

FABRICATION OF HASTELLOY® CORROSION-RESISTANT ALLOYS

General Guidelines for
Welding, Brazing, Hot and
Cold Working, Heat Treating,
Pickling and Finishing

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INTRODUCTION

This brochure is a general guide to the fabrication of the corrosion-resistant alloys produced by Haynes International, Inc. It is not meant to be an instruction manual.

The following corrosion-resistant alloys are covered in this brochure:

HASTELLOY B-3® alloy

HASTELLOY C-4 alloy

HASTELLOY C-22® alloy

HASTELLOY C-2000® alloy

HASTELLOY C-276 alloy

HASTELLOY G-30® alloy

HASTELLOY N alloy

HASTELLOY B-3 alloy is an additional member of the nickel-molybdenum family of alloys with excellent resistance to hydrochloric acid at all concentrations and temperatures. It also withstands sulfuric, acetic, formic and phosphoric acids, and other nonoxidizing media. B-3 alloy has a special chemistry designed to achieve a level of thermal stability greatly superior to that of its predecessors, e.g. HASTELLOY B-2 alloy. B-3 alloy has excellent resistance to pitting corrosion, to stress-corrosion cracking and to knife-line and heat-affected zone attack.

Ask for Bulletin H-2104

HASTELLOY C-4 alloy is a nickel-chromium-molybdenum alloy with outstanding high-temperature stability, as evidenced by high ductility and corrosion resistance even after longtime aging at 1200 to 1900 deg. F (649 to 1038 deg. C). The alloy also has excellent resistance to stress corrosion cracking and to oxidizing atmospheres up to 1900 deg. F (1038 deg. C).

Ask for Bulletin H-2007

HASTELLOY C-22 alloy – a versatile nickel-chromium-molybdenum-tungsten alloy with better overall corrosion resistance than other Ni-Cr-Mo-W alloys available today, including HASTELLOY C-276 and C-4 alloys and HAYNES 625 alloy. C-22 alloy has outstanding resistance to pitting, crevice corrosion and stress corrosion cracking. By virtue of its higher chromium content, C-22 alloy is more resistant than C-4 and C-276 alloys to oxidizing acids and to acid streams containing oxidizing residuals such as dissolved oxygen, ferric ions and wet chlorine. In fact, it is second only to

C-2000 alloy in its versatility. Because of such versatility it can be used in multi-purpose processes and where "upset" conditions are likely to occur.

Ask for Bulletin H-2019

HASTELLOY® C-22HS® alloy

is corrosion-resistant, nickel-chromium-molybdenum alloy which can be heat treated to obtain a strength approximately double that of other C-type alloys. Importantly, the corrosion resistance and ductility of the alloy remain excellent when in the high strength condition. In addition to its high uniform corrosion resistance in oxidizing as well as reducing environments, the as-heat treated C-22HS alloy possesses high resistance to chloride-induced pitting and crevice corrosion attack.

Ask for Bulletin H-2122

HASTELLOY C-2000 alloy was designed to resist an extensive range of corrosive chemicals, including sulfuric, hydrochloric, and hydrofluoric acids. Unlike previous Ni-Cr-Mo alloys, which were optimized for use in either oxidizing or reducing acids, C-2000 alloy extends corrosion resistance in both types of environments. The combination of molybdenum and copper provide the outstanding resistance to reducing media, while oxidizing acid resistance is provided by a high chromium content. C-2000 alloy also exhibits pitting resistance and crevice corrosion resistance superior to the industry standard, C-276 alloy. Its forming, welding and machining characteristics are similar to C-276 alloy.

Ask for Bulletin H-2111

HASTELLOY C-276 alloy has excellent resistance to pitting, stress corrosion cracking, and acid environments. It has exceptional resistance to a wide variety of chemical process environments, including strong oxidizers such as ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic and acetic acids, acetic anhydride, and seawater and brine solutions.

Ask for Bulletin H-2002

HASTELLOY G-30 alloy is a high chromium nickel-base alloy which shows superior corrosion resistance over most other nickel- and iron-base alloys in commercial phosphoric acids as well as many complex environments containing highly oxidizing acids such

as nitric/hydrochloric, nitric/hydrofluoric and sulfuric acids. The resistance of G-30 alloy to the formation of grain boundary precipitates in the heat-affected zone makes it suitable for use in the as-welded condition.

Ask for Bulletin H-2028

HASTELLOY® G-35® alloy

was designed to resist "wet process" phosphoric acid, which is widely used in the production of fertilizers. Tests indicate that it is far superior to HASTELLOY G-30 alloy and stainless steels, in this chemical. It was also designed to resist localized attack in the presence of chlorides, since under-deposit attack is potential problem in evaporators used to concentrate "wet process" phosphoric acid. As a result of its high-chromium content, G-35 alloy is extremely resistant to other oxidizing acids, such as nitric, and mixtures containing nitric acid. It possesses moderate resistance to reducing acids, as a result of its appreciable molybdenum content, and, unlike other nickel-chromium-molybdenum alloys, it is very resistant to "caustic dealloying" in hot sodium hydroxide. Finally, G-35 alloy is much less susceptible to chloride-induced stress corrosion cracking than the high-chromium stainless steels and nickel-chromium-iron alloys traditionally used in "wet process" phosphoric acid.

Ask for Bulletin H-2121

HASTELLOY N alloy is a nickel-base alloy that was developed as a container material for molten fluoride salts. It has good oxidation resistance to hot fluoride salts in the temperature range of 1300 to 1600 deg. F (704 to 871 deg. C). Alloy N is most useful in environments involving fluorides at high temperatures; however, the alloy compares favorably with other HASTELLOY alloys in various other corrosive media. It is especially suggested that the alloy be tested in molten halides of zirconium, beryllium, lithium, sodium, potassium, thorium or uranium.

Ask for Bulletin H-2052

The nominal chemical compositions of these alloys and the available product forms can be found in Tables A-1 and A-2, respectively, in the Appendix.

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WELDING

General Welding

The welding characteristics of the HASTELLOY® corrosion-resistant alloys are similar in many ways to those of the austenitic stainless steels and present no special welding problems, if proper techniques and procedures are followed.

As a way of achieving quality production welds, development and qualification of welding procedure specifications is suggested. Such procedures are usually required for code fabrication, and should take into account parameters such as, but not limited to, base and filler materials, welding process, joint design, electrical characteristics, preheat/interpass control, and postweld heat treatment requirements.

Any modern welding power supply with adequate output and controls may be used with the common fusion welding processes. Generally, welding heat input is controlled in the low to moderate range. Wide weave beads are not recommended. Stringer bead welding techniques, with some electrode/torch manipulation, are preferred.

In general, nickel-based alloys will exhibit both sluggish welding and shallow penetration characteristics. Therefore, care must be used with respect to joint design and weld bead placement to insure that sound welds with proper weld bead tie-in are achieved. The nickel-based alloys have a tendency to crater crack, so grinding of starts and stops is recommended.

Cleanliness is considered an important aspect of welding of the corrosion-resistant nickel-based alloys. Contamination by greases, oils, corrosion products, lead, sulfur, and other low melting point elements can lead to severe cracking problems.

It is recommended that welding be performed on base materials that are in the solution annealed condition. Materials with > 7% outer Fiber Elongations of cold work should be solution annealed before welding. The welding of materials have large amounts of residual cold work can lead to cracking in the weld metal and/or the weld heat affected zone. Welding processes that are commonly used with the corrosion-resistant alloys are shown in Table 1.

In addition to these common arc welding processes, other welding processes such as plasma arc welding, resistance spot welding, laser beam welding, electron beam welding, and submerged arc welding can be used. Because of the possibility of hot cracking, parameter selection is extremely important when using the submerged arc welding process to weld nickel-based alloys. Contact Haynes International for welding parameter and wire/flux recommendations.

The plasma arc cutting process is commonly used to cut alloy plate into desired shapes and prepare weld angles.

The use of oxyacetylene welding and cutting is not recommended, because of carbon pick-up from the flame.

TABLE 1

Process	American Welding Society Designation	Common Designation
Gas Tungsten Arc Welding, Manual and Machine	GTAW	TIG
Gas Metal Arc Welding, Manual and Machine	GMAW	MIG
Shielded Metal Arc Welding	SMAW	Stick or Coated Electrode

SELECTION OF WELDING FILLER MATERIAL

Selection of welding filler materials is a critical element in the design of a corrosion-resistant welded structure. Often, several types of corrosion-resistant alloys are used at various locations in the same structure. The selection of welding filler materials for dissimilar metal joining applications is also critical.

Two methods of welding filler material selection are possible. They are (1) selection of matching filler materials and (2) selection of overalloyed filler materials. When the matching filler material technique is used, the filler material is of the same chemical composition as one or both of the base materials. In dissimilar welding applications, using the matching filler material technique, the filler material is chosen to match the base material which is generally more highly alloyed (more corrosion resistant).

With the overalloyed filler material selection technique, a highly alloyed, highly corrosion-resistant welding filler material is used. (Figures 1 and 2).

Overalloyed filler metal selection reduces the chance of preferential weld metal corrosion attack. In addition, the use of a single overalloyed filler material on a job site greatly reduces the chance of filler metal mix-up. HASTELLOY C-22 and C-2000 alloys are used extensively as such overalloyed welding filler materials.

Additional information concerning overalloyed welding filler metal selection is contained in Brochure H-2062, Universal Weld Filler Metal.

Table 2A contains a list of filler materials which are available from Haynes International, Inc. Table 2B offers suggestions for selection of filler materials, under both similar and dissimilar welding applications, using both matching and overalloyed selection techniques.

The base material combinations, which apply to a particular application, are selected along a horizontal row and a vertical column of Table 2B. The numbers listed at

that intersection represent possible welding filler materials as listed in Table 2A.

The information included here uses the same filler metal "alloy class" designation as is used in Brochure H-3167. It is possible, then, to cross-reference the information listed in Brochure H-3167 without confusion.

When joining the HASTELLOY alloy base materials to carbon steel or low-alloy steel, the arc may have a tendency to play onto the steel side of the weld joint. Proper grounding techniques, a short arc length and torch/electrode manipulation are necessary to compensate for this problem.

Additional information on applicable filler metal specifications and product forms are contained in the Appendix at the end of this brochure.

Figure 1

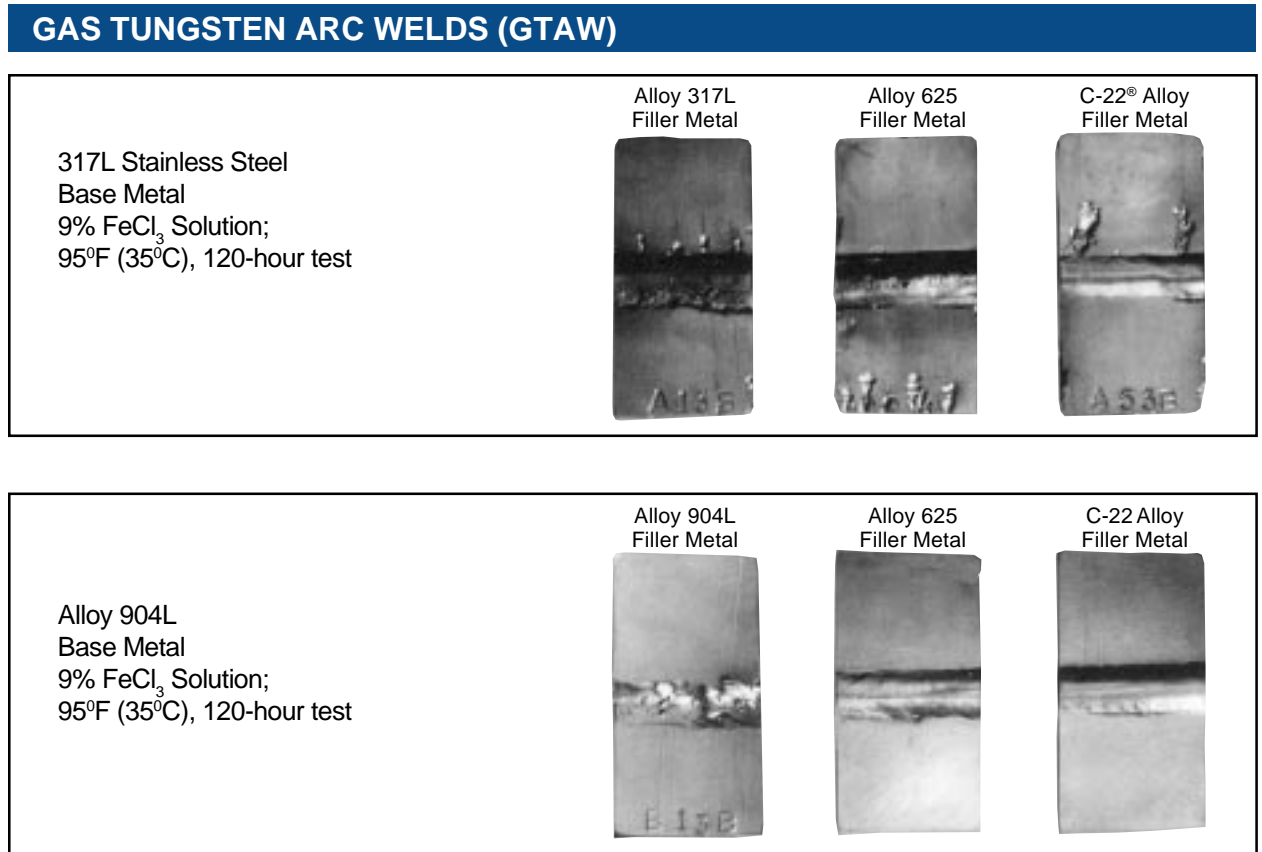


Figure 2

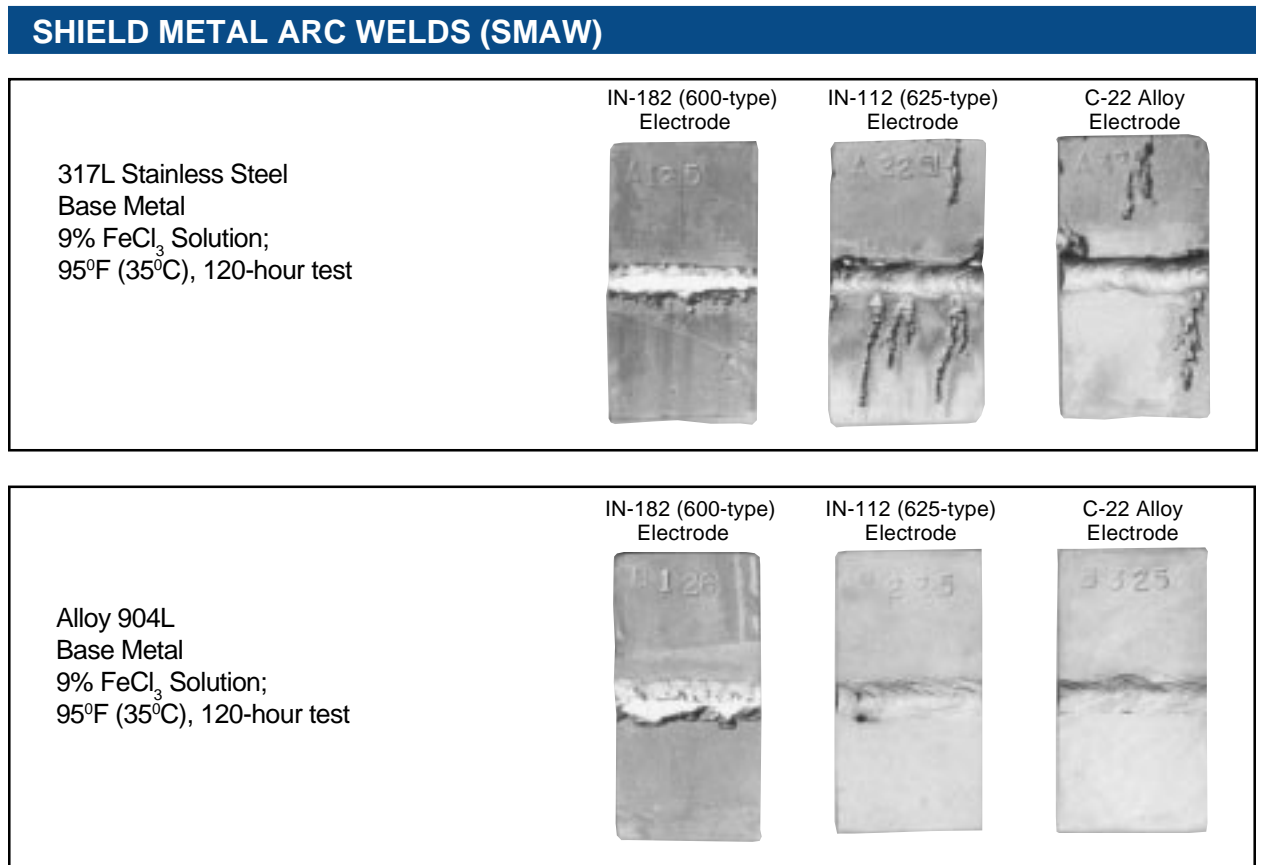


Table 2A

WELDING FILLER MATERIALS		
Filler Materials	AWS A5.11/A5.14	Alloy Class
HASTELLOY® B-2 alloy	E*/ER**NiMo-7	10
HASTELLOY B-3® alloy	E/ERNiMo-10	11
HASTELLOY C-276 alloy	E/ERNiCrMo-4	12
HASTELLOY C-22® alloy	E/ERNiCrMo-10	13
HASTELLOY C-4 alloy	E/ERNiCrMo-7	14
HASTELLOY C-2000® alloy	E/ERNiCrMo-17	15
HASTELLOY G-30® alloy	E/ERNiCrMo-11	17
HASTELLOY W alloy	E/ERNiMo-3	20
HAYNES® 242™ alloy	-	9
HAYNES 625 alloy	ERNiCrMo-3	8

*E - Coated Electrodes
**ER - Bare Wire

Table 2B

SUGGESTED FILLER METAL SELECTION GUIDE								
For both Matching and Overalloyed Filler Materials								
Alloys	B-2	B-3®	C-4	C-276	C-22®	C-2000®	G-30®	N
HASTELLOY® B-2 alloy	10 11							
HASTELLOY B-3 alloy	11 10	11 10						
HASTELLOY C-4 alloy	10 11 13 14	11 10 13 14	14 13					
HASTELLOY C-276 alloy	10 11 13 12	11 10 13 12	13 14 12	12 13				
HASTELLOY C-22 alloy	10 11 13	11 10 13	13 14	13 12	13			
HASTELLOY C-2000 alloy	10 11 13 15	11 10 13 15	13 14 15	13 15 12	13 15	15 13		
HASTELLOY G-30 alloy	10 11 13 17	11 10 13 17	13 14 17	13 12 17	13 17	13 15 17	17	
HASTELLOY N alloy	9 20 10 11	9 20 11 10	9 20 14	9 20 12	9 20 13	9 20 15	9 20 17	9 20
200/201	10 11	11 10	14 13	12 13	13	15 13	17 13	8 9
400	8	8	8	8	8	8	8	8
600	10 8	11 8	14 8	12 8	13 8	15 8	17 8	9 8
825	10 13	11 13	14 13	12 13	13	15 13	17 13	9 13
Stainless and Carbon Steel	10 13 8	11 13 8	14 13 8	12 13 8	13 8	15 13 8	17 13 8	9 13 8

WELDING JOINT DESIGN

Selection of a correct weld joint design is critical to the successful fabrication of HASTELLOY corrosion-resistant alloys. Poor joint design can negate even the most optimum selection of welding filler metal.

Various welding documents are available to assist in the design of welded joints. Two such documents that provide guidance are American Welding Society, *Welding Handbook*, Volume 1, Eighth Edition, Chapter 5 and ASM International, *Metals Handbook*, Volume 6, Welding, Brazing and Soldering, Joint Design and Preparation. In addition, fabrication codes such as the ASME Pressure Vessel and Piping Code may impose design requirements.

Typical butt joint designs that are used with the gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and

shielded metal arc welding (SMAW) processes are (I) Square-Groove, (II) Single-V-Groove, and (III) Double-V-Groove shown in Figure 3. Gas tungsten arc welding is often the preferred method for depositing the root pass associated with the square-groove (Joint I) or single-groove (Joint II) where access to only one side of the joint is possible. The remainder of the joint can then be filled using other welding processes as appropriate. For groove welds on heavy section plates greater than 3/4 inch (19 mm) thick, a J-groove is permissible. Such a joint reduces the amount of filler metal and time required to complete the weld. Other typical welding joint designs are shown in Figure 4. The actual number of passes required to fill the joint depends upon a number of factors that include the filler metal size (electrode or wire diameter), the amperage, and the travel speed.

It should be recognized that nickel-based alloy weld metal is sluggish (not as fluid as carbon steel) and does not flow out as readily and "wet" the sidewalls. Therefore, the welding arc and filler metal must be manipulated so as to place the molten metal where needed. In addition to the sluggishness, the joint penetration is also less than that of a typical carbon or stainless steel weld. With this low penetration pattern, the possibility of incomplete fusion increases. As a result of these factors, care must be taken to insure that the groove opening is wide enough to allow proper torch or electrode manipulation and placement of the weld bead.

A general estimate of filler metal requirements is about four to five percent (by weight) of the base plate requirement. Estimated weight of weld metal required per unit length of welding is given in Table 3.

Figure 3

TYPICAL BUTT JOINTS FOR MANUAL WELDING

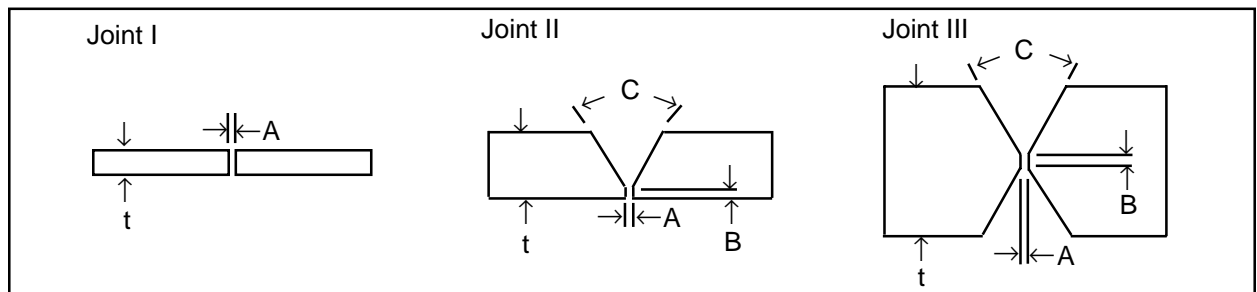
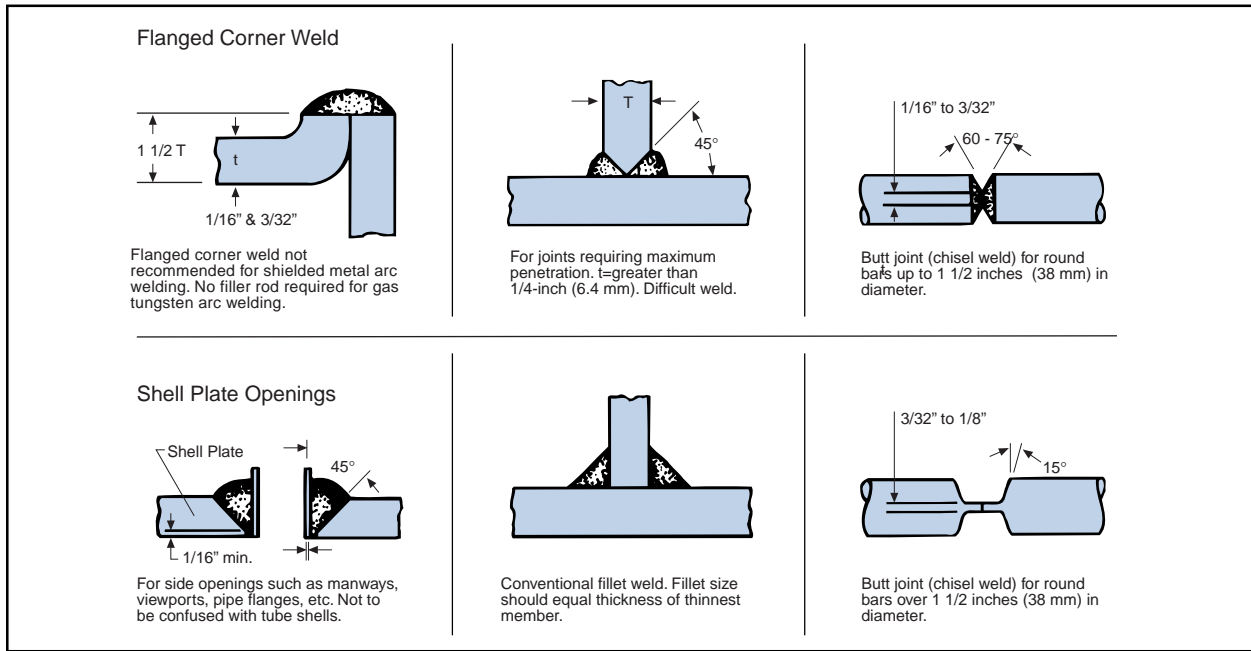


TABLE 3

Material Thickness (t), in. (mm)	Preferred Joint Design	Root Opening (A), in (mm)	Land Thickness (B) in (mm)	Included Weld Angle (C), degrees	Approx. Weight of Weld Metal Required, lbs/ft (kg/m)
1/16 (1.6)	I	0-1/16 (0-1.6)	N/A	None	0.02 (0.03)
3/32 (2.4)	I	0-3/32 (0-2.4)	N/A	None	0.04 (0.06)
1/8 (3.2)	I	0-1/8 (0-3.2)	N/A	None	0.06 (0.09)
1/4 (6.3)	II	1/16-1/8 (1.6-3.2)		60-75	0.30 (0.45)
3/8 (9.5)	II			60-75	0.60 (0.89)
1/2 (12.7)	II			60-75	0.95 (1.41)
1/2 (12.7)	III	1/32-5/32	1/32-3/32	60-75	0.60 (0.89)
5/8 (15.9)	II	(0.8-4.0)	(0.8-2.4)	60-75	1.40 (2.08)
5/8 (15.9)	III			60-75	0.82 (1.22)
3/4 (19.1)	II			60-75	1.90 (2.83)
3/4 (19.1)	III			60-75	1.20 (1.79)

Figure 4

OTHER JOINT DESIGNS FOR SPECIFIC SITUATIONS



Cleaning, Edge Preparation and Fit-Up

Proper preparation of the weld joint region is considered a very important part of welding the corrosion-resistant nickel-based alloys. A variety of mechanical and thermal cutting methods are available for the preparation of weld angles. Plasma cutting/gouging, machining, grinding, and air carbon arc gouging are all potential processes. It is necessary to condition all thermal cut edges to bright, shiny metal prior to welding. (This is particularly important if air arc gouging is being used due to the extreme possibility of carbon pick-up from the carbon electrode).

In addition to the weld angle, a one-inch (25 mm) wide band on the top and bottom (face and root) surface of the weld zone should be conditioned to bright metal with about an 80 grit flapper wheel or disk. This is essential when shielded metal arc welding HASTELLOY B-2/B-3 alloys. If the mill scale is not removed, the B-2/B-3 alloys welding flux can interact with the mill scale and cause cracking at the toe of the weld in the base material.

The welding surface and adjacent regions should be thoroughly cleaned with an appropriate solvent prior to any welding

operation. All greases, cutting oils, crayon marks, machining solutions, corrosion products, paints, scale, dye penetrant solutions, and other foreign matter should be completely removed.

Stainless steel wire brushing is normally sufficient for interpass cleaning of GTAW and GMAW weldments. The grinding of starts and stops is recommended for all fusion welding processes. If oxygen or carbon dioxide bearing shielding gases are used during gas metal arc welding, light grinding is necessary between passes prior to wire brushing. Slag removal during shielded metal arc welding will require chipping and grinding followed by wire brushing.

Surface iron contamination (rust staining) resulting from contact of carbon steel with the nickel-based alloys is not considered a serious problem and, therefore, it is generally not necessary to remove such rust stains prior to service. In addition, melting of small amounts of such surface iron contamination, into the weld puddle, is not expected to affect weld metal corrosion resistance.

While such contamination is not considered a serious problem, it is assumed that reasonable care is exercised to avoid the problem to begin with. If such care is

exercised, no particular corrective measures should be necessary prior to service.

Preheat, Interpass Temperature, and Cooling Techniques

Preheat of the HASTELLOY alloys is not required. Preheat is generally specified as room temperature (typical shop conditions). Interpass temperature should be maintained below 200°F (93°C).

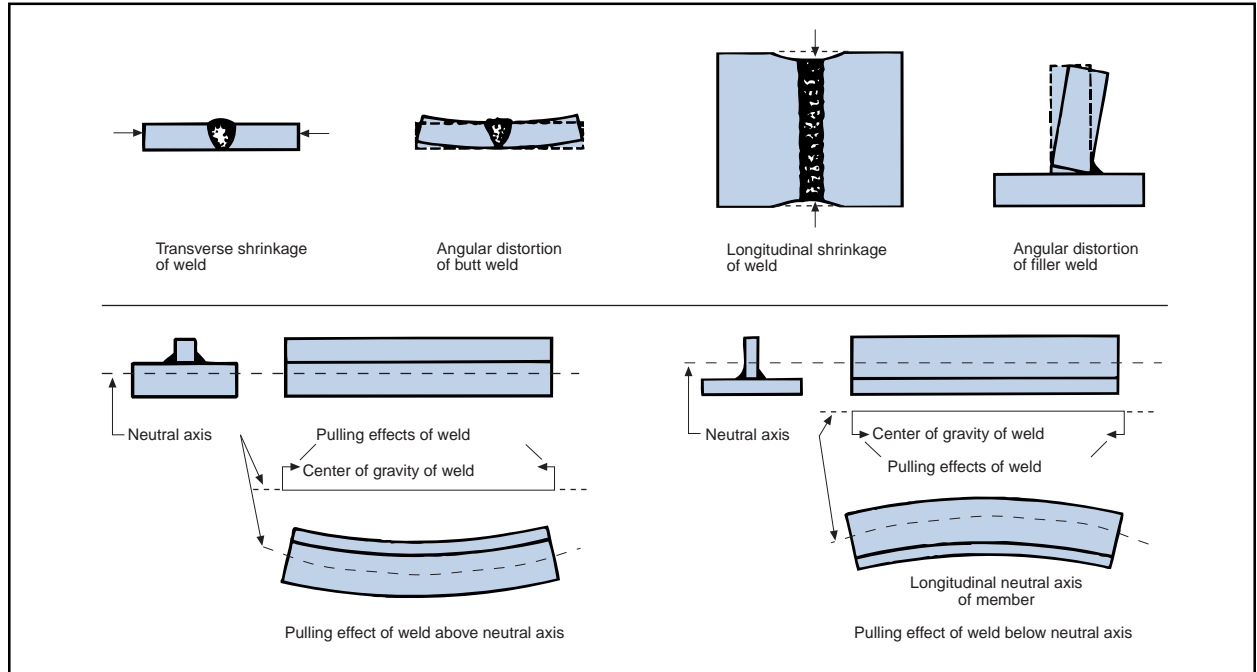
The base plate may require warming to raise the temperature of the alloy above freezing or to prevent condensation of moisture. Condensation may occur if the alloy is brought into a warm shop from cold outdoor storage. Warming should be accomplished by indirect heating if possible (infrared heaters or natural heating to room temperature).

If oxyacetylene warming is used, the heat should be applied evenly over the base metal rather than in the weld zone. The torch should be adjusted so that the flame is not carburizing. A "rosebud" tip, which distributes the flame evenly, is recommended. Care should be taken to avoid local or incipient melting as a result of the warming process.

Figure 5

CONTROL OF DISTORTION

Drawings are courtesy of WELDING ENCYCLOPEDIA, Monticello Books, Inc.



Auxiliary cooling methods may be used to control the interpass temperature. Water quenching is acceptable. Care must be taken to insure that the weld zone is not contaminated with traces of oil from shop air lines, grease or dirt from soiled water-soaked rags, or mineral deposits from hard water used to cool the weld joint. The safest way to maintain a low interpass temperature is to allow the assembly to cool naturally. When attaching hardware to the outside of a thin-walled vessel, it is good practice to provide auxiliary cooling to the inside (process side) to minimize the extent of the heat-affected zone.

Postweld Heat Treatment

HASTELLOY corrosion-resistant alloys, under the vast majority of corrosive environments, are used in the as-welded condition. Postweld heat treatments, either full solution anneal heat treatment, 1900 to 2150°F (1038 to 1177°C) depending on alloy, or stress relief heat treatment, typically 1100 to 1200°F (593 to 649°C), are normally not required.

Specific discussions concerning solution annealing requirements are presented in the Heat Treatment section of this brochure.

Stress relief heat treatments are normally considered to be ineffective with these alloys and can in some cases affect mechanical properties. HASTELLOY B-2 and B-3 alloys for example, should never be heat treated or postweld stress relieved in the 1000 to 1500°F (538 to 816°C) temperature range. If stress relief heat treatment of attendant carbon steel component sections is required to meet code requirement, contact Haynes International, Inc. for detailed information.

Inspection and Repair

Good manufacturing practice suggests that some degree of nondestructive testing (NDT) be conducted. For code fabrications, certain mandatory NDT inspections may be required. For non-code fabrication, NDT may be as simple as visual inspection or dye penetrant inspection. NDT should be considered for both intermediate quality control inspections during fabrication, as well as for final acceptance tests.

Welding defects that are believed to affect quality or mechanical integrity should be removed and weld repaired. Removal techniques include grinding,

plasma arc gouging, and air carbon arc gouging. Extreme care must be used during air carbon arc gouging to insure that carbon contamination of the weld zone does not occur.

Generally the prepared cavity is dye penetrant inspected to insure that all objectionable defects have been removed and then thoroughly cleaned prior to welding repair. Because these alloys have low penetration characteristics, the ground cavity must be broad enough and have sufficient sidewall clearance in the weld groove to allow for weld rod/weld bead manipulation. "Healing cracks" or "washing out" defects by autogeneously remelting weld beads or by depositing additional filler metal over the defect is not recommended.

Control of Distortion

Distortion characteristics of the nickel-based alloys are similar to those of the austenitic stainless steels. Figure 5 is included to show possible changes in weld joint shape.

Jigs, fixturing, cross supports, bracing, and bead placement/ weld sequence will help to hold distortion to a minimum. Where possible, balanced welding about the neutral axis will assist in keeping distortion to a minimum. Proper fixturing and clamping of the assembly makes the welding operation easier and minimizes buckling and warping of thin sections.

It is suggested that, where possible, extra stock be allowed to the overall width and length. Excess material can then be removed to hold final dimensions.

Cracking Considerations

During normal fabrication of the HASTELLOY alloys, cracking is rare and one should expect to fabricate large, complex components with few problems. Fabrication cracking, when noted, can include hot cracking, stress cracking, and cracking related to heat treatment.

Hot cracking is a condition generally confined to the fusion zone but occasionally can occur in the heat-affected zone. Two conditions are necessary to produce hot cracking: stress and a "strain intolerant microstructure".

The creation of stress is inevitable during welding because of the complex thermal stresses that are created when metal solidifies. "Strain intolerant microstructures" temporarily occur at elevated temperatures near the melting and solidification point of all alloys. Surface contaminants such as sulfur can contribute to hot cracking. Certain geometric features such as concave weld deposits and tear-drop shaped weld pools can also lead to hot cracking. For each alloy system, a critical combination of these conditions can produce hot cracking.

For the HASTELLOY corrosion-resistant alloys, the onset of hot cracking has been observed when welding current reaches about 350 amps in restrained, uncontaminated GMAW (spray transfer mode) welds. Hot cracking has also been found in C-276 alloy submerged arc welds when the amperage was above 400 amps.

Cold cracking will occur in solidified weld metal and in base material only when externally applied stresses exceed the tensile strength of the alloy. Classical hydrogen embrittlement is not a fabrication cracking problem in nickel-based alloys.

Bead shape can play a role in weld metal cracking. Root pass weld beads that have a concave shape can crack during root pass welding. This results from the applied stresses exceeding the strength limit of the very small weld bead cross-section. Convex weld beads and clamps/fixtures can control this cracking problem.

Weldments of HASTELLOY B-2 alloy can suffer cracking during heat treatment. Such cracking occurs in the temperature range 1000 to 1500°F (538 to 816°C) upon heat-up during solution heat treatment. In this temperature range the alloy becomes very strong, with an attendant decrease in ductility due to the metallurgical condition known as long range ordering. Residual tensile stresses in conjunction with the high strength causes the alloy to crack. This condition is controlled by rapid heating during annealing and shot peening high residual stress areas. More information concerning this problem is included in the Heat Treatment section of this brochure. B-3 alloy is a significant improvement; however, cracking will occur with longer exposure time in the deleterious temperature range.

SPECIFIC WELDING PROCESS CONSIDERATIONS



Gas Tungsten Arc Welding (GTAW)

The gas tungsten arc welding process is a very versatile, all-position welding process. It can be used in production as well as repair situations. It can be used manually or adapted to automatic equipment to weld thin sheet or plate material. It is a process that offers great control and is therefore routinely used during tack welding and root pass welding. The major drawback of the process is productivity. For manual welding situations, GTAW weld metal deposition rates are low.

Generally, power supplies equipped with high frequency start, pre-purge/post-purge and up-slope/down-slope (or foot pedal) controls are recommended. It is recommended that the GTAW welding torch be equipped with a gas diffuser screen ("gas lens") to provide optimum shielding gas coverage. Generally, the gas cup should be as large as practical.

Typical welding parameters, which are suggested for the HASTELLOY corrosion-resistant alloys, are presented in Table 4. Electrical polarity should be direct current electrode negative (DCEN).

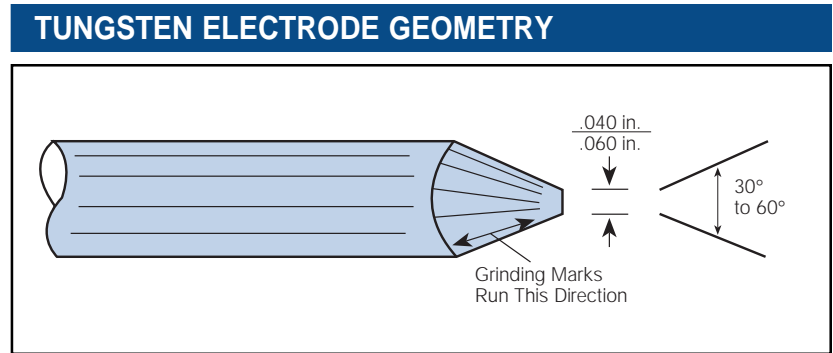
Two percent thoriated tungsten electrodes are recommended. The classification for these electrodes is EWTh-2 (American Welding Society Specification A5.12). The diameter of the tungsten electrode will vary with amperage. General recommendations for electrode diameter selection are given in Table 4. It is recommended that the electrode be ground to a cone shape (included angle of 30 to 60 degrees) with a small 1/16 inch (1.6 mm) flat ground at the point. See Figure 6 for details.

Welding grade argon (99.996 percent minimum purity) shielding gas is recommended for all normal fabrication situations. The flow rates are normally in the 25-30 cubic feet per hour range. When proper shielding is achieved, the as-deposited weld metal should have a bright-shiny appearance and require only minor wire brushing between passes. On special occasions, argon-helium or argon-hydrogen shielding gases are used in high travel speed, highly specialized mechanized welding systems.

In addition to welding torch shielding gas, a back-purge at the root side of the weld joint is recommended (welding grade argon). The flow rates are normally in the 5 to 10 cubic feet per hour range. Often backing bars (usually copper) are used to assist in bead shape on the root side of GTAW welds. Backing gas is often introduced through small holes along the length of the backing bar.

There are situations where backing bars cannot be used. Under these conditions, open-butt welding is often performed. Such welding conditions are often encountered during pipe or tube

Figure 6



circumferential butt welding. Under these conditions where access to the root side of the joint is not possible, special gas flow conditions have been established which differ from the industry recommendations published elsewhere. Under these open-butt pipe welding conditions, the torch flow rates are reduced to about 10 cubic feet per hour and the back purge flow rates are increased to about 40 cubic feet per hour. A detailed brochure is available concerning back-purging during pipe welding (ask for Brochure H-2065).

It is recommended that the torch be held essentially perpendicular to the work piece. Stringer bead techniques, using only enough

current to melt the base material and allow proper fusion of the filler, are recommended. During welding, the tip of the welding filler material should always be held under the shielding gas to prevent oxidation of the hot welding filler wire. Standing still or puddling the weld adds to the welding heat input is not recommended.

Since the welder controls filler metal additions to the weld puddle, care must be taken to ensure that the resultant weld bead dilution of the base materials is minimized.

Table 4

TYPICAL MANUAL GAS TUNGSTEN ARC PARAMETERS (FLAT POSITION)*

Joint Thickness in (mm)	Tungsten Electrode Diameter in (mm)	Filler Wire Diameter in (mm)	Welding Current	
			Amps	Volts
0.030-0.063 (0.8-1.6)	0.063 (1.6)	0.063 (1.6)	15-60	9-12
0.063-0.125 (1.6-3.2)	0.063/0.094 (1.6/2.4)	0.063/0.094 (1.6/2.4)	50-95	9-12
0.125-0.250 (3.2-6.3)	0.094/0.125 (2.4/3.2)	0.094/0.125 (2.4/3.2)	75-150	10-13
0.250 (6.3) and up	0.094/0.125 (2.4/3.2)	0.094/0.125 (2.4/3.2)	95-200	10-13

* DCEN



Gas Metal Arc Welding (GMAW)

The gas metal arc welding process provides a considerable increase in productivity when compared to the gas tungsten arc welding process. It is well suited for both manual and automatic welding situations. The weld metal deposition rate is considerably higher but to some extent, control and ease of operation are reduced with the GMAW process.

Three modes of weld metal transfer are possible with gas metal arc welding. They are short circuiting transfer, globular transfer, and spray transfer. The short arc

transfer mode is used in all welding positions, provides good weld puddle control, and is considered to be a low heat input welding process. However, because the process operates at low amperage, it is often regarded as a defect (cold lap) prone process. The globular mode of weld metal transfer is rarely recommended by Haynes International, except for weld overlay cladding applications. The spray transfer mode is useful only in the flat position and is characterized as a moderate to high heat input welding process with relatively high deposition rates. The pulse-spray mode (a modified spray transfer mode) is useful in all welding positions and

is less susceptible to cold lap defects when compared to short circuiting mode.

Constant current, fixed frequency pulse, variable slope/inductance and synergic welding power supplies can all be used with the GMAW welding process. The selection of weld metal transfer mode (spray, synergic, pulse-spray or short circuiting mode) must be decided upon first. Such a decision requires information on joint design/thickness, welding position to be used, required deposition rates, and welder skill levels. From that information, the welding power supply and welding parameter selections can be made.

Table 5

TYPICAL GAS METAL ARC WELDING PARAMETERS (FLAT POSITION)*					
Wire Diameter in. (mm)	Shielding Gas**	Welding Current, Amps	Welding Voltage, Volts	Wire Feed Speed, in./min. (m/min.)	Joint Thickness in. (mm)
Short Circuiting Mode					
0.035 (0.9)	Ar+He	70-90	18-20	150-200	0.050-3/16
	He+Ar+CO ₂	70-90	17-20	(3.8-5.1)	(1.3-4.8)
	Ar+He+CO ₂	70-90	17-20		
0.045 (1.1)	Ar+He	100-160	19-22	175-225	1/8-3/4
	He+Ar+CO ₂	100-160	19-22	(4.4-5.7)	(3.2-19.1)
	Ar+He+CO ₂	100-160	19-22		
Spray Transfer Mode					
0.045 (1.1)	Ar	190-250	30-32	300-350	3/8 (9.5) and up
	Ar+He+CO ₂	190-225	30-32	275-325 (7.0-8.3)	
Fixed Frequency Pulse Mode (60 & 120 CPS)					
0.045 (1.1)	Ar+He	120-150	18-20	175-225	1/8-3/4
		peak, 250-300		(4.4-5.7)	(3.2-19.1)
	Ar+He+CO ₂	120-150	18-20	175-225	1/8-3/4
		peak, 250-300		(4.4-5.7)	(3.2-19.1)
Synergic Mode***					
0.035 (0.9)	Ar+He	50-125	-	-	0.062 (1.6) and up
	Ar+He+CO ₂	50-125	-	-	0.062 (1.6) and up
0.045 (1.1)	Ar+He	100-175	-	-	3/16 (4.8) and up
	Ar+He+CO ₂	100-175	-	-	3/16 (4.8) and up

* DCEP

** Ar+He=75% argon+25% helium; He+Ar+Co₂=90% helium+7.5% argon+2.5% carbon dioxide; Ar+He+Co₂=69% argon+30% helium+1% carbon dioxide; Ar=100% argon.

*** Detailed welding parameters are difficult to report because each welding machine uses unique set-up parameters to achieve proper welding characteristics.

Typical welding parameters, for the various weld metal transfer modes, are documented in Table 5. Electrical polarity is direct current electrode positive (DCEP).

Shielding gas selection is critical during GMAW procedure development. Five welding grade shielding gases are suggested for the HASTELLOY alloys. Those gases are 75 percent argon +25 percent helium (Ar+He), 90 percent helium +7.5 percent argon +2.5 percent carbon dioxide (He+Ar+CO₂), 66.1 percent argon +33 percent helium +0.9 percent carbon dioxide (Ar+He+CO₂), a proprietary argon-helium-carbon dioxide mixture known as NiCoBRITE™ gas, and 100 percent argon (Ar).

Generally, shielding gas flow rates are in the 35 cubic feet per hour range. The welding torch gas cup size is suggested to be as large as possible. It is suggested that the welding torch be held nearly perpendicular to the work piece. If the torch angle is held too far from perpendicular, oxygen from the atmosphere may be drawn into the weld zone and contaminate the molten metal.

As noted in Table 5, either, Ar+He+CO₂, He+Ar+CO₂, or NiCoBRITE shielding gases produces a very stable arc, excellent out-of-position

characteristics, and excellent alloy-to-carbon steel welding characteristics. However, because carbon dioxide is present, the weld metal surface will be highly oxidized. This oxidized condition can increase the possibility of lack-of-fusion defects. It is therefore strongly recommended that multipass welds, made with CO₂ containing gases, be lightly ground between passes to remove the oxidized surface.

The use of Ar+He in the short circuit mode is characterized by some spatter and some degree of arc instability when compared to welds made with CO₂ bearing gases. Because this shielding gas is inert, the surface is expected to be bright and shiny with minimal oxidation. During multipass welding, it is not mandatory to grind between passes. This situation also applies to the other modes of weld metal transfer when using Ar+He shielding gas.

In spray transfer welding, even though 100 percent argon shielding gas is used, some oxidation and "soot" may be noted on the weld surface. Heavy wire brushing and/or light grinding/conditioning (80 grit) between passes is recommended.

During spray transfer welding, a water cooled welding torch is always recommended. During

synergic welding, a water cooled torch is recommended when amperages exceed approximately 120 amps.

As with gas tungsten arc welding, back-purging is required to ensure the root side of the weld joint is not heavily oxidized. As an alternative, many fabricators weld without back-purge shielding. They then grind the root side after welding to remove all oxidized weld metal and defects, dye penetrant check the weld zone, and then fill the weld joint from both sides as needed.

It should be recognized that the filler wire conduit liner assembly and contact tips (parts of the GMAW welding torch) are high wear items and should be expected to be replaced periodically. Wear of the liner occurs as a result of galling between the carbon steel liner and the alloy filler wire. A worn liner will cause erratic wire feed which will result in arc instability. Some welding torches can be fitted with a nylon conduit liner. Such a liner would be expected to reduce wear and thus increase conduit life.

It is recommended that sharp bends in the GMAW torch cable be minimized. If possible, move the wire feeder so that the torch cable is nearly straight during welding.



Shielded Metal Arc Welding (SMAW)

The shielded metal arc welding process is well known for its versatility because it can be used in all welding positions, and in both production and repair situations. It is generally not useful on thin-sheet material. It requires no special equipment and can be operated easily in remote locations. It is strictly a manual welding process.

Welding electrodes available from Haynes International use lime-titania based coating formulations and are generally classified as slightly basic to slightly acidic depending on the particular alloy. All electrodes are classified as AC-DC, but are recommended to be used with direct current electrode positive (DCEP) electrical characteristics.

All welding electrodes should be stored in a dry rod oven after the canister has been opened. It is recommended that the dry rod oven be maintained at about 250 to 400°F (121 to 204°C). The HASTELLOY B-2 and B-3 alloys

coating formulation are considered a low moisture formulation and therefore it is mandatory that those electrodes be carefully controlled. If electrodes are exposed to an uncontrolled atmosphere, they can be reconditioned by heating in a reconditioning oven at 600 to 700°F (316 to 371°C) for 2 to 3 hours.

Typical welding parameters are presented in Table 6 for flat position welding. For maximum arc stability and control of the molten puddle, it is important to maintain a short arc length. The electrode is generally directed back toward the molten puddle (backhand welding) with about a 20 to 40 degree drag angle. As a general statement, stringer bead welding techniques are recommended. Some electrode manipulation is required to place the molten weld metal where needed. The maximum manipulation width is about three times the electrode core wire diameter.

Out-of-position welding is recommended only with the 3/32 inch and 1/8 inch (2.4 mm and 3.2 mm) diameter electrodes. During out-of-position welding, the

amperage is reduced to the low end of the range. In order to keep the bead profile relatively flat during vertical welding, a weave bead technique is necessary. Using 3/32 inch (2.4 mm) electrodes will reduce the weave width and produce flatter beads. In vertical welding, a range of electrode positions is possible from forehand (up to 20 degree push angle) to backhand welding (up to 20 degree drag angle), depending on welder preference. In over head welding, backhand welding (drag angle 0 to 20 degrees) is required.

Starting porosity may occur because the electrode requires a short time to begin generating a protective atmosphere. This is a particular problem with HASTELLOY B-2 and B-3 alloys. The problem can be minimized by using a starting tab of the same alloy as the work piece or by grinding each start to sound weld metal. Small crater cracks may also occur at the stops. These can be minimized by using a slight back-stepping motion to fill the crater just prior to breaking the arc. It is recommended that all starts and stops be ground to sound weld metal.

Table 6

Electrode Diameter in. (mm)	Approximate Welding Voltage Volts	Welding Current	
		Aim Amps	Range Amps
3/32 (2.4)	22-24	65 - 70	55 - 75
1/8 (3.2)	22-24	90 - 100	80 - 100
5/32 (4.0)	22-25	130 - 140	125 - 150
3/16 (4.8)	24-26	160 - 170	150 - 180

SAFETY AND HEALTH CONSIDERATIONS

Those involved with the welding industry are obligated to provide safe working conditions and be aware of the potential hazards associated with welding fumes, gases, radiation, electrical shock, heat, eye injuries, burns, etc. Various local, municipal, state, and federal regulations (OSHA, for example) relative to the welding and cutting processes must be considered.

Nickel-, cobalt-, and iron-based alloy products may contain, in varying concentrations, the following elemental constituents: aluminum, cobalt, chromium, copper, iron, manganese, molybdenum, nickel, and tungsten. For specific concentrations of these and other elements present, refer to the Material Safety Data Sheets (MSDS) H2071 and H1072 for the product.

The operation and maintenance of welding and cutting equipment should conform to the provisions of American National Standard ANSI Z49.1, Safety in Welding and Cutting. Attention is especially called to Section 4 (Protection of Personnel), Section 5 (Ventilation), and Section 7 (Confined Spaces) of that document. Adequate ventilation is required during all welding and cutting operations. Specific requirements are included in Section 5 for natural ventilation versus mechanical ventilation methods. When welding in confined spaces, ventilation shall also be sufficient to assure adequate oxygen for life support.

The following precautionary warning, which is supplied with all welding products, should be provided to, and fully understood by, all employees involved with welding.

Caution

Welding may produce fumes and gases hazardous to health. Avoid breathing these fumes and gases.

Use adequate ventilation. See ANSI/AWS Z49.1, Safety in Welding and Cutting published by the American Welding Society.

EXPOSURES: *Maintain all exposures below the limits shown in the Material Safety Data Sheet, and the product label. Use industrial hygiene air monitoring to ensure compliance with the recommended exposure limits. ALWAYS USE EXHAUST VENTILATION .*

RESPIRATORY PROTECTION: *Be sure to use a fume respirator or air supplied respirator when welding in confined spaces or where local exhaust or ventilation does not keep exposure below the PEL and TLV limits.*

WARNING: *Protect yourself and others. Be sure the label is read and understood by the welder. FUMES and GASES can be dangerous to your health. Overexposure to fumes and gases can result in LUNG DAMAGE. ARC RAYS can injure eyes and burn skin. ELECTRIC SHOCK can kill.*

BRAZING

Brazing is defined as the joining of metals using a filler metal whose melting temperature is less than that of the base material but over 840°F (449°C). It is usually characterized by the distribution of filler metal between closely fitted surfaces. The filler metal then flows with the application of heat by capillary action.

Note: The HASTELLOY alloys are typically used in situations where their corrosion resistance is of prime consideration. Typical brazing alloys do not possess the same degree of corrosion resistance. Brazing should therefore only be used for joining when the braze joint will be isolated from the environment. Secondly, furnace brazing operations are typically performed in vacuum and involve a slow cooling step. Care should be taken to make sure that the respective brazing cycle does not produce precipitation in the HASTELLOY alloy part.

The keys to successful brazing of HASTELLOY alloys are:

- 1) Thorough cleaning of base-metal surfaces.
- 2) Proper filler metal selection for the intended application.
- 3) Proper fit-up and freedom of restraint during brazing.
- 4) Proper protective atmosphere during brazing.
- 5) Short heating and cooling cycles to minimize aging.

Preparation

All forms of surface contamination such as dirt, paint, ink, chemical residues, oxides, and scale must be removed from the mating parts prior to brazing. Otherwise, the molten brazing material will not "wet" and flow along the surface of the base material. Surfaces must be cleaned by solvent scrubbing or degreasing and then by mechanical cleaning or pickling. Once cleaned, the parts should be assembled as soon as possible with the assembler using clean gloves to prevent subsequent contamination.

Filler Metal Selection

Selection of filler metal depends upon the end use of the HASTELLOY alloy being joined. For low-temperature service applications, <700°F (371°C), silver-base brazing alloys have been used successfully. In high temperature service applications, nickel-based brazing alloys are generally employed. Table 7 shows a number of possible filler metals for use with the HASTELLOY alloys.

Brazing alloys containing large amounts of copper should be treated with caution, especially if used to braze cobalt- and iron-based alloys.

The best approach is to consult both the brazing filler-metal manufacturer and the base material manufacturer when selecting a brazing alloy system.

Table 7

SUITABLE FILLER METALS FOR USE WITH HASTELLOY® CORROSION-RESISTANT

Designation		Composition, %	Brazing Temperature	
AWS	AMS		°F	(°C)
BAG-1	4769	45 Ag, 24 Cd, 16 Zn, 15 Cu	1145-1400	(618-760)
BAG-2	4768	35 Ag, 26 Cu, 21 Zn, 18 Cd	1295-1550	(702-843)
BAG-3	4771	50 Ag, 16 Cd, 15.5 Cu, 15.5 Zn, 3 Ni	1270-1500	(688-816)
BAG-4	–	40 Ag, 30 Cu, 28 Zn	1435-1650	(779-899)
BAG-8	–	72 Ag, 28 Cu	1435-1650	(779-899)
BAU-4	–	82 Au, 18 Ni	1740-1840	(949-1004)
–	–	70 Au, 22 Ni, 8 Pd	1925	(1052)
–	–	54 Pd, 36 Ni, 10 Cu	2300	(1260)
–	–	36 Ni, 34 Pd, 30 Au	2175	(1191)

Proper Fit-Up

Proper fit-up of the parts, prior to brazing, is just as important as precleaning since most brazing alloys flow under the force of capillary action. Joint gap clearances on the order of 0.001 to 0.005 inches (0.02 to 0.13 mm) must be maintained at the brazing temperature. If possible, parts should be brazed in the solution annealed condition (i.e., not cold worked). Excessive external stresses or strains imposed on the part during brazing may cause cracking problems, especially when brazing fluxes are involved.

Protective Atmospheres

Manual torch brazing with silver-base brazing alloys invariably requires the application of a flux (available from the brazing alloy manufacturer). Flux protected brazing operations can also be carried out by using an induction coil heating source, or in a furnace with a reducing atmosphere.

Furnace brazing is the usual method of brazing HASTELLOY alloys, especially when high-temperature brazing filler metals are employed. Nickel-based brazing alloys, for instance, are commonly used in conjunction with vacuum furnaces, in high purity argon atmospheres or in hydrogen (reducing) atmospheres. The purity of the brazing atmosphere is very important to ensure successful brazing alloy flow characteristics. A high "leak rate" through a vacuum furnace, for instance, will easily cause a thin oxide film to form on the HASTELLOY base material thereby impeding the flow of filler metal.

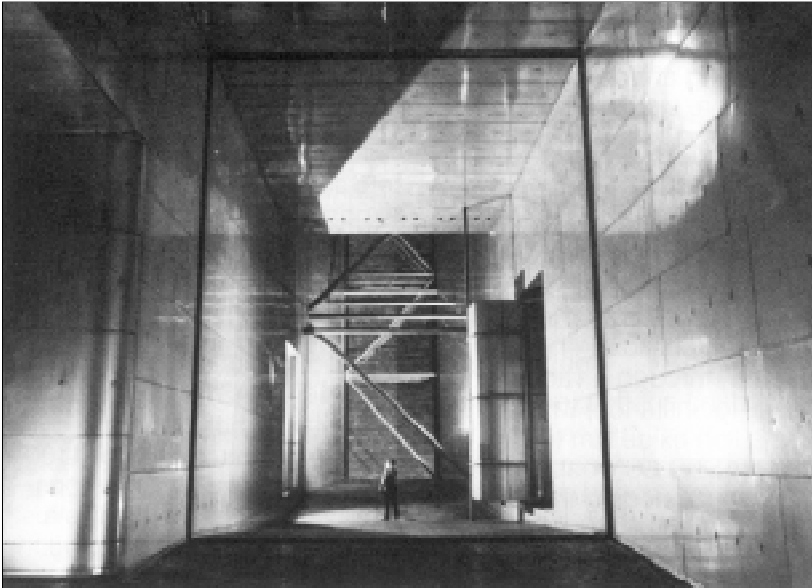
It should be recognized that most HASTELLOY alloys are designed to form tough oxide films which help them to resist harsh service environments. These same oxide films will cause problems during brazing if atmospheres are not rigorously controlled.

Heating and Cooling Cycles

The heating and cooling times associated with the brazing operation should be controlled to minimize exposure to intermediate temperatures. The HASTELLOY corrosion-resistant alloys tend to precipitate secondary phases when exposed in the temperature range of 1300 to 1850°F (704 to 1010°C). Such secondary precipitation will strongly influence corrosion resistance. In addition to the concern about secondary precipitation, HASTELLOY B-2 and B-3 alloys should not be exposed in the temperature range of 1000 to 1500°F (538 to 816°C) due to the possibility of loss of ductility as a result of long range ordering. Cooling rates, in vacuum from elevated temperatures, can be increased by backfilling the furnace with argon or helium.

CORROSION-RESISTANT LINING

Figure 7



Metallic Lining HASTELLOY C-22 alloy
Lower Colorado River Authority Power Project.

The use of solid HASTELLOY corrosion-resistant alloy is generally the preferred method of construction. For many applications, however, it may be more economical to use a steel (or lower alloy) substrate which is then

lined with a corrosion-resistant alloy. The point where lining a substrate material becomes economical, as compared to solid construction, depends on a number of factors which include: the corrosive environment

involved, the corrosion-resistant alloy to be used, design concerns, stresses, the complexity of the component, and the particular lining method to be used.

Four possible methods of construction are presented which provide alternatives to solid alloy construction. Those methods are:

- 1) Thin-sheet metallic lining.
- 2) Clad plate construction.
- 3) CORFACING™ weld overlay.
- 4) Thermal spray processes.



Thin-Sheet Metallic Lining

Thin-sheet metallic lining (often referred to as the "Wallpaper Concept") is a method of applying thin-gage, high-performance, corrosion-resistant alloy sheet to a variety of metal substrates. This process has found wide acceptance in the ducting of electric power flue gas desulfurization equipment. A typical installation is shown in Figure 7. Such a process is equally applicable to many other corrosive service applications. Figure 8 demonstrates the capability of this technique for protection of chemical processing industry equipment.

Figure 8



Heat exchanger inlet section thin-sheet lined with
HASTELLOY C-276 alloy.

GENERAL WELDING AND LAYOUT CONFIGURATION

The fabrication techniques are considered straight forward and require no special tools, equipment, or highly trained personnel. Figure 9A shows the general configuration of this fabrication technique for flue gas desulfurization construction. As an alternative (Figure 9B), batten strips can be applied to cover the joints. This method is generally used in the chemical process industry.

Key points to consider during fabrication include:

- Lay out the installation pattern in advance.
- Develop welding parameters and train welders in advance.
- Preform sheet in shop whenever possible.
- Prepare substrate surface as necessary.
- Structurally attach sheets to the substrate.
- Seal weld all-around.
- Inspect and test welds for leak tight condition.
- Repair questionable areas as necessary.

One of the important features of this fabrication technique is the lack of concern with substrate dilution of the weld metal during seal welding. As shown in Figure 9A, all seal welding is performed in an alloy to alloy configuration. Additionally, this technique reduces fabrication time due to the simplicity of overlapping one sheet onto another. Midsheet attachment can be used to insure the sheet is held flush with the substrate and to lessen concern about damage due to vibration.

There are several areas where shop formed parts can save time and effort. Edge and corner molding can be placed

Figure 9A

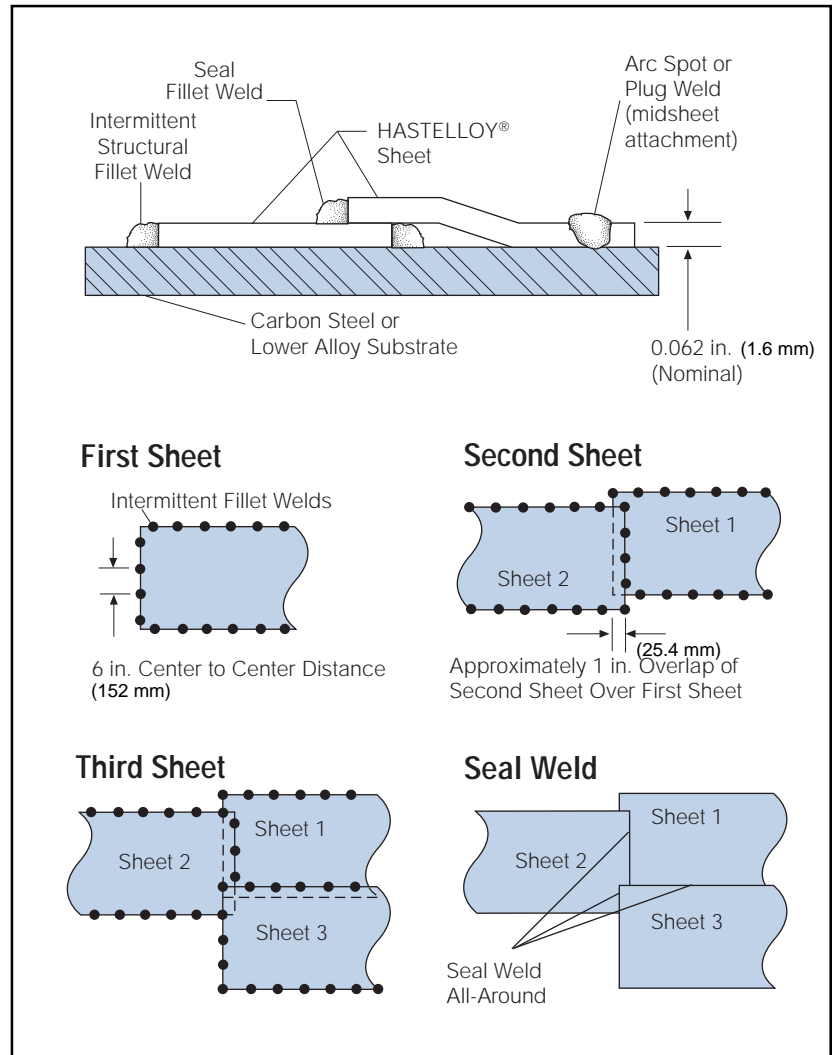


Figure 9B

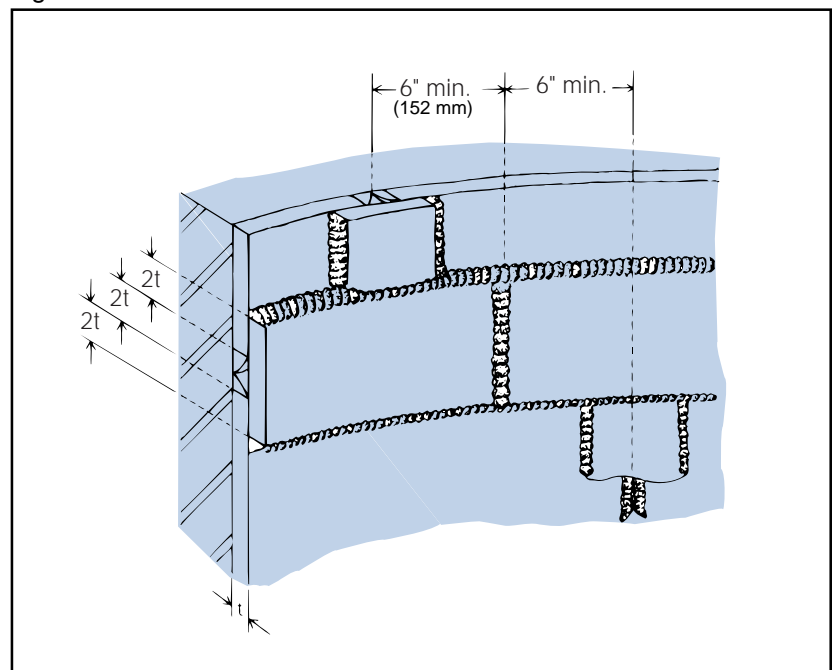


Figure 10A

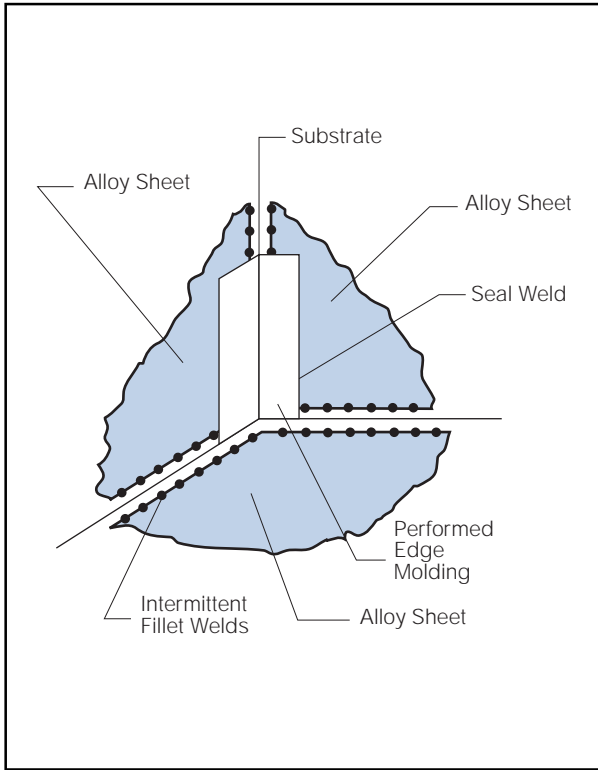


Figure 10B

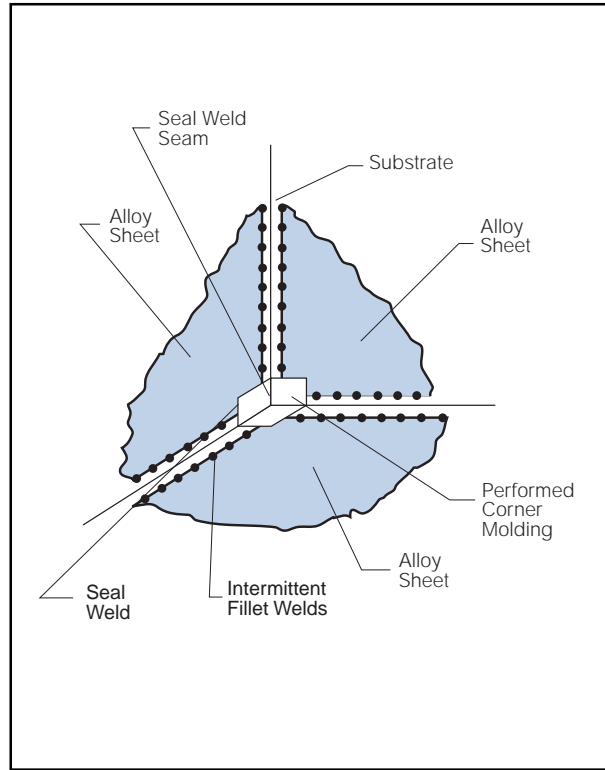


Figure 10C

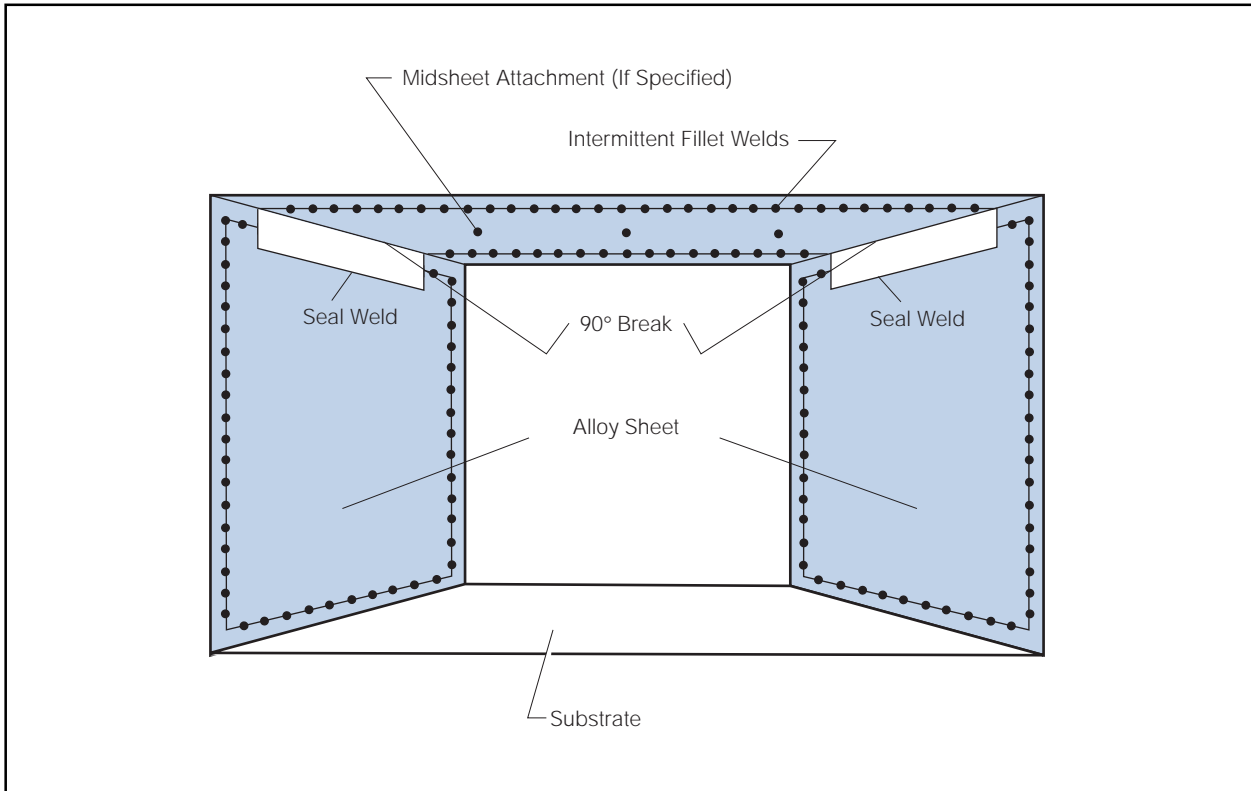
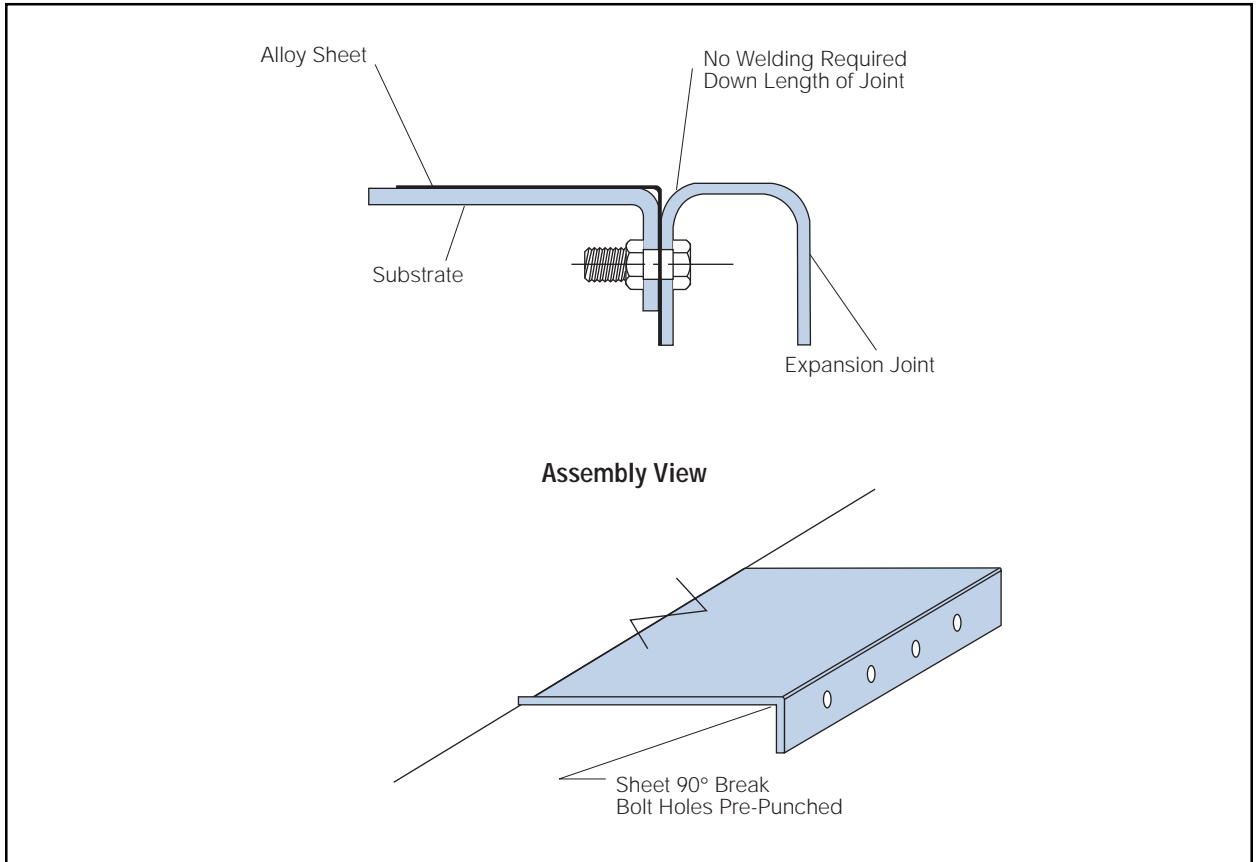


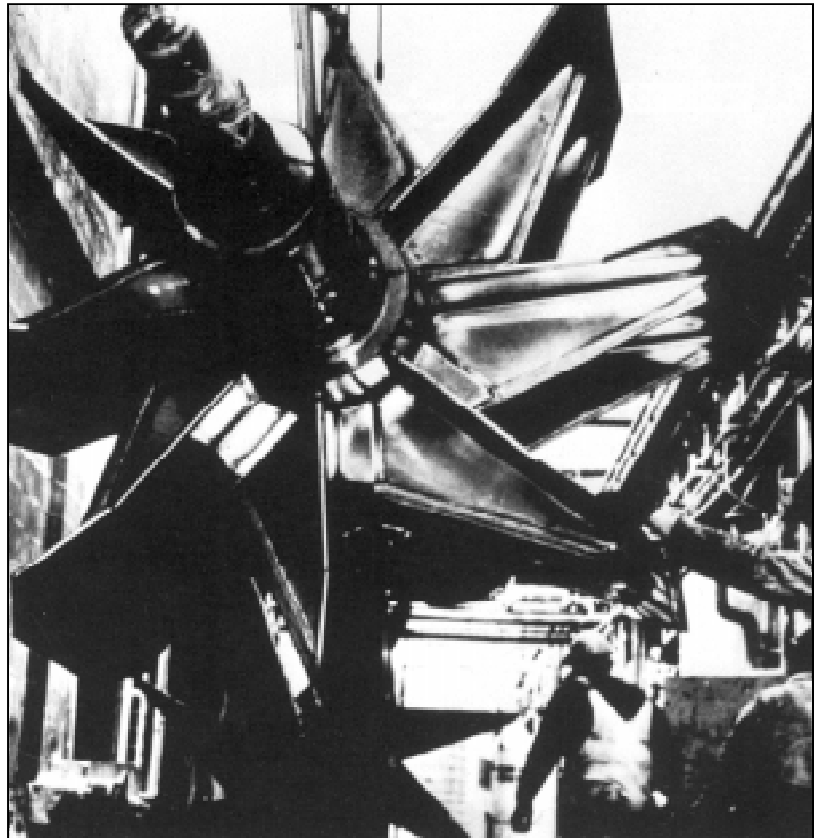
Figure 10D



over the intersection of wall sheets to form a sealed joint as shown in Figures 10A and 10B. Preformed sheets with one or two edges bent 90 degrees can be fitted onto the ceiling or floor as shown in Figure 10C. Finally, preformed sheets with prepunched holes (Figure 10D) can be used to form an expansion joint seal.

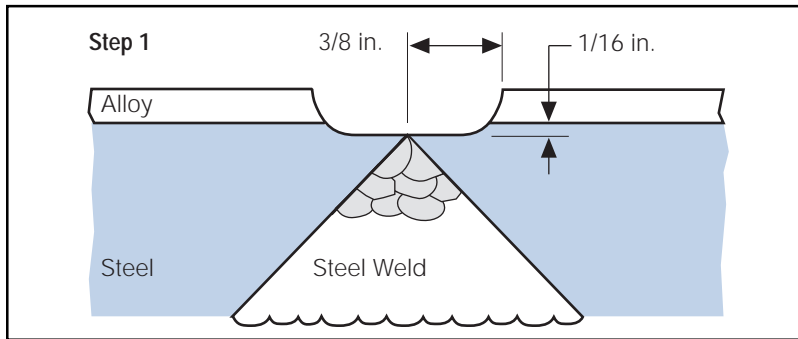
While this method of lining does not produce a metallurgical bond between the alloy lining and the substrate, the process does produce equipment with excellent mechanical properties. Figure 11 shows a large fan which was built from carbon steel and then lined with HASTELLOY C-276 alloy. This fan rotates at high speed and has not suffered any mechanical difficulties in service. Detailed information concerning thin-sheet metallic lining can be found in Haynes publication H-2037.

Figure 11



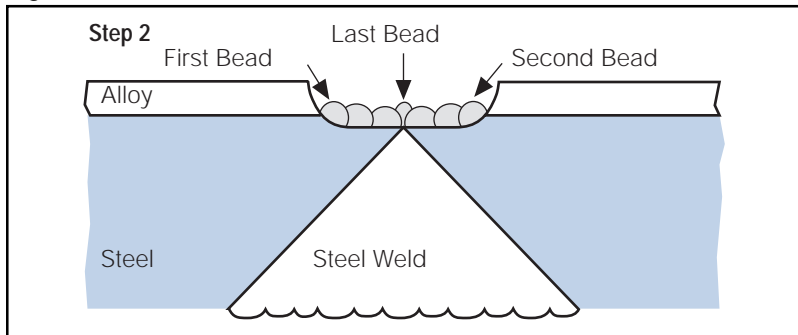
Induced draft fan thin-sheet lined with HASTELLOY C-276 alloy.

Figure 12A



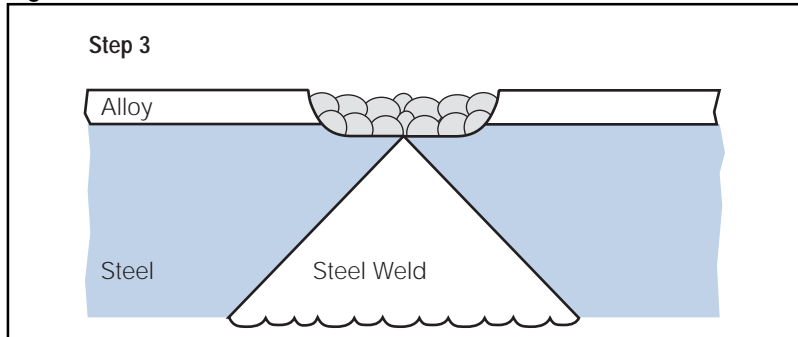
Grind back the HASTELLOY alloy adjacent to the weld to avoid melting the alloy while welding the steel. Prepare the joint as shown above and complete the steel weld.

Figure 12B



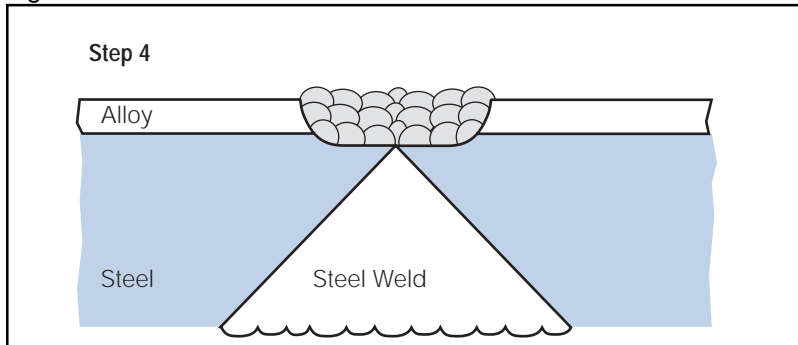
Complete the first layer of HASTELLOY alloy weld metal as shown above.

Figure 12C



Complete the second layer of HASTELLOY alloy weld metal as shown above.

Figure 12D



Complete the third layer of HASTELLOY alloy weld metal as shown above. Use a fourth layer of alloy weld metal if necessary.



Clad Plate Construction

Two types of clad plate are available for the HASTELLOY alloys. Hot-roll bonded plate and explosion bonded plate have both been used to fabricate corrosion-resistant components. The nature of the equipment to be fabricated will dictate the manufacturing route for the plate which would be acceptable.

Hot-Roll Bonded Plate

In projects, such as flue gas desulfurization ductwork, where large plates are required with a total thickness less than 0.375 inch (9.5 mm) and an alloy thickness of approximately 0.062 inch (1.6 mm), hot-roll bonded plate can offer an appropriate alternative to the thin-sheet metallic lining. Since annealing is required to obtain the best corrosion resistance in the alloy material, the backing steels are usually limited to very low carbon grade materials. This allows for annealing and water quenching of the hot-roll bonded plate without producing a brittle steel backer. Mechanical properties of this product will reflect the combined properties of the alloy and the low carbon steel.

Fabrication, of components from this product, is generally accomplished by welding with filler metal which matches the composition of the alloy sheet. Overalloyed filler metal may be used if localized attack is expected, such as in a flue gas desulfurization environment.

Explosive Bonded Plate

For the construction of chemical process equipment, explosive bonded plate is the predominant source of the material. This process allows the use of the traditional grades of high strength steels for vessel fabrication.

Conventional techniques can be used to fabricate equipment from the clad plate. The tube holes of tube-sheets usually have the grooves machined so that at least one is located in the cladding and the balance are in the base materials.

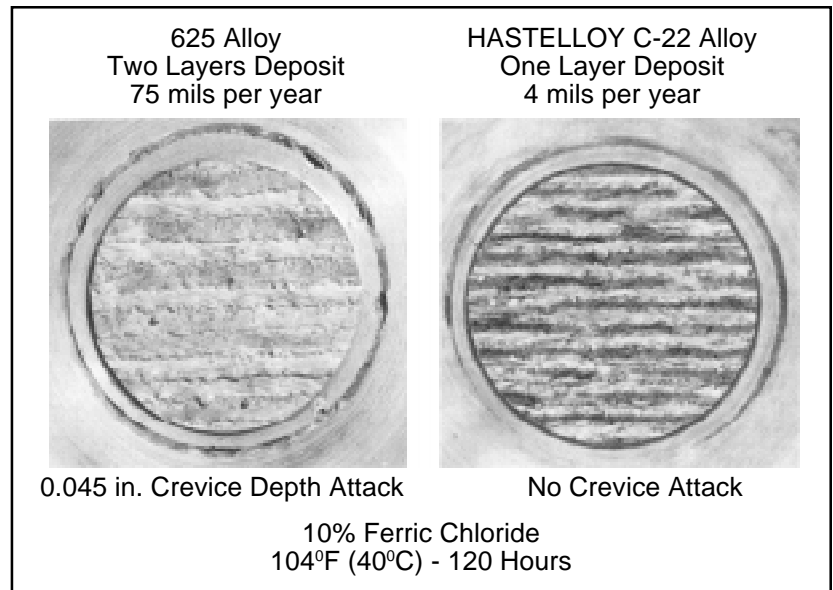
Care must be taken during weld fabrication to avoid dilution of the cladding alloy by the base material. Figures 12A thru 12D illustrate the suggested method for joining clad plates.

After preparation of the weld angles, the alloy is ground back slightly on either side of the joint and below the base metal surface (Figure 12A). The root weld is made and the base metal joint completed from the back side (Figure 12A). The first layer of alloy filler is deposited on the joint using a practice that will minimize dilution. This layer may be ground to a uniform thickness to help control dilution of the next layer (Figure 12B). Two additional layers of alloy are then deposited to complete the joint (Figures 12C & 12D). During all welding operations the interpass temperature should be maintained below 200°F (93°C).

During explosion-bonding, the explosive force produces a zone adjacent to the bond line that contains considerable cold deformation. Presence of this cold work can accelerate aging of some of the alloys during certain subsequent stress-relieving heat treatments for the carbon steel.

HASTELLOY B-2 and B-3 alloys should not be explosive bonded. Results have been inconsistent with a high risk of cracking during the bonding process.

Figure 13



CORFACING™ Weld Overlay
Weld overlay cladding, using high-performance, corrosion-resistant alloys is an accepted alternative to solid alloy construction for many applications. Weld overlay cladding of tube sheets and of large diameter shafts are common applications. In both cases, the heavy section carbon steel substrate components are surfaced with a relatively thin layer of corrosion-resistant alloy. A second area where weld overlay cladding is used is in the local repair and refurbishment of chemical process components. In this case, the substrate is probably not carbon steel.

It is important to recognize, however, that the corrosion resistance of a weld overlay deposit is not equivalent to the wrought base material, of similar composition. Several factors strongly influence the corrosion-resistance of a weld overlay deposit. By far the most important controllable factor is substrate (base metal) dilution. A second factor, which affects all weld metal deposits, is alloying element segregation.

Base metal dilution is the melting and mixing of the substrate with the corrosion-resistant weld overlay filler material. As substrate base material is mixed with the alloy filler metal, the iron content of weld overlay deposit increases. This increase in iron content of the critical elements (chromium, molybdenum, tungsten) of a high-performance alloy system. This increase in iron, coupled with the lowering of other alloying elements, leads to lower weld overlay corrosion resistance. Welding techniques must, therefore, be employed which minimize base metal dilution.

The most common method to overcome base metal dilution is to use multiple weld layers. As a general rule, a three layer deposit, even with relatively high base metal dilution, will approach the filler wire composition. With careful control of welding parameters, a two layer deposit may approach filler wire composition.

Dilution can be controlled by using welding processes that have low penetration patterns. For example, gas metal arc welding in the globular and short-arc transfer modes have lower penetration patterns when compared to the spray transfer mode. In addition, oscillation of the welding torch will lower penetration (dilution). Finally, bead placement affects total substrate dilution. In some cases, gas metal arc welding (short-arc mode) beads are overlapped in such a way that part of the weld penetration is in the previous alloy weld bead, rather than in the substrate base material.

Welding parameters which have been shown to give low base metal dilution are provided in Table 8. In this case, a low penetration

welding process is coupled with welding torch oscillation. Such a process would be expected to produce dilution under ten percent in a two layer deposit.

Figure 13 illustrates gas metal arc welding in the short-arc mode where bead overlap was used to control dilution. Because HASTELLOY C-22 alloy has inherently higher crevice corrosion resistance, when compared to 625 alloy, a one layer C-22 weld deposit has significantly lower corrosion attack when compared to a two layer 625 deposit.

Additional information concerning weld overlaying with HASTELLOY C-22 filler material can be found in Technical Brochure H-2054, CORFACING Weld Overlays with HASTELLOY C-22 alloy.



Thermal Spray Processes

Corrosion protection by nonfusion welding processes (i.e., thermal spray techniques) has been done successfully. Use of these processes has received increased attention by the pulp and paper and power utility industries as a method of refurbishing digester interiors and boiler tubes. However, it should be recognized that most thermal spray methods do not achieve a 100 percent dense deposit and are usually only mechanically bonded to the substrate.

Thin coatings, offering some protection, can be made by plasma spray (powders), wire flame spray and by electric-arc spraying (wire), however it is not a recommended practice for long term aqueous corrosion service.

Table 8

GAS METAL ARC WELD OVERLAY PROCESS (FLAT POSITION)*					
Wire Diameter in. (mm)	Shielding Gas	Flow Rate ft. ³ /hr.	Approx. Welding Current Amps	Approx. Volts	Approx. Travel Speed in./min.
Globular Transfer					
0.045 (1.1)	100% Argon	50	170-180	26-28	6.8

*Technique: Mechanical weave 5/8 in. wide, minimum dwell, 100 cycles/minutes, 200°F (max.) interpass temperature.

HOT WORKING

HASTELLOY corrosion-resistant alloys are readily hot worked into a variety of shapes and product forms. However, these alloys are somewhat more sensitive to strain and strain rates than are typical austenitic stainless steels. The hot working temperature ranges for these alloys tend to be narrow. Care must be exercised during hot working to achieve satisfactory results.

The characteristics of HASTELLOY alloys that must be considered during hot working include relatively low melting temperatures, high hot strength, high strain rate sensitivity, low thermal conductivity, and relatively high strain hardening coefficients. Furthermore, the strength of these alloys increases rapidly as the temperature decreases in the hot working range.

Because of these factors, relatively moderate reductions per pass and frequent reheating operations give the best results. Also, relatively slow hot deformation processing

tends to achieve better results, because lower forces are required and the heat buildup due to working is kept within reasonable limits.

Forging

The following are general guidelines to follow in forging HASTELLOY corrosion-resistant alloys:

- Soak billets or ingots at least 1/2 hour at forging temperature for each inch of thickness. The use of a calibrated optical pyrometer is essential.
- The stock should be turned frequently to present the cooler side to the furnace atmosphere. Direct flame impingement on the alloy must be avoided.
- Forging should begin immediately after withdrawal from the furnace. A short time lapse may allow surface temperature to drop as much as 100 to 200°F (38 to 93°C). Do not raise the forging temperature

to compensate for heat loss, as this may cause incipient melting.

- Moderately heavy reductions (25 to 40 percent) are beneficial to maintain as much internal heat as possible, thus minimizing grain coarsening and the number of reheatings. Reductions greater than 40 percent per pass should be avoided.
- Do not make radical changes in the cross sectional shape, such as going from a square directly to a round, during initial forming stages. Instead go from square to round cornered square to octagon to round.
- Condition (remove) any cracks or tears developed during forging. Very often this can be done at intermediate stages between forging sessions.
- The temperature ranges recommended for forging HASTELLOY alloys are shown in Table 9.

Table 9

FORGING TEMPERATURES

Alloy	Forging Temperature			
	Start*		Finish**	
	°F	(°C)	°F	(°C)
HASTELLOY® B-2 alloy	2250	(1232)	1800	(982)
HASTELLOY B-3 alloy	2250	(1232)	1800	(982)
HASTELLOY C-4 alloy	2150	(1177)	1750	(954)
HASTELLOY C-22 alloy	2250	(1232)	1750	(954)
HASTELLOY C-276 alloy	2250	(1232)	1750	(954)
HASTELLOY C-2000 alloy	2250	(1232)	1750	(954)
HASTELLOY G-30 alloy	2100	(1149)	1700	(927)
HASTELLOY N alloy	2200	(1204)	1600	(871)

*Maximum

**Depends on nature and degree of working.

Hot Rolling

Hot rolling of HASTELLOY alloys can be performed to produce any conventional rolled forms. The considerations listed above for forging generally apply to hot rolling also. Moderate reductions per pass (15 to 20 percent reduction in area) and rolling speeds of 200 to 300 surface feet per minute tend to give good results without overloading the mill.

Frequent reheatings are usually required to keep the temperature of the work piece in the hot working range. Because of the low thermal conductivity and the somewhat sluggish minor phase dissolution kinetics associated with these alloys, it is good practice to soak the work piece thoroughly at the hot working temperature before rolling.

Hot Upsetting

HASTELLOY alloys can be hot upset when the length of the part to be upset is no greater than about three times the diameter. Care should be taken to ensure that the temperature of the piece to be upset is in the upper end of the forging temperature range.

Impact Extrusion

Parts such as engine valves, pump rotors, jet engine bolting, and gears can be produced from HASTELLOY alloys by impact extrusion. Impact extrusion is carried out at the solution heat-treating temperature so that the alloy is forged in its most plastic state. Accurate temperature control and maintenance of a uniform temperature throughout the work piece are essential. Restrikes should be avoided.

Hot Forming

The forming of plate into components such as dished heads

is normally done by cold pressing or spinning with intermediate anneals. However sometimes the size and thickness of material requires that hot forming be utilized. When this is required, the furnace temperature is usually set at an intermediate temperature between that suggested for annealing (Heat Treatment section, Table 10) and lower forging temperature (Table 9). Temperature during hot work should not be less than the finish forging temperature. Reheat as necessary to maintain the proper temperature. Dies should be warmed so that excessive chilling of the surface does not occur.

Annealing

Following any hot working operations, HASTELLOY alloys should be reannealed for optimum corrosion resistance. Annealing techniques are detailed in the Heat Treatment section (Table 10) of this brochure.

COLD WORKING

Cold working is the preferable method of forming the HASTELLOY corrosion-resistant alloys. Since they are generally stiffer than the austenitic stainless steels, more energy is required during cold forming. In addition, these alloys tend to work harden more readily than do the austenitic stainless steels. Depending on the severity of deformation, they may require a number of intermediate forming stages to produce the final part. Figure 14 shows the effect of cold work on the hardness of the HASTELLOY alloys. A curve for type 304 stainless steel has been included for comparison.

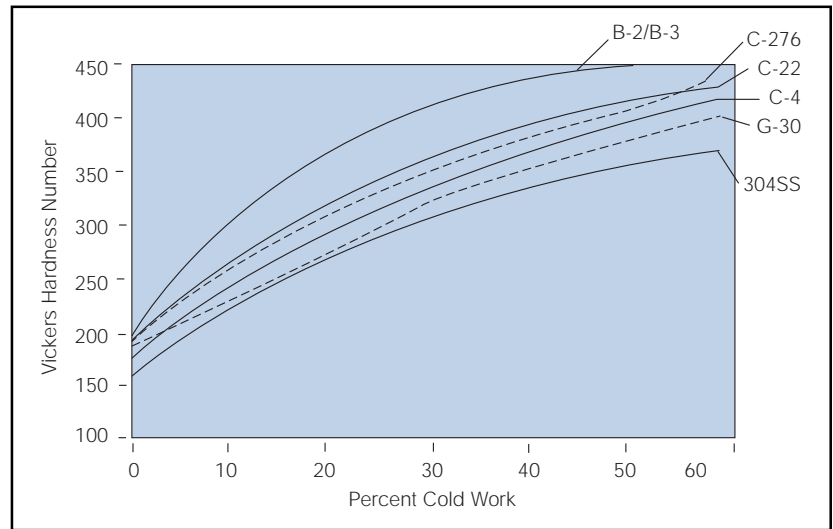
Generally, mill annealed sheet has sufficient ductility for mild forming without the need for subsequent heat treatment. Generally, the presence of cold work does not effect either the uniform or pitting corrosion resistance of the HASTELLOY corrosion-resistant alloys. The presence of heavy cold deformation can increase the stress corrosion cracking susceptibility in certain environments. Annealing components with deformation greater than about 7 to 10 percent outer fiber elongation will reduce that susceptibility.

For more severe cold deformation, where cracking is possible due to reduction in ductility, a series of successive forming operations are recommended, each followed by an intermediate anneal. Under most conditions, intermediate annealing should be performed at the recommended solution annealing temperature. It is highly desirable to remove scale from the part prior to the next forming operation either by pickling or mechanical means. A final solution anneal is recommended after such successive intermediate cold work/annealing operations.

Care should be taken to avoid a "critical cold reduction" of about 2 to 10 percent, if solution annealing is specified. Under these conditions, abnormal grain growth is possible which can lead to a

Figure 14

EFFECT OF COLD WORK ON HARDNESS



surface condition often referred to as "orange peel" or "alligator hide surface."

Cold formed components with residual tensile stresses, in conjunction with the possibility of intermediate temperature embrittlement, caused by exposure at intermediate temperatures for critical periods of time, have been observed to produce intergranular cracking during the heat treatment of HASTELLOY B-2 alloy. It has been observed that shot peening the knuckle radius and straight flange regions of a cold-formed head, prior to heat treatment, can help reduce intermediate temperature intergranular cracking of B-2 alloy by lowering the tensile residual stress patterns at the surface of the cold formed component.

In the case of cold formed heads of HASTELLOY B-2 or B-3 alloys, a solution anneal should be done when deformation is greater than 7% outer fiber elongation of cold work. Without the anneal these alloys are very susceptible to cracking at welds and heat affected zones during subsequent fabrication. The cracking may not become obvious until the unit has been

put into service. HASTELLOY B-3 alloy is more resistant to heat treat cracking than B-2 alloy. In any event, annealing of cold formed components (>7% outer fiber elongation) is required and care should be taken to use well controlled furnaces (fast heat-up rate, good temperature control, and rapid cool down rate).

Lubrication is a significant consideration for successfully cold working these alloys. Although lubrication is seldom required for a simple "U" bend on a brake press, heavy duty lubricants are required for cold drawing. Mild forming operations can be successfully completed by using a lard oil or castor oil, which are easily removed. More severe forming operations require metallic soaps, or chlorinated or sulfochlorinated oils. NOTE: When the sulfochlorinated oils are used, the work piece must be carefully cleaned in a degreaser or alkaline cleaner.

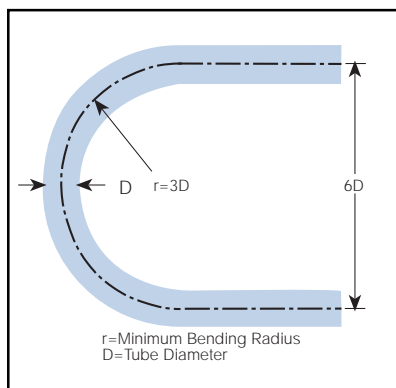
Lubricants that contain white lead, zinc compounds, or molybdenum disulfide are not recommended because they are difficult to remove prior to the final anneal. Also, lead, zinc, and sulfur tend to embrittle these alloys. Care should be taken to remove die material, lubricants, or other foreign

materials from the part before annealing as many of these products can affect the mechanical and corrosion properties of the alloys.

Tube Forming

HASTELLOY corrosion-resistant alloys can readily be formed cold in standard pipe and tube bending equipment. The minimum recommended bending radius from the radius point to the centerline of the tube is three times the tube diameter for most bending operations. When measured from centerline to centerline of the "hairpin" straight legs, it is six times the tube diameter (see Figure 15). Under special circumstances (tube diameter and wall thickness), the minimum bending radius can be reduced to twice the tube diameter.

Figure 15
Minimum Bending Radius



As the ratio of tube diameter to wall thickness increases, the need for internal and external support becomes increasingly important in order to prevent distortion. If too small a bending radius is used, wrinkles, poor ovality, and buckling can occur in addition to thinning. When forming tubing for heat exchangers, a minimum of three inches should be added to the total developed length of each tube

before bending. This additional length is necessary to allow for mismatch of the ends after forming and for trimming the ends of the tubes for stuffing the tube bundle. Heating during forming is not recommended, nor is stress relieving of the tubes after cold forming because of the possible formation of precipitates that decrease the corrosion resistance. If the corrosion application is severe or if stress relieving is required, annealing the entire tube should be done as described in the Heat Treatment section of this brochure.

Spinning

Spinning is a deformation process of forming sheet metal or tubing into seamless hollow cylinders, cone hemispheres, or other symmetrical circular shapes by a combination of rotation and force. There are two basic forms known as manual spinning and power or shear spinning. In the former method no appreciable thinning of metal occurs, whereas in the latter, metal is thinned as a result of shear forces.

Nearly all HASTELLOY corrosion-resistant alloys can be spin formed, generally at room temperature. The control of quality including freedom from wrinkles and scratches as well as dimensional accuracy is largely dependent on operator skill. The primary parameters that should be considered when spinning these alloys are:

- Speed
- Feed Rate
- Lubrication
- Material
- Strain Hardening Characteristics
- Tool Material, Design and Surface Finish
- Power of the Machine

The minimum speeds normally employed are about 200 surface feet per minute but generally low speeds are seldom used except for spinning small diameter work pieces. Speeds of 400 to 1500 surface feet per minute are most widely used. The feed rates normally used are 0.010 to 0.080 inches per revolution. Feed rate is important since it controls the work piece finish. To find the optimum combination of speed, feed, and pressure, a few pieces should be spun experimentally when a "new job" is set up. During continuous operation, the temperature of the mandrel and spinning tool changes may necessitate the adjustment of pressure, speed, and feed to obtain uniform results.

Lubrication should be used in all spinning operations. The usual practice is to apply lubricant to the blank prior to loading in the machine. It may be necessary to add lubricants during operation. During spinning, the work piece and tools should be flooded with a coolant such as an emulsion of soluble oil in water. Sulfurized or chlorinated lubricants should not be used since the operation of spinning may burnish the lubricant into the surface.

In cone spinning, metal deformation is such that forming is in accordance with the sine law. This law states that the wall thickness of the starting blank and that of the finished work piece are related as:

$$t_2 = t_1 \sin \alpha$$

where t_1 = thickness of starting blank

where t_2 = thickness of spun piece

where α = one half the apex angle of cone

When spinning cones with small angles (less than 35 degrees including angle), the best practice is to use more than one spinning pass with a different cone angle for each pass. HASTELLOY alloys can be reduced 30 to 50 percent between process anneals depending on the material and its strain hardening characteristics.

The tool material and work piece design and surface finish are very important in achieving a trouble-free operation. Mandrels used in spinning must be hard, wear resistant, and resistant to fatigue resulting from normal eccentric loading. Finish of mandrels should be no rougher than 50 microinches, preferably 15 to 32 microinches. The various diameters should be true concentric with each other.

Power spinning is a severe, cold working operation which markedly increases the ultimate and yield strengths of the alloy. In many applications, this increase is highly desirable, but for some applications the spun piece should subsequently be annealed depending on the alloy and the service environment.

Drop Hammering

HASTELLOY corrosion-resistant alloys can be formed by using the same techniques that are used in stainless steel drop-hammer operations. Annealing is essential if the depth of the draw is severe. Particular care should be taken to remove all foreign material from the part before annealing.

Punching

Punching is usually performed cold. Perforation should be limited to a minimum diameter of twice the gage thickness. The center-to-center dimension should be approximately three to four times the hole diameters. The punch to die clearances per side are:

Cold rolled and annealed sheet Up to 1/8 in. (3.2 mm) incl.	3-5% of sheet thickness
Hot rolled and annealed sheet Over 1/8 in. (3.2 mm)	5-10% of sheet thickness

Shearing

Because of the toughness of these alloys, compared to carbon steels and austenitic stainless steels, shearing equipment with greater power is required. For example, a scissor type shear capable of shearing 3/8 inch (9.5 mm) thick mild carbon steel could be used to shear HASTELLOY alloys up to 1/4 (6.4 mm) inch thick. Generally, HASTELLOY alloys 3/8 inch (9.5 mm) or less in thickness are sheared and thicknesses above 3/8 inch (6.4 mm) are abrasive saw cut or plasma arc cut.

HEAT TREATMENT

Wrought products of HASTELLOY alloys are supplied in the mill-annealed condition unless otherwise specified. This annealing procedure has been designed to place the material in the optimum condition with respect to mechanical properties and corrosion resistance. Following all hot-forming operations, a reanneal of the material should always be done to restore those properties.

Annealing is often performed after cold working operations to restore ductility and lower the yield and ultimate tensile properties. Generally, annealing is not required if the cold work is below seven percent outer fiber elongation.

In general, the only heat treatment that is acceptable for these alloys is a full solution anneal. Stress relief temperatures commonly used for steels, stainless steels, and some other nickel-based alloys are not effective for these alloys. If the heat treatment is done at an intermediate temperature, high enough to actually relieve the stresses, it may also promote some precipitation that could be detrimental to corrosion resistance.

Annealing may be performed to reduce residual stresses which can play a role in stress corrosion cracking resistance. It is generally held that stresses above 7 to 10 percent outer fiber elongation can cause increased stress corrosion cracking in some environments.

Because of the very low carbon contents or stabilizing elements, welded wrought HASTELLOY corrosion-resistant alloys do not require heat treatment after welding. Annealing can be used to increase the corrosion resistance of the weld fusion zone.

Before heat treatment, make absolutely sure that grease, graphite, and other foreign materials are removed from all surfaces. Carburization of these materials at the heat-treating temperatures can reduce corrosion resistance. Proper control of temperature and time cycle are also important. Table 10 lists the proper heat-treating temperatures and type of quench.

Table 10

HEAT-TREATING TEMPERATURES

Alloy	Temperature*		Type of Quench
	°F	(°C)	
HASTELLOY® B-2 alloy	1950	(1066)	WQ or RAC
HASTELLOY B-3 alloy	1950	(1066)	WQ or RAC
HASTELLOY C-4 alloy	1950	(1066)	WQ or RAC
HASTELLOY C-22 alloy	2050	(1121)	WQ or RAC
HASTELLOY C-2000 alloy	2075	(1135)	WQ or RAC
HASTELLOY C-276 alloy	2050	(1121)	WQ or RAC
HASTELLOY G-30 alloy	2150	(1177)	WQ or RAC
HASTELLOY N alloy	2150	(1177)	WQ or RAC

WQ=water quench.

RAC=rapid air cool.

*± 25 deg. F.

Holding Time

An inflexible set of rules governing soaking-annealing time is not feasible because of the many variations in types of furnaces, furnace operation, facilities for loading and unloading the furnace, etc. Temperature should be measured with a thermocouple attached to the piece being annealed. The actual holding time should be measured starting when the "entire section" is at the specified annealing temperature. It is important to remember that the center of a section does not reach the solutioning temperature as soon as the surface.

Normally, hold time is specified in the range of 10 to 30 minutes depending on section thickness. Thin-sheet components are held at the shorter time, while heavier sections are held at the longer times. The effect of cold working that result from stamping, deep drawing, bending, etc. can be eliminated by holding a minimum of 5 to 10 minutes, depending on gage size, at the solution annealing temperature.

Quenching

Rapid cooling is essential after solution heat treatment to prevent the precipitation of secondary phases and the resultant lowering of the corrosion resistance of these alloys. Water quenching is recommended on material thicker than 3/8 inch (9.5 mm). Rapid air cooling can be used on sections

thinner than 3/8 inch (9.5 mm), however, water quenching is preferred. The time from the furnace to the quench tank or to the start of rapid air cooling, must be as short as possible (less than three minutes).

HASTELLOY B-2 alloy

The method of annealing HASTELLOY B-2 alloy is demanding and the following items should be considered very carefully. Extended exposure in an intermediate temperature range of 1100 to 1500°F (593 to 816°C), especially for cold work condition material, can cause intergranular cracking.

The following steps are designed to minimize intermediate temperature cracking of HASTELLOY B-2 alloy.

- Furnace must be at the annealing temperature. The thermal capacity of the furnace should be large to insure a quick recovery of furnace temperature.
- It has been observed that shot peening the knuckle radius and straight flange regions of a cold-formed head, prior to heat treatment, can help reduce intermediate temperature intergranular cracking, of HASTELLOY B-2 alloy by lowering the tensile residual stress patterns at the surface of the cold formed component.

The improved thermal stability of HASTELLOY B-3 alloy

minimized the problems associated with fabrication of B-2 alloy components. This is due to the reduced tendency to precipitate deleterious intermetallic phases in B-3 alloy, thereby, affording it greater ductility than B-2 alloy during and following various thermal cycling conditions. Nevertheless for heavy section weldments or for those weldments characterized by high residual welding stresses, fabricators may wish to follow the heat treat requirements recommended for B-2 alloy.

Shot Peening

Cold formed components with residual tensile stresses, exposed at intermediate temperatures for critical periods of time, have been observed to produce intergranular cracking during the heat treatment of HASTELLOY B-2 alloy. It has been observed that shot peening the knuckle radius and straight flange regions of a cold-formed head, prior to heat treatment, can help reduce intermediate temperature, intergranular cracking of B-2 alloy by lowering the tensile residual stress patterns at the surface of the cold formed component.

HASTELLOY B-3 alloy is less sensitive to the above issues, however, the same methods for B-2 alloy should be used to eliminate the risk of cracking of B-3 alloy.

DESCALING AND PICKLING

Because of their inherent corrosion resistance, HASTELLOY alloys are relatively inert to cold acid pickling solutions. After heat treatment, the oxide film is more adherent than that of stainless steels. Molten caustic baths followed by acid pickling are the most effective descaling methods. Baths of VIRGO descaling salt, sodium hydride (DuPont), or DGS oxidizing salt have been used effectively.

Tables 11, 12 and 13 provide pickling media, temperatures and times for each method. The compositions of the pickling solutions are listed in Table 14. Sand, shot, or vapor blasting are acceptable for removing scale under certain conditions. The blasting material should be such that it provides for a rapid cutting action rather than smearing the surface. Sand should not be reused especially if contaminated

with iron. After blasting, it is desirable to give the part an acid pickle to remove any imbedded iron or other impurities. Extreme care should be taken when sand blasting thin-gage parts because of the danger of distortion and of embedding sand or scale in the metal surface. Sand blasting also tends to work harden the metal's surface.

Table 11

VIRGO DESCALING SALT BATH

Alloy	VIRGO Descaling Salt Bath		Water Rinse Time, min.	Sulfuric-Hydrochloric Acid Bath 165°F (74°C)	Nitric-Hydrofluoric Acid Bath 125-160°F (52-71°C)	Water Rinse Time, min.
	Temp.	Time min.		Time, min.	Time, min.	
B-2, B-3	800°F (427°C)	1-3	1-2	25-45	–	3 (Steam spray)
C-276, C-4, C-2000, C-22, G-30, N	970°F (521°C)	1-3	1-2	3	25	3 (Steam spray)

Table 12

SODIUM HYDRIDE (REDUCING SALT BATH) PROCESS

Alloy	Sodium Hydride Bath*		Sulfuric-Hydrochloric Acid Bath 165°F (74°C)	Permanganate-Sodium Hydroxide Bath 135-155°F (57-68°C)	Nitric-Hydrochloric Acid Bath 165°F (74°C)	Nitric-Hydrofluoric Acid Bath 125-160°F (52-71°C)	Water Rinse
	Temp.	Time min.	Time, min.*	Time, min.*	Time, min.*	Time, min.*	
B-2, B-3	750-800°F (399-427°C)	15-20	20-30	20-30	20-30	1 max.	Steam spray
C-276, C-4, C-2000, C-22, G-30, N	750-800°F (399-427°C)	15	–	15	–	15	Dip

*Followed by a water rinse.

Table 13

DGS OXIDIZING SALT BATH PROCESS

Alloy	DGS Oxidizing Salt Bath			Nitric-Hydrofluoric Acid Bath	Water Rinse
	Temp.	Time min.	Water Rinse	130-150°F (54-66°C) Time, min.	
B-2, B-3	850-950°F (454-510°C)	2-7	Dip	1-4	Dip and steam spray
C-276, C-4, C-2000 C-22, G-30, N	850-950°F (454-510°C)	2-7	Dip	10-20	Dip and steam spray

Table 14

COMPOSITION OF PICKLING SOLUTIONS

Descaling Method	Composition of Pickling Solution, Percent by Weight		
	Sulfuric-Hydrochloric Acid Bath	Permanganate-Sodium Hydroxide Bath	Nitric-Hydrofluoric Acid Bath
VIRGO Descaling Salt Bath	15-17% sulfuric acid 0.5-1.0% hydrochloric acid	Not used	7-8% nitric acid 3-4% hydrofluoric acid
Sodium Hydride Process	15-17% sulfuric acid 0.5-10% hydrochloric acid (used only for B-2 alloy)	4-6% potassium permanganate 1-2% sodium hydroxide	8-12% nitric acid 2-3% hydrofluoric acid
DGS (Oxidizing Salt Bath) Process	Not used	Not used	15-25% nitric acid 3-5% hydrofluoric acid

GRINDING AND MACHINING

When very close tolerances are required, grinding is

recommended for finishing HASTELLOY alloys.

Recommended wheels and coolants are listed in Table 15.

Table 15

GRINDING OF HASTELLOY ALLOYS

Type of Grinding	Wheels*	Manufacturer	Type of Work	Coolant
Cylinder Grinding				
Straight or Tapered O.D.'s	53A80-J8V127	Norton	Sharp corners and fine finish	Heavy duty soluble coolant 25:1 mix CASTROL 653
Form Work, Single Wheel Section Method	38A60-J8-VBE	Norton	Removing stock Sharp corner work Straight radius work	Dry
Form Work, Crush-Roll Method	53A220-L9VB	Norton	Precision forms Radius	Straight oil
Centerless	53A80-J8VCN	Norton	Thin-walled material Solid or heavy-walled material	Heavy duty soluble coolant 25:1 mix CASTROL 653
Internal Grinding				
Straight or Tapered	23A54-L8VBE	Norton	Small holes Medium-size holes Large holes Small counterbores	Heavy duty soluble coolant 25:1 mix CASTROL 709
Surface Grinding				
Straight Wheel	32A46-H8VBE 38A46-I-V	Norton Norton		Dry or any heavy duty soluble coolant 25:1 mix CASTROL 653
Double Opposed Disk Type	87A46-G12-BV 87A46-J11-BW	Gardner Gardner	Through-feed work Ferris wheel work Thin work	Heavy duty soluble coolant 10:1 mix CASTROL 653
Cylinder or Segmental Type	32A46-F12VBE	Norton	Thin work, bevels and close tolerance work	Sal-soda in water CASTROL 653
Single Wheel Section Method	32A46-F12VBEP	Norton	Profile work	Dry
Thread Grinding				
External Threads	A100-T9BH	Norton		VANTOL 5299-M or equivalent
Honing				
Internal	C120-E12-V32 C220-K4VE J45-J57	Bay State Carborundum Sunnen		VANTROL 5299-C or equivalent
Rough Grinding				
Cut-off (Wet)	86A461-LB25W	Norton		CASTROL 653
Cut-off (Dry)	4NZA24-TB65N	Norton		Dry
Snagging	4ZF1634-Q5B38	Norton		Dry

*The wheels indicated have been optimized for speeds between 6000 and 6500 sfpm.

MACHINING

HASTELLOY corrosion-resistant alloys are classified as moderate to difficult when machining, however, it should be emphasized that these alloys can be machined using conventional production methods at satisfactory rates. During machining these alloys work harden rapidly, generate high heat during cutting, weld to the cutting tool surface, and offer high resistance to metal removal because of their high shear strengths. The following are key points which should be considered during machining operations:

- **CAPACITY** - Machine should be rigid and overpowered as much as possible.
- **RIGIDITY** - Work piece and tool should be held rigid. Minimize tool overhang.
- **TOOL SHARPNESS** - Make sure tools are sharp at all times. Change to sharpened tools at regular intervals rather than out of necessity. A 0.015 inch (0.4 mm) wear land is considered a dull tool.
- **TOOLS** - Use positive rake angle tools for most machining operations. Negative rake angle tools can be considered for intermittent cuts and heavy stock removal. Carbide-tipped tools are suggested for most applications. High speed tools can be used, with lower production rates, and are often recommended for intermittent cuts.
- **POSITIVE CUTS** - Use heavy, constant, feeds to maintain positive cutting action. If feed slows and the tool dwells in the cut, work hardening occurs, tool life deteriorates and close tolerances are impossible.
- **LUBRICATION** - lubricants are desirable, soluble oils are recommended, especially when using carbide tooling.

Detailed machining parameters are presented in Tables 16 and 17. General plasma cutting recommendations are presented in Table 18.

Table 16

RECOMMENDED TOOL TYPES AND MACHINING CONDITIONS

Operations	Carbide Tools
Roughing, with severe interruptions; Turning or Facing	C-2 or C-3 grade: Negative rake square insert, 45° SCEA ¹ , 1/32 in. nose radius. Tool holder: 5° neg. back rake, 5° neg. side rake. Speed: 30-50 sfm, 0.004-0.008 in. feed, 0.150 in. depth of cut. Dry ² , oil ³ , or water-base coolant ⁴ .
Normal roughing; Turning or Facing	C-2 or C-3 grade: Negative rake square insert, 45° SCEA, 1/32 in. nose radius. Tool holder: 5° neg. back rake, 5° neg. side rake. Speed: 90 sfm depending on rigidity of set up, 0.010 in. feed, 0.150 in. depth of cut. Dry, oil, or water-base coolant.
Finishing; Turning or Facing	C-2 or C-3 grade: Positive rake square insert, if possible, 45° SCEA, 1/32 in. nose radius. Tool holder: 5° pos. back rake, 5° pos. side rake. Speed: 95-110 sfm, 0.005-0.007 in. feed, 0.040 in. depth of cut. Dry or water-base coolant.
Rough Boring	C-2 or C-3 grade: If insert type boring bar, use standard positive rake tools with largest possible SCEA and 1/16 in. nose radius. If brazed tool bar, grind 0° back rake, 10° pos. side rake, 1/32 in. nose radius and largest possible SCEA. Speed: 70 sfm depending on the rigidity of setup, 0.005-0.008 in. feed, 1/8 in. depth of cut. Dry, oil, or water-base coolant.
Finish Boring	C-2 or C-3 grade: Use standard positive rake tools on insert type bars. Grind brazed tools as for finish turning and facing except back rake may be best at 0°. Speed: 95-110 sfm, 0.002-0.004 in. feed. Water-base coolant.

NOTES: 1 SCEA – Side cutting edge angle or lead angle of the tool.

2 At any point where dry cutting is recommended, an air jet directed on the tool may provide substantial tool life increases. A water-base coolant mist may also be effective.

3 Oil coolant should be a premium quality, sulfochlorinated oil with extreme pressure additives. A viscosity at 100°F from 50 to 125 SSU.

4 Water-base coolant should be premium quality, sulfochlorinated water soluble oil or chemical emulsion with extreme pressure additives. Dilute with water to make 15:1 mix. Water-base coolant may cause chipping and rapid failure of carbide tools in interrupted cuts.

Table 17

RECOMMENDED TOOL TYPES AND MACHINING CONDITIONS		
Operations	High Speed Steel Tools	Carbide Tools
Facing Milling	M-2, M-7, or M-40 series ⁵ : Radial and axial rake 0°-pos. 10°, 45° corner angle, 100 relief angle. Speed: 20-30 sfm. Feed: 0.003-0.005 in. Oil ⁶ or water-base coolant ⁷ .	Carbide not generally successful, C-grade may work. Use positive axial and radial rake, 45° corner angle, 10° relief angle. Speed: 50-60 sfm. Feed: 0.005-0.008 in. Oil or water-base coolants will reduce thermal shock damage of carbide cutter teeth.
End Milling	M-40 series or T-15: If possible, use short mills with 4 or more flutes for rigidity. Speed: 20-25 sfm. Feed: 0.002 in. tooth 1/4 in. dia. 0.002 in. tooth 1/2 in. dia. 0.003 in. tooth 3/4 in. dia. 0.004 in. tooth 1 in. dia. Oil or water-base coolant.	Not recommended, but C-2 grades may be successful on good setups. Use positive rake. Speed: 50-60 sfm. Feed: Same as high speed steel. Oil or water-base coolants will reduce thermal shock damage.
Drilling	M-33, M-40 series or T-15: Use short drills, heavy web, 135° crank-shaft, grind points wherever possible. Speed: 10-15 sfm. Feed: 0.001 in. rev. 1/8 in. dia. 0.002 in. rev. 1/4 in. dia. 0.003 in. rev. 1/2 in. dia. 0.005 in. rev. 3/4 in. dia. 0.007 in. rev. 1 in. dia. Oil or water-base coolant Use coolant feed drills if possible.	C-2 grade not recommended, but tipped drills may be successful on rigid setup if no great depth. The web must be thinned to reduce thrust. Use 135° included angle on point. Gun drill can be used. Speed: 50 sfm. Oil or water-base coolant. Coolant-feed carbide tipped drills may be economical in some setups.
Reaming	M-33, M-40 series or T-15: Use 45° corner angle, narrow primary land and 10° relief angle. Speed: 10-20 sfm. Feed: 0.003 in. tooth 1/2 in. dia. 0.008 in. tooth 2 in. dia. Oil or water-base coolant.	C-2 or C-3 grade: Tipped reamers recommended, solid carbide reamers require very good setup. Tool geometry same as high speed steel. Speed: 50 sfm. Feed: Same as high speed steel.
Tapping	M-1, M-7, M-10: 2 flute, spiral point, plug tap 0°-10° hook angle nitrided surface may be helpful by increasing wear resistance but may cause chipping or breakage. Tap drill for 60-65% thread, if possible, to increase tool life. Speed: 7 sfm (cutting). Use best possible tapping compound. sulfochlorinated oil base preferred.	Not recommended
Electrical Discharge Machining	HASTELLOY alloys can be easily cut using any conventional electrical discharge machining system (EDM) or wire EDM.	

NOTES: 5 M-40 series High Speed Steels include M-41, M-42, M-43, M-44, M-45 and M-46 at the time of writing. Others may be added and should be equally suitable.

6 Oil coolant should be a premium quality, sulfochlorinated oil with extreme pressure additives. A viscosity at 100°F from 50 to 125 SSU.

7 Water-base coolant should be premium quality, sulfochlorinated water soluble oil or chemical emulsion with extreme pressure additives. Dilute with water to make 15:1 mix.

Table 18

Plasma Arc Cutting	HASTELLOY [®] alloys can be cut using any conventional plasma arc cutting system. The best arc quality is achieved using a mixture of argon and hydrogen gases. Nitrogen gas can be substituted for hydrogen gases, but the cut quality will deteriorate slightly. Shop air or any oxygen bearing gases should be avoided when plasma cutting the HASTELLOY alloys.
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APPENDIX—SELECTED DATA AND INFORMATION

Table A-1

NOMINAL CHEMICAL COMPOSITIONS, PERCENT ¹										
Alloy	Ni	Co	Cr	Mo	W	Fe	Si	Mn	C	Others
HASTELLOY® B-2 alloy	69 ^a	1 [*]	1 [*]	28	–	2 [*]	0.1 [*]	1 [*]	0.01 [*]	–
HASTELLOY B-3 alloy	65 ^b	3 [*]	1.5	28.5	3 [*]	1.5	0.1 [*]	3 [*]	0.01 [*]	Al-0.5 [*] Ti-0.2 [*]
HASTELLOY C-4 alloy	65 ^a	2 [*]	16	16	–	3 [*]	0.08 [*]	1 [*]	0.01 [*]	Ti-0.7 [*]
HASTELLOY C-2000 alloy	59 ^a	2 [*]	23	16	–	3 [*]	0.08 [*]	–	0.01 [*]	Cu-1.6
HASTELLOY C-22 alloy	56 ^a	2.5 [*]	22	13	3	3	0.08 [*]	0.5 [*]	0.01 [*]	V-0.35 [*]
HASTELLOY C-276 alloy	57 ^a	2.5 [*]	16	16	4	5	0.08 [*]	1 [*]	0.01 [*]	V-0.35 [*]
HASTELLOY G-30 alloy	43 ^a	2 [*]	30	5.5	2.5	15	1 [*]	1.5 [*]	0.03 [*]	Cb-0.8 [*] Cu-2 [*]
HASTELLOY N alloy	71 ^a	0.2 [*]	7	16	0.5 [*]	5 [*]	1 [*]	0.8 [*]	0.08 [*]	Al+Ti-0.5 [*] Cu-0.35 [*]
HASTELLOY W alloy	63 ^a	2.5 [*]	5	24	–	6	1 [*]	1 [*]	0.12 [*]	V-0.6 [*]

¹ The undiluted deposited chemical composition of covered electrodes of some of these alloys may vary beyond the limits shown.

*Maximum ^a As Balance ^b Minimum

Table A-2

AVAILABLE FORMS								
Alloy	Sheet and Strip	Plate	Bar	Wire	Billet	Covered Electrodes	Tubing	Pipe
HASTELLOY® B-2 alloy	X	X	X	X	X	X	X	X
HASTELLOY B-3 alloy	X	X	X	X	X	X	X	X
HASTELLOY C-276 alloy	X	X	X	X	X	X	X	X
HASTELLOY C-2000 alloy	X	X	X	X	X	X	X	X
HASTELLOY C-4 alloy	X	X	X	X	X	X	X	X
HASTELLOY C-22 alloy	X	X	X	X	X	X	X	X
HASTELLOY G-30 alloy	X	X	X	X	X	X	X	X
HASTELLOY N alloy	X	X	X	–	X	–	X	X
HASTELLOY W alloy	–	–	X	X	–	X	–	–

Table A-3

WELDING WIRE AND COVERED ELECTRODE SIZES		
Form	Alloy	Available Sizes, in.*
Loose Coils ¹	B-2, C-4, C-22, C-2000, C-276, G-30, W	3/16, 5/32, 1/8, 3/32, 1/16, 0.045, 0.035
Layer Wound Coils ²	B-2, C-4, C-22, C-2000, C-276, G-30, W	1/16, 0.045, 0.035
Cut Lengths ³	B-2, C-4, C-22, C-2000, C-276, G-30, W	3/16, 5/32, 1/8, 3/32, 1/16, 0.045, 0.035
Covered Electrodes	B-2, C-4**, C-22, C-2000, C-276, G-30, W	3/16, 5/32, 1/8, 3/32, 5/64

* Not all sizes shown are stocked.

** Not available in 3/16 in. electrodes.

1 Packaged in 25, 50, and 100 lb. coils. Diameters 3/32 in. and smaller may be sold in minimum quantities of 10 lb.

2 Packaged in 25, 50, and 100 lb. coils. Diameters 1/8 in. and larger are on 24.5 in. x 4.25 in. cardboard rims and diameters less than 1/8 in. are on 12 in. x 3 in. wide flanged disposable spools.

3 Standard 36 in. cut lengths in 5, 10, and 25 lb. packages. Other lengths available on request.

Table A-4

APPLICABLE ASME AND AWS SPECIFICATIONS								
Alloy	Base Metal UNS No.	Plate/Sheet/Strip ASME	Round Bar to 3 1/2 in. (89 mm) Dia. ASME	Welded Pipe ASME	Seamless Tubing ASME	Welded Tubing ASME	Weld Filler Metal	
							Bare	Covered
							AWS A 5.14 ASME SFA 5.14	AWS A 5.11 ASME SFA 5.11
B-2	N10665	SB-333	SB-335	SB-619	SB-622	SB-626	ERNiMo-7	ENiMo-7
B-3	N10675	SB-333	SB-335	SB-619	SS-622	SB-626	ERNiMo-10	ENiMo-10
C-276	N10276	SB-575	SB-574	SB-619	SB-622	SB-626	ERNiCrMo-4	ENiCrMo-4
C-2000	N06200	SB-575	SB-574	SB-619	SB-622	SB-626	ERNiCrMo-17	ENiCrMo-17
C-4	N06455	SB-575	SB-574	SB-619	SB-622	SB-626	ERNiCrMo-7	ENiCrMo-7
C-22	N06022	SB-575	SB-574	SB-619	SB-622	SB-626	ERNiCrMo-10	ENiCrMo-10
G-30	N06030	SB-582	SB-581	SB-619	SB-622	SB-626	ERNiCrMo-11	ENiCrMo-11
N	N10003	SB-434	SB-573	–	–	–	ERNiMo-2	–
W	N10004	–	–	–	–	–	ERNiMo-3	ENiMo-3

Table A-5

COMPARATIVE AVERAGE PROPERTIES DATA AT ROOM TEMPERATURE*

Alloy	Density lb./in ³	Ultimate Tensile Strength		Yield Strength at 0.2% offset		Elongation in 2 in. %	Rockwell Hardness
		Ksi	MPa	Ksi	MPa		
HASTELLOY® B-2 alloy	0.333	132.5	914	57.5	396	55	B-98
HASTELLOY B-3 alloy	0.333	128.3	885	58.3	400	58	B-98
HASTELLOY C-276 alloy	0.321	114.9	790	51.6	355	61	B-90
HASTELLOY C-2000 alloy	0.307	113.0	777	55.0	378	62	B-88
HASTELLOY C-4 alloy	0.312	114.8	789	58.1	400	54	B-92
HASTELLOY C-22 alloy	0.314	115.0	791	56.5	389	59	B-90
HASTELLOY G-30 alloy	0.297	100.0	688	47.0	323	56	B-88
HASTELLOY N alloy	0.320	115.1	792	45.5	313	51	B-96

*Sheet heat-treated in accordance with Table 10 page 30.

Table A-6

THERMAL EXPANSION

Alloy	British Units		Metric Units	
	Temp., °F	Microinches/ in.-°F	Temp., °C	µm/m-k
HASTELLOY® B-2 alloy	68-600	6.2	20-316	11.2
HASTELLOY B-3 alloy	78-600	6.3	25-300	11.4
HASTELLOY C-276 alloy	75-600	7.1	24-316	12.8
HASTELLOY C-2000 alloy	77-600	7.0	25-300	12.6
HASTELLOY C-22 alloy	68-600	7.0	20-316	12.6
HASTELLOY C-4 alloy	68-600	7.0	20-316	12.6
HASTELLOY G-30 alloy	86-600	8.0	30-316	14.4
HASTELLOY N alloy	70-600	6.8	21-316	12.3
HASTELLOY W alloy	73-300	6.3	23-50	11.4

Table A-7

THERMAL CONDUCTIVITY

Alloy	British Units		Metric Units	
	Temp., °F	Btu-in./ft ² - in.-°F	Temp., °C	W/m-K
HASTELLOY® B-2 alloy	572	102	300	14.6
HASTELLOY B-3 alloy	600	104	300	14.8
HASTELLOY C-276 alloy	600	104	316	15.0
HASTELLOY C-2000 alloy	600	99	300	14.1
HASTELLOY C-4 alloy	572	104	300	15.0
HASTELLOY C-22 alloy	572	108	300	15.5
HASTELLOY G-30 alloy	572	116	300	16.7
HASTELLOY N alloy	572	100	300	14.4

STANDARD PRODUCTS

By Brand or Alloy Designation:

HAYNES

International

HASTELLOY® Family of Corrosion-Resistant Alloys

B-3®, C-4, C-22®, C-276, C-2000®, C-22HS®, G-30®, G-35®, G-50®, HYBRID-BC1™, and N

HASTELLOY Family of Heat-Resistant Alloys

S, W, and X

HAYNES® Family of Heat-Resistant Alloys

25, R-41, 75, HR-120®, HR-160®, 188, 214®, 230®, 230-W®, 242®, 263, 282®, 556®, 617, 625, 65SQ®, 718, X-750, MULTIMET®, NS-163™, and Waspaloy

Corrosion-Wear Resistant Alloy

ULTIMET®

Wear-Resistant Alloy

6B

HAYNES Titanium Alloy Tubular

Ti-3Al-2.5V

Standard Forms: Bar, Billet, Plate, Sheet, Strip, Coils, Seamless or Welded Pipe & Tubing, Pipe Fittings, Flanges, Fittings, Welding Wire, and Coated Electrodes

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Global Headquarters

1020 West Park Avenue

P.O. Box 9013

Kokomo, Indiana 46904-9013 (USA)

Phone: 1-800-354-0806 or (765) 456-6012

Fax: (765) 456-6905

www.haynesintl.com