NiDI

Nickel
Development
Institute

Guidelines for the welded fabrication of nickel alloys for corrosion-resistant service

A Nickel Development Institute
Reference Book
Series Nº 11 012, 1994

This report was prepared by
Richard E. Avery and
Arthur H. Tuthill
Consultants in the United States
to the Nickel Development Institute

Guidelines for
the welded fabrication of
nickel alloys for
corrosion-resistant service

Contents

Introduction i

PART I – For the welder 1
- Physical properties of nickel alloys 1
- Corrosion resistance of nickel alloy welds 1
  - Avoid crevices 2
  - Embedded iron 2
  - Effect of surface oxides from welding 2
  - Other welding-related defects 2
- Welding qualifications 3
- Welder training 3
- Weld joint penetration 3
- Weld joint design 4
- Preparation for welding 4
  - Cutting and joint preparation 5
  - Oxides and other surface layers 5
  - Contaminating elements 5
  - Chlorinated solvents 6
  - Health hazards 7
  - Fixtures and positioners 7
  - Backing materials 7
  - Tack welding 7
- Welding processes 8
  - Shielded metal arc welding 8
    - Electrode types 8
    - Electrode storage 9
    - Welding current 10
    - Electrode handling 10
      - Arc Starting and Stopping 10
      - Weld Puddle Control 10
      - Out-of-Position Welding 10
      - Weld Spatter 10
  - Gas tungsten arc welding 10
    - GTAW equipment 11
      - Power 11
      - Current controls 11
      - Cooling 11
      - Electrodes 11
      - Nozzles 11
      - System leaks 11
      - Shielding gases 11
      - Filler metals 11
  - Operator guidelines 12
      - Arc initiation 12
      - Arc stopping 12
      - Arc shielding 12
      - Nickel alloy filler metals 12
  - Gas metal arc welding 12
    - GMAW arc types 13
    - GMAW equipment 13
    - Consumables 13
  - Other welding processes 14
- Welding nickel alloy pipe 14
  - Types of pipe welding 14
  - Instrument piping 14
  - Automatic welding 14

Manual welding 14
Purging during pipe root welding 16
Post-fabrication cleaning 16
Surface contaminants 16
Embedded iron 16
Mechanical damage 17
Safety and welding fumes 17

PART II – For the materials engineer 19
General guidelines for nickel alloys 20
Preheat and interpass temperature 20
Post-weld heat treatment 20
Filler metal selection for corrosive environments 20
Group A- Nickel and nickel-copper alloys 20
Alloys 200 and 201 20
Alloy 400 and R405 20
Salt and brine environments 21
Hydrofluoric acid service 21
Group B - Chromium-bearing alloys 21
Group C - Nickel-molybdenum alloys 21
Group D - Precipitation-hardening nickel alloys 21
Dissimilar-metal welds 22
Procurement guidelines 22
Surface finish 22
Nickel alloy castings 23
Source Inspections 24
Radiographic inspection 24
Liquid penetrant inspection 25
Weldability test 26
Pressure test 26
Certification 26
Heat Treatment 26
NiCrMo alloys 26
Nickel, Nickel-copper, Nickel Molybdenum alloys 26
Chemistry 26
Casting repair by welding 27
Ni, NiCu and NiMo alloys, Group A and C alloys 27
Filler metals 27
Post-weld repair heat treatment 27
Welding nickel alloy castings 27
Procurement checklist for nickel alloy castings 27

PART III – For the design engineer 29
Design for corrosion service 29
Tank bottoms 29
Tank bottom outlets 29
Bottom corner welds 30
Attachments and structurals 30
Heaters and Inlets 31
Pipe Welds 31
Weld overlay, sheet lining, and clad plate 32
Weld overlay 32
Submerged arc welding 32
Gas metal arc welding 33
Shielded metal arc welding 33
Weld overlay guidelines 33
Base metal dilution 33
Base metal interface 33
Sheet lining 33
Clad steel 34

Bibliography 35

Acknowledgement 35

Tables

Table 1 – Wrought nickel alloys by group 1
Table 2 – Influence of physical properties on welding nickel alloys 1
Table 3 – Nickel alloy cutting methods 5
Table 4 – Embrittling elements 6
Table 5 – Matching composition filler metals for nickel alloys 9
Table 6 – Comparison of GMAW arc modes for nickel alloys 13
Table 7 – Nominal composition of groups A – D wrought nickel and nickel alloys 19
Table 8 – Nominal composition of cast corrosion resistant nickel alloys 19
Table 9 – Matching filler metals of the comparable solid solution alloys 22
Table 10-A – Filler metal alloy identification for bare and covered electrodes 22
Table 10-B – Suggested filler metals for dissimilar metal welds 23
Table 10-C – Suggested filler metals for dissimilar metal welds 24
Table 11 – Specifications for procurement of groups A – D wrought nickel and nickel alloys 25
Table 12 – Surface finishes for nickel base alloy sheet, strip, and plate 25
Table 13 – Comparisons of weld overlay, sheet lining, and clad plate 33

Figures

Figure 1 – Incomplete fusion in pipe root pass weld 2
Figure 2-1 to 2-5 – Typical joint designs for sheet and plate 4
Figure 3 – Sample showing sulphur embrittlement of a Nickel 200 sheet 6
Figure 4 – Typical backing bar designs for use with and without a backing gas 7
Figure 5 – Tack weld sequence to provide uniform weld gap 8
Figure 6 – The arc zone in the SMAW process 8
Figure 7 – The Gas Tungsten Arc Weld (GTAW) process 10
Figure 8 – The basic components of the Gas Metal Arc Weld (GMAW) process 12
Figure 9 – Typical joint design for pipe with consumable insert 15
Figure 10 – Typical joint design for pipe welded with open root joint and hand-fed filler metal 15
Figure 11 – Standard consumable insert shapes, ANSI/AWS D10.11 15
Figure 12 – Typical pipe purging fixtures 16
Figure 13 – Flat bottom, square corners – worst 29
Figure 14 – Flat bottom, rounded corners – good corners – poor outside 29
Figure 15 – Flat bottom, rounded corners, grouted –good inside, poor outside 29
Figure 16 – Flat bottom, rounded corners, drip skirt – good inside, good outside 29
Figure 17 – Concave bottom rounded corners–good inside, good outside, fatigue resistant 29
Figure 18 – Dished head – best inside, best outside, fatigue resistant 29
Figure 19 – Side outlet above bottom – poor 29
Figure 20 – Centre outlet, above bottom – poor 29
Figure 21 – Side outlet, flush – good 29
Figure 22 – Centre outlet recessed – good 29
Figure 23 – Side outlet, flush, sloped – best 30
Figure 24 – Centre outlet, recessed, sloped – best 30
Figure 25 – Corner weld from inside – poor inside, worst outside 30
Figure 26 – Corner weld from both sides – poor inside, good outside 30
Figure 27 – Side wall in lieu of corner weld – best inside, good outside, fatigue resistant 30
Figure 28 – Tray support, staggered strength weld – severe crevice 30
Figure 29 – Tray support, full seal weld top – good crevice resistance 30
Figure 30 – Tray support, full seal weld top & bottom – best crevice resistance 30
Figure 31 – Reinforcing pad, staggered welds – adequate strength 30
Figure 32 – Reinforced pad, seal weld – best crevice resistance 30
Figure 33 – Position of angles 31

Figure 34 – Position of angles 31
Figure 35 – Position of channels 31
Figure 36 – Stiffeners and baffles 31
Figure 37 – Corner baffle cut-out – good 31
Figure 38 – Heat exchanger, baffle cut-out–good 31
Figure 39 – Poor and good designs for the location of heaters in a vessel 31
Figure 40 – Poor and good designs for mixing concentrated and dilute solutions 31
Figure 41 – Pipe weld with incomplete penetration – severe crevice 32
Figure 42 – Pipe recessed, flange and pipe, same alloy – good 32
Figure 43 – Pipe flush, pipe and flange same alloy – better 32
Figure 44 – Stub–end, flange carbon steel or ductile iron – very good 32
Figure 45 – (A) Horizontal (standard) – poor 32
(B) Sloped – very good 32
Figure 46 – Weld joints for liners 34
Figure 47 – Joint designs for clad steel 34

Introduction

This publication is presented in three parts with each, in turn, focused toward the primary interests of the welder, the materials engineer, and the design engineer.

Part I, FOR THE WELDER, assumes that the welders and others involved in welded fabrication are familiar with the basic techniques used in carbon steel fabrication and have had limited experience with nickel alloys. The discussion treats many areas of concern to the welder and gives practical suggestions concerning the effects of shop practices in maintaining the corrosion resisting properties of the nickel alloys. The importance of proper storage and protection of the surfaces, proper cleaning combined with the proper cleaning materials is stressed both before and after welding. Welding and welding training and qualification are discussed as well as arc management during the welding process. A number of commonly used welding processes are covered to furnish a perspective of the particular features that ensure improved results. Finally a brief discussion introduces the particular considerations involved in welding pipe. The discussion takes a “how to” approach useful to the non-engineer but the material covered is also a good reference for the materials and design engineer.

Part II, FOR THE MATERIALS ENGINEER, describes the types of nickel alloys; it reviews how their metallurgical and corrosion characteristics are affected by welding and covers some of the more specialized aspects of fabrication such as heat treating. A number of useful references are included to assist in the selection of electrodes, rods, and filler metals for solid solution alloys. Additional tables cover the selection of electrodes and rods for dissimilar metal welds. Guidelines are included for material procurement of castings along with suggestions for supplementing the specifications with additional requirements and tests to assure the quality of the finished castings.

Part III, FOR THE DESIGN ENGINEER, provides a number of design examples showing how the corrosion performance of nickel alloys used in process tanks can be enhanced through thoughtful design. A generous number of figures illustrate the configurations which improve the prospects for successful performance in corrosive environments. The discussion also treats weld overlay, sheet lining, and clad plate as alternative means of providing corrosion protection using nickel alloys. A number of welding processes are briefly evaluated as tools for achieving the desired results with each of these alternates.

Part I
For the welder

Part I focuses on the fabrication and welding of nickel alloys as they relate to the welders and production personnel engaged in fabrication of nickel alloys for corrosion service. *Table 1* shows the wrought and cast nickel alloys by group.

Physical properties of nickel alloys

The physical properties of solid solution nickel alloys, Groups A, B, and C, are quite similar to the 300 Series austenitic stainless steels. The solid solution nickel alloys cannot be strengthened by heat treatment, only by cold working. Group D alloys, the precipitation hardening nickel alloys, are strengthened by special heat treatments similar to those for the precipitation-aging stainless steels. Some physical properties and their influence on welding are shown in *Table 2.*

Corrosion resistance of nickel alloy welds

The performance of nickel alloy equipment in corrosive service is subject to the care taken by welders and others on the shop floor. Sound, high-quality welds are the single most important objective; however, to achieve this objective, there are a number of factors that require attention during fabrication. These factors will be addressed in detail.

Table 1
Wrought nickel alloys by group

Wrought alloys		Wrought alloys		Cast alloys ASTM A494A 494M	
Alloy No.	UNS No.	Alloy No.	UNS No.	Alloy No.	UNS No.
Group A – Nickel and nickel-copper solid solutions alloys					
200	N02200	400	N04400	CZ-100	N02100
201	N02201	R-405	N04405	M-35-1	N24135
Group B – Chromium-bearing solid solution alloys					
825	N08825	59	N06059	CW-6MC	N26625
G-3	N06985	686	N06686	CY-40	N06040
G-30	N06030	622	N06022	CW-2M	N26455
600	N06600	C-22	N06022	CX2MW	N26022
690	N06690	C-276	N10276		
625	N06625				
Group C – Nickel-molybdenum alloys					
B-2	N10665	B-4	N10629	N-7M	N30007
B-3	N10675				
Group D – Precipitation hardening alloys (used for corrosive service)					
K-500	N05500	725	N07725		
625 PLUS®	N07716	718	N07718		

Table 2
Influence of physical properties on welding nickel alloys

Property	Alloy(s)	Remarks
Melting Point	All	Melting point is 55°-165°C (100-300°F) lower than SAE 1020 steel, tending to allow faster welding for the same heat or less heat for the same speed.
Magnetic Response	Nickel 200, 201	Magnetic up to 360°C (680°F) subject to arc blow similar to carbon steels.
	Alloys 400, R-405	May be magnetic or non-magnetic at room temperature, depending on composition variations.
	All others	Similar to austenitic stainless steels .
Electrical Resistance	Nickel 200, 201	Low, similar to SAE 1020 steel.
	Others	Varies with composition. Compared to Type 304, alloy 400 is 25% lower while the chromium-bearing alloys are up to 200% higher. High electrical resistance may cause overheating in some covered electrodes.
Thermal Expansion	All	All nickel alloys are closer to carbon steels than are the austenitic stainless steels. This results in less warpage and distortion than comparable stainless steel fabrications and lower residual stresses in welding to low alloy steels.

Note: While wrought austenitic stainless steels are non-magnetic, some stainless welds and castings may be slightly magnetic as a result of the presence of a delta ferrite. Nickel-chromium and nickel-chromium-iron wrought and cast alloys do not contain ferrite and do not exhibit a magnetic response.

Avoid crevices

It is well-recognized that butt welds should be full-penetration welds to provide optimum strength. In corrosion service, there is another reason for full penetration welds. Crevices resulting from inadequate penetration, when exposed to certain corrosive environments, are potential sites for crevice corrosion. Avoiding crevices is mainly a design responsibility, but it is helpful for those actually making the equipment to assist in eliminating crevices wherever possible. A typical example of an undesirable crevice resulting from incomplete fusion of a pipe root pass weld is shown in *Figure 1.*

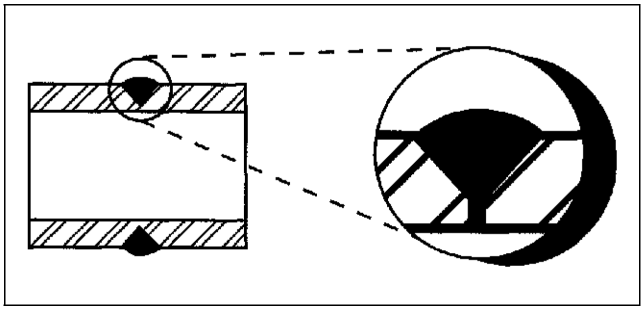


Figure 1 Incomplete fusion in pipe root pass weld

Embedded iron

When new nickel alloy equipment develops rust spots, it is nearly always the result of embedded free iron. Surface rusting is objectionable from an appearance point of view and might also be the cause of pitting corrosion as it is with austenitic stainless steels in certain environments. Furthermore, the iron or rust may act as a contaminant in the process that it services, thus affecting the product purity.

Following are a few common sense precautions that can greatly reduce the chances of contamination.

- Protect iron and steel surfaces that might come into intimate contact with nickel alloys by using wood, plastic, or cardboard to prevent iron contamination.
- Use clean stainless steel wire brushes or abrasive disks or wheels that have never been used on iron or steel. Iron-contaminated wire brushes or abrasive disks may introduce embedded iron to the nickel alloy surface.
- Do not leave nickel alloy sheets or plates on the floor where they are exposed to traffic. Store sheet and plate stock in a vertical position.
- Separate nickel alloy fabrication from other types of metal fabrication. Steel grinding, cutting, and blasting operations can introduce embedded iron to the nickel alloy surfaces.

The detection and treatment of embedded iron is discussed under the topic entitled Post-fabrication cleaning, later in this section.

Effect of surface oxides from welding

It is a well-established fact that heat tint may reduce the pitting and crevice corrosion resistance of austenitic stainless steels in some environments. Surface oxides in the form of heat tint result from welding on the reverse side of a plate or sheet or from the oxide formed in the heat-affected zone (HAZ) next to the weld surface. For example, oxides that form on the inside of a vessel from welding lifting lugs, stiffeners, or similar items, on the outside can be particularly damaging. Such oxides should be removed down to clean metal.

Studies by Silence and Flasche have shown that there is less need for heat tint removal from chromium-containing nickel alloys than from austenitic stainless steels. The tests were made on three nickel alloys and three iron-base alloys using a range of FGD-representative oxidizing, reducing, and oxidizing acid-chloride environments. These findings are in general agreement with field experience. The authors have, however, encountered cases in non-FGD environments where heat tint removal was essential to corrosion-resistance in nickel-chromium-molybdenum alloys. Such cases are infrequent but do suggest that the best practice is to remove heat tint on the wetted side of the fabrication, whether it occurs on the welded side or on the side opposite the welded surface, for example, where lugs or stiffeners may be welded to the outer surface of a tank.

Data on the effect of surface films on the non-chromium-bearing nickel alloys is even more sparse. In the absence of such data for the wide range of potentially corrosive environments where nickel alloys are applied, the conservative approach is to provide the cleanest and most oxide-free surfaces that are economically practical.

Other welding-related defects

A number of additional welding-related defects and their suggested treatments follow.

- Arc strikes on the parent material damage the alloy’s protective film and create crevice-like imperfections. Weld stop points may create pinpoint defects in the weld metal. Both imperfections can be avoided by using proper techniques and, if they occur, should be removed by light grinding with clean, fine-grit abrasive tools.
- Weld spatter creates a tiny weld where the

molten slug of metal touches and adheres to the surface. The protective film is penetrated and tiny crevices are created where the film is weakened.

- Weld spatter can easily be eliminated by applying a commercial spatter-prevention paste to either side of the joint to be welded. The paste and spatter are washed off during cleanup.
- Some nickel alloy electrode coatings contain fluorides which can leach out and cause corrosion if the slag is not completely removed. Slag particles can also create crevices, additional places for corrosion to begin. Slag is difficult to remove, particularly small particles, when there is a slight undercut or other irregularity. The usual removal is done with wire brushing, light grinding, or abrasive blasting with iron-free abrasives.

Welding qualifications

It is standard practice for fabricators of process equipment to develop and maintain Welding Procedure Specifications (WPS) for the various types of welding. The individual welders and welding operators are tested and certified by satisfactorily making acceptable qualification weldments. There are a number of society or industry codes that govern welding qualifications, but the two most widely used in the U.S. for corrosion resistance equipment are:

- American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code — Section IX, Welding and Brazing Qualification;
- American Welding Society, Standard for Welding Procedure and Performance Qualification — AWS B2.1.

Each country typically has its own individual codes or standards. Fortunately, there is a trend toward the acceptance and interchange of specifications in the interest of eliminating unmerited requalification.

The identification of essential variables that establish the need for a new procedure qualification test is the common element of these codes. These essential variables differ for each welding process, however, they also share some common factors. Changes in any of the following items are considered to be essential changes.

- base metal (P-Number);
- filler metal (F-Number);
- metal thickness;
- shielding gas;
- welding process.

ASME Section IX classification of P-Numbers is often the first determinant as to whether a separate WPS is needed. A change in a base metal from one P-Number to another P-Number requires requalification. Joints made between two base metals of different P-Numbers require a separate WPS, even though qualification tests have been made for each of the two base metals welded to themselves. The P-Numbers of common nickel alloys follow.

P-number	Base metal
41	Nickel 200, 201
42	Alloy 400
43	Alloys 600, 625, 690
44	Alloys B-2, C-22, C-276

Not all alloys have been assigned a P-Number. For example, cast alloys and Group D, the precipitation hardening alloys, do not have P-Numbers. Alloys without a P-Number require individual qualification even though similar in composition to an alloy already qualified. If an alloy is not listed in the P-Number tables, the alloy manufacturer can advise if a P-Number has been recently assigned.

Welder training

In complying with welding specification codes such as ASME and AWS, welders must pass a performance test. A welding training program is essential to prepare welders for the performance test and training is equally essential to assure quality production over the long term.

Ample training and practice time should be provided for welders who have not had experience with the particular nickel alloys. For example, the welding characteristics of chromium-bearing solid solution nickel alloys, Group B, are similar to those of austenitic stainless steels. Skilled stainless steel welders can usually adjust quickly to welding Group B alloys. The same welders, however, may find Nickel 200 and Alloy 400 welding fillers rather different because of the sluggish nature of the molten weld metal. Once briefed on the specific elements that change for any alloy or filler metal, they can proceed confidently and productively to make high quality welds.

In addition to the particular base metal and welding process, training should include information and practice on unusual welding positions as well as on the shapes to be welded such as pipe and thin sheets.

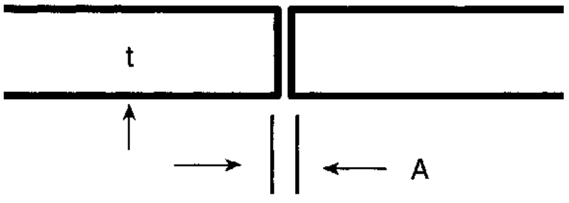
Weld joint penetration

Butt welds should be full-penetration welds to produce full strength and optimum performance in corrosion service. Fillet welds need not be full-penetration welds as long as the sides and ends are welded to seal off voids that might collect product. Pipe welds that lack full penetration invite crevice corrosion which creates a high stress point at the root. For this reason, pipe welds should be full-penetration welds for best performance.

Weld joint design

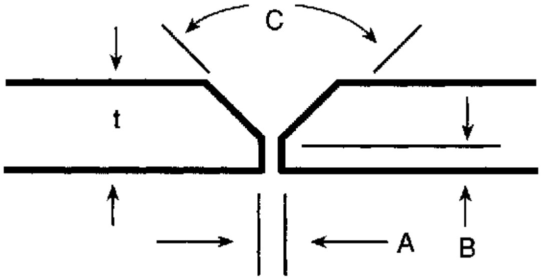
Molten nickel alloy weld metal is considerably less fluid than carbon steel and somewhat less fluid than stainless steel. The depth of weld penetration is also not as great. Within the nickel alloy group, there is a difference in fluidity and weld penetration depending upon the amount of nickel that is present. For example, commercially pure Nickel 200/201 is most viscous and yields a shallow weld bead. To compensate for these features, nickel alloy joints have a wider bevel, narrower root face, and wider root opening. The welding process also influences weld joint dimensions. For example, a spray arc gas metal arc weld (GMAW) has a deeper penetration weld bead than other arc welding processes so thicker root faces may be used.

Typical joint designs for sheet and plate are shown in *Figure 2-1* through *2-5.*



Maximum t = 3.2 mm (.125 in)
Gap A = .8 mm min., 2.3 mm max (.03 – .093 in.)

Figure 2-1 Typical square butt joint for sheet.

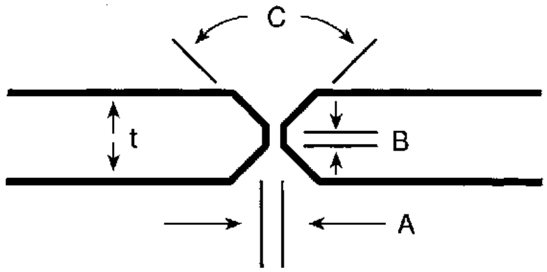


Maximum t = 12.7 mm (.5 in.)
Gap A = .8 mm min., 2.3 mm max (.03 – .093 in.)
Land B = 1.6 mm to 2.4 mm (.062 – .093 in.)
Angle C = 60 to 80°

Figure 2-2 Typical single "V" joint for sheet and plate.

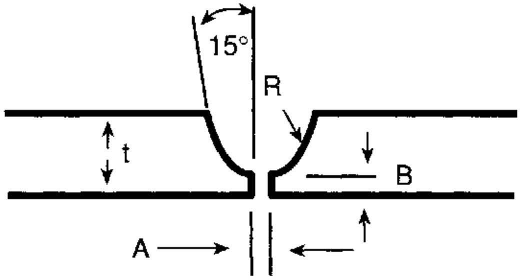
Preparation for welding

The care taken in preparation for welding is time that yields improved weld quality and a finished product that gives optimum service. Important preparation steps follow.



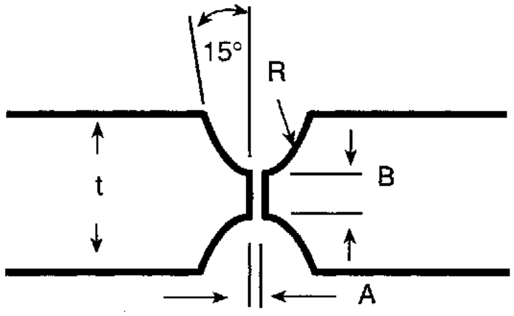
Maximum t = 12.7 mm (.5 in.)
Gap A = .8 mm min., 2.3 mm max (.03 – .093 in.)
Land B = 1.6 mm to 2.4 mm (.062 – .093 in.)
Angle C = 60 to 80°

Figure 2-3 Typical double "V" joint for plate.



t = 19 mm (.75 in.) and over
Gap A = 1.6 mm min., 3.2 mm max (.062 – .125 in.)
Land B = 1.6 to 2.4 mm (.062 to .093 in.)
Radius R = 6.4 mm min. (.25 in.)

Figure 2-4 Typical single "U" joint for plate.



t = 19 mm (.75 in.) and over
Gap A = 1.6 mm min., 3.2 mm max (.062 – .125 in.)
Land B = 1.6 to 2.4 mm (.062 to .093 in.)
Radius R = 6.4 mm min. (.25 in.)

Figure 2-5 Typical double "U" joint for plate.

Cutting and joint preparation

Nickel alloys are cut as shown in *Table 3*. They share the same cutting methods as those used for stainless steels. Oxyacetylene cutting of nickel alloys (without iron-rich powder additions) results in the formation of refractory oxides, preventing accurate, smooth cuts. As you will observe in *Table 3*, the thickness and shape of the parts being cut largely dictates which of the cutting methods is most appropriate.

Oxides and other surface layers

All oxides and dross from thermal cutting should be removed by grinding, machining, or abrasive blasting. Oxides of elements in nickel alloys such as chromium, nickel and particularly titanium and aluminum in the precipitation hardening alloys, are high melting point oxides and are not fused by the weld metal. An oxide film can become trapped in the solidifying weld, resulting in a defect that is difficult or impossible to detect by radiography.

Surface oxides may be present as a result of heat treating or they may exist on equipment that has been exposed to high temperatures. In some high temperature service environments, a carburized or sulphurised surface layer can develop. All such layers should be removed by grinding or machining the area to be welded. Wire brushing does not remove the tightly adhering oxides or other surface layers. While wrought product forms or castings in the as-received condition are normally free of oxides, it is good practice to condition a one-inch wide band on both the top and bottom surface of the weld zone to bright metal with a medium grit flapper wheel or disk. This is particularly important when nickel-molybdenum, Group C, alloys are welded by shielded metal arc welding (SMAW). The slag can interact with any mill scale and cause cracking at the toe of the weld.

Surface oxides or a rough surface can have more of an influence on the depth of penetration and bead shape of gas tungsten arc welds (GTAW) than on arc welds made with higher heat input arc welding processes. Pre-weld cleaning of thin gauge sheet or strip, e.g., 0.5mm (0.020 in.) and thinner, is a critical requirement to prevent weld defects. Vapor blasting is a common cleaning method for this gauge of material.

When repair welding is required on equipment used in chemical service, it is especially important to ensure the removal of surface contamination with careful pre-weld cleaning. The cleaning objective is to remove the embedded contamination by grinding, abrasive blasting, or neutralizing the surface prior to repair welding. Acid-contaminated surfaces, are neutralized with a mild basic solution and alkaline-contaminated surfaces are neutralized with a mild acid solution. A thorough hot water rinse should always follow the neutralizing treatment.

For example, if caustic has been in contact with the nickel alloys for an extended period of time it may be embedded. If not removed prior to welding, the weld and heat-affected zone often develops cracks. Removal requires grinding, abrasive blasting, or neutralizing with an acid solution such as 10% (by volume) hydrochloric acid (followed by a thorough hot water rinse).

Contaminating elements

There are a number of elements and compounds that must be removed from the surface prior to welding or heat treating. If not removed, the heat from welding can cause cracking, weld defects, or reduced corrosion resistance of the weld or HAZ. The elements penetrate at the grain boundaries and the metal is said to be "embrittled". The elements to be avoided, the type of defect generated, and the common sources of the elements are shown in *Table 4*.

Weld defects, reduced corrosion resistance, or embrittlement are caused by a combination of temperature along with the presence of one of the

Table 3
Nickel alloy cutting methods

Method	Material thickness	Comments
Shearing	Sheet/Strip, Thin Plate	Prepare edge exposed to environment to remove tear crevices
Sawing & Abrasive Cutting	Wide range of thicknesses	Remove lubricant or cutting fluid before welding or heat treating
Machining	Wide range of shapes	Remove lubricant or cutting fluid before welding or heat treating
Plasma Arc Cutting (PAC)	Wide range of thicknesses May be used for gouging backside of weld	Grind cut surfaces to clean metal
Powder metal cutting with iron-rich powder	Wide range of thicknesses	Cut less accurate than PAC, must remove all dross
Carbon Arc Cutting	Used for gouging backside of weld and cutting irregular shapes	Grind cut surfaces to clean metal

Figure 3 Nickel 200 showing sulphur embrittlement of sheet on the right side caused by inadequate cleaning. Photo courtesy Inco Alloys International Inc.

listed elements. The depth of attack varies with the embrittling element, its concentration, and the heating time and temperature. Group A nickel alloys are most susceptible. *Figure 3* shows a typical example of sulphur embrittlement on a Nickel 200 sheet. The area of an alloy that becomes embrittled cannot be restored and must be discarded. Carbon or carbonaceous materials left on the surface during welding may be taken into solution. The resulting high carbon layer lowers the corrosion resistance in many environments.

A number of methods and materials exist for removing the kinds of contaminants mentioned earlier. Metallic contaminants and materials which are not oil or grease-based can be removed by mechanical means such as abrasive blasting or light grinding. It is essential that the blasting material or abrasive disk be free of contaminants such as free iron. A nitric acid treatment, followed by neutralization can effectively remove some low melting point metals without damage to Group B, chromium-bearing alloys, but this treatment may attack other nickel alloys.

Oil or grease based (hydrocarbon-based) contaminants must be removed by solvent cleaning; they are not removed by water or acid rinses. Large weldments are usually hand-cleaned by wiping with solvent-saturated cloths. Other acceptable methods include immersion in, swabbing with, or spraying with alkaline emulsion, solvent, or detergent cleaners, or a combination of these. Vapor degreasing, steam, with or without a cleaner; or high-pressure water jetting can also be utilized. American Society of Testing and Materials, ASTM A380, *Standard Recommended Practice for Cleaning and Descaling Stainless Steel Parts, Equipment, and Systems*, is an excellent guide for fabricators and users.

A typical procedure to remove oil or grease includes the following steps:

- Remove excess contaminant by wiping with clean cloth;
- Swab the weld area (at least 5cm (2 in.) each side of the weld) with an organic solvent such as an aliphatic petroleum, a chlorinated hydrocarbon, or blends of the two. (See cautionary remarks which follow.) Use only clean solvent (uncontaminated with acid, alkali, oil, or other foreign material) and clean cloths;
- Remove all solvent by wiping with clean, dry cloth;
- Check to assure complete cleaning. A residue on the drying cloth can indicate incomplete cleaning. Where size allows, either the water-break or atomized test are effective checks.

If alkaline cleaners containing sodium carbonate are used, the cleaners themselves must be removed prior to welding by spraying or scrubbing with hot water. Selecting the solvent cleaner involves considerations beyond just the ability to remove oil and grease. Two precautions follow.

Chlorinated solvents

Many commercial solvents contain chlorides and are effective in cleaning machined parts and crevice-free components. While chlorinated solvents are acceptable for use on nickel alloy, they can present a corrosion problem to stainless steel alloys. Fabricators often use a non-chlorinated solvent for both stainless and nickel alloys to avoid the risk of using a chlorinated solvent on stainless steel.

Table 4
Embrittling elements

Elements	Effect/Defect	Common Sources of Elements
Sulphur, Carbon	Reduced corrosion resistance	Hydrocarbons such as cutting fluids, grease, oil waxes, and primers
Sulphur, Phosphorous	Cracking in welds and HAZ	Marking crayons, paints, and temperature-indicating markers
Lead, Zinc, Copper (low melting point metals)	Cracking in welds and HAZ	Tools such as lead hammers, copper hold-down or backing bars, zinc-rich paint, galvanized steel
Shop dirt	Any of the above	Any of the above

Health hazards

The term health hazard has been defined as including carcinogens, toxic agents, irritants, corrosives, sensitizers, and any agent that damages the lungs, skin, eyes, or mucous membranes. Each organization should assure that the solvents used are not harmful to personnel or equipment. In addition to the toxic effect, consideration must be given to the venting of explosive fumes, safe disposal of spent solutions, and other related handling practices. Knowledge of, and compliance with federal, state, and local regulations is a necessity.

Solvents used for pre-weld cleaning include, but are not limited to the following:

- Non-chlorinated: toluene, methyl-ethyl-ketone, and acetone;
- Chlorinated solvent: 1-1-1 trichloroethane.

All of the aforementioned solvents must be handled in compliance with the regulator requirements and the manufacturer's instructions.

Fixtures and positioners

Fixtures are usually designed for each particular assembly and hold the parts together throughout the welding operation. When fixtures are attached to positioners, there is a further advantage in that welding can be done in the most convenient position. Some advantages of using fixtures are summarized as follows:

- Better joint match-up;
- Less tacking and welding time;
- Minimized distortion;
- Accurate assembly.

It is essential that the mating pieces be carefully aligned and matched for good quality welding. When one member is considerably thicker than the other, for example, a tank head that is thicker than the shell, the head-side should be machined to a taper of 3:1 or more to reduce stress concentrations. Joints with varying root gap require special adjustment by the welder to avoid burn-through or lack of penetration. When the volume of identical parts is large, use of fixtures is more easily justified.

Backing materials

A backing material should be used in welding sheet or plate, unless both sides of the joint can be welded. Without a backing, the back side may have erratic penetration with crevices, voids and excessive oxidation. Such defects reduce weld strength and can initiate accelerated corrosion. Copper, with its high thermal conductivity, is the material most-often used for backing bars. Typical backing bar designs for use with and without a backing gas are shown in *Figure 4.* During welding, the copper bar chills the weld to solid metal without melting the copper. The arc should not be misdirected to the extent that copper is melted and incorporated into the alloy weld or weld cracking can result. It is good practice to pickle after welding to remove traces of copper from the surface, particularly if solution annealing is to follow welding.

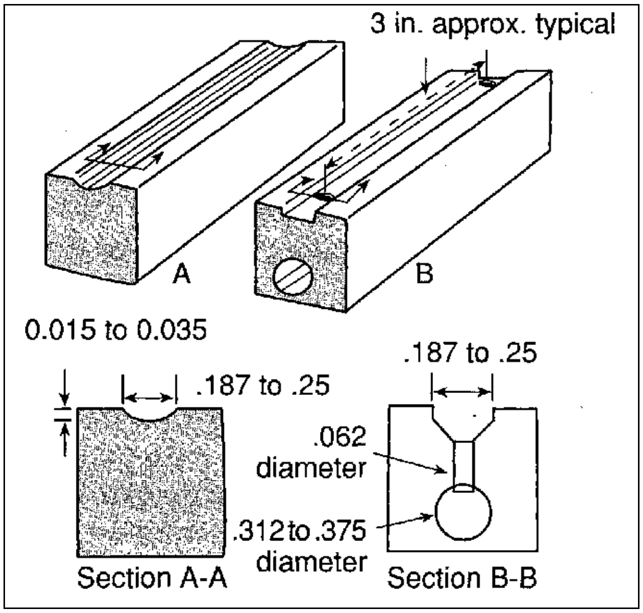


Figure 4 Typical backing bar designs for use with and without a backing gas

Argon backing gas provides excellent protection to the back side of gas tungsten arc welds (GTAW). It helps control penetration and maintain a bright, clean surface.

While nitrogen has been used as a backing gas for stainless steels and chromium-bearing nickel, Group B alloys, it should never be used for Group A or C, non-chromium-containing alloys. Nitrogen might also cause weld metal porosity in welds made with the GTAW process which have inadequate filler metal.

When copper backing bar or an inert gas backing purge is impractical, there are commercially available tapes, pastes, and ceramic backing products that can be utilized. These offer some protection from burn-through but little protection from oxidation, so final cleaning by abrasive means or acid pickling is needed after welding when these backing materials are used.

Tack welding

Joints not held in fixtures must be tack-welded to maintain a uniform gap and alignment along the entire length. The tacks should be placed in a sequence to minimize the effect of shrinkage. In fitting two sheets, tack welds should be placed at each end and then the middle section as a shown in *Figure 5 (A). Figure 5 (B)* shows how the sheets close up when the tack welding progresses from one end.

Nickel alloys have a thermal expansion close to that of ordinary steel so distortion from welding is less than is experienced with stainless steel. Tack welds in nickel alloy fabrications are about the same number and size as those required for carbon steel.

The length of tack welds may be as short as 3mm (0. 125 in.), or a small spot of weld metal for thin material to over 25mm (1 in.) long for heavy plate sections. More importantly, the shape of the tack should not cause a defect in the final weld. Heavy or high tacks or abrupt starts and stops should be contour-ground. Bead shape is easier to control with the GTAW process, making it a good choice for tack welding. Before tack welds are incorporated into the final weld, they must be wire-brushed or ground to clean metal. They should be inspected for crater cracks and any cracks should be ground out.

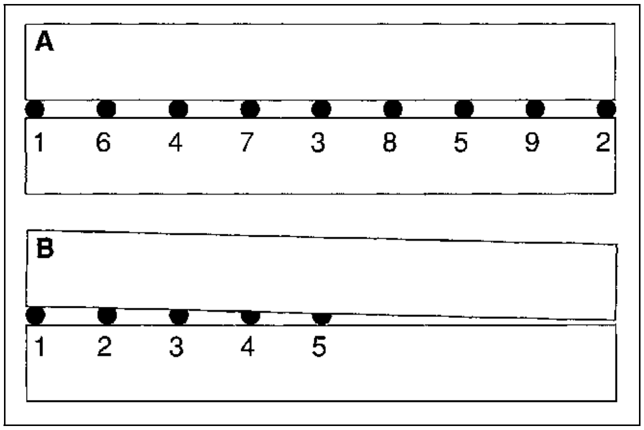


Figure 5 Tack weld sequence to provide uniform weld gap

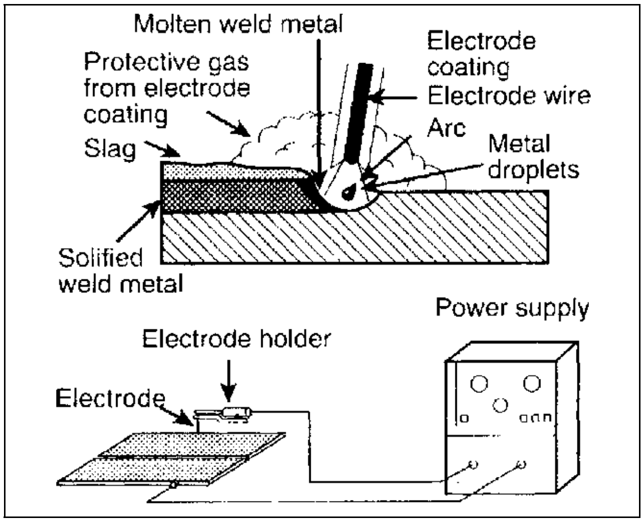


Figure 6 The arc zone in the SMAW process

Welding processes

This section provides information to assist in formulating nickel alloy welding procedures for the shielded metal arc welding (SMAW), GTAW, and gas shielded metal arc welding (GMAW) processes. The areas covered in earlier sections of this publication such as base metal properties, joint designs and preparation for welding are common to all welding processes and are not repeated.

Shielded metal arc welding

SMAW is a versatile process, widely used for welding nickel alloys when the shapes or quantities do not justify automatic welding. The welding is performed manually with the welder maintaining control over the arc length while directing the arc into the weld joint.

SMAW is frequently referred to as covered electrode or stick welding. The electrode is a solid wire covered by an extruded flux coating, although some manufacturers use a cored wire in lieu of the solid core wire.

The electrode coating supports the following functions:

- Initially at the arc start, the electrode core burns back faster to form a cup which in turn projects droplets and increases the pinch affect. This action supports the capability to weld out-of-position;
- It may provide alloy addition to the weld deposit. Usually the core wire is of similar composition to the deposited weld metal, but some electrode manufacturers make very large alloy additions through the coating and rely on complete mixing or alloying in the weld puddle. Because of this practice, it is not advisable to remove the flux in order to use the uncoated core wire for GTAW or any other process;
- The gaseous envelope from the flux decomposition excludes oxygen and nitrogen from the molten weld metal;
- The molten slag formed on top of the weld protects the weld metal from contamination by the atmosphere and helps to shape the bead.

Electrodes for SMAW are available for all solid solution nickel alloys, Groups A, B, and C but not for the precipitation hardening alloys, Group D.

The arc zone in the SMAW process is shown in *Figure 6.*

Electrode types — Nickel alloy covered electrodes are classified according to chemical composition of undiluted weld metal. The matching composition filler metals for nickel and nickel

Table 5
Matching composition filler metals for nickel alloys

Base metal		Bare electrode and rod		Coverage electrode and rod	
Common Name	UNS No.	ANSI/AWS A5.11-90	UNS No.	ANSI/AWS 5.14-89	UNS No.
Nickel 200	N02200	ERNi-1	N02061	ENi-1	W82141
Nickel 201	N02201				
Alloy 400	N04400	ERNi Cu-7	N04060	ENiCu-7	W84190
Alloy R-405	Note [1]			ENiCu-7	W84190
Alloy 825	N08825	ERNiCrMo-3 *or* ERNiFeCr-1	N06625	ENi CrMo-3 *or* Incoloy™ W.E.135	W86112
Alloy G-3	N06985	ERNiCrMo-9	N06985	ENiCrMo-9	W86985
Alloy G-30	N06030	ERNiCrMo-11	N06030	ENiCrMo-11	W86030
Alloy 600	N06600	ERNiCr-3	N06082	ENiCrFe-3	W86182
Alloy 690	N06690	Inconel™ F.M.52		Inconel™ W.E.152	
Alloy 59	N06059	Nicrofer™ S5923	N06059	VDM 2.4609	None
Alloy 625	N06625	ERNiCrMo-3	N06625	ENiCrMo-3	W86112
Alloy C-22 *and* 622	N06022	ERNiCrMo-10	N06022	ENiCrMo-10	W86022
Alloy C-276	N10276	ERNiCrMo-4	N10276	ENiCrMo-4	W80276
Alloy 686	None	Inco-Weld™ F.M. 686 CPT	None	Inco-Weld™ W.E. 686 CPT	None
Alloy B-2	N10665	ERNiMo-7	N01665	ENiMo-7	W80665
Alloy B-3	N10675	ERNiMo-7	N10665	ENiMo-7	W80665
Alloy B-4	N10629	ERNiMo-7	N10665	ENiMo-7	W80665
CW-2M	N26455	ERNiCrMo-4	N10276	ENiCrMo-4	W80276
CW-6MC	N26625	ERNiCrMo-3	N06625	ENiCrMo-3	W86112
CY-40	N06040	ERNiCr-3	N06082	ENiCrFe-3	W86182
CX2MW	N26022	ERNiCrMo-10	N06022	ENiCrMo-10	W86022
CZ-100	N02100	ERNi-1	N02061	ENO	W82141
M-35-1	N24135	ERNiCu-7	N04060	ENiCu-7	W84190
N-7M	N30007	ERNiMo-7	N10665	ENiMo-7	W80665

Note [1]: SMAW is the preferred welding process.
Note [2]: Group D – Precipitation hardening alloys. Contact the base metal producers for filler recommendations
Note [3]: Inconel, Incoloy, and Inco-weld are registered trademarks of the Inco family of companies. Nicrofer is a registered trademark of VDM Nickel Technologies AG.

alloys are shown in *Table 5*. Most nickel alloy electrodes are designed to operate on direct current, electrode positive, although some can operate on alternating current.

The type of coating is not identified in nickel alloy electrodes as it is for carbon and stainless steel electrodes. As with covered electrodes of other alloys, the flux formula is the proprietary secret of its manufacturer. Nickel alloy electrode coatings are best described as lime-titania type coatings; they cannot be classified as either lime or titania types because both compounds are used.

Electrode storage — Nickel alloy electrodes are normally furnished in packages suitable for long storage. After the package is opened, the electrodes should be stored in heated cabinets at the temperature recommended by the manufacturer. If the electrodes have been over-exposed to moisture, they should be reconditioned by a higher temperature bake using the manufacturer's suggested time and temperature. It is preferable to obtain the manufacturer's specific recommendations, since the temperature often varies with the particular coating, but lacking this information, commonly used temperatures are as follows:

- Storage of opened electrodes: 110°C (225°F);
- Recondition bake: 260-315°C (500-600°F).

The nickel-molybdenum Group C coating formulation is a low hydrogen type and moisture pick-up must be closely controlled. If the electrodes are exposed to moisture pick-up, they can be reconditioned by heating to 315-370°C (600-700°F) for two to three hours.

Moisture in the coating can cause hydrogen gas generation in the weld, leading to weld porosity. The porosity may be within the weld metal or may reach the surface just as the metal solidifies, forming visible surface pores. The porosity can occur in butt welds when the moisture content of the coating is high, but more often, it occurs in fillet welds.

Moisture in the weld is not the only cause of weld metal porosity. Welding on painted, greasy, or oily surfaces may lead to porosity of the worm-hole type.

Welding current — The recommended current ranges for each package of electrodes is usually printed on the package. The current ranges may vary significantly from one alloy family to another. The electrical resistance of Group B core wires is much higher than Group A core wires so the recommended currents for Group B are substantially lower. Excessive current overheats the electrode coating which, in turn, causes a loss of arc force and difficulty in directing the arc near the end of the electrode.

Electrode handling — *Arc Starting and Stopping* — The same techniques for arc starting and stopping used for low hydrogen carbon steel electrodes, such as type E7018, are applicable to nickel alloy welding.

Some guidelines follow:

- Strike the arc at some point in the joint so that the metal is remelted. An arc strike away from the weld may have cracks and unless removed, may result in lower corrosion resistance in that area;
- Do not abruptly extinguish the arc, leaving a large weld crater. A depression will form as the metal solidifies, often with a slag-filled pipe or cracks in the center of the crater depression. One acceptable technique is to hold the arc over the weld pool for a few moments and then move quickly back, lifting the arc from the completed weld. Another technique is to extinguish the arc against one of the joint side walls after filling the crater.

Weld puddle control — It is necessary to maintain a short arc length for control of the weld puddle. In downhand welding, the electrode is positioned ahead of the puddle and at an incline of 20 or more degrees from the vertical (a drag angle). This is also described as backhand welding. The angle improves control of the molter flux and eliminates slag entrapment.

Out-of-position welding — Out of position welding should be done with a 3.2mm (0.125 in.) or smaller diameter electrode using a shorter arc and lower current than for downhand welding. In vertical welding, a range of electrode angles is often used varying from 20 degrees drag (backhand) to 20 degrees push (forehand) depending on welder preference.

Nickel alloy weld metal does not flow or spread like most other metals and requires placing it to the desired spot in the joint. For proper bead placement, some weave or manipulation is needed. The amount of weave depends on such factors as joint design, welding position, and the type of electrode. With a little practice, welders soon learn the amount of weave needed to obtain the correct bead contour for various joint conditions. The acceptable width of weave is limited to a dimension no wider than three times the electrode core diameter.

Weld spatter — Under correct welding conditions, there should not be excessive spatter. When high spatter does occur, it may be caused by one of the following factors: excessive arc length, excessive amperage, incorrect polarity, or excessive moisture in the electrode coating. All of these factors are under the control of welding personnel and can be readily corrected. Magnetic arc blow can also cause excessive spatter. The corrective measures are the same as those used for other metals such as ordinary steel.

Gas tungsten arc welding

The gas tungsten arc weld (GTAW) process or tungsten inert gas process (TIG), as it is frequently called, is widely used and is well-suited for welding nickel alloys. It frequently is the only process used for welding precipitation hardening, Group D alloys. An inert gas (usually argon) is used to protect the molten weld metal and the tungsten electrode from the air. Filler metal in the form of bare wire is added as needed, either by manual or automatic feeding into the arc. The process is illustrated in *Figure 7*. GTAW can be used to weld material as thin as a few mils or as thick as the heavy gauges. Usually, faster weld-

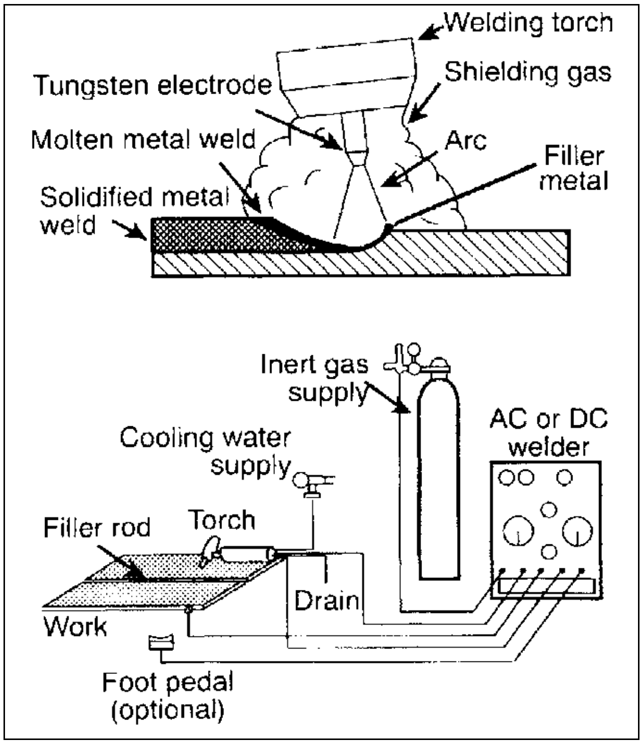


Figure 7 The Gas Tungsten Arc Weld (GTAW) process

ing processes are used for material thicknesses over 3.2mm (0.125 in.).

Some of the advantages of the GTAW process for welding nickel alloys follow.

- No slag to remove — minimizes post-weld cleanup;
- All position welding capability — particularly useful for pipe welding;
- No weld spatter;
- No alloy loss during welding;
- Good as-welded surface — minimal finishing required.

GTAW equipment — *Power* — Direct current, electrode negative, (DCEN), (straight polarity) current is standard. Pulsed-current power is another option. In this type there is a pulsating high rate of current rise and decay. This current mode is well-suited to welding thin materials and joints which have poor fit-up. Pulsed-current is also useful in making the root pass of pipe joints. A high-frequency or capacitor discharge starting feature is often included in the power source. This starting feature is also available in a separate "arc starter" control for use with conventional constant current power sources. This allows an arc to be initiated without a scratch start, a procedure that risks contamination of the tungsten electrode.

Newer power sources provide a "lift start" feature that allows the electrode to be positioned on the work before applying power. The arc is established when the torch is lifted from the work. The power source controls the current during the lift start and practically eliminates the risk of electrode contamination. The advantage of this method over high frequency starting is that it eliminates possible interference to nearby electronic equipment such as telephones, radios, and computers.

Current controls — In addition to the current controls at the power source, it is often useful to have a foot pedal or torch-mounted hand current control. This control allows the welder to increase or decrease current during welding to adjust to conditions such as poor fit-up. A further advantage to this type of control is that the welder can slowly reduce the current (and the weld pool) at arc stops to eliminate crater cracks.

Cooling — Torches are either air or water cooled. The air-cooled variety is limited to lower currents than the water cooled units.

Electrodes — The 2% thoriated tungsten electrodes are in most popular use because of their excellent emissive qualities, although other tungsten electrode types are acceptable. Opinions differ regarding electrode size for various amperages. Some favour using different diameters for a number of specific current ranges while others use a size such as 2.4mm (0.09 in.) for a much wider current range. Also, the electrode end preparation preferences vary. One commonly used configuration is a 20° to 25° taper with the tip blunted to a 2.5mm (0.10 in.) diameter.

Nozzles — Nozzle or gas cups come in a wide variety of shapes and sizes and it is often best to match the nozzle to the weld joint or application. Larger cup diameters provide better shielding gas protection to the weld while smaller nozzles help maintain a more stable arc and allow better visibility. An alternate is the gas lens which creates a laminar flow through use of special screens inside the nozzle. The flow of inert gas is projected a considerable distance beyond the end of the nozzle, giving both better gas protection and good visibility.

System leaks — With any welding process using inert gas, it is important that all gas lines and connections be checked to ensure freedom from leaks in the system. If a leak is present, for example, in a gas line, air will aspirate into the inert gas stream rather than the internal gas escaping, as might be expected.

Shielding gases — Pure argon, helium, or mixtures of the two are used for shielding gas in welding nickel alloys. The oxygen-bearing argon mixtures used in GMAW welding should not be used in GTAW welding because of rapid deterioration of the tungsten electrode. Nitrogen additions are not recommended for the same reason and also because they introduce the possibility of weld metal porosity in the non-chromium-bearing nickel alloys. In manual welding, argon is the preferred shielding gas. It provides good penetration at lower flow rates than helium and less chance of melt-through. Helium produces a higher heat input and deeper penetrating arc which may be an advantage in some automatic welding applications. Argon-helium mixtures may improve the bead contour and wettability. Hydrogen additions (up to 5%) maybe added to argon for a hotter arc and more uniform bead surface in single pass automated welds.

Filler metals — The correct filler metals for GTAW welding of nickel alloys are shown in

Table 5. Straight lengths are normally used for manual welding and spool or coil wire is used for automatic welding. Conventional quality control practices to assure clean wire and avoidance of material mix-up are essential. Bare wire for GTAW should be wiped clean before using and stored in a covered area.

Operator guidelines

Arc initiation — Arc initiation is made easier by devices such as high frequency, capacitor, or lift start features (described earlier), or pilot arcs. In the absence of these devices, a scratch start is used which risks contaminating the electrode and the metal being welded. Where practical, starting tabs adjacent to the weld joint are useful in eliminating damage to the base metal.

Arc stopping — Take care when extinguishing the arc to decrease the size of the weld pool, otherwise crater cracking is likely as the weld solidifies. In the absence of a foot pedal or hand current control described earlier, or a power source current decay system, decrease the arc pool by increasing the travel speed before lifting the electrode from the joint. Good arc-stopping practice is particularly important in the root pass of welds that are welded from only one side. If cracks occur in this situation, they may extend completely through the root, presenting a difficult repair. After the arc is broken, hold the torch over the crater for several seconds to allow the weld to cool under protection of the argon atmosphere.

Arc shielding — Nickel alloys are easy to weld with the GTAW process. The alloys are relatively insensitive to marginal shielding compared to reactive metals such as titanium or zirconium. It is good practice, however, to provide ample shielding protection to both the weld puddle and backside. It is also a good idea to keep the filler metal within the inert gas envelope during welding.

If the process has a potential short-coming, it is that the weld may look good but may have inadequate filler metal. In some weld joints, inadequate filler can result in a concave bead that has a tendency for centerline cracking. Adequate filler metal addition produces a slightly convex weld bead. Another result of inadequate filler metal may be porosity in the weld, particularly in the non-chromium bearing nickel alloys.

Nickel alloy filler metals — Nickel alloy filler metals often contain elements that are not in the base metal to control porosity or improve resistance to cracking. Welds of the desired composition are possible only when ample filler metal additions are made. It is difficult to define just how much is ample and to measure it. Experience suggests that at least 50% of the weld metal should be from filler metal addition. With adequate amounts of filler metal in the joint, it then becomes important that filler metal mixing takes place before the weld solidifies, otherwise segregated spots of melted base metal and melted filler metal may exist. Uneven melting of filler metal along with fast solidification rates can cause this type of segregation.

Gas metal arc welding

In the GMAW process, an arc is established between a consumable, bare wire electrode and the work piece. The arc and the deposited weld metal are protected from the atmosphere by a gas shield, comprised mainly of the inert gases, argon and/or helium. Small amounts of carbon dioxide may be used for better wetting, arc action, and bead control. The process is referred to as MIG when an inert shielded gas is used and MAG when an active gas is used.

The advantages of GMAW over GTAW and SMAW are summarized as follows:

- Faster welding speeds;
- No slag, minimizing post-weld cleanup;
- Ease of automation;
- Good transfer of elements across the arc.

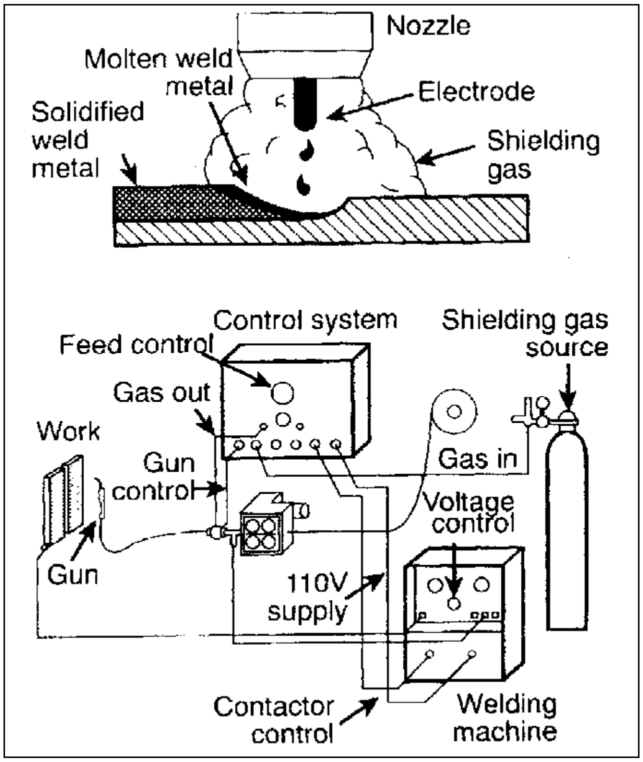


Figure 8 The basic components of the Gas Metal Arc Weld (GMAW) process

The basic components of the GMAW process are shown in *Figure 8*.

GMAW arc types — The type of metal transfer in GMAW has a profound influence on the process characteristics to the extent that it is often misleading to make general statements about GMAW without indicating the arc transfer mode. The three modes in most frequent use in welding nickel alloys are spray arc, short circuiting arc, and the pulsed arc.

The spray arc process is characterized by high deposit rates and high heat input. The arc is quite stable, but welding is generally limited to the flat position.

The short circuiting arc provides a low heat input transfer mode and therefore minimizes distortion in welding thin gauge material. It is most useful for single-pass welding, but has limitations when used on multiple pass, thick joints. The process is somewhat prone to lack of fusion defects. In addition, the weld beads tend to be rather convex; this may necessitate grinding each bead to assure full penetration to the side wall.

The pulsed arc mode of gas metal arc welding is an excellent compromise between spray arc and short circuiting arc modes in the general fabrication of nickel alloys as shown in *Table 6*.

GMAW equipment — The same power sources, wire feed mechanisms, and torches used for welding ordinary steels are used for nickel alloys. Plastic liners in the wire feed conduit are helpful in reducing drag. The GMAW process has more weld parameter controls than the GTAW and SMAW processes. The GMAW process controls amperage, voltage, current slope wire feed, pulse rate, and transfer mode; consequently, the process is more complex and expensive. The new synergic pulsed arc power source has made operation simpler by providing only one or two control dials for the operator. The remaining parameters are adjusted automatically or are programmed into the power source. The synergic mode power source has many advantages over the original fixed frequency pulse mode and is largely replacing fixed frequency units.

The welding current used in most power sources is the direct current electrode positive (DCEP) – reversed polarity. This current gives deeper penetration and a more stable arc than direct current electrode negative (DCEN) – straight polarity. The DCEN approach finds its best use in applications requiring shallow penetration such as overlay welding.

Consumables — Some of the most popular shielding gases used in GMAW are shown in *Table 6*. Argon is the shielding gas that is usually used for spray arc GMAW. Short circuiting and pulsed arc GMAW use a variety of shielding gases. A mixture of 90% helium, 7.5% argon, and 2.5% CO_2 is a popular mixture in North America. In Europe, helium is quite expensive so a mixture of 90% argon, 7.5% helium, and 2.5% CO_2 is often the mixture of choice. Whatever the combination, the shielding gas should contain at least 97.5% inert gases (argon, helium, or a mixture of the two).

In MAG welding, the use of active gas such as carbon dioxide often presents extra work in multiple-pass welds. Many nickel alloy filler metals contain elements such as aluminum and titanium that form very refractory and tightly-

Table 6
Comparison of GMAW arc modes for nickel alloys

Material/weld variables	Spray arc mode	Short circuiting mode	Pulsed arc mode
Typical thickness welded	3mm (0.125 in.) min., 6mm (0.25 in.) and thicker is normal	1.6mm (0.062 in.) and up	1.6mm (0.062 in.) and up
Welding positions	flat	all	all
Relative deposition rate	highest	lowest	intermediate
Typical wire diameter	1.6mm (0.062 in.) 1.2mm (0.045 in.)	0.8 or 0.9mm (0.030 or 0.035 in.)	0.9 or 1.2mm (0.035 or 0.045 in.)
Typical welding current	250-350 amps	70-130 amps	60 to 150 amps
Shielding gas (1)	Argon	90% Helium 7.5% Argon 2.5% CO_2 or 69% Argon 30% Helium 1% CO_2 or 75% Argon 25% Helium	75% Argon 25% Helium or 75% Helium 25% Argon or 90% Argon 7.5% Helium 2.5% CO_2

(1) Other gas mixtures are used, however, the shielding gas normally contains at least 97.5% inert gas, i.e., argon, helium, or a mixture of the two.

adhering oxides that must be removed prior to the next weld pass. Frequent interpass or interlayer grinding is required to remove the oxides from the surface. For this reason shielding gases with carbon dioxide additions are often limited to single-pass welds of Group B, chromium-bearing alloys where the better wetting and more stable arc is important in short circuiting and pulsed arc welding.

The preferred filler metals in GMAW nickel alloys are shown in *Table 5*. The most widely used diameters are 0.9mm,1.2mm, and 1.6mm (0.035 in., 0.045 in., and 0.062 in.) but other diameters are available.

Other welding processes

The most frequently used solid solution alloys in Groups A and B can be welded by most of the other commercial welding processes. The use of another process may offer advantages over those available from the SMAW, GTAW, and GMAW processes and should be evaluated for high production or special fabrications.

Submerged arc welding, SAW, has been used for welding thicknesses starting around 6.4mm (0.25 in.) and thicker and for overlay welding. Commercial fluxes are available for use with standard filler metals for welding Nickel 200 (N02200), and alloys 400 (N04400), 600 (N06600), and 625 (N06625). Contact the manufacturers of fluxes and filler metals for information on SAW or other solid solution alloys.

Plasma arc, electron beam, and laser welding are used with increasing frequency and the resistance welding processes; spot, seam, projection, and flush welding are readily adaptable to most nickel alloys. The development of nickel alloy flux-cored arc products has been slow and few alloy fillers are available

Oxyfuel welding, OFW, is seldom used today. Many nickel alloys can readily pick up carbon from the flame which reduces their corrosion resistance.

Brazing can be used to join nickel alloys to themselves or to a number of other alloys. Brazing is not usually used for severe corrosion environments such as the applications discussed herein.

Welding nickel alloy pipe

Piping systems are a very vital part of many industrial process plants. The fabrication and welding techniques for pipe are somewhat different from those used for tanks, pressure vessels, and similar equipment. One major difference is that in piping systems, the internal root is seldom accessible for backside welding so the root pass must be made correctly from the outside. Since pipe welding procedure and technique is such an extensive topic, it is only highlighted in this publication.

Types of pipe welding

The pipe size, equipment available, and welder skill or experience determine to a large extent the type of pipe weld and joint design that is best for a particular application. The particular nickel alloy is usually of secondary significance. In fact, there is a great deal of commonality in welding a range of alloys from carbon steel to stainless steel to the nickel alloys. A discussion on some of the most common piping joints follows.

Instrument piping

Instrument piping, usually about 13mm (0.5 in.) and less in diameter, is often joined by socket welds or it may be mechanically joined. Elements of a good socket welding procedure include GTAW root and cap pass and a gap of 1.6mm (0.062 in.) between the end of the pipe and the socket face. Use of an internal purge prevents oxide formation on the pipe ID which may be of significance in some piping systems. SMAW for the root pass is difficult because of the small pipe diameter, but more importantly, this process presents the possibility of slag entrapment with its attendant risk of contributing to corrosion.

Automatic welding

There are a number of commercially available GTAW orbital pipe welding units that can be used for welding nickel alloys. Orbital welds are preferred on all 75 mm (3 in.) and smaller diameter piping as compared to threaded joints and socket welds which have built-in failure-prone crevices. In welding other metals such as thin-wall stainless steel, orbital welds are often made using a tight butt with no filler metal addition. In welding nickel alloys, however, it is most desirable to add filler metal for Group A alloys and is often preferable for Groups B and C alloys.

In welding wall thicknesses over about 1.6mm (0.062 in.), a bevel is used and a consumable insert or automatically fed filler is used for the root pass. After the root pass, the joint is completed with the automatic GTAW or a higher deposition process depending upon the wall thickness and piping configuration.

Manual welding

A large quantity of nickel alloy piping is manually welded. Manual welding may be the choice when automatic welding equipment is not available, the project does not merit the expenditure, or the pipe configuration and accessibility are better-suited to manual welding.

In manual welding nickel alloys, as with steel piping over about 13mm (0.5 in.), the three likely procedures are:

- The use of backing rings;
- Consumable inserts;
- Open root joints with hand-fed filler metal.

Backing rings are a very poor choice for nickel alloy process piping. If the SMAW process is used, slag may be trapped between the pipe ID and the backing ring creating a potential corrosion site. In addition, backing rings can reduce flow in the pipe and they become a site for crevice corrosion.

The remaining two procedures, the use of consumable inserts and the open root joint with hand-fed filler metal, are equally good selections for the root pass manual welding of nickel alloys with the GTAW process. Both procedures produce high quality root welds in the hands of capable welders. The two types of joint designs in popular use are shown in *Figures 9* and *10*.

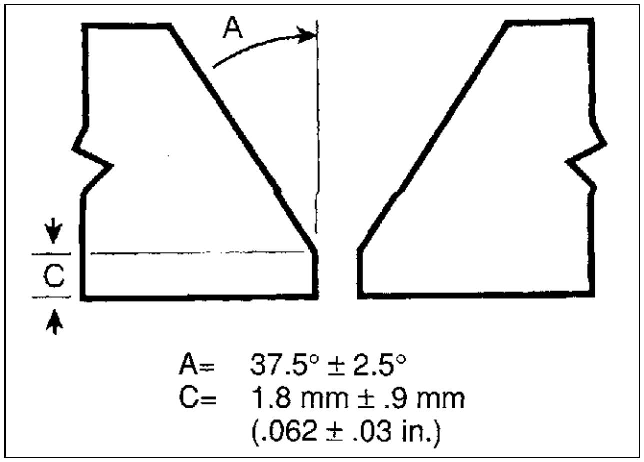


Figure 9 Typical joint design for pipe with consumable insert

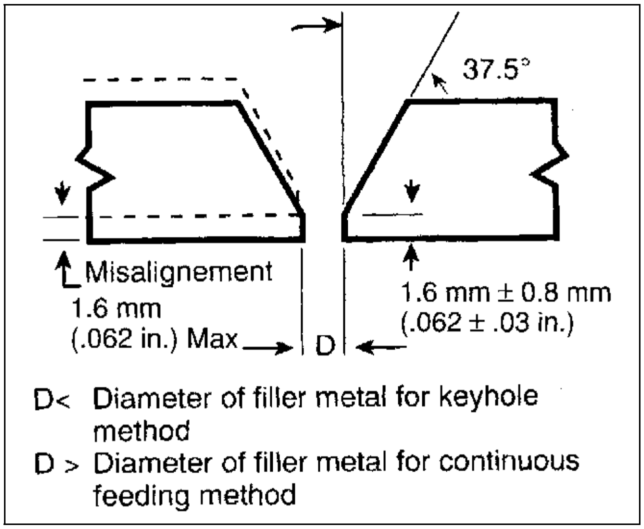


Figure 10 Typical joint design for pipe welded with open root joint and hand-fed filler metal

The standard consumable insert shapes are shown in *Figure 11* and are available in a number of nickel filler alloys to ANSI/AWS A5.30 — 79. Class 1; 3, and 5 are often used for nickel alloys. Classes 3 and 5 are often easier to fuse than the larger volume of Class 1. The consumable insert is placed into the joint and tacks are made between the insert and the pipe. The interior of the pipe must be purged to prevent oxidizing the tacks. The rise of the molten pool indicates that the insert is completely fused. With experience, the welder observes this change and adjusts travel speed accordingly. When the pipe can be rotated, the root pass is completed without stopping. When the pipe is in a fixed position, welding is usually done in sectors, alternating from side to side.

In tacking joints without consumable inserts, or open root welds, as they are called, there is a strong tendency for the shrinking forces to pull the joint closed. To maintain the desired gap, it maybe necessary to use spacers and to increase the size and number of tack welds. Spacers are usually short lengths of suitable diameter, clean filler wire. Any cracked or defective tack welds should be ground out. Both ends of the tacks on open root welds should be tapered to aid in fusing into the root weld.

The need to maintain a proper gap during root pass welding is two-fold. First, a consistent and uniform gap aids the welder in producing the optimum ID root contour. The other reason for a uniform root gap is the need to maintain the optimum root pass chemical composition.

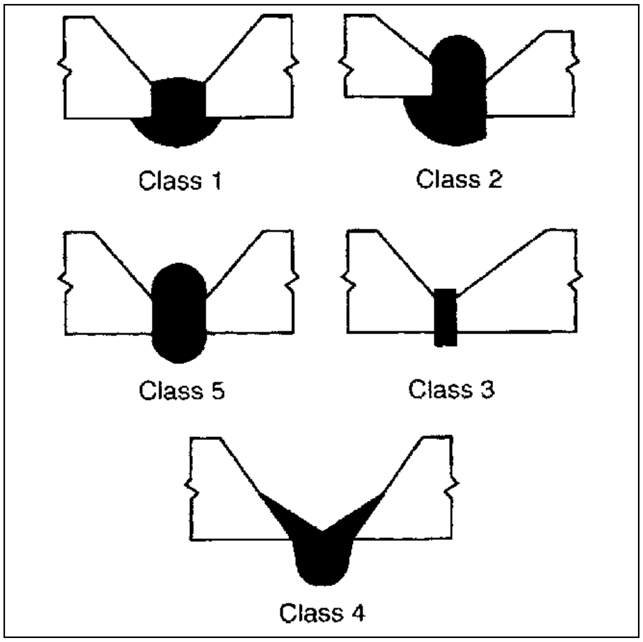


Figure 11 Standard consumable insert shapes, ANSI/AWS D10.11

Purging during pipe root welding

The pipe interior must be purged with an inert gas prior to and during the GTAW root pass. Failure to use a purge can result in heavily oxidized ID root surface with substantially lower corrosion resistance. Purging is usually done with pure argon, but helium may also be used.

Purging is a two-step operation, the first being done prior to welding to displace air inside the pipe. To save time and purging gas, baffles on either side of the weld joint are often used to reduce the purge area.

Open root weld joints should be taped and dead air spaces vented prior to purging. The internal purge atmosphere should be essentially free of oxygen and moisture in order to obtain a root surface with little or no surface oxide. In practice, it is difficult to specify a single oxygen limit that can be consistently obtained with all piping configurations, joint fitup conditions and other variations. The maximum amount of oxygen should be in the order of 0.5% but every effort should be made to obtain a lower level. At about 0.5% oxygen, the root is oxidized, but not to the degree that a “sugary” weld bead is obtained. Typical purging fixtures are shown in *Figure 12*.

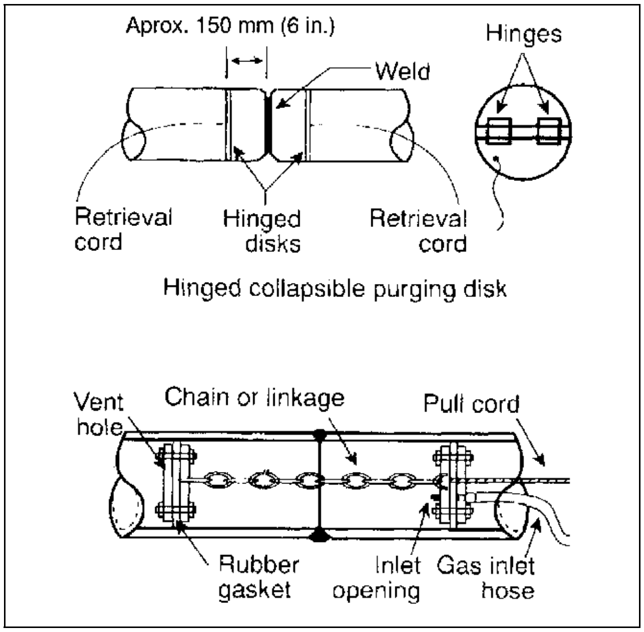


Figure 12 Typical pipe purging fixtures

After the proper purity level has been reached, the purge flow rate is adjusted. When welding carbon steel and stainless steel, the common practice is to use a purge flow rate of about 5L/min. (10 ft^3/hr.) and a torch flow in the order of 16L/min. (35 ft^3/hr.). In welding nickel alloys with an open butt, Haynes International has found that there is less root oxidation with the rates reversed, that is, about 19L/min. (40 ft.^{3}/hr.) purge and 5L/min. (10 ft.^{3}/hr.) torch.

In either practice an internal pressure build-up must be avoided or a concave root will result. In extreme cases, a hole may occur completely through the root. The purge gas exit hole should be sufficiently large that it does not contribute to pressure build-up in the pipe. The tape on the outside of the joint is peeled back in advance of the weld arc. Near the end of the root pass, the purge flow rate should be reduced to a very low level to prevent a blow-back.

After the root pass, the internal purge should be maintained during the next two fill passes in order to minimize heat tint (oxidation) on the inside weld surface. This is especially important when it is impractical to pickle after welding.

For those needing more information on GTAW root pass pipe welding, there are a number of technical articles and specifications available. Two excellent sources are the American Welding Society publications listed in the general references to this publication. While they are written mainly for steel, most information is applicable to nickel alloys.

Post-fabrication cleaning

All too often, it is assumed that the fabrication, be it a tank, pressure vessel, or pipe assembly, is ready for service after the final weld is made and inspected. Post-fabrication cleaning may be as important as any of the fabrication steps discussed. The surface condition of the nickel alloy is equally important where the product must not be contaminated, as in a pharmaceutical, food, or nuclear plant; as well as where the alloy must resist an aggressive environment, as in a chemical or other process industry plant.

Some guidelines on post-fabrication clean-up follow.

Surface contaminants — Examples of typical contaminants include grease, oil, crayon markers, paint, adhesive tape and other sticky deposits. Such contaminants can adversely affect product purity and in some environments may foster crevice corrosion. Typically, these contaminants can be removed by spraying or scrubbing with a detergent or solvent.

Embedded iron — During fabrication operations, iron particles can become embedded, then they corrode in moist air or when wetted, leaving tell-tale rust streaks. In addition to creating an unsightly condition, the iron particles might initiate local attack or, when used in process equipment, they might affect product purity.

Some tests to detect embedded iron follow:

- Spray the surface with clean water and inspect for rust streaks after 24 hours;
- Immerse the surface in a 1% sodium chloride solution for 12 to 24 hours or use as a spray in enclosed spaces such as tanks;
- For small areas, use a ferroxyl test. Apply as a warm solution and allow at least two hours before checking. The solution jells as it cools. The formation of blue spots indicates the presence of free iron.

The composition of one ferroxyl test solution is as follows:

Agar-agar	10g
Potassium ferricyanide	1 g
Sodium chloride	1 g
Water	1000 ml

Free iron can be removed by an acid pickle treatment. First, the surface must be cleaned of any oil or grease, otherwise the acid is ineffective. An effective pickling solution for Group A and C alloys follows:

Hydrochloric acid	30ml
Ferric chloride	11 g
Water	1000ml

For Group B chromium-bearing alloys, a nitric-hydrofluoric acid solution of 10 to 20% nitric acid and 2% hydrofluoric acid is quite effective.

When pickling is not practical, abrasive blasting, fine grit flapper wheels, or disks can be used. Glass-bead blasting or walnut shells produce good results. With any blasting, care must be taken to assure that the abrasive is free from iron or other foreign material that could contaminate the surface.

Mechanical damage

When reconditioning is needed to repair surface damage, the repair is usually made by grinding or by welding and grinding. Shallow defects are first removed by grinding, with a clean, fine-grit abrasive disk, a flapper wheel , or a pencil-type grinder. The maximum grinding depth to remove defects is often specified by the fabrication specification and may vary from 10% to 25% of the total thickness. When weld repair is needed, it can be made by SMAW, GMAW, or GTAW processes.

GTAW is usually used because of greater ease in making small repair welds. Filler metal should always be added and wash passes or cosmetic welds should never be allowed because of the risk of weld cracking and reduced corrosion resistance.

Safety and welding fumes

Safety rules for welding nickel alloys are essentially the same as for all metals as they pertain to areas such as electrical equipment, gas equipment, eye and face protection, fire protection, labelling hazardous materials, and similar items. The American Welding Society publishes a good reference guide on welding safety, entitled *Safety in Welding and Cutting* (American National Standard Institute/Accredited Standards Committee, ANSI/ASD, Z49 1-88).

Proper ventilation to minimize the welder’s exposure to fumes is important in welding and cutting all metals, including nickel alloys. In addition to good ventilation, the welders and cutters should avoid breathing the fume plume directly, by positioning the work so that their heads are away from the plume. The composition of welding fumes varies with the welding filler metal and welding process.

Arc processes also produce gaseous products such as ozone and oxides of nitrogen. Concern has been expressed in welding with nickel alloy consumables because of the chromium and, to a lesser extent, the nickel, usually present in the welding fume. Good ventilation minimizes the potential health risk. The International Institute of Welding has developed a series entitled *Fume Information Sheets for Welders* which offer internationally accepted guidelines for fume control.

Part II
For the materials engineer

This section is for the engineer who needs further information about the metallurgy and fabrication practices that are appropriate for wrought and cast nickel alloys. Refer to Part I for suggestions concerning good storage practices. Additional information in this discussion, which was not included in Part I, may be useful for formulating Welding Procedure Specifications or Quality Control documents. Topics covered include the effect of welding on corrosion resistance, post-fabrication heat treatment, and guides for material procurement.

Table 7 shows the nominal composition of wrought nickel and nickel alloys. *Table 8* shows the nominal composition of cast nickel alloys.

Table 7
Nominal composition of groups A through D and nickel alloys

Alloy	UNS No.	Ni(1)	C	Cr	Mo	Fe	Co	Cu	Al	Ti	Cb(2)	Mn	Si	W	B	Other
Group A Nickel and nickel-copper solid solution alloys – Composition percent																
200	N02200	99.5	0.08			0.2		0.1				0.2	0.2			
201	N02201	99.5	0.01			0.2		0.1				0.2	0.2			
400	N04400	66.5	0.2			1.2		31.5				1	0.2			
R-405	N04405	66.5	0.2			1.2		31.5				1	0.02			S.04
Group B Chromium-bearing solid solution alloys – Composition percent																
825	N08825	42	0.03	21.5	3	30		2.25	0.1	0.9		0.5	0.25			
G-3	N06985	46	0.01	22.2	7	19.5	2.5	2				0.5	0.50			
G-30	N06030	42	0.01	29.7	5	15	2.5	1.8				0.7	0.40			
600	N06600	76	0.08	15.5		8		0.2				0.5	0.2			
690	N06690	61.5	0.02	29		9						0.2	0.2			
59	N06059	60	0.01	23	15.7	0.7										
625	N06625	61	0.05	21.5	9	2.5			0.2	0.2	3.6	0.2	0.2			
686	N06686	56	0.01	21	16	2.5			0.2	0.1		0.5	0.04	3.7		
622	N06022	56	0.01	21.2	13.5	4	1					0.2		3		
C-22	N06022	56	0.01	21.2	13.5	4	1					0.2		3		
C-276	N10276	58	0.01	15.5	16	5.5	1					0.5		3.7		
Group C Nickel-molybdenum alloys – Composition percent																
B-2	N10665	70.5	0.01		28							0.5				
B-3	N10675	63	0.005	2	30	2						1.5		1.5		
B-4	N10629	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Group D Precipitation-hardening alloys – Composition percent																
K-500	N05500	64	0.2			1.0		30	2.7	0.6		0.8	0.2			
725	N07725	57	0.1	20.7	8	9			0.25	1.3	3.3	0.2				
625Plus®	N07716	60	0.1	21.5	8.2	5			0.2	1.3	3.3	0.1				
718	N07718	52.5	0.04	19	3	18			0.5	0.9	5.2	0.2	0.2			

(1) Includes small amount of cobalt if cobalt content is not specified.
(2) Includes tantalum also.
625 Plus® is a registered trademark of Carpenter Technology Corp.

Table 8
Nominal composition of cast corrosion resistant nickel alloys ASTM A494

			Ni, NiCu, NiMo Groups Composition percent			
Alloy Designation	UNS No.	Ni	Cr	Mo	Other	Wrought Counterpart
CZ-100	N02100	97			0.75 Cu, 1 Si	Nickel 200
M-35-1	N24135	65			29.5 Cu, 2 Fe,0.3 Cb	Alloy 400
N-7M	N30007	66	0.5	31.5	1.5 Fe	Alloy B2
			NiCrFe & NiCrMo Groups Composition percent			
CW-6MC	N26625	60	21.5	9.0	Fe, 3.8 Cb	Alloy 625
CY-40	N06040	75	15		7 Fe	Alloy 600
CW-2M(1)	N26455	65	16	16	1 Fe, 0.5 W	Alloy C (1)
CX2MW	N26022	56	21	13.5	4 Fe, 3 W	Alloy C-22

(1) CW- 6M and CW-12MW, two earlier cast counterparts of alloy C have been superseded by CW-2M and are therefore omitted from this compilation. CW-2M is a cast counterpart of the older wrought alloy C. There is no true cast counterpart of alloy C-276.

General guidelines for nickel alloys

Guidelines that apply to all nickel alloys are discussed first. Since the general guidelines are not appropriate to all groups, specific headings indicate the appropriate considerations for Groups A, B, C, and D alloys.

Preheat and interpass temperature

Preheat of nickel alloys is not required except to bang the metal in the area to be welded to room temperature or to a typical shop temperature to prevent moisture condensation. A maximum interpass temperature of 175°C (350°F) is widely used although one base metal producer is more conservative and recommends a maximum of 95^{o}C (200°F).

Post-weld heat treatment

In most all instances, solid solution nickel alloys do not require a post-weld heat treatment for corrosion resisting service. Precipitation hardening alloys require heat treatment after welding to develop full strength. When heat treatment or stress relief is required for specific applications; for example, to anneal following cold forming, or for dimensional stability, the user should consult the nickel alloy producer's literature or its staff for specific recommendations.

Prior to any heat treatment, it is essential that all alloy surfaces be thoroughly cleaned of oil, grease, paint, or markings, and similar contaminants to avoid catastrophic corrosion during heat treatment. The method of heating and cooling and the amount of sulphur in the furnace atmosphere must be controlled or the alloys can be damaged.

Filler metal selection for corrosive environments

Nickel alloys are normally welded with matching composition filler metals as shown in *Table 5*, Part I. In sea water and some environments, nickel-copper (Group A) alloy welds made with matching composition filler metals may be anodic to the base metal and corrode preferentially by galvanic corrosion. This condition may be attributed largely to the fact that many "matching composition" filler metals are not of identical composition; some elements have been added or amounts adjusted for better weldability. Another factor to consider is that weld metal may also become anodic to the base metal as a result of segregation as it solidifies.

When experience demonstrates that matching composition welds corrode preferentially to the base metal, non-matching composition filler metals should be used that are both compatible metallurgically with the base metal and are cathodic to the base metal in the particular environment. Selection should be made by knowledgeable material specialist or by on-site evaluation tests.

It is important to remember that most welding codes specify that the non-matching filler metal welds be treated as a dissimilar metal welds and indicate the need for a separate welding procedure specification and welding procedure test.

Group A — Nickel and nickel-copper alloys

Welders soon discover that the welding characteristics of nickel and, to a lesser degree, nickel-copper alloys are somewhat different from the chromium-bearing nickel alloys or the austenitic stainless steels. Primary among the differences is the low viscosity or inability of the molten weld metal to spread or flow in the joint; however, competent welders soon become accustomed to this and are able to produce quality welds. The materials engineer who is aware of this viscosity difference in advance is better prepared to cope with the false "materials problem" reports from uninitiated shop personnel.

Alloys 200 and 201 — Nickel 200 and 201 differ in the amount of carbon, 0.15% maximum in Nickel 200 and 0.02% maximum in 201. Prolonged exposure of Nickel 200 in the temperature range of 425-650°C (800-1200°F) precipitates graphite. For this reason Nickel 201 is recommended for service in the 315-650°C (600-1200°F) temperature range. Nickel filler metal welds (ENi-1 and ERNi-1) are not subject to graphite precipitation and are used for welding both Nickel 200 and 201.

Equipment intended for caustic service provides an exception to the general rule that post-fabrication heat treatment is not normally required. A stress relief treatment of 700°C (1300°F) for 1/2 hour followed by a cooling rate of 90°C (200°F) per hour is a standard procedure to relieve stresses as a safeguard against corrosion cracking in caustic service for these alloys.

Alloy 400 and R405 — Alloy 400 is readily welded by all the common welding processes discussed in Part I. Alloy R-405 is a free-machining grade of alloy 400, containing 0.025-0.060% sulphur and is available as rods or bars. Parts made of alloy R-405 usually involve little or no welding, but when welding is required, it is good practice to make generous filler metal additions and to minimize the amount of base metal melted, thus reducing the amount of sulphur in the weld. Alloy R-405 welds made with the SMAW process are often less affected by sulphur from the base metal than welds made by GTAW or GMAW.

Salt and brine environments — The standard matching composition filler metals for welding alloy 400 are shown in *Table 5*, in Part I. It is important to note, however, that in salt or brine environments, alloy 400 matching composition welds may become anodic to the base metal and suffer galvanic corrosion attack. To solve this problem in brine environments, nickel-chromium type electrodes are used such as ENiCrFe-2 and ENiCrMo-3. Welds made with these electrodes are cathodic to the base metal and thus, resist galvanic corrosion.

Hydrofluoric acid service — Welded alloy 400 equipment used in hydrofluoric acid service should receive a post-weld stress relief to avoid stress corrosion cracking. The stress relief treatment is performed at 540-650°C (1000-1200°F) for one hour followed by slow cooling.

Group B — Chromium-bearing alloys

The nickel-chromium, nickel-iron-chromium, and nickel-chromium-molybdenum alloys may exhibit carbide precipitation in the weld heat-affected zone, a condition similar to that encountered in austenitic stainless steels. In most environments, however, the sensitization of these nickel alloys is not sufficient to affect the corrosion resistance; as a result, solution annealing is seldom required. Two factors function to reduce sensitization: very low carbon levels (as a result of recent improved melting practices), and the use of stabilizing additions of titanium and columbium in many alloys.

A post-weld heat treatment to prevent stress corrosion cracking is recommended when alloy 600 is used in high-temperature, high-strength-caustic-alkali service. The stress relief treatment is performed at a temperature of 900°C (1650°F) for one hour or at 790°C (1450°F) for four hours with a slow cool.

Group C — Nickel-molybdenum alloys

The materials engineer involved in fabrication of nickel-molybdenum alloy equipment should be aware of the background behind the three grades; alloys B-2, B-3, and B-4, along with the precautions required in post-fabrication heat-treating. The welder will use matching filler metals for all three alloys and should detect no difference between the three alloys. For this reason the subject was not discussed in *Part I, For the welder*.

Alloy B-2 has been the standard nickel-molybdenum alloy for a number of years, having replaced the older alloy B. Alloy B had a shortcoming in that it required a solution anneal at a temperature of 1175°C (2150°F) after welding to eliminate carbide precipitates in the weld heat-affected zone and to restore corrosion resistance. A modification of the alloy composition resulted in the formulation of alloy B-2 which demonstrates acceptable corrosion resistance in the as-welded condition. This development made possible the construction of fabrications too large to be solution annealed.

Work with alloy B-2, however, revealed a problem: it experiences a phase transformation during brief exposure to temperatures in the range of 595-815°C (1100-1500°F). Such exposure can result in cracking during base metal manufacturing operations or annealing by fabricators after cold working. Recent alloy modifications by two different metal producers have overcome the 595-815°C (1100-1500°F) low ductility problem and associated cracking of alloy B-2. The result of their work is the introduction of the two alloys: B-3 and B-4.

This is a very brief treatment of the nickel-molybdenum alloys. Fabricators new to these alloys should contact the producers before undertaking complex fabrications.

Group D — Precipitation-hardening nickel alloys

The precipitation-hardening nickel alloys have limited use in corrosion resisting service so this publication covers only the most important guidelines. Consult with the alloy manufacturers for more detailed information.

The precipitation-hardening nickel alloys are used in applications requiring corrosion resistance and a need for greater mechanical strength or higher hardness than is obtainable with the corresponding solid solution alloys. The precipitation-hardening or age hardening, as it is often called, is accomplished by the addition of increased amounts of titanium and aluminum along with special heat treatments. The heat treating temperatures vary from 600-760°C (1100-1400°F) depending upon the alloy and specific properties desired. The hardenable alloys in the soft or solution-annealed condition have about the same strength as the comparable solid solution alloy.

Of the hardenable alloys covered in this publication, i.e., alloys K-500, 725, 625 PLUS® and 718, only alloy 718 has a matching composition filler metal (ANSI/AWS A5.14 ERNiFeCr-2) that can be strengthened by heat treatment. In practice this has seldom presented a problem since most applications do not involve welds that must develop the same strength as the base metals. An example is the fillet weld used for attachments. When full weld metal strength is not required, the practice is to use a filler metal of the comparable solid solution alloy as shown in *Table 9* that follows.

Table 9 Matching Filler metals of the comparable solid solution alloys

Alloy	Bare Electrodes ANSI/AWS A5.14	Coated Electrodes ANSI/AWS A5.11
K-500	ERNiCu-7	ENiCu-7
725 & 625 PLUS®	ERNiCrMo-3	ENiCrMo-3
718	ERNiCrMo-3	ENiCrMo-3

Dissimilar-metal welds

In dissimilar-metal welding, the properties of three metals must be considered; the two metals being joined and the filler metal used to join them. For example, if one of the metals being joined is welded using preheat when welding to itself, preheat should be used in making a dissimilar-metal weld (DMW). Another variable might be the need for a post-weld heat treatment. On occasion there may be a conflict in that the optimum control for one metal is undesirable for the other. In this case, a compromise is needed. This is one reason the development of a DMW procedure often requires more study than for a conventional similar-metal welding procedure. (ref. NiDI 14018)

Table 10-A, which follows, presents the filler metal alloy identifications which are referenced in *Tables 10-B* and *10-C*. *Tables 10-B* and *10-C* list the dissimilar metal weld (DMWs) and the suggested filler metals by identification (shown in *Table 10-A*). These DMWs represent the nickel alloys covered in this document welded to each other and to some of the common steels.

The fillers indicated are those that are capable of making metallurgically sound welds using proper welding procedures with the SMAW, GMAW, and GTAW processes. In making DMWs, it is desirable to keep the base metal dilution to a minimum and to keep the amount of base metal melted into the weld uniform along the length of the weld.

Base metal dilution is more easily controlled with the SMAW process and to almost the same degree with the GMAW process. In the manual GTAW process, the amount of filler metal added (and conversely the amount of base metal melted) may vary considerably depending on welder technique. For this reason, welder training and qualification is particularly important for DMWs made with the GTAW process.

Procurement guidelines

Table 11 shows the principal wrought nickel and nickel alloys, UNS numbers, and specifications for the product forms. The seamless and welded tube and pipe material specifications reference a general requirement specification that governs areas common to all nickel and nickel alloy pipe and tubing such as dimensional tolerance, check analysis, and inspection methods. The specifications are: *B751*, *General Requirements for Nickel and Nickel Alloy Seamless and Welded Tubing* and *B775*, *General Requirements for Nickel and Nickel Alloy Seamless and Welded Pipe*. It is good practice to order material to the specifications shown in the table rather than by trade name.

Surface finish

Surface finish, an important factor, is not covered in the alloy-product form specifications

Table 10-A
Filler metal alloy identification for bare and covered electrodes

Class No.	Base alloy	Bare electrodes and rods ANSI/AWS A5.14-89	Covered electrodes ANSI/AWS 5.11-90
1	Alloy 200	ERNi-1	ENi-1
2	Alloy 400	ERNiCu-7	ENiCu-7
3	Alloy G-3	ERNiCrMo-9	ENiCrMo-9
4	Alloy G-30	ERNiCrMo-11	ENiCrMo-11
5	Alloy 600	ERNiCr-3	ENiCrFe-3
6	Alloy 600	—	ENiCrFe-2
7	Alloy 625	ERNiCrMo-3	ENiCrMo-3
8	Alloy C-22	ERNiCrMo-10	ENiCrMo-10
9	Alloy C-276	ERNiCrMo-4	ENiCrMo-4
10	Alloy B -2	ERNiMo-7	ENiMo-7

Table 10-B
Suggested filler metals for dissimilar metal welds

Alloy (UNS)	200 201 CZ-100	400 K-500 M-35-1	825 20 Mo-4 20 Mo-6	G-3	G-30	600 CY-40	690
200 (N02200) 201 (N02201) CZ-100 (N02100)							
400 (N04400) K-500 (N05500) M-35-1(N24135)	1,2						
825 (N08825)	1, 5, 6, 7	5, 6, 7					
G-3 (N06985)	1, 8, 3	5, 6	3, 7, 8				
G-30 (N06030)	1, 3, 4	5, 6	4, 7, 8	4, 7, 8			
600 (N06600) CY-40 (N06040)	1, 5, 6	5, 6	5, 6, 7, 8	3, 7, 8	4, 7, 8		
690 (N06690)	1, 5, 6	5, 6	5, 6, 7, 8	3, 7, 8	4, 7, 8	5, 6	
625 (N06625) 725 (N07725) 625 Plus (N07716) 718 (N07718) CW-6MC (N26625)	1, 5, 6, 7	5, 6, 7	5, 6, 7, 8	3, 7, 8	4, 7, 8	5, 6	5, 6
59 (N06059) 686 (N06686)	1, 5, 6, 7	5, 6, 7	5, 6, 7, 8	3, 7, 8	4, 7, 8	5, 6	5, 6
C-22 (N06022) 622 (N06022) CX2MW (N26022)	1, 8	5, 6	7, 8	3, 7, 8	4, 7, 8	5, 6	5, 6
C-276 (N10276) CW-2M (N26455)	1, 5, 6, 9	5, 6	7, 8, 9	3, 7, 8, 9	4, 7, 8, 9	5, 6	5, 6
B-2 (N10665) B-3 (N10675) B-4 (None)	1, 10	10	7, 10	3, 8, 10	4, 8,10	7, 8, 10	7, 8, 10
4 & 6% Mo Stainless steels	1, 7, 8	5, 6	7, 8	3, 7, 8	4, 7, 8	5, 6, 7	5, 6, 7
300 Series Stainless Steels	1, 5, 6	5, 6	7, 8	3, 7, 8	4, 7, 8	5, 6	5, 6
Carbon *and* Low alloy steels	1, 5, 6	2	5, 6	3, 7, 8	4, 7, 8	5, 6	5, 6

presented previously. Surface finish for nickel alloy sheet, strip, and plate is not standardized as it is for stainless steel. *Table 12* presents information on surface finishes available from two nickel base alloy producers. Where surface finish is important, the purchaser must review and negotiate the requirements with individual nickel alloy producers.

Nickel alloy castings

The principal cast nickel alloy designations, UNS numbers, compositions, and wrought counterparts are shown in *Table 8*. The suggested filler metals are shown in *Table 5*, Part I. Procurement of nickel alloy castings would seem to be straightforward because all castings are covered by one specification, ASTM A494. Specifying nickel alloy castings to this ASTM specification, however, does not assure quality castings. The best assurance of obtaining quality castings lies with the capability, experience, and integrity of the producing foundry. Unfortunately this point is too often overlooked and factors such as price prevail. Large users of castings can profit by visiting potential foundry suppliers to assess their technical and production capabilities. The purchasers should consider the supplemental ordering requirements which follow.

Direct procurement of nickel alloy castings by end users is unusual. The end user normally buys castings in the form of pumps, valves and components already assembled into OEM-furnished equipment. The following considerations apply to the entity actually purchasing the cast-

Table 10-C

Suggested filler metals for dissimilar metal welds

Alloy (UNS)	625,725 625 Plus, 718, CW-6MC	59 686	C-22 622 CX2MW	CW-2M CW-2M	B-2 B-3 B-4
200 (N02200) 201(N02201) CZ-100 (N02100)					
400 (N04400) K-500 (N05500) M-35-1 (N24135)					
825 (N08825)					
G-3 (N06985)					
G-30 (N06030)					
600 (N06600) CY-40 (N06040)					
690 (N06690)					
625 (N06625) 725 (N07725) 625 Plus (N07716) 718 (N07718) CW-6MC (N26455)					
59 (N06059) 686 (N06686)	7, 8				
C-22 (N06022) 622 (N06022) CX2MW (N26022)	7, 8	7, 8			
C-276 (N10276) CW-2M (N26455)	7, 8, 9	7, 8, 9	7, 8, 9		
B-2 (N10665) B-3 (N10675) B-4 (None)	7, 10	7, 8, 10	8, 10	9, 10	
4 & 6% Mo Stainless steels	7, 8	7, 8	7, 8	8, 9	8, 10
300 Series Stainless Steels	7, 8	7, 8	7, 8	8, 9	8, 10
Carbon *and* Low alloy steels	7, 8	7, 8	7, 8	8, 9	8, 10

ings. The supplying foundry should thoroughly review and understand the specifications which must be carefully written by the purchaser.

A very important property of nickel alloys is their corrosion resistance ASTM A494, to which nickel alloy castings are normally procured for corrosion resisting service, covers composition, mechanical properties, and heat treatment. Corrosion tests are not a part of ASTM A494 and, therefore, require a special arrangement between the purchaser and supplier. In practice, however, corrosion testing of each lot or heat of material is seldom justified except for unusual services.

There are supplemental requirements that can assist users in obtaining nickel alloy castings which embody the inherent corrosion resistance of these alloys. Source inspections utilizing radiographic examination, liquid penetrant examination, weldability tests, and pressure tests are examples of some measures that are available to further control the quality of nickel alloy castings. These additional quality assurance provisions may be specified by the purchaser and should be substantiated by certification that the foundry complied with the specifications. A few observations concerning the effective use of these supplemental measures follow.

Source Inspections

Radiographic inspection — Radiographic inspection should be considered when the castings are subject to high and/or cyclical stresses and when mechanical strength, as well as corrosion resistance, is important. In addition, if

Table 11
Specifications for procurement of groups A through D wrought nickel and nickel alloys

		ASTM Specifications unless otherwise noted					
Alloy	UNS No.	Plate sheet strip	Rod bar forgings	Seamless[1] tube pipe	Welded[1] tube & pipe	Fittings	Condenser tubing
Group A Nickel & nickel-copper solid solution alloys							
200	N02200	B162	B160	B161	B725 B730	B366	B163
201	N02201	B162	B160	B161	B725 B730	B366	B163
400	N04400	B127	B164	B165	B725	B366	B163
R-405	N04405	N/A	B164	N/A	N/A	N/A	N/A
Group B Chromium-bearing solid solution alloys							
825	N08825	B424	B425		B423 B705	B704	B366 B163
G-3	N06985	B582	B581	B622	B619 B626	B366	N/A
G-30	N06030	B582	B581	B622	B619	B366	
600	N06600	B168	B166	B167	B516 B517	B366	B163
690	N06690	B168	B166	B167	N/A	N/A	B163
59	N06059	B575	B574	B622	B619 B626	N/A	N/A
625	N06625	B443	B446	B444	B704 B705	B366	N/A
686	N06686	N/A	N/A	N/A	N/A	N/A	N/A
622	N06022	B575	B574	B622	B619 B626	B366	N/A
C-22	N06022	B575	B574	B622	B619 B626	B366	N/A
C-276	N10276	B575	B574	B622	B619 B626	B366	N/A
Group C Nickel-molybdenum alloys							
B-2	N10665	B333	B335	B622	B619 B626	B366	N/A
B-3	N10675	B333	B335	B622	B619 B626	B366	N/A
B-4	N10629	N/A	N/A	N/A	N/A	N/A	N/A
Group D Precipitation-hardening alloys							
K-500	N05500	QQN286 Mil-N-17506	QQN286 Mil-N-17506	QQN286 Mil-N-17506	QQN286	N/A	N/A
725	N07725	N/A	B805	N/A	N/A	N/A	N/A
625-Plus®	N07716	N/A	B805	N/A	N/A	N/A	N/A
718	N07718	B670	B637	AMS 5589/90	N/A	N/A	N/A

(1) B751 "Standard Specification for General Requirements for Nickel and Nickel Alloy Seamless and Welded Tube" also applies in addition to the individual alloy pipe or tube specification.

N/A Alloy is not available in this product form to an ASTM specification.

Table 12
Surface finishes for nickel base alloy sheet, strip, and plate

Producer A	
Thickness	Finish
Sheet and strip	CR Cold Rolled or
up to 0.64cm (0.25 in.)	Pickled Plate
Sheet and strip	Descaled or
0.48cm (0.19 in.) and up	as Rolled (Hot Rolled)
Producer B	
Thickness	Finish
Sheet and strip	CR (Cold Rolled) (2B)
up to 0.32cm (0.125 in.)	
Plate over 0.32cm (0.125 in.)	HRAP (Hot Rolled, Annealed, and Pickled)

surface conditions allow corrosion to proceed beyond the casting surface, subsurface defects may allow the degradation of the longer term corrosion resistance of the casting. For such applications, radiographic inspection may be justified.

The added expense of radiographic inspection is usually not justified for castings where sound metal on the wetted surfaces and flange faces is the primary service requirement. In such cases, a liquid penetrant examination is a less expensive choice.

Liquid penetrant inspection — Liquid penetrant inspection after rough machining can identify surface defects that may become sites for corrosion and cracking. Wetted surfaces and flange faces inside the bolt circle are examples of surfaces where such defects can be removed with light grinding or minimal weld repair.

Liquid penetrant inspection of non-wetted surfaces can lead to unnecessary cosmetic repairs and should be avoided unless justified by unusual circumstances. The fillet areas on the outer surfaces of castings between the bodies and flanges are good examples of areas that are particularly prone to persistent minor penetrant indications. These indications are usually inconsequential and difficult to eliminate completely.

Weldability test —The weldability test as specified in ASTM A494 is optional, but can be one of the best assurances that the alloy does not have harmful levels of trace elements and that the heat treatment, if required, has been properly performed. The test, *Figure 1*(b) of ASTM A494, is the preferred test and includes a bend test and macro examination.

Tramp or unwanted elements usually result from poor material and scrap circuit control. Foundries with good quality control programs seldom encounter weldability problems.

The purchaser must decide how extensively the weldability test should be applied, i.e., to every heat of material or to a selected or random number of heats. Generally, the test should be applied to all heats supplied by a new foundry source. It is prudent to follow the same policy for alloys new to a particular foundry until a confidence level has been established.

Pressure test — Hydrostatic or air testing is performed by many foundries on pressure type castings. Although these tests are not a requirement of ASTM A494, they should be specified as an additional requirement. Pressure tests should be performed after rough machining and before weld repair.

Certification —To assure that the requirements have been met, the purchaser can, and should, request the manufacturer's certification stating that the material was manufactured, sampled, tested, and inspected in accordance with the full material specification including all supplemental tests requested.

Heat Treatment — *NiCrMo alloys* — ASTM A494 requires a solution annealing temperature of 1175°C (2150°F) followed by a water quench for the NiCrMo alloys: CW-6MC, CW-2M, and CX2MW shown in *Table 8*. Experience has shown that a solution annealing temperature of 1220°C (2225°F) is better for alloys CW-2M and CX2MW. The annealing temperature as well as the water quench can present problems to some suppliers. The higher furnace temperature is needed to put potentially harmful precipitates into solution. The water quench is needed to ensure that these potentially harmful precipitates remain in solution and do not precipitate out during cooling.

Many foundries do not have furnaces capable of reaching the required solution annealing temperatures. They may offer to heat treat at somewhat lower temperatures for longer times. Both of these exceptions are detrimental to the finished product quality and should be refused. Lower solution annealing temperatures allow precipitates to form which are harmful to corrosion resistance and longer times allow more of the harmful precipitates to form. To verify that these conditions do not occur, procurement documents should require that furnace charts be supplied showing that the specified solution annealing temperature was actually reached.

Some foundries may request exception to a water quench fearing that the casting may crack. While the water quench is an excellent check on general quality in addition to preventing precipitation of undesirable second phases, there may be configurations that are prone to cracks. These need to be reviewed on a case by case basis by qualified and experienced metallurgical specialists. No exception to the water quench test should be allowed without this qualified evaluation.

Nickel, Nickel-copper, Nickel-Molybdenum alloys — Ni, NiCu and NiMo alloys are less sensitive to heat treatment and weld repair than NiCrMo alloys. Nickel and NiCu do not require a solution annealing treatment and are used in the as-cast condition. NiMo alloys are annealed at a temperature of 1093°C (2000°F) followed by a water quench. A temperature of 1093°C (2000°F) is easily reached in most alloy foundry furnaces.

Chemistry

It is essential that the alloy composition of all nickel alloys be within the ranges specified by ASTM A494, however, not all of the tramp elements which can be deleterious to the welding of nickel alloys or to their corrosion resistance are identified in ASTM A494.

The composition of the as-cast surface of the casting may differ from the specified composition due to carbon pickup from some molding materials, chromium depletion during annealing, or other casting-related surface changes. When the casting is machined, the surface layer is removed and the composition of the machined surface closely approaches the bulk chemistry.

The following three suggestions can help to ensure the chemical integrity of the castings you receive.

1. Require a weldability test, described earlier, to assure that tramp elements are not present in an amount to cause defects from welding.
2. Assure that the foundry has the capability to make reliable chemical analyses. This can be confirmed by an audit performed by a qualified analytical chemist and/or by a check analysis performed by an outside laboratory skilled in analysing nickel alloys.
3. When the as-cast surface is the surface that must resist corrosion, it is prudent to require that the composition at the surface be within the ranges applicable to the particular alloy.

Casting repair by welding

It is good practice to rough-machine and pressure-test all nickel alloy castings before weld repairs are made. This procedure allows weld repairs to be made before final heat treatment and avoids most of the problems that arise when defects are uncovered in machining.

Major weld repairs are defined in ASTM A494. Welding heats the area adjacent to the weld into a range where phases may precipitate that can be deleterious to corrosion resistance of the NiCrMo alloys. Post weld heat treatment (PWHT) and rapid quenching after weld repairs restores full corrosion resistance — if and only if — the high temperatures required for solution annealing are actually reached.

Ni, NiCu and NiMo alloys, Group A and C alloys — Although welding heats the area adjacent to the weld of Ni, NiCu and NiMo alloys to high temperatures, there are no deleterious phases that precipitate in these solid solution alloys. Since PWHT is not required, procurement is simplified.

Filler metals — The filler metals shown in *Table 5*, Part I should be used for all weld repairs unless experience has shown over-matching composition filler metals are required for the specific environment of concern. An example of a need for over-matching filler metal is discussed earlier in Part II, in the topic entitled *Salt & brine environment*.

Post-weld repair heat treatment — ASTM A494 leaves post weld heat treatment (PWHT) after foundry weld repairs as an optional operation. Procurement documents should require PWHT and water quench after all weld repairs as an exception to ASTM A494 for the NiCrMo alloys. The quench is as important as actually reaching the required solution annealing temperature. The quench keeps the deleterious phases in solution and is an excellent check on the general quality of the casting.

Welding nickel alloy castings

The guidelines for welding wrought nickel alloys covered in Part I should also be used in welding nickel alloy castings, whether making casting repairs or incorporating the castings into fabrications. All oil, grease, machining lubricants, and similar substances should be removed with a suitable solvent. All surface oxides and “casting skin” should be removed next to the weld joint by machining or abrasive grinding. Failure to remove this layer usually contributes to weld defects. Abrasive grinding wheels should be dedicated to grinding only nickel alloy castings and should not be previously used on carbon or low alloy steel.

In fabrication welding, nickel alloy castings are joined with the same welding processes used for the wrought forms. In the repair of castings, the welding process employed often depends upon the size of the casting and size of the defect. GTAW is the process of choice in repairing small castings and in repairing small, shallow defects on any size of casting. Similar composition filler metal should be added in making GTAW repairs. The SMAW process is most-often used by foundries for the repair of larger defects and has the advantage of lower heat input than GTAW for similar repairs. Some foundries have developed GMAW procedures for welding repair and are able to realize greater welding efficiencies.

Procurement checklist for nickel alloy castings

In procurement, recognize that nickel alloys have been selected for their extreme corrosion resistance. Using ASTM Specifications is an essential first step, but does not protect the user from receiving nickel alloy castings with degraded corrosion resistance. Assurance of quality is up to the purchaser and the supplemental requirements he places on the foundry, above and beyond the basic ASTM requirements. Following is a checklist of requirements supplementary to those in ASTM A494 that are frequently necessary in order to obtain the quality and corrosion resistance inherent in the basic composition:

1. Source inspections, including one or more of the following:
    a. Radiographic inspection;
    b. Liquid penetrant inspection;
    c. Analysis of surface and/or bulk chemistry by supplier or by a qualified laboratory;
    d. Weldability tests;
    e. Rough machining and pressure tests;
    f. Certification.
2. Process control requirements and verification:
    a. Higher solution annealing temperature;
    b. Furnace charts;
    c. Water quench;
    d. Weld repair and post weld repair heat treatment.

PART III
For the design engineer

Design for corrosion service

Thoughtful design can improve corrosion resistance and obtain better service from less expensive grades of nickel alloys. There are two cardinal rules to keep in mind.

1. Design for complete and free drainage.
2. Eliminate or seal weld crevices.

Tank bottoms

Figures 13 through *18* show six common tank bottom designs. The square-corner-flat-bottom design shown in *Figure 13* invites early failure from the inside at the corner weld where sediment collects, increasing the probability of under-sediment crevice attack. In addition, the flat bottom-to-pad support invites rapid crevice corrosion when moisture penetrates the underside.

The rounded-bottom design shown in *Figure 14* is much more resistant from the inside, but is actually worse from the outside as condensation is funnelled directly into the bottom-to-pad crevice. The grout used to divert such condensation, *Figure 15*, helps initially, but soon shrinks and becomes a source of maintenance.

The drip skirt shown in *Figure 16* is the best arrangement for flat-bottom tanks. The concave bottom and the dished-head bottom on supports, *Figures 17* and *18*, are very good and are superior to all flat-bottom tanks not only in corrosion resistance but also in fatigue resistance.

Fatigue stresses from filling and emptying are seldom considered in design, but they can be significant and have led to failures in flat-bottom tanks. The concave and dished-head designs can withstand much greater fatigue loadings than can flat bottoms.

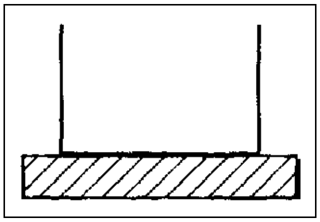


Figure 13 Flat bottom, square corners — worst

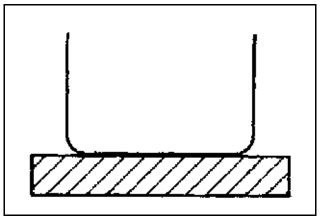


Figure 14 Flat bottom, rounded corners — good corners — poor outside

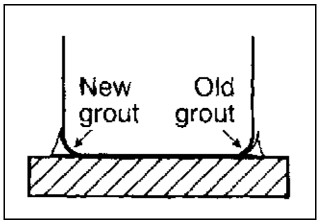


Figure 15 Flat bottom, rounded corners, grouted — good inside, poor outside

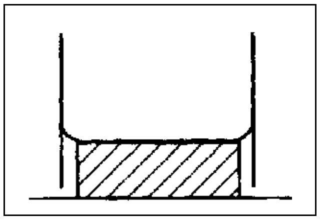


Figure 16 Flat bottom, rounded corners, drip skirt — good inside, good outside

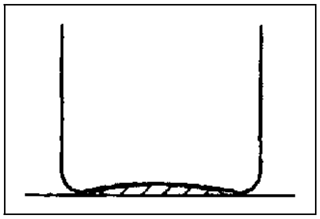


Figure 17 Concave bottom rounded corners — good inside, good outside, fatigue resistant

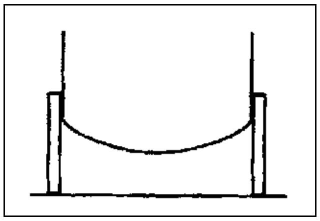


Figure 18 Dished head — best inside, best outside, fatigue resistant

Tank bottom outlets

Residual water in the bottom of nickel alloy tanks is a potential source of tank bottom failures. Side outlets and centre outlets shown in *Figures 19* and *20* provide a convenient construction configuration but invite early failure of tank bottoms. Not only is a layer of stagnant liquid held on the tank bottom, but sediment and accumulated contamination cannot easily be flushed out. The flush side outlet and the recessed bottom outlet as shown in *Figures 21* and *22* allow the bottom to be completely drained of sediment,

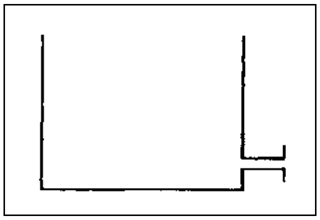


Figure 19 Side outlet above bottom — poor

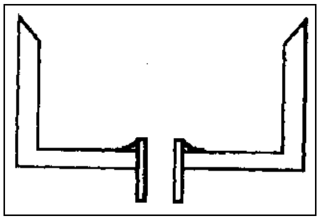


Figure 20 Centre outlet, above bottom — poor

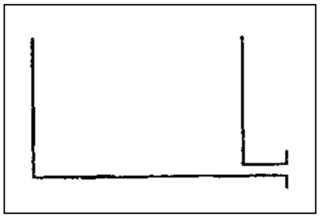


Figure 21 Side outlet, flush — good

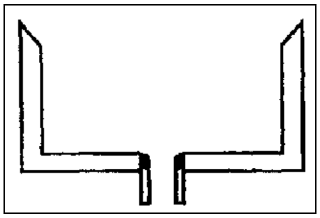


Figure 22 Centre outlet recessed — good

leaving it clean and dry. The sloped designs shown in *Figures 23* and *24* improve further on these designs, facilitating the drainage of residual liquid and sediment.

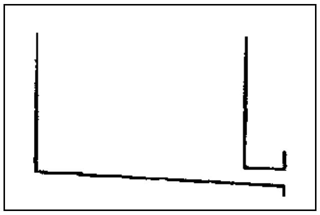


Figure 23 Side outlet, flush, sloped — best

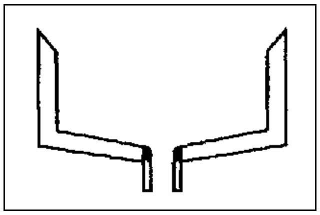


Figure 24 Centre outlet, recessed, sloped — best

Bottom corner welds

When the sidewall forms a right angle with the bottom, the fillet weld is seldom as smooth as shown in the cross section of *Figure 25*. It is usually rough and it frequently varies in width to compensate for variations in fit-up. Sediment tends to collect along the weld. It is difficult to remove, and leads to under-sediment crevice attack. Welding along the outside as shown in *Figure 26* improves the resistance of the joint to crevice attack from the outside; however, rounding the corner and moving the weld to the sidewall as shown in *Figure 27*, improves it further. The corrosion resistance from both sides as well as the fatigue resistance are improved by this last refinement.

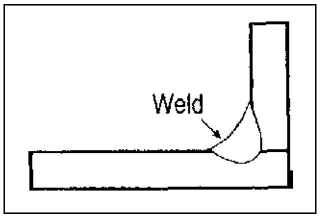


Figure 25 Corner weld from inside — poor inside, worst outside

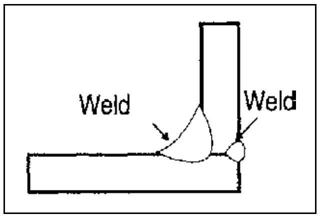


Figure 26 Corner weld from both sides — poor inside, good outside

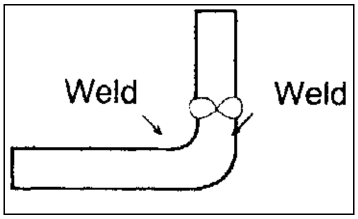


Figure 27 Side wall in lieu of corner weld — best inside, good outside, fatigue resistant

Attachments and structurals

Attachments create potential crevice corrosion sites. *Figure 28* shows a tray support angle with intermittent welds made with the intention of providing adequate strength, however, there is a severe crevice between the angle and the inside wall of the vessel. Over time, this crevice fills with sediment and other contaminants, inviting premature failure from crevice corrosion.

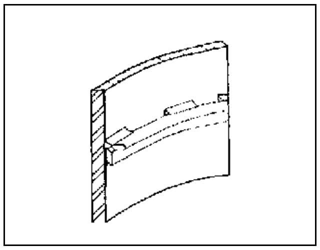


Figure 28 Tray support, staggered strength weld — severe crevice

Figure 29 shows the same tray support with a continuout seal weld at the top. This change prevents contaminants from migrating into the crevice. The angle-to-sidewall crevice is still open from the bottom, but this is a much less severe crevice. While this crevice is still subject to vapor penetration, it is not vulnerable to the lodging of solids. *Figure 30* shows a full seal weld at the top and bottom of the tray support angle. With this addition, the crevice is fully sealed and represents the best design for crevice corrosion resistance.

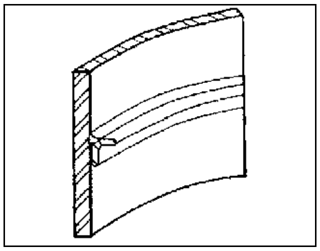


Figure 29 Tray support, full seal weld top — good crevice resistance

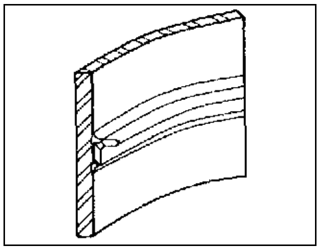


Figure 30 Tray support, full seal weld top & bottom — best crevice resistance

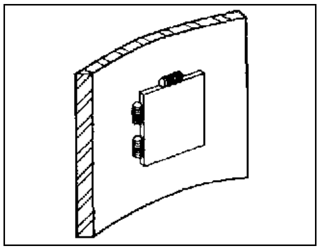


Figure 31 Reinforcing pad, staggered welds — adequate strength

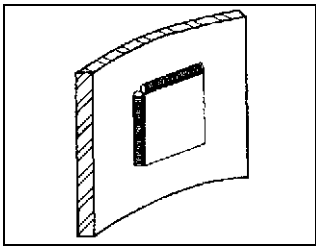


Figure 32 Reinforced pad, seal weld — best crevice resistance

Figure 31 shows a reinforcing pad frequently used to weld other attachments. The intermittent weld creates a severe pad-to-sidewall crevice inviting premature failure. Completing the seal weld as shown in *Figure 32* requires very little additional time but greatly improves the corrosion resistance of the pad.

Figure 33 shows structural angles positioned to allow drainage, an important factor in preventing crevice corrosion. Angles should never be positioned as shown in the top view of *Figure 34*.

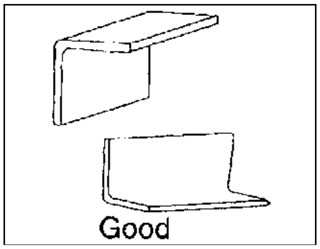


Figure 33 Position of angles

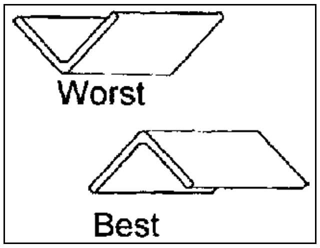


Figure 34 Position of angles

The best position for complete drainage is shown in the lower view.

When structural shapes are used, they should be positioned with open side down so that liquids will drain freely. When this preferred positioning is not possible, drain holes should be drilled about every 305mm (12 in.) in the centre as shown in the middle view of *Figure 35*.

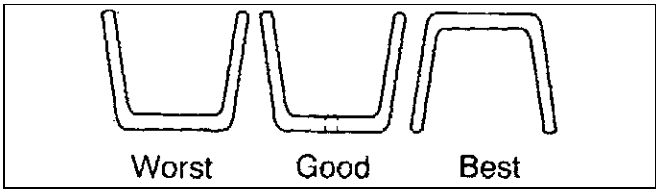


Figure 35 Position of channels

Continuous fillet welds on stiffeners and baffles, as shown on the right side of *Figure 36*, seal the severe stiffener/baffle-to-horizontal-plate crevice. The staggered fillet welds shown on the left side of *Figure 36* leave the joint vulnerable to crevice corrosion.

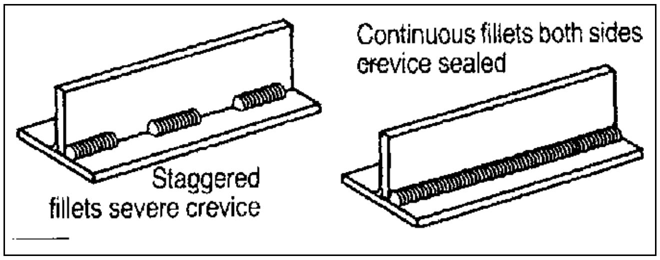


Figure 36 Stiffeners and baffles

Baffles in tanks and heat exchangers create dead spaces where contaminants and sediment can collect and where full cleaning is difficult. *Figure 37* shows a cut-out at the lower corner of a tank baffle and *Figure 38* shows a cut-out in the lower portion of a heat exchanger tube support plate. Both arrangements reduce the likelihood of the accumulation of contaminants and facilitate cleaning.

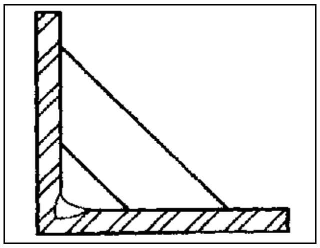


Figure 37 Corner baffle cut-out — good

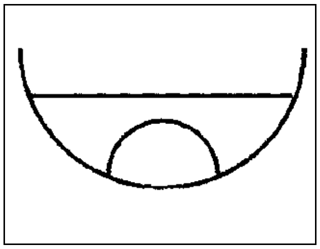


Figure 38 Heat exchanger, baffle cut-out — good

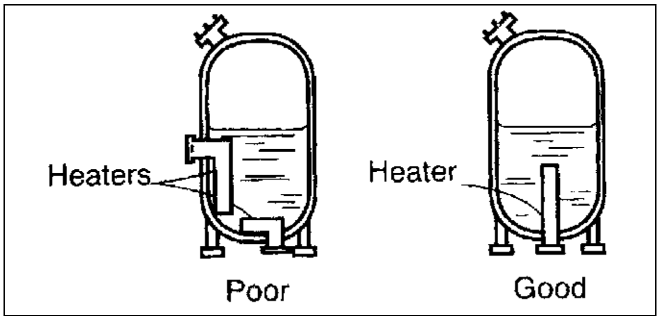


Figure 39 Poor and good designs for the location of heaters in a vessel

Heaters and Inlets

Heaters should be located so they do not cause hot spots on the vessel wall. In *Figure 39*, the poor location of heaters creates hot spots which, in turn, may result in higher corrosion in the area between the heater and the vessel wall. The good design avoids hot spots by centrally locating the heater.

When a concentrated solution is added to a vessel, it should not be introduced at the side as shown in the poor design of *Figure 40*. Side introduction causes concentration and uneven mixing at the sidewall. With the good design, mixing takes place away from the sidewall. It is also good design practice to introduce feed below the liquid level to avoid splashing and drying above the liquid line.

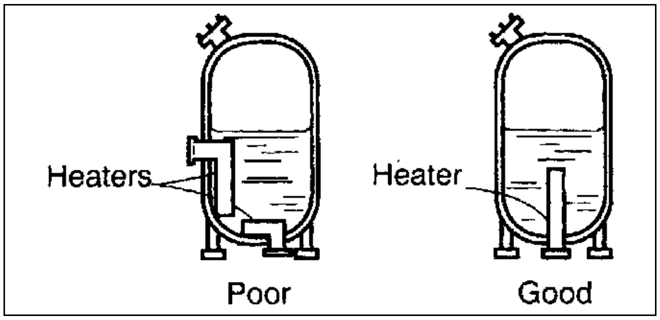


Figure 40 Poor and good designs for mixing concentrated and dilute solutions

Pipe Welds

Small diameter nickel base alloy piping, 51 mm (2 in.) and less in diameter is more frequently socket welded than butt welded. The emergence of automatic orbital welding promises to greatly reduce the use of socket welds. The crevice of a socket weld joint is less damaging to nickel alloys than to stainless steel due to the considerably greater corrosion resistance of the nickel alloys. Nevertheless, the crevice provides a site of lower corrosion resistance in some aggressive environments. To circumvent this weakness, specify orbital butt welds wherever practical.

Figure 41 shows a circumferential pipe weld with incomplete penetration. Pipe welds should be full penetration welds for best corrosion performance and for full weld joint efficiency. Welding codes such as those of the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API) require full penetration butt welds. When such codes are not imposed, the purchaser should specify that pipe welds be full penetration welds. In addition, limits should be placed on the weld concavity and convexity. Common limits are maximums of 0.8mm (0.03 in.) concavity and 1.6mm (0.06 in.) convexity.

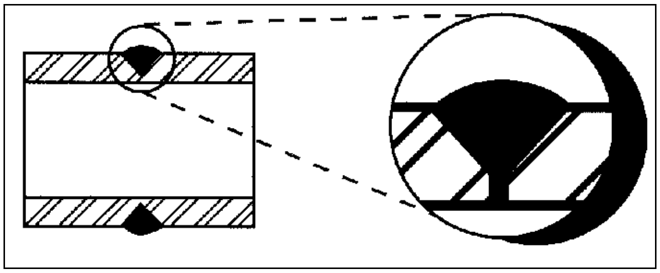


Figure 41 Pipe weld with incomplete penetration — severe crevice

Three good pipe-to-flange welding designs are shown in *Figures 42, 43,* and *44*. The recessed arrangement shown in *Figure 42* avoids the need for machining or grinding smooth the surface of the weld on the flange face in *Figure 43*. Both of these are suitable when the flange is of the same material as the pipe. Neither is suitable when carbon steel or ductile iron flanges are used on nickel alloy pipe. In this case a stub-end arrangement as shown in *Figure 44* is preferred.

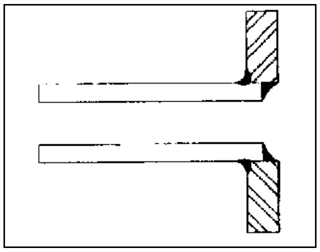


Figure 42 Pipe recessed, flange and pipe, same alloy — good

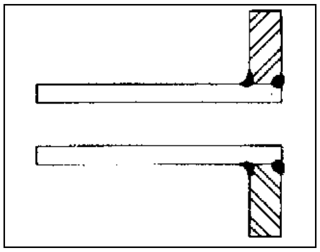


Figure 43 Pipe flush, pipe and flange same alloy — better

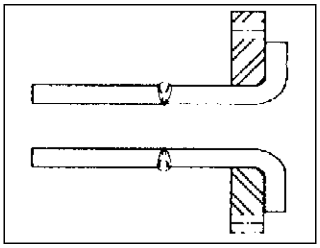


Figure 44 Stub-end, flange carbon steel or ductile iron — very good

In order for piping and heat exchanger tubing to drain completely, it is necessary to slope the piping or heat exchanger tubing just enough so that water is not trapped in the slight sag between supports. *Figure 45* shows how a water film tends to remain in horizontal runs of pipe or tubing, and how water drains when sloped.

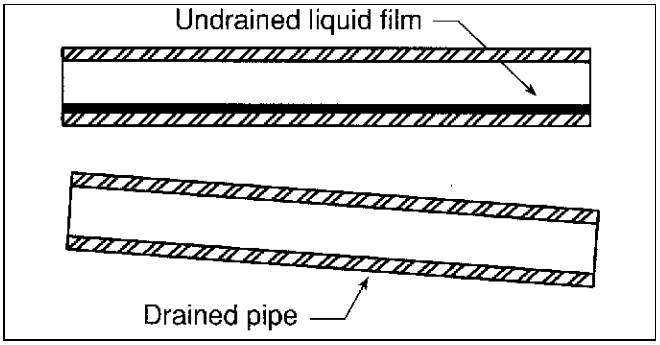


Figure 45 (A) Horizontal (standard) — poor
(B) Sloped — very good

Weld overlay, sheet lining, and clad plate

To offset the relatively high cost of solid nickel alloy construction and still provide a highly corrosion-resistant layer of alloy, weld overlaying, sheet lining, or clad plate are often viable design options. Construction using these techniques or products is well-suited to those applications where the full metal thickness is not required for mechanical purposes or corrosion resistance. For economic reasons, the backing material is usually carbon steel, but other steels are feasible. Some features of the three designs are summarized in *Table 13*.

A discussion on welding and fabrication techniques of each of the processes follows.

Weld overlay

Weld overlay surfacing is well-suited to covering thick sections of items such as tube sheets, large diameter shafts, and the walls of thick-section pressure vessels. The substrate is usually carbon steel or, on occasion, a low alloy steel. The weld overlay may be made by a number of different welding processes; the choice is usually based on the process that gives the highest deposition rate and acceptable quality overlay for the particular application.

Comments on the welding processes for overlay welding follow.

Submerged arc welding — Deposition rates using SAW are high, a 35 to 50% increase over

GMAW overlay capability. SAW fluxes are commercially available for use with most of the common nickel alloy bare wire and strip filler metals. With wire electrodes, a diameter of 1.6mm (0.062 in.) yields better results than the larger diameters characteristic of steel or stainless steel SAW. Base metal dilution is normally controlled so that only two weld layers are needed unless the surface is to be machined, in which case three weld layers may be required. The as-welded surfaces are smooth enough to be dye-penetrant inspected with no special surface preparation other than wire brushing. All welding must be done in the flat position unless the equipment is specially adapted for horizontal welding.

Gas metal arc welding — GMAW overlays are usually made using the spray arc or pulsed arc mode. The spray arc mode has the advantage of higher deposition rates, but all welding must be performed in the flat position. Base metal dilution tends to be higher with GMAW welding than with other processes. The favoured method employs automatic welding with an oscillating torch movement.

Pulsed GMAW overlays are usually done with a filler wire diameter of 1.2mm (0.045 in.), compared to a wire diameter of 1.6mm (0.062 in.) used with the spray arc mode. Deposition rates are lower, but all-position welding is possible. Pulsed arc mode GMAW may be done with either manual or automatic set-up.

Shielded metal arc welding — Deposition rates are relatively low, but the process is useful in overlaying small areas and irregular, out-of-position surfaces where automation is not justified. Facings on vessel outlets and trim on valves are good examples of suitable applications.

Weld overlay guidelines — The effect of base metal dilution and the profile of the overlay/base metal interface are two areas of concern in weld overlay work. These concerns are common to overlays made with any welding process.

Base metal dilution — Usually the objective is to provide a weld overlay in which the top weld surface has a composition equivalent to the base metal to achieve a similar corrosion resistance. This means a minimum of two weld layers and often three along with careful control of welding parameters to minimize penetration into the base metal. Each additional layer adds significantly to the total cost, so there is a strong incentive to minimize the number of weld layers. Two ways to do this follow:

- Where the overlay composition is a chromium-bearing alloy containing iron, use a low iron, high alloy filler metal. This suggestion might be implemented, for example, by substituting filler metals such as ERNiCrMo-3, ERNiCrMo-4 or ERNiCrMo-10 in an overlay weld which calls for alloys such as 825 or G-3.
- For nickel and nickel-copper overlays, do not specify lower iron limits than are needed for satisfactory corrosion performance.

Base metal interface — The second concern is the interface profile. Ideally the interface profile perpendicular to the direction of welding should be a nearly straight line, free of “spikes” of base metal between weld beads. An uneven profile is more prone to weld cracking and may fail to pass a side bend test which is often required by codes.

Sheet lining

Sheet lining has been used for over 60 years to cover metal substrates with a more corrosion

Table 13
Comparisons of weld overlay, sheet lining, and clad plate

Design	Applications	Remarks
Weld overlay	Covering substrate sections of unlimited thickness and varied shapes, such as tube sheets. Multi-layers (2 or 3 minimum) needed to compensate for dilution	Solid bond of alloy to substrate providing good heat transfer and mechanical strength Generally not competitive where sheet lining or clad plate is acceptable Local repair of alloys in process equipment
Sheet lining	Covering broad areas of existing or new construction substrate with thin alloy sheet Extensive sheet forming is required in applying to complex shapes	Applying liner to selective high corrosion/erosion areas Not suited to vacuum or heat transfer applications Need for plug or arc spot welds for mid-sheet attachment
Clad plates	Constructions where large size plates are an advantage Roll-bonded plates limited to 64-76mm (2.5-3 in.) thickness	Where an integral bond between alloy and backing is needed for vacuum or heat transfer applications or for construction of storage and pressure vessels Tight welding controls are required for minimum iron dilution on the alloy side

resistant alloy. Stainless steels, nickel, and copper alloys are common lining alloys. Essentially the same application technique is used for all alloys. The sheet characteristics and the welding practices used in the sheet lining process are summarized below; further details are available in NiDI technical series publications Nos. 10,027 and 10,039 which are included in the Bibliography.

- All pre-weld cleaning and preparation practices covered in Part I should be followed in welding the alloy sheet to the substrate.
- Sheet thickness/size — A sheet thickness of 1.6mm (0.062 in.) is most widely used; thinner sheet is more difficult to weld. To minimize the amount of welding, the sheet sizes used are as large as are practical to form and handle.
- Liner weld joints are usually either the overlap joint or three-bead method shown in *Figure 46*. The overlap joint is preferred with 1.6mm (0.062 in.) sheets when minimum weld dilution from the substrate is essential. The three-bead method is more often used for alloy sheets that are 3.2mm (0.125 in.) and thicker.
- Mid-sheet attachments, when needed, are made with plug welds through pre-punched holes or, alternately, with a GMAW spot weld through the sheet.
- Seal welds can be made by SMAW or GTAW, but the pulsed GMAW process is most widely used.

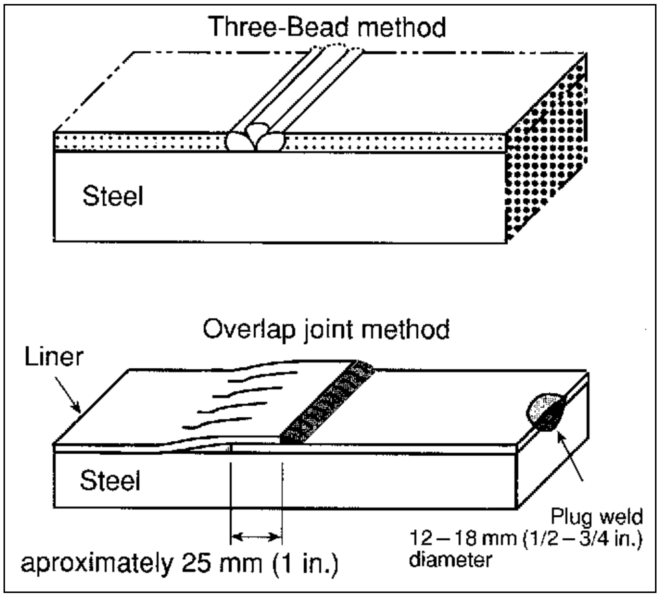


Figure 46 Weld joints for liners

Clad steel

Nickel alloy clad steel is available as either a roll-bonded or explosion-bonded product. Roll-bonded clad is produced by hot-rolling a thick section sandwich of steel and alloy starter plates. In the course of hot-working, a metallurgical bond is formed between the two metals. The normal thickness of roll-bonded clad plates is 5mm (0.187 in.) up to 64-76mm (2.5 or 3 in.) with the alloy representing 10 to 20 % of the total thickness. In explosion-bonding, there is usually no reduction after bonding, so the starting and finish alloy and steel thicknesses are the same. This allows relatively thin alloy sheet to be applied to backing steel several inches thick.

Recommended joint designs for butt welding clad steel are shown in *Figure 47*. Both designs include a small root face of steel, i.e., the edge of unbeveled portion of the joint, above the cladding to protect the cladding during welding of the steel. The steel side should be welded first with a steel filler metal, usually by SMAW with a low hydrogen electrode. It is important to avoid penetration into the cladding when welding the first pass. Dilution of the steel weld with the nickel alloy cladding can cause weld cracking. Upon completion of the steel side, the clad side is prepared by grinding or chipping. Welding is done with the filler metal recommended for welding solid alloy sections in *Table 5*, Part I. To compensate for dilution by steel, at least two and preferably three alloy layers should be applied.

If the clad plate is 8mm (0.312 in.) or less, it is generally more economical to use the nickel filler metal for both sides of the joint. Refer to the Lukens Steel Publication, included in the Bibliography, for further details on welding roll-bonded clad metals.

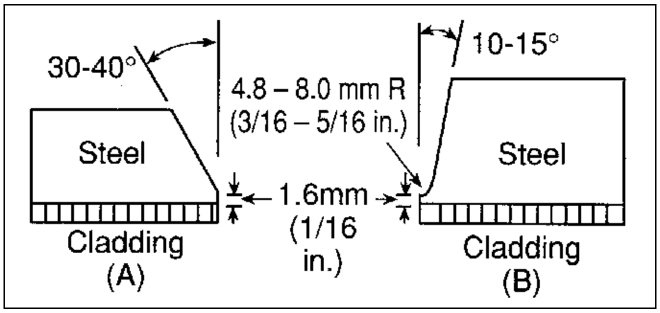


Figure 47 Joint designs for clad steel. (A) Material 4.8 to 16mm (3/16 to 5/8 in.) thick.
(B) Material 16 to 25mm (5/8 to 1 in.) thick (courtesy of Inco Alloys International — Joining Technical Bulletin)

Bibliography

American Welding Society- AWS B2.1, *Standard for Welding Procedure and Performance Qualification*.

American National Standard Institute/Accredited Standards Committee.

ANSI/ASD, Z49 1 — 88, *Safety in Welding and Cutting.*

American Society of Testing and Materials, ASTM A380, *Standard Recommended Practice for Cleaning and Descaling Stainless Steel Parts Equipment, and Systems.*

ANSI/AWS D10.11 — 87, *Recommended Practices for Root Pass Welding of Pipe Without Backing.*

ASM International Metals Handbook, Volume 6, *Welding, Brazing, and Soldering*.

ASME Boiler and Pressure Vessel Code, Section Nine, *Welding and Brazing Qualifications*.

Fabrication of HASTELLOY® Corrosion-Resistant Alloys, Haynes International Inc., Kokomo, IN.

Fabrication of Lukens Clad Steels, Lukens Steel Company, Coatesville, PA

Guidelines for the Welded Fabrication of Nickel-Containing Stainless Steels for Corrosion Resistant Services, NiDI Technical Series No.11 007.

Guidelines for Welding Dissimilar Metals, by Richard E. Avery, NiDI Technical Series No. 14 018.

Joining Technical Bulletin, Inco Alloys International, Inc., Huntington, WV.

Specifying Stainless Steel Surface Treatment, by Arthur H. Tuthill and Richard E. Avery, NiDI Technical Series No. 10 068.

Stainless Steel Sheet Lining of Steel Tanks and Pressure Vessels, by Richard E. Avery, Jonathan D. Harrington, and William L. Mathay, NiDI Technical Series No. 10 039.

The Affect of Heat-Tint on Corrosion Resistance of Alloys Used in FGD Systems, by W.L. Silence and L.H. Flasche, Paper 358 NACE CORROSION '86.

The Back Purging and Welding Requirements for Fabrication of HASTELLOY ® Alloy Pipe Systems, Haynes International, Inc., Huntington, WV.

Welding and Fabrication of Nickel Alloys in FGD Systems, by Richard E. Avery and W. H. D. Plant, NiDI Technical Series No. 10 027.

Acknowledgement

The authors are indebted to Lee H. Flasche, Haynes International, Inc.; Leo E. Wildenthaller, Hobart Welding Products; S. D. Kiser, Inco Alloys International, and Nickel Development Institute, D. J. Heath, D. E. Jordan and Warren M. Spear for their valuable technical comments. We also want to recognize Raymond V. Gendron, Tech. Text, for his technical writing assistance.