

Guide for the Joining of Wrought Nickel-Based Alloys



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An American National Standard

Approved by the
American National Standards Institute
October 16, 2012

Guide for the Joining of Wrought Nickel-Based Alloys

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

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This document describes the welding of different wrought nickel-based alloys, including solid solution and precipitation hardening alloys.



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Personnel

AWS G2 Committee on Joining Metals and Alloys

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G. Dunn, Vice Chair	<i>ExxonMobil Development Company</i>
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R. E. Avery	<i>Consultant to Nickel Institute</i>
S. O. Luke	<i>Black & Veatch</i>
R. C. Sutherlin	<i>ATI Wah Chang</i>
D. J. Tillack	<i>Consultant to Nickel Institute</i>

AWS G2C Subcommittee on Nickel Alloys

D. J. Tillack, Chair	<i>Consultant to Nickel Institute</i>
A. L. Diaz, Secretary	<i>American Welding Society</i>
G. Dunn	<i>ExxonMobil Development Company</i>
W. E. Layo	<i>Midalloy</i>
S. O. Luke	<i>Black & Veatch</i>
S. B. Seitz	<i>Shawkim Technologies, Incorporated</i>

Advisors to the AWS G2C Subcommittee on Nickel Alloys

R. E. Avery	<i>Consultant to Nickel Institute</i>
C. D. Ersig	<i>Special Metals Welding Products Company</i>
V. W. Hartmann	<i>Westinghouse Electric Company</i>
G. L. Hoback	<i>Haynes International</i>
F. A. Schweighardt	<i>Air Liquide Industrial US LP</i>

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Foreword

This foreword is not part of [AWS G2.1M/G2.1:2012](#), *Guide for the Joining of Wrought Nickel-Based Alloys*, 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 is the second edition of this document; the first was published in 2002.

Underlined text in clauses, tables, or figures indicates an editorial or technical change from the 2002 edition. A vertical line in the margin also indicates a revision from the 2002 edition.

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

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Guide for the Joining of Wrought Nickel-Based Alloys

1. General Requirements

1.1 Scope. This guide presents a description of wrought nickel-based alloys and the processes and procedures that can be used to join these materials. It stresses the process basics, parameters, applications, 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 these materials.

1.2 Units of Measure. This standard makes use of 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 here.

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) Material 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:¹

[AWS A2.4, *Standard Symbols for Welding, Brazing, and Nondestructive Examination*](#);

[AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*](#);

¹ AWS standards are published by the American Welding Society, 8669 Doral Blvd., Suite 130, Doral, FL 33166.

[AWS A5.11/A5.11M](#), *Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding*;
[AWS A5.14/A5.14M](#), *Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods*;
[AWS A5.34/A5.34M](#), *Specification for Nickel-Alloy Electrodes for Flux Cored Arc Welding*; and
[AWS B2.1/B2.1M](#), *Specification for Welding Procedure and Performance Qualification*.

American National Standards Institute (ANSI) standard:²

ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

American National Standards Institute (ANSI) standard:³

ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection*

ASM International standard:⁴

ASM Handbook, Volume 6, *Welding, Brazing, and Soldering*

American Society of Mechanical Engineers (ASME) standard:⁵

ASME Boiler and Pressure Vessel Code, Section IX

ASTM International standard:⁶

[ASTM A380](#), *Standard Recommended Practice for Cleaning and Descaling and Passivation of Stainless Steel Parts, Equipment and Systems*

Occupational Safety and Health Administration (OSHA) standard:⁷

OSHA, *Code of Federal Regulations*, Title 29, Labor, Chapter XV11, Part 1910, "Occupational Safety and Health Standards"

SAE International standard:⁸

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

3. Terms and Definitions

[AWS A3.0M/A30](#), *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, provides the basis for terminology used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

solid solution strengthened nickel-based alloys. Single phase (i.e., homogenous alloy mixture with a single type of microstructure) nickel-based alloys with alloy additions not exceeding the limits of solubility. The most common alloy additions, either alone or in combination, are copper, chromium, molybdenum, and iron. Solid solution alloys can only be strengthened by cold working and not by heat treatment.

precipitation hardenable (strengthened) nickel-base alloys. Nickel-base alloys that can be strengthened by exposure to a certain temperature range long enough to cause very small phases (e.g., small particles having a different chemical composition and structure than the surrounding material) to form and strengthen the matrix. Elements such as alumi-

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³ ANSI standards are published by the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036-7406.

⁴ ASM standards are published by ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002.

⁵ ASME standards are published by the American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016-5990.

⁶ ASTM International standards are published by ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

⁷ OSHA standards are published by the Occupational Safety and Health Administration, 200 Constitution Avenue, Washington D.C. 20210.

⁸ SAE International standards are published by SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

num and/or titanium form the phases in nickel, nickel-copper, nickel-chromium-iron, nickel-iron-chromium, and nickel-iron-cobalt alloys.

4. Introduction

The family of wrought nickel-based alloys can be divided into two categories and numerous classes according to composition. The categories include solid solution strengthened alloys and precipitation hardenable alloys.

The classes of solid solution nickel-based alloys are: nickel, nickel-copper, nickel-molybdenum, nickel-chromium and nickel-chromium-iron, nickel-iron-chromium, nickel-iron, and nickel-chromium-molybdenum. These classes are listed in Table 1.

The classes of precipitation hardenable nickel-based alloys are: nickel, nickel-copper, nickel-iron-cobalt and nickel-chromium-iron, nickel-iron-chromium, and nickel-iron. These classes are listed in Table 2.

There are no precipitation hardenable nickel-chromium or nickel-molybdenum alloys.

In general, the nickel-based alloys can be welded with practices and procedures similar to the austenitic series (300) stainless steels.

This standard addresses these two categories of wrought nickel-based alloys. The first category addresses solid solution nickel alloys, which can be hardened only by cold working. The second category addresses precipitation hardening alloys, which can be hardened by heat treating in addition to cold working. Additionally, Annex A addresses safety and health issues associated with welding nickel-based alloys.

5. The Solid Solution Strengthened Nickel-Based Alloys

Solid solution strengthening occurs when one or more elements are added to another element to form a homogenous composition. Strengthening occurs when the dissolving of one or more elements (such as chromium) in the other (such as nickel) stiffens the new resulting metal. There is no appreciable increase in room temperature hardness after a solid solution alloy is exposed for relatively short period of time (such as 2 hours) to the intermediate temperature range (such as 650°C [1200°F]) (as a comparison, such temperature exposure would harden precipitation hardening alloys).

5.1 General Alloy Background Data

5.1.1 Descriptions of the Alloys and Typical Applications. The chemical composition limits of many of the common solid solution strengthened nickel-based alloys are given in Table 1. Solid solution strengthening occurs when one or more elements (such as chromium) are added to another element (such as nickel) to form a homogenous composition. Alloying elements are added to nickel to strengthen the metal and to improve its corrosion resistance. Depending on the alloy, some of the primary alloying elements added to nickel for solid solution strengthening include chromium, molybdenum, iron, cobalt, tungsten, and carbon. The material's structure, even after alloying, is homogenous. These solid solution alloys cannot be strengthened by heat treatment and can only be further strengthened and hardened by cold working. For example, quenching a solid solution nickel-base alloy from a high temperature will not harden the alloy—neither will heating the alloy at elevated temperatures. Precipitation-hardenable nickel-base alloys, however, can experience a dramatic increase in strength by heating (aging) in the 540°C–815°C [1000°F–1500°F] range.

In addition to strengthening by the addition of solid solution alloying elements, the nickel-base “precipitation hardened” alloys are also strengthened by the inclusion of specific elements such as aluminum, titanium, and niobium. When appropriately heat treated, very small and discrete particles are produced and interspersed within the material's structure. The presence of these small particles (termed “precipitates”) can greatly increase the material's strength. These alloys are also able to be strengthened by cold working. The chemical composition limits of many of the common precipitation strengthened nickel-based alloys are given in Table 2. Precipitation strengthened nickel-based alloys is fully discussed in 6.1.

Table 1
Limiting Chemical Composition of Typical Solid Solution Nickel Alloy Composition

UNS No.	Common Designation ^a	Ni	Cr	Fe	C	Cu	Mo	Mn	Si	Co	Al	Ti	Other
Commercially Pure Nickels													
N02200	Nickel 200	99.0m	—	0.40M	0.15M	0.25M	—	0.35M	0.35M	—	—	—	—
N02201	Nickel 201	99.0m	—	0.40M	0.02M	0.25M	—	0.35M	0.35M	—	—	—	—
Nickel-Copper Alloys													
N04400	Alloy 400	63.0m	—	2.5M	0.3M	28.0–34.0	—	2.0M	0.5M	—	—	—	—
N04405	Alloy R-405	63.0m	—	2.5M	0.3M	28.0–34.0	—	2.0M	0.5M	—	—	—	S = 0.025–0.060
Nickel-Molybdenum Alloys													
N10665	Alloy B-2	Balance	1.0M	2.0M	0.02M	—	26.0–30.0	1.0M	0.10M	1.0	—	—	—
N10675	Alloy B-3 ^{®c}	Balance	1.0–3.0	1.0–3.0	0.01M	—	27.0–32.0	3.0M	0.10M	3.0M	—	—	Nb (Cb) = 0.20M, P = 0.030M S = 0.010M
N10629	Alloy B-4	65.0m	0.1–1.5	1.0–6.0	0.01M	0.5M	26.0–30.0	1.5M	0.05M	2.5M	0.5M	—	P = 0.04M S = 0.01M
Nickel-Chromium-Iron and Nickel-Iron-Chromium													
N06600	Alloy 600	72m	14.0–17.0	6.0–10.0	0.15M	0.50M	—	1.0M	0.50M	—	—	—	—
N06601	Alloy 601	58.0–63.0	21.0–25.0	Balance	0.10	1.0M	—	1.0M	0.50M	—	1.0–1.7	—	—
N06690	Alloy 690	58.0m	27.0–31.0	7.0–11.0	0.05M	0.50M	—	0.5M	0.50M	—	—	—	—
N08330	RA-330	34.0–37.0	17.0–20.0	Balance	0.08M	1.0M	—	2.0M	0.75–1.50	—	—	—	—
N08120	HR-120 ^{®c}	35.0–39.0	23.0–27.0	Balance	0.02–0.1	—	2.50M	1.5M	1.0M	3.0M	0.40M	0.20M	—
N08800	Alloy 800	30.0–35.0	19.0–23.0	Balance	0.10M	0.75M	—	1.5	1.0M	—	0.15–0.60	0.15–0.60	—
S35045	Alloy 803	32–37	25–29	Balance	0.06–0.10	0.75M	—	1.5M	1.0M	—	0.15–0.60	0.15–0.60	—
Nickel-Chromium-Molybdenum Alloys													
N06202	Alloy X	Balance	20.5–23.0	17.0–20.0	0.05–0.15	—	8.0–10.0	1.0M	1.0M	0.5–2.5	—	—	W = 0.2–1.0
N06022	Alloy C-22 ^{®c} , 622	Balance	20.0–22.5	2.0–6.0	0.015M	—	12.5–14.5	0.5M	0.08M	2.5M	—	—	—

(Continued)

Table 1 (Continued)
Limiting Chemical Composition of Typical Solid Solution Nickel Alloy Composition

UNS No.	Common Designation ^a	Ni ^b	Cr	Fe	C	Cu	Mo	Mn	Si	Co	Al	Ti	Other
Nickel-Chromium-Molybdenum Alloys (Continued)													
N06030	Alloy G-30 ^{®c}	Balance	28.0–31.5	13.0–17.0	0.03M	1.0–2.4	4.0–6.0	1.5M	0.8M	5.0M	—	—	Nb = 0.30–1.50 W = 1.5–4.0
N06059	Alloy 5923hMo	Balance	22.0–24.0	1.5M	0.01M	—	15.0–16.5	0.5M	0.10M	0.3M	0.1–0.4	—	—
N06200	Alloy C-2000 ^{®c}	Balance	22.0–24.0	3.0M	0.010M	1.3–1.9	15.0–17.0	0.50M	0.08M	2.0M	—	—	—
N06231	Alloy 230 ^{®c}	Balance	20.0–24.0	3.0M	0.05–0.15	—	1.0–3.0	0.3–1.0	0.25–0.75	5.0M	0.20–0.50	—	W = 13.0–15.0 La = 0.005–0.050
N06333	RA333	44.0–47.0	24.0–27.0	Balance	0.08M	0.5M	2.5–4.0	2.0M	0.75–1.50	2.5–4.0	—	—	W = 2.5–4.0
N06455	Alloy C-4	Balance	14.0–18.0	3.0M	0.015M	—	14.0–17.0	1.0M	0.08M	2.0M	—	0.70M	—
N06617	Alloy 617	44.5m	20.0–24.0	3.0M	0.05–0.15	0.50M	8.0–10.0	1.0M	1.0M	10.0–15.0	0.8–1.50	0.60M	B = 0.006M
N06625	Alloy 625	Balance	20.0–23.0	5.0M	0.10M	—	8.0–10.0	0.5M	0.5M	—	0.40M	0.40M	Nb = 3.15–4.15
N06686	Alloy 686	Balance	19.0–23.0	5M	0.01M	—	15–17	0.75M	0.08M	—	—	0.02–0.25	W = 3.0–4.0
N06985	Alloy G-3	Balance	21.0–23.5	18.0–21.0	0.015M	1.5–2.5	6.0–8.0	1.0M	1.0M	5.0M	—	—	Nb + Ta = 0.50M W = 1.5M
N08020	Alloy 20Cb3	32.0–38.0	19.0–21.0	Balance	0.07M	3.0–4.0	2.0–3.0	2.0M	1.0M	—	—	—	—
N08024	Alloy 20Mo4	35.0–40.0	22.5–25.0	Balance	0.03M	0.50–1.50	3.5–5.0	1.0M	0.5M	—	—	—	Nb = 0.15–0.35
N08026	Alloy 20Mo6	33.0–37.2	22.0–26.0	Balance	0.03M	2.0–4.0	5.0–6.7	1.0M	0.5M	—	—	—	—
N08825	Alloy 825	38.0–46.0	19.5–23.5	Balance	0.05M	1.5–3.0	2.5–3.5	1.0M	0.5M	—	0.2M	0.6–1.2	—
N10276	Alloy C-276	Balance	14.5–16.5	4.0–7.0	0.02M	—	15.0–17.0	1.0M	0.08M	2.5M	—	—	V = 0.35 Max. W = 3.0–4.5
R30556	Alloy 556 ^{®c}	19.0–22.5	21.0–23.0	Balance	0.05–0.15	—	2.5–4.0	0.50–2.00	0.20–0.80	16.0–21.0	0.10–0.50	—	Ta = 0.30–1.25 W = 2.0–3.5
Nickel-Iron Alloys													
K93600	Invar	36	—	Balance	0.12M	—	—	1.0M	0.35M	—	—	—	—
K94200	Alloy 42	42	—	Balance	0.10M	—	—	0.5M	0.25M	—	—	—	—

^a Nominal value adjusted to meet expansion requirements: M = maximum, m = minimum.
^b Includes small amount of cobalt if cobalt content is not specified.
^c This alloy is a registered trademark of Haynes International.

Table 2
Chemical Compositions of Precipitation-Hardenable Nickel Alloys (wt %)

UNS No.	Alloy	Ni	Cr	Fe	Co	Cu	C	Al	Ti	Nb (Cb)	Mo	B	Other
Nickel and Nickel-Copper Alloys													
N03301	301	93.0m	—	0.60M	—	0.25M	0.30M	4.00–4.75	0.25–1.00	—	—	—	0.50M Mn
N05500	K-500	63.0–70.0	—	2.0M	—	Balance	0.25M	2.30–3.15	0.35–0.85	—	—	—	1.50M Mn
Nickel-Chromium-Iron and Nickel-Iron-Chromium Alloys													
N07001	Wasp	Balance	18.0–21.0	2.0M	12–15	0.50M	0.03–0.10	1.2–1.6	2.75–3.25	—	3.5–5.0	0.003–0.010	0.03–0.12 Zr
N07041	R-41	Balance	18.0–20.0	5.0M	10–12	—	0.12M	1.4–1.8	3.0–3.3	—	9.0–10.5	0.003–0.010	0.10M Mn, 0.015M S 0.50M Si
N07080	80A	Balance	18.0–21.0	3.0M	2.0M	0.2M	0.10M	1.0–1.8	1.8–2.7	—	—	0.008M	0.045M P, 0.015M S 1.0M Si, 0.06 Zr
N07090	90	Balance	18.0–21.0	3.0M	15–21	—	0.13M	0.8–2.8	1.8–3.0	—	—	0.006M	1.0M Mn, 1.5M Si
N07252	M252	Balance	18.0–20.0	5.0M	9–11	—	0.1–0.2	0.75–1.25	2.25–2.75	—	9.0–10.5	0.003–0.010	0.50M Mn, 0.05M P 0.015M S, 0.5M Si
N07500	U-500	Balance	15.0–20.0	4.0M	13–22	—	0.15M	2.50–3.25	2.5–3.25	—	3.0–5.0	0.003–0.010	0.75M Mn, 0.015M P 0.015M S, 0.75M Si
N07520	U-520	Balance	18.0–20.0	—	11–13	—	0.10M	1.5–2.5	2.75–3.25	—	5.0–7.0	0.003–0.010	0.5–1.5 W
N07700	U-700	Balance	14.0–16.0	—	17–20	—	0.13M	4.00–4.75	3.0–3.75	—	4.0–6.0	0.003–0.010	0.03–0.12 Zr
N07718	718	50–55	15.0–17.0	Balance	—	—	0.08M	0.2–0.8	0.65–1.15	4.75–5.50	2.8–3.3	0.006M	0.35M Mn, 0.015M P 0.015M S, 0.35M Si
N07725	725	55–59	19.0–22.5	Balance	—	—	0.03M	0.35M	1.0–1.7	2.75–4.00	7.0–9.5	—	0.35M Mn, 0.015M P 0.010M S, 0.20M Si
N07750	X-750	70.0m	14.0–17.0	5.0–9.0	—	0.5M	0.08M	0.40–1.0	2.25–2.75	0.7–1.0	—	—	1.0M Mn, 0.015M P 0.010M S, 0.50M Si
N09706	706	39.0–44.0	14.5–17.5	Balance	—	0.30M	0.06M	0.40M	1.5–2.0	2.5–3.3	—	—	0.35M Mn, 0.020M P0.015M S, 0.35M Si
N09901	901	40.0–45.0	11.0–14.0	Balance	—	0.50M	0.1M	0.35M	2.35–3.10	—	5.0–7.0	0.010–0.020	1.0M Mn, 0.030M S 0.60M Si

(Continued)

Table 2 (Continued)
Chemical Compositions of Precipitation-Hardenable Nickel Alloys (wt %)

UNS No.	Alloy	Ni	Cr	Fe	Co	Cu	C	Al	Ti	Nb (Cb)	Mo	B	Other
N09902	902	41.0–43.5	4.90–5.75	Balance	—	—	006M	0.30–0.80	2.20–2.75	—	—	—	0.8M Mn, 0.040M S
N09925	925	38.0–46.0	19.5–23.5	22.0M	—	1.5–3.0	0.03M	0.10–0.50	1.90–2.40	—	2.5–3.5	—	1.0M Mn, 0.030M S 0.50M Si
Nickel-Iron-Cobalt Alloys													
N19903	903	36.0–40.0	1.0M	Balance	13–17	0.50M	0.06M	0.30–1.15	1.00–1.25	2.4–3.5	—	—	1.0M Mn, 0.015M S 0.35M Si
N19907	907	35.0–40.0	1.0M	Balance	12–16	0.5M	0.06M	0.020M	1.2–1.8	4.3–5.2	—	0.012M	1.0M Mn, 0.015M P 0.015M S, 0.35M Si
N19909	909	35.0–40.0	1.0M	Balance	12–16	0.5M	0.06M	0.15M	1.3–1.8	4.3–5.2	—	0.012M	1.0M Mn, 0.015M P 0.015M S, 0.25–0.50M Si
R30783	783	26–30	2.5–3.5	24–27	Balance	—	0.03M	5–6	0.4M	2.5–3.5	—	0.003	—
Nickel-Iron Alloys													
<u>TBD^a</u>	<u>365</u>	<u>40.0–46.0</u>	<u>50M</u>	<u>Balance</u>	<u>2.0M</u>	<u>60M</u>	<u>0.05M</u>	<u>0.50M</u>	<u>1.15–1.8</u>	<u>3.0–4.25</u>	—	—	0.60M Si

^a At time of publication, a UNS number for this alloy has not been assigned.

Notes:

1. Nominal value adjusted to meet expansion requirements: M = maximum, m = minimum.
2. Includes small amount of cobalt if cobalt content is not specified.

Any of the nickel alloys have good toughness at extremely low, or cryogenic, temperatures. Generally speaking, nickel and its alloys can be readily formed and fabricated. The nickel alloys are used because of their resistance to severe environmental conditions and because they have attractive mechanical properties. The commercially pure nickel alloys are almost pure nickel with minor additions of one or more additional elements. Nickel 200 is the most common alloy of this group. The commercially pure nickel alloys are used extensively in applications that take advantage of their electronic or magnetic characteristics, such as in transducers and as plated pins for printed circuit board connectors. The nickel alloys are also used in applications utilizing their corrosion resistance, such as in the handling of hot concentrated caustic soda and dry chlorine. Most of these applications involve temperatures below 315°C [600°F]. For applications above 315°C [600°F], a low carbon grade of nickel Alloy 201 is used because it does not suffer embrittlement by graphite precipitation during exposure at these higher temperatures.

The nickel-copper group of nickel alloys generally has the ratio of two parts nickel and one part copper, typified by alloy 400. These alloys are only used at relatively low temperatures because they have poor high-temperature oxidation resistance. The nickel-copper alloys are used extensively in sea water applications because of their excellent resistance to corrosion, cavitation, and erosion. Other significant applications include propeller shafting, marine fixtures and fasteners, valves and pumps, chemical process equipment, process vessels and piping, and heat exchangers. Like the commercially pure nickel grades, they are readily fabricated, have excellent ductility, and can be formed easily into a variety of shapes.

The nickel-molybdenum alloys have relatively high levels of molybdenum that give increased resistance to the corrosive effects of strong reducing acids (nonoxidizing) such as hydrochloric acid.

Nickel-chromium, nickel-chromium-iron, and nickel-iron-chromium alloys are a very versatile collection of alloys that are used in a wide cross section of industries and applications and over a broad spectrum of temperatures. The nickel-chromium-iron alloys are used in a variety of industries, from chemical processing and nuclear power components operating at relatively low temperatures, to high temperature applications in turbine engines and heat treating equipment. These alloys are slightly more difficult to fabricate than steels because of their higher strengths. The nickel-iron-chromium alloys are typically used in oxidizing and carburizing applications because of their resistance to these environments and their high strength. Typical applications include furnace components, heat exchangers and process piping, electric range heating-element sheathing, extruded tubing for ethylene and steam methane reforming furnaces, and chemical process equipment.

The nickel-chromium-molybdenum alloys have excellent corrosion resistance in a wide range of severe environments that range from highly oxidizing to moderately nonoxidizing (reducing) environments. The high molybdenum contents make the alloys especially resistant to pitting and crevice corrosion attack. The nickel-chromium-molybdenum alloys are used extensively in pollution control, chemical processing, pulp and paper production, waste treatment systems, and marine environments.

The nickel-iron alloys can be designed to have specific thermal-expansion characteristics. They can be designed to have very low thermal expansion or to display uniform and predictable expansion over certain temperature ranges. The nickel-iron alloys are used in controlled thermal expansion applications where variations in temperature can cause malfunctioning or imprecise operation if thermal expansion of components is not minimized or controlled. The applications include measuring devices, measurement standards, glass-to-metal seals, electrical leads for semiconductors, tanks and piping for cryogenic fluids, and dies for forming metals and composites.

5.1.2 Metallurgy. Nickel is a very versatile element and will alloy easily with most metals. For example, it completely mixes with copper to form single phase alloys in all ratios of copper and nickel; this is called complete solid solubility and is the simplest alloy system. When some other metals combine with nickel, however, two or more phases may be formed and the mechanical properties of the alloy are more difficult to predict. This is particularly important in welding dissimilar materials because there are at least two, and often three, different alloys contributing to the weld structure—the two base materials and the filler metal.

5.1.3 Heat Treatment. The solid solution strengthened nickel-based alloys are heat treated for two main reasons: first, to provide an optimum microstructure thereby providing optimum performance in a particular environment (such as to provide corrosion resistance or to maximize creep rupture properties), and second, to relieve fabrication and welding stresses. These heat treatment conditions falls into two temperature ranges, the low temperature treatment is referred to as a stress relief anneal, and the high temperature heat treatment is referred to as a solution anneal.

A stress relieve anneal is performed to relieve the stresses in the material and is not intended to increase the grain size. A solution anneal is performed at higher temperatures than a stress relief anneal and is usually done to improve the material's high temperature properties by increasing the grain size. Excessive grain growth can be undesirable, however, and close monitoring of the postweld heat treatment is required since base material and weld material properties can be dramatically altered as grain size is altered. Once the grain size has increased, the only way to refine it is to cold work the material and perform a recrystallization heat treatment. Unfortunately, further cold work on a fabrication is often impractical.

Although postweld heat treatments are usually not required for solid solution nickel and nickel alloys, postweld heat treating of fabricated vessels or structures may be useful in some instances. Unrelieved welding stresses can sometimes cause failures when the combination of service, fabrication, and welding stresses exceed the strength limits of the material. If the welded structure is too large to furnace stress relieve, localized heat treatment using strip heaters, or similar methods can be used.

The ASME *Boiler and Pressure Vessel Code for Unfired Pressure Vessels* does not make postweld heat treatment a requirement except as agreed upon between the user and the manufacturer. An exception is a dissimilar weldment between a nickel alloy and a steel alloy when a postweld heat treatment is required for the steel side of the joint. In this case, there normally will be little consequence of the heat treatment on the nickel alloy. Table 3 lists the typical annealing temperatures for many of the solid solution nickel alloys. Table 4 lists the liquidus/solidus (melting points) for the same solid solution nickel alloys.

A postweld heat treatment may be beneficial for weldments exposed to certain environments. Two examples of this are caustic service for Alloys 200, 201, and 600 and hydrofluoric acid service for Alloy 400. The recommended heat treatment procedures for these materials in these service environments are as follows:

(1) Alloys 200 and 201 for caustic service, hold at 700°C [1300°F] for a minimum of 1/2 hour per 25 mm [1 in] of thickness.

(2) Alloy 600 for caustic service, hold at 900°C [1650°F] for a minimum of one hour per 25 mm [1 in] of thickness or at 790°C [1450°F] for a minimum of four hours per 25 mm [1 in] of thickness.

(3) Alloy 400 for hydrofluoric acid service, hold at 600°C [1100°F] for a minimum of 1/2 hour per 25 mm [1 in] of thickness.

NOTE: Heating and cooling rate varies with the shape of the part. Complex shapes with nonuniform thicknesses should have heating and cooling rates of no more than 110°C [200°F] per hour. Shapes with uniform thicknesses can use fast heating and air cooling.

The rate of heating and cooling during postweld heat treating seldom creates a problem with the solid solution nickel alloys, but they generally should be cooled by air cooling or faster methods. When there are large differences in cross-sectional areas in a welded structure the heating and cooling rates may have to be controlled in order to minimize distortion that might occur with rapid heating or cooling rates. Such structures can experience distortion sufficient to cause fit-up or assembly problems if a too-rapid cooling rate causes excessive stresses.

Specific heat treatment parameters should be obtained from the manufacturer or producer of the nickel alloy.

5.1.3.1 Furnace Atmosphere Requirements. The usual precautions regarding furnace atmosphere and temperature control should be followed when heat treating, including postweld heat treating, these nickel-based alloys. Either electricity or various gases and fuel oils can be used for heating. A low sulfur content is an important requirement for any fuel, and the generally accepted maximum limit of 690 mg of sulfur per cubic meter [30 grains per 100 ft³] of fuel gas should be considered to be marginal, especially when heating the very high nickel content alloys. Oil can be a satisfactory fuel provided it has a low sulfur content—not more than 0.5% by weight of sulfur (the equivalent of ASTM Grade 1 or Grade 2 fuel oil). If the quality of the furnace gas is unknown, it can be checked before-hand by heating a small piece of the material to the required temperature and holding it at temperature for 10–15 minutes. The piece is then air cooled or water quenched and bent through 180° flat on itself. If heating conditions are correct, there will be no evidence of cracking. High-nickel alloys are subject to surface oxidation unless heating is performed in a protective atmosphere or in a vacuum. A protective atmosphere can be provided either by controlling the ratio of fuel and air to minimize oxidation or by surrounding the metal being heated with a prepared atmosphere (such as dissociated ammonia or hydrogen).

Accurate control of temperature is one of the most important factors in achieving good results in heating. Furnaces should be equipped with automatic temperature controls and maintained at the temperature that is recommended for the

Table 3
Typical Annealing Temperatures for Solid Solution Nickel Alloys

Alloy	UNS No.	Temperature ^a	
		°C	°F
200	N02200	830–870	1525–1600
400	N04400	870	1600
X	N06002	1175	2150
C-22 ^{®b}	N06022	1120	2050
G-30 ^{®b}	N06030	1175	2150
C-2000 ^{®b}	N06200	1150	2100
230 ^{®b}	N06230	1230	2250
C-4	N06455	1065	1950
600	N06600	925–1040	1700–1900
601	N06601	1175	2150
G-3	N06985	1150	2100
HR-120 ^{®b}	N08120	1200	2200
601	N06601	1175	2150
800	N08800	1010–1175	1850–2150
825	N08825	940	1725
C-276	N10276	1120	2050
B-2	N10665	1065	1950
B-3 ^{®b}	N10675	1065	1950
556 ^{®b}	R30556	1175	2150

^a Temperature tolerance is $\pm 15^{\circ}\text{C}$ [27°F].

^b This alloy is a registered trademark of Haynes International.

Notes:

1. Cooling method: air cool or water quench.
2. Typical holding time at temperature is 1 h per 25 mm [1 in] of thickness.

alloy being heated. Complete information concerning temperature measurement and control is available from manufacturers of pyrometric equipment. Thermocouples should be checked for accuracy at least once during each day of use. Thermocouples are subject to poisoning by various atmospheres and contaminants and their accuracy can be impaired in a matter of minutes. Most heat treatments are specified with an accuracy of $\pm 15^{\circ}\text{C}$ [$\pm 25^{\circ}\text{F}$] from the set point, but consistency in temperature will help guarantee reproducible results. The temperature distribution in the work zone of the furnace should also be uniform and periodically verified by a temperature survey at various locations in the work zone. This ensures that large temperature differences do not exist in the furnace work zone.

Often it is recommended that a thermocouple be attached to the part being heat treated and this temperature governs the heat treat operation. This can help to ensure that the part is at the appropriate temperature regardless of any set point control inaccuracies.