as outside corner joints.¹⁰

¹⁰ Kotecki, D., 2000, Stainless Q & A, *Welding Journal* 79(1): 94.

Cooling rates during the solidification process can also influence the amount of ferrite.¹¹

For these reasons, in the development of welding procedures, it is important to know the predicted ferrite content of the filler metal as well as the influence of the welding process, techniques, and variables.

5.1.5 Hot Cracking (i.e., solidification cracking) and Ferrite. Welds produced with welding consumables that produce completely austenitic weld deposits can be prone to hot cracking. Hot cracking of many weld deposit types can be prevented or minimized by using a filler metal that produces ferrite during the solidification process and retains a minimum amount of ferrite in the solidified weld. Many of the 300 series stainless steel weld deposits contain much ferrite at the moment of solidification, and most of this ferrite transforms to austenite during cooling from the solidification temperature. What is observed at room temperature is known as retained ferrite and is actually the amount of ferrite that has not transformed. For example, a typical weld on 304-SS may initially contain up to 80% ferrite during the solidification process but during cooling the majority of ferrite transforms to austenite and only about 5%–10% ferrite typically remains at room temperature.¹²

Ferrite-containing weld deposits provide ferrite-austenite boundaries that are able to tolerate low melting temperature compounds of sulfur and phosphorous so that they reduce hot cracking susceptibility. It should be noted, however, that some design conditions require fully austenitic microstructures where ferrite in the final weld deposit is not permitted. These types of alloys at the point of solidification are fully austenitic and thus do not transform.

Whether or not there will be ferrite during the solidification process and in the solidified weld (discussed further in this subclause) has been found to be strongly dependent on the ratio of the “Cr equivalent” to the “Ni equivalent” (Cr_{eq}/Ni_{eq}) determined from the specific filler metal heat being used. Weld deposits for which Cr_{eq}/Ni_{eq} is less than about 1.5 (based on the Schaeffler diagram) tend to solidify fully austenitic (without ferrite).¹³ This value may vary somewhat depending on the equivalency relations used (e.g., Schaeffler vs. Delong, or WRC).

In some filler metal types such as types 310, 320, 330, 383, and 385, adjusting the composition to provide a small amount of ferrite is not possible because of the relatively high percentage of austenite promoters (such as nickel). Crack susceptibility in these grades is minimized by control of other variables as described below.

Other methods for reducing hot cracking include reducing the restraint on the weld joint (e.g., relocating the weld joint to areas of lower stress or utilizing thinner base materials if the design permits), keeping the heat input as low as practical, and maintaining a 175°C [350°F] maximum interpass temperature. Using filler metals with very low sulfur and phosphorous contents may also help reduce the tendency for solidification cracking. Convex weld beads are more resistant to cracking than concave weld beads. Backfilling weld craters before terminating the welding arc is also a good practice.

High manganese content in some fully austenitic type weld deposits is used as an alternative means to minimize hot cracking tendencies. European and some other electrode standards recognize the benefit of relatively high manganese additions to consumables as a means for minimizing hot cracking tendencies. As a comparison, for welding type 310 stainless steel, the European Standard BS EN ISO 3581:2016, *Welding Consumables—Covered electrodes for manual metal arc welding of stainless and heat-resisting steels—Classification*, manganese range for alloy type 25 20 SMAW electrodes is 1.0% to 5.0% while the AWS A5.4/A5.4M manganese range for type E310 is 1.0%–2.5%. Also, the SMAW electrodes are generally more resistant to hot cracking than the comparable bare wire filler metals.

Refer to 7.1 for additional discussion on hot cracking (i.e., solidification cracking).

In addition to estimating the ferrite number of a weld deposit, the WRC-1992 Diagram can be used to predict the solidification mode and final structure of the weld deposit. After calculating and plotting the Cr- and Ni-equivalents on the WRC-1992 Diagram, the resulting plotted FN point will fall within a specific region of the diagram identified as “A,”

¹¹ Vitek, J. M., S. A. David, and C. R. Hinman, 2003, Improved Ferrite Number Prediction Model that Accounts for Cooling Rate Effects—Part 1: Model Development, *Welding Journal* 82(1): 10-s.

¹² V. Kujanpää, N. Suutala, T. Takalo, and T. Moisio, “Correlation Between Solidification Cracking and Microstructure in Austenitic and Austenitic-Ferritic Stainless Steel Weld,” *Welding Research Intl.*, Vol. 9(2) (1979) pp. 55–76.

¹³ See footnote 12.

“AF,” “FA,” or “F.” These regions define both the grain structure immediately after solidification and the final structure after cooling and transformations (if any) are complete. In all instances defined below, the WRC Diagram can be used to estimate the final amount of retained ferrite.

Type “A” solidification regions define compositions that solidify directly to an austenitic microstructure. The austenite does not transform during cooling. When weld specimens are suitably prepared, etched, and viewed under a microscope, the microstructure will be fully austenitic.

Type “AF” regions define compositions that solidify directly to an austenitic microstructure, except that some of the very last liquid to solidify will do so directly to ferrite. The microstructure remains relatively unchanged through cooling, and at its final stage will show austenitic dendrite (grains) branches with small amounts of retained ferrite located between them.

Type “FA” regions define compositions that solidify directly to a ferritic microstructure, except that some of the very last liquid to solidify will do so directly as austenite. Upon cooling, the austenite remains unchanged, and most of the ferrite is transformed into austenite. The final microstructure typically shows continuous austenite along original ferrite solidification grain boundaries. The structure of the ferrite/austenite can take on several forms depending on the Cr_{eq}/Ni_{eq} ratio including skeletal ferrite along the dendrite cores and lathy ferrite.

Type “F” regions define compositions that solidify directly to a completely ferritic microstructure. Upon cooling in the solid state, austenite nucleates on the ferrite solidification grain boundaries and grows inward toward the dendrite cores. The final microstructure may show parallel plates of ferrite and austenite; it is often called Widmanstätten austenite. This microstructure is very unusual in austenitic stainless steels.

Type “FA” solidification is very effective in minimizing or preventing hot cracking—normally a ferrite content of 4 FN minimum is sufficient to ensure that Type FA solidification has occurred. If the weldment is intended for high-temperature service or very low-temperature service, the amount of ferrite normally should not be greater than necessary to prevent hot cracking. At levels of 12 FN to 15 FN, the ferrite phase starts to be interconnected.

Refer to 7.3 for additional information on controlling the solidification mode.

5.1.6 Possible Detrimental Effects of Ferrite. Weld metal ferrite can adversely affect weld metal corrosion resistance in a few environments, for example, in the production of uric acid. Examples of fully austenitic grades used in extremely corrosive environments such as fertilizer production or acidic service are grades 310, 383, and 385.

In cryogenic applications, ferrite reduces toughness and is consequently kept as low as possible to optimize low-temperature ductility as reflected in Charpy V-notch testing. A desirable limit for the processes using wire flux combination is about 2 FN maximum.¹⁴ However, at least one electrode manufacturer tests and certifies their electrodes for cryogenic service with higher ferrite limits and good impact properties.

For high temperature applications, excessive ferrite may result in reduced creep resistance. Thomas¹⁵ observed in type 316 deposits that resistance to creep deteriorates at high ferrite levels (e.g., in the presence of continuous ferrite networks).

For these reasons, ferrite ranges are often specified by the fabricator or end user.

5.2 The Ferrite-Sigma Phase Relationship. Although a small amount of weld metal ferrite is very beneficial in preventing hot cracking, too much ferrite may be detrimental. In long term service in the temperature range of 400°C to 540°C [750°F to 1000°F] alpha-prime forms causing 475°C [885°F] embrittlement. If the metal is heated within 600°C to 925°C [1100°F to 1700°F] sigma phase may form. The materials room temperature ductility can be significantly reduced by the formation of alpha-prime or sigma formation.

¹⁴ Avery, R. E., 1995, Welding Stainless and 9% Nickel Steel Cryogenic Vessels, *Welding Journal* 74(11): 45.

¹⁵ Thomas, R., 1978, The Effect of Delta Ferrite on the Creep Rupture Properties of Austenitic Weld Metals, *Welding Journal* 57(3): 81.