

Welding and Fabrication

Overview

The HAYNES® and HASTELLOY® alloys fall into two main categories:

Corrosion-resistant Alloys (CRA), which are generally used at temperatures below 1000°F, and are able to withstand corrosive liquids.

High-temperature Alloys (HTA), which are generally used above 1000°F, at which temperatures they possess considerable strength and resistance to hot air and/or other hot gases.

The high-temperature alloys can also be sub-categorized according to the mechanism used to provide their strength. Many of the alloys contain significant quantities of atomically-large elements; these provide strength through a mechanism known as solid-solution strengthening. Other HTA materials use a mechanism known as age-hardening (also known as precipitation-hardening) to attain the required strength levels. There is also one age-hardenable, corrosion-resistant alloy.

The heat treatments required to strengthen the age-hardenable materials are normally performed after welding and hot/cold-working, and prior to these heat treatments, there is much in common with the fabrication techniques/parameters employed with the solid-solution strengthened alloys, as long as they are supplied in the annealed condition.

As with the stainless steels and other alloy systems, it is advantageous to have a rudimentary understanding of the metallurgical changes that might occur in the HAYNES® and HASTELLOY® alloys, if exposed to the heat of welding, the high temperatures involved with hot-working, or the effects of annealing after cold-working. If brazing is to be attempted, it is very important to understand how the temperatures involved with brazing might affect the HAYNES® and HASTELLOY® materials, or conversely how subsequent age-hardening (in the case of the age-hardenable alloys) or annealing treatments (in the case of any of the alloys) might affect the brazed joint.

In addition to the general purpose alloys manufactured by Haynes International, there are several special purpose alloys, requiring different fabrication approaches. One is a titanium alloy made only in the form of tubulars, and for which fabrication references are given. One is a high-temperature, nickel-based alloy that requires a nitrogen diffusion treatment to impart strength to the material, and for which there are some specific fabrication issues. The other two are cobalt-based, wear-resistant alloys, one of which is not normally welded or formed; the other is easily welded, but somewhat resistant to cold-working due to a high work-hardening rate.

Overview

Haynes International Alloys

Base	Corrosion-resistant Alloys (CRA)	
	Solid-Solution	Age-Hardenable
Nickel	B-3® C-4, C-22®, C-276, C-2000® G-30®, G-35® HYBRID-BC1®	C-22HS®

Base	High-temperature Alloys (HTA)	
	Solid-Solution	Age-Hardenable
Nickel	N, S, W, X 75 214®, 230® 617®, 625, 625SQ® HR-120®, HR-160®, HR-224®, HR-235™	242®, 244™, 263, 282® 718 R-41 Waspaloy X-750
Cobalt	25, 188	-
Iron	556®, MULTIMET®	-

Base	Lightweight Alloy (LA)
	Age-Hardenable
Titanium	Ti-3Al-2.5V

Base	High-temperature Alloy (HTA-NS)
	Nitrogen-Strengthenable
Cobalt	NS-163®

Base	Wear-resistant Alloy (WRA)
Cobalt	6B

Base	Wear & Corrosion-resistant Alloy (WCRA)
Cobalt	ULTIMET®

Hot-Working

The HAYNES® and HASTELLOY® alloys can be hot-worked into various shapes; however, they can be more sensitive to the amounts and rates of hot-reduction than the austenitic stainless steels. In addition, the hot-working temperature ranges for the HAYNES® and HASTELLOY® alloys are quite narrow, and careful attention to hot-working parameters is necessary

In developing suitable hot-working practices, particular attention should be paid to the solidus of the alloy in question (the temperature at which the alloy begins to melt), the high strengths of the HAYNES® and HASTELLOY® alloys at elevated temperatures, their high work-hardening rates, and their low-thermal conductivities. Furthermore, their resistance to deformation increases markedly as the temperature falls to the low end of the hot-working range.

Accordingly, hot-working practices that incorporate high (heavy) initial reductions, followed by moderate final reductions, coupled with frequent re-heating, generally yield the best results. In addition, slow deformation rates tend to minimize adiabatic heating and applied force requirements.

****Following any hot-working operation, the HAYNES® and HASTELLOY® alloys should be annealed, to return them to their optimal condition for service, age-hardening (in the case of the age-hardenable alloys), or for further fabrication. Annealing temperatures and techniques are detailed in the heat treatment section.***

Hot-Working Continued

Melting Temperature Ranges

Alloy	Melting Temperature Range			
	Solidus*		Liquidus**	
	°F	°C	°F	°C
B-3®	2500	1370	2585	1418
C-4	-		-	
C-22®	2475	1357	2550	1399
C-22HS®	2380	1304	2495	1368
C-276	2415	1323	2500	1371
C-2000®	2422	328	2476	1358
G-30®	-		-	
G-35®	2430	1332	2482	1361
HYBRID-BC1®	2448	1342	2509	1376
N	2375	1302	2550	1399
ULTIMET®	2430	1332	2470	1354
25	2425	1329	2570	1410
75	2445	1341	2515	1379
188	2400	1316	2570	1410
214®	2475	1357	2550	1399
230®	2375	1302	2500	1371
242®	2350	1288	2510	1377
244®	2480	1360	2550	1399
263	2370	1299	2470	1354
282®	2370	1299	2510	1377
556®	2425	1329	2480	1360
617	2430	1332	2510	1377
625	2350	1288	2460	1349
625SQ®	2350	1288	2460	1349
718	2300	1260	2435	1335
HR-120®	2478	1359	2542	1395
HR-160®	2360	1293	2500	1371
HR-224®	2449	1343	2510	1377
HR-235®	2401	1316	2473	1356
MULTIMET®	2350	1288	2470	1354
R-41	2385	1307	2450	1343
S	2435	1335	2516	1380
W	2350	1288	2510	1377
Waspaloy	2425	132	2475	1357
X	2300	1260	2470	1354
X-750	2540	1393	2600	1427

*Temperature at which alloy starts to melt

**Temperature at which alloy is fully molten

Hot-Working Continued

Forging

Recommended Procedures and Temperatures Applicable to: Corrosion-resistant Alloys High-temperature Alloys Wear & Corrosion-resistant Alloy

The following procedures are recommended for forging of the HAYNES® and HASTELLOY® alloys:

- Soak billets or ingots at the forging start temperature for at least 30 minutes per inch of thickness. The use of a calibrated optical pyrometer is essential.
- The stock should be turned frequently to make sure that it is heated evenly. 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 temperatures to drop as much as 100-200°F (55-110°C). Do not raise the forging temperature to compensate for heat loss, as this may cause incipient melting.
- Moderately heavy reductions (25-40%) are beneficial, to maintain as much internal heat as possible, thus minimizing grain coarsening and the number of re-heatings. Reductions greater than 40% per pass should be avoided.
- Care must be taken to impart sufficient hot-work during forging to ensure that the appropriate structure and properties are achieved in the final part. For parts with large cross-sections, it is advisable to include a number of forging upsets in the hot-working schedule, to allow for adequate forging reductions. Upset L/D ratios of 3:1 are generally acceptable.
- Light-reduction finish sizing sessions should generally be avoided. If required, they should be performed at the lower end of the forging temperature range.
- Do not make radical changes in the cross-sectional shape, such as going directly from a square to a round, during initial forming stages. Instead, go from a square to a “round cornered square”, then to an octagon, then to a round.
- Remove (condition) any cracks or tears developed during forging. This can be done at intermediate stages, between forging sessions.

Hot-Working Continued

Forging/Hot-working Temperature Ranges

Alloy	Forging/Hot-Working Temperature			
	Start Temperature*		Finish Temperature**	
	°F	°C	°F	°C
B-3®	2275	1246	1750	954
C-4	2200	1204	1750	954
C-22®	2250	1232	1750	954
C-22HS®	2250	1232	1750	954
C-276	2250	1232	1750	954
C-2000®	2250	1232	1750	954
G-30®	2200	1204	1800	982
G-35®	2200	1204	1750	954
HYBRID-BC1®	2250	1232	-	
N	2200	1204	1750	954
ULTIMET®	2200	1204	1750	954
25	2200	1204	1750	954
75	2200	1204	1700	927
188	2150	1177	1700	927
214®	2150	1177	1800	982
230®	2200	1204	1700	927
242®	2125	1163	1750	954
244®	-		-	
263	2150	1177	1750	954
282®	2125	1163	1850	1010
556®	2150	1177	1750	954
617	2125	1163	1600	871
625	2150	1177	1600	871
625SQ®	-		-	
718	2050	1121	1650	899
HR-120®	2150	1177	1700	927
HR-160®	2050	1121	1600	871
HR-224®	-		-	
HR-235®	2250	1232	1750	954
MULTIMET®	2150	1177	1700	927
R-41	2150	1177	1850	1010
S	2100	1149	1700	927
W	2240	1227	1800	982
Waspaloy	2150	1177	1850	1010
X	2100	1149	1750	954
X-750	2150	1177	1750	954

*Maximum

**Dependent upon the nature and degree of working

Hot-Working Continued

Hot-rolling

Recommended Procedures and Temperatures Applicable to:
Corrosion-resistant Alloys
High-temperature Alloys
Wear & Corrosion-resistant Alloy

Hot rolling of the HAYNES® and HASTELLOY® alloys can be performed to produce conventional rolled forms, such as bars, rings, and flats. The hot rolling temperature range is the same as that listed above (in the Forging section, under Forging/Hot-working Temperature Ranges).

Moderate reductions per pass (15 to 20 percent reduction in area), and rolling speeds of 200 to 300 surface feet per minute tend to provide good results, without overloading the mill. The total reduction per session should be at least 20 to 30 percent. It is usual to finish at the low end of the hot-working temperature range, since this generally provides the optimum structure and properties.

Care should be taken to ensure that the work piece is thoroughly soaked at the hot working start temperature before rolling. Frequent re-heating may be required during hot-rolling, to keep the temperature of the work piece in the hot working range.

Hot-forming

Recommended Procedures and Temperatures Applicable to:
Corrosion-resistant Alloys
High-temperature Alloys
Wear & Corrosion-resistant Alloy

The hot-forming of plates into components, such as dished heads is normally performed by cold-pressing or spinning, with intermediate anneals. However, sometimes the size and thickness of the material is such that hot-forming is necessary.

When hot-forming is required, the start temperature (to which the furnace is heated) is approximately mid-way between the annealing temperature (of the alloy in question) and its lower (finish) forging temperature. During hot-forming, the temperature of the piece should not fall below the lower (finish) forging temperature. Re-heating may be necessary to maintain the correct hot forming temperature, and dies should be warmed to avoid excessive chilling of the surfaces.

Other Hot-Working Processes

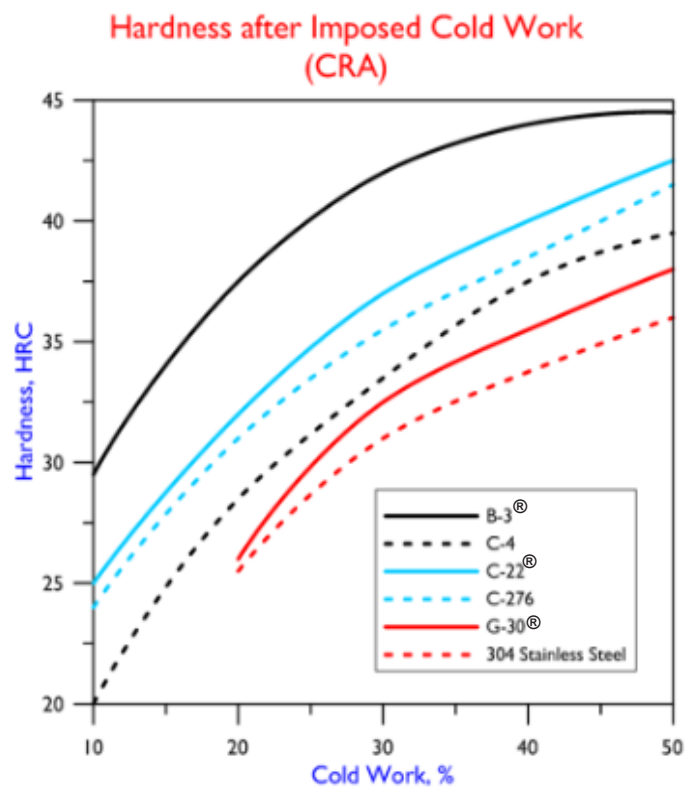
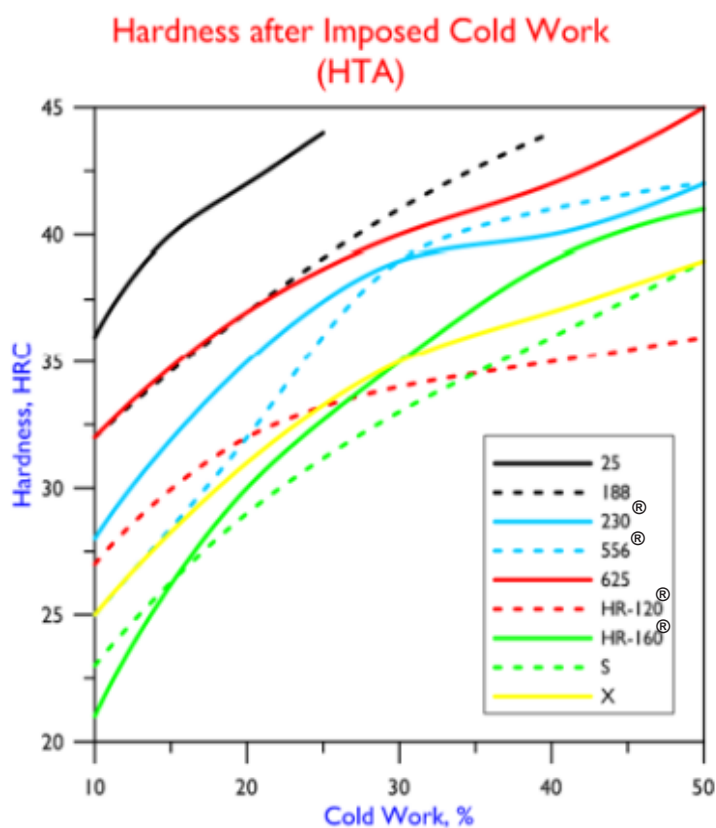
Recommended Procedures and Temperatures Applicable to:
Corrosion-resistant Alloys
High-temperature Alloys
Wear & Corrosion-resistant Alloy

The HAYNES® and HASTELLOY® alloys are amenable to several other hot-working processes, such as hot-extrusion and hot-spinning. Impact extrusion should be performed at the solution annealing temperature of the alloy involved. Uniform and accurate temperatures throughout the work-piece are necessary during impact extrusion, and re-strikes should be avoided. The parameters for hot extrusion and hot spinning are specific to the exact nature of the intended work and material. For more information, please contact our technical support team.

Cold-working

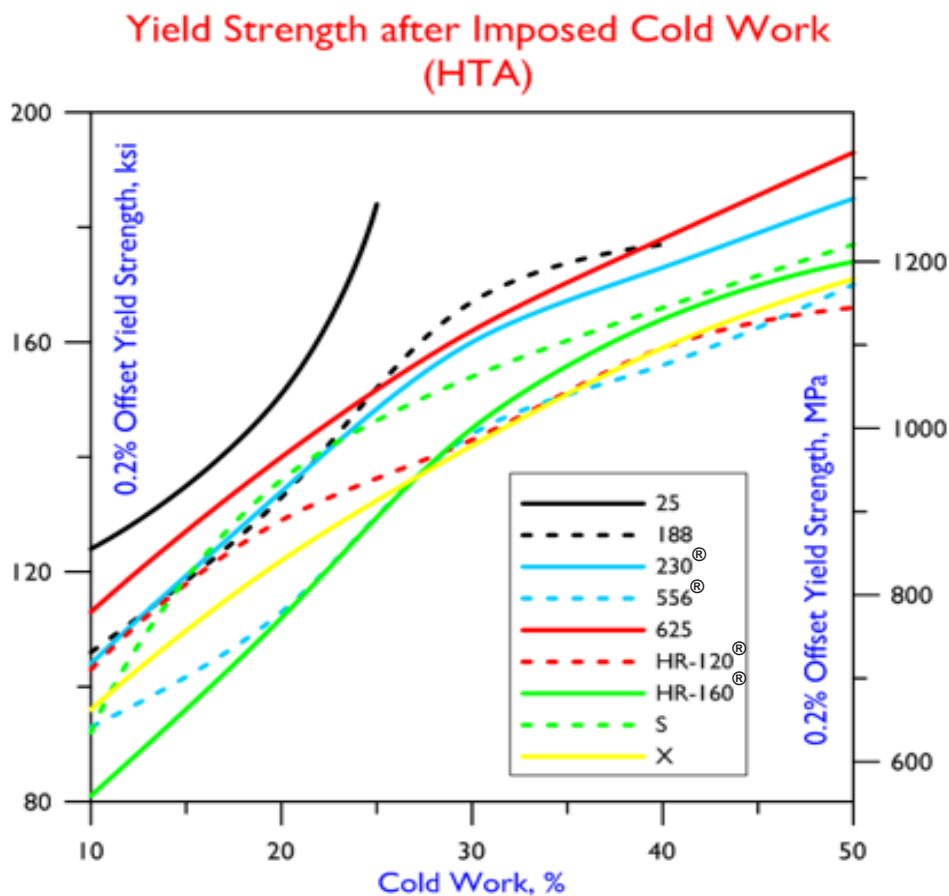
The HAYNES® and HASTELLOY® alloys can be readily formed into various configurations by cold-working. Since they are generally stronger, and work harden more rapidly, than the austenitic stainless steels, the application of greater force is normally required to achieve the same amount of cold deformation. The higher yield strengths of the HAYNES® and HASTELLOY® alloys may also result in greater spring-back after cold forming, relative to the austenitic stainless steels. Furthermore, rapid work hardening may necessitate more frequent annealing treatments between forming steps, to attain the final shape. Graphs illustrating the effects of cold-work upon the hardness, yield strength, and ductility of some of the HAYNES® and HASTELLOY® alloys are shown below.

Effect of Cold-work on Hardness Applicable to: Corrosion-resistant Alloys High-temperature Alloys

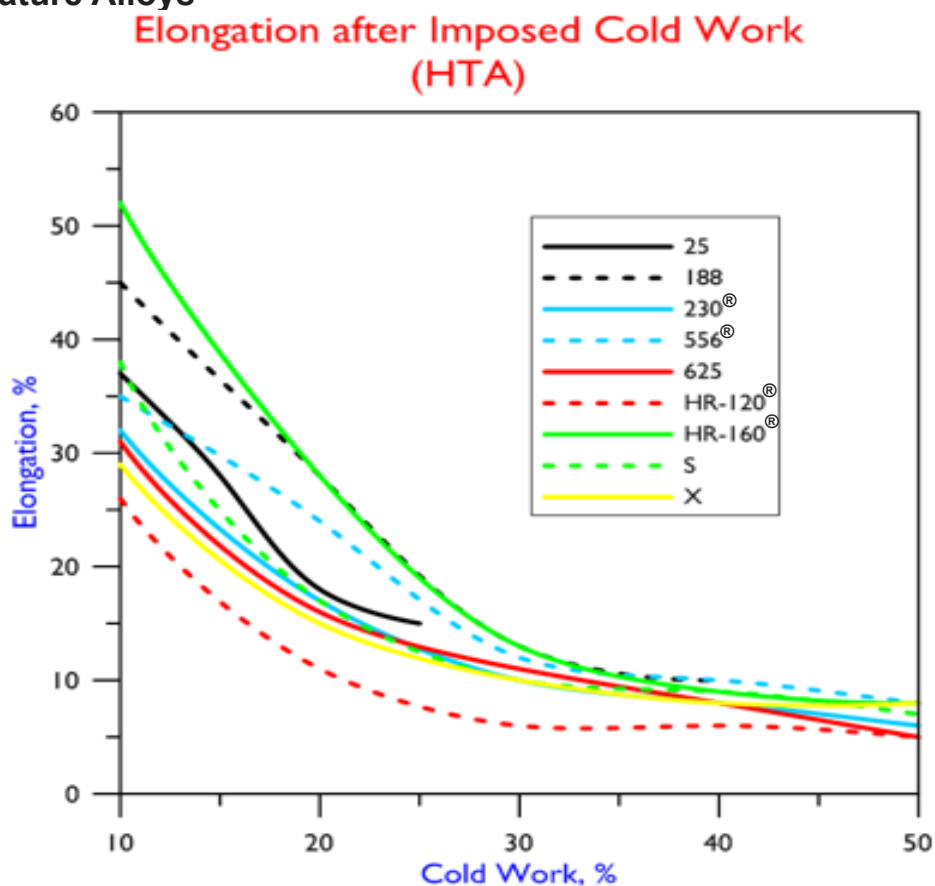


Cold-working Continued

Effect of Cold-Work on Yield Strength: High-temperature Alloys



Effect of Cold-work on Elongation Applicable to: High-temperature Alloys



Cold-working Continued

Generally, as-supplied materials (annealed at the Haynes International mills) have sufficient ductility for mild forming. However, for higher levels of cold deformation, where cracking is a possibility due to a reduction in ductility, a series of successive forming operations is recommended, each followed by an intermediate annealing treatment. Under most circumstances, this should be a solution anneal (the temperatures for which are given in the Heat Treatment section). A final (solution) anneal is recommended after the completion of such successive forming/annealing operations, to restore the material to its optimum condition and properties. This is particularly important for restoring resistance to stress corrosion cracking, in the case of the corrosion-resistant alloys.

However, the annealing of material subjected to low levels of cold-work (less than about 7 to 10% outer fiber elongation) is generally not suggested since it can result in abnormal grain growth, leading to a surface condition known as “orange peel” or “alligator hide”, and significantly affect properties. Please refer to any additional ‘Fabrication and Welding’ information for the specific alloy or contact Haynes International for further guidance.

As discussed below, it is very important that any lubricants, or other foreign matter, be carefully removed from the surfaces of the workpiece prior to any intermediate (or final) annealing treatment, to prevent the diffusion of detrimental elements into the alloy.

It is highly recommended that any scales (i.e. surface films) caused by intermediate annealing treatments be removed prior to the next forming operation by pickling or mechanical means.

Lubrication is a significant consideration for successfully cold-working the HAYNES® and HASTELLOY® alloys. Although lubrication is not normally required for simple bending operations, the use of lubricants may be essential for other forming operations, such as cold-drawing. Mild forming operations can be successfully completed using lard oil or castor oil, which are easily removed. More severe forming operations require metallic soaps or chlorinated/sulfo-chlorinated oils. When sulfo-chlorinated oils are used, the workpiece must be carefully cleaned in a de-greaser or alkaline cleaner, after each step (to prevent sulfur diffusion into the alloy during subsequent annealing).

Lubricants that contain white lead, zinc compounds, or molybdenum disulfide are not recommended because they are difficult to remove and can cause lead, zinc, or sulfur to diffuse into the alloy during subsequent annealing, resulting in severe embrittlement. For the same reason, any die materials, lubricants, or foreign matter should be carefully removed from the work-piece before any intermediate or final annealing treatments.

Cold-working Continued

Bending, Roll-Forming, Roll-Bending, and Press-Braking

Recommended Procedures Applicable to:

Corrosion-resistant Alloys

High-temperature Alloys

HAYNES® and HASTELLOY® sheets and plates are amenable to simple bending, roll-forming, roll-bending, and press-braking operations. Lubrication is not generally required for such operations. Minimum bend radius guidelines are given in the table below, but may vary from alloy to alloy.

Material Thickness		Suggested
in	mm	Minimum Bend Radius*
<0.050	<1.27	1T
0.050-0.187	1.27-4.75	1.5T
0.188-0.500	4.76-12.70	2T
0.501-0.750	12.71-19.05	3T
0.751-1.000	19.06-25.40	4T

*T = Material thickness

Thick sections may require multiple steps, with intermediate annealing treatments to restore ductility. These treatments should be performed in accordance with the recommendations given in the Heat Treatment section, and again care must be taken to clean the surfaces of the work-piece prior to annealing.

Cold-working Continued

Deep Drawing, Stretch Forming, and Hydroforming

Recommended Procedures Applicable to: Corrosion-resistant Alloys High-temperature Alloys

The HAYNES® and HASTELLOY® alloys are amenable to deep drawing, stretch forming, hydro-forming, and such like. Lubrication is generally required for these processes. In the case of the high temperature alloys, fine-grained starting material possessing superior forming characteristics may be available. As with bending operations, thick sections may require multiple steps, with intermediate annealing treatments to restore ductility. These treatments should be performed in accordance with the recommendations given in the Heat Treatment section, and again care must be taken to clean the surfaces of the work-piece prior to annealing.

As a guide to the formability of the high-temperature alloys, Olsen Cup (lubricated) test results are provided below for some of the alloys, along with 310 stainless steel for comparison.

Alloy	Average Olsen Cup Depth*	
	in	mm
25	0.443	11.3
188	0.49	12.4
230®	0.46	11.7
556®	0.48	12.2
625	0.44	11.2
S	0.513	13
X	0.484	12.3
310 Stainless Steel	0.505	12.8

*Average of 3 to 12 measurements on 0.040-0.070 in (1.0-1.75 mm) thick sheet

Cold-working Continued

Spinning and Shear Spinning

Recommended Procedures Applicable to: Corrosion-resistant Alloys High-temperature Alloys

Spinning is a deformation process for 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 the metal occurs, whereas in the latter, metal is thinned as a result of shear forces.

Nearly all HAYNES® and HASTELLOY® alloys can be spin formed, generally at room temperature. The control of quality, including freedom from wrinkles and scratches, in addition to dimensional accuracy, is largely dependent upon 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

Optimum combinations of speed, feed, and pressure are normally determined experimentally when a “new job” is set up. During continuous operation, changes in the temperature of the mandrel and spinning tool 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 of 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 spinning operation might burnish the lubricant into the surface, resulting in detrimental surface effects (due to diffusion of sulfur and/or chlorine) during any subsequent annealing treatments. If these types of lubricant are used accidentally, they should be thoroughly removed (by grinding, polishing, or pickling) prior to any intermediate or final anneal.

The tool material, work-piece design, and surface finish are all very important in achieving trouble-free operation. Mandrels used in spinning must be hard, wear-resistant, and resistant to the fatigue resulting from normal eccentric loading.

As is the case for other cold-forming operations, parts produced by cold spinning should be intermediate and final annealed in accordance with the recommendations in the Heat-Treatment section of this guide.

Cold-working Continued

Tube-forming

Recommended Procedures Applicable to: Corrosion-resistant Alloys High-temperature Alloys

The HAYNES® and HASTELLOY® alloys can be cold formed 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. On the other hand, there are some combinations of tube diameter and wall thickness where a bending radius of twice the tube diameter is possible (from the radius point to the centerline of the tube).

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, then wrinkles, poor ovality, and buckling can occur (in addition to wall thinning).

Punching

Recommended Procedures Applicable to: Corrosion-resistant Alloys High-temperature Alloys

Punching of the HAYNES® and HASTELLOY® alloys is usually performed at room temperature. 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 diameter of the hole.

Punch to Die Clearances per Side	
Annealed Sheet up to 0.125 in (3.2 mm)	3-5% of Thickness
Annealed Sheet or Plate over 0.125 in (3.2 mm)	5-10% of Thickness

Cold-working Continued

Cutting and Shearing

Recommended Procedures Applicable to: Corrosion-resistant Alloys High-temperature Alloys

In view of the high strengths and high work-hardening rates of the HAYNES® and HASTELLOY® alloys (relative to many austenitic stainless steels), band saw cutting is generally ineffective. For flat products, shearing can be successful on “scissor-type” shears rated for carbon steel thicknesses at least 50% above the alloy thickness involved.

Generally, alloy thicknesses up to 0.4375 in (11.1 mm) are shear-able, while thicker material is normally cut by abrasive saw or plasma arc. Abrasive water-jet cutting is not normally recommended, but may be practical in some cases. Bar and tubular products are normally cut using abrasive saws.

Resin-bonded, aluminum oxide wheels are used to successfully cut the HAYNES® and HASTELLOY® alloys. A typical grain and grade designation is 86A361-LB25W EXC-E.

The HAYNES® and HASTELLOY® alloys can be plasma arc cut using any conventional system. The best arc quality is achieved using a mixture of argon and hydrogen gases. Nitrogen gas can be substituted for hydrogen; however, this will result in a cut of reduced quality. Shop air and oxygen-containing gases are unsuitable and should be avoided when plasma cutting these alloys.

Oxy-acetylene cutting of these alloys is not recommended. Air carbon arc cutting is feasible, but subsequent grinding, to remove any carbon contamination, is likely to be required.

Welding and Joining Guidelines

The HASTELLOY® and HAYNES® alloys are known for their good weldability, which is defined as the ability of a material to be welded and to perform satisfactorily in the imposed service environment. The service performance of the welded component should be given the utmost importance when determining a suitable weld process or procedure. If proper welding techniques and procedures are followed, high-quality welds can be produced with conventional arc welding processes. However, please be aware of the proper techniques for welding these types of alloys and the differences compared to the more common carbon and stainless steels. The following information should provide a basis for properly welding the HASTELLOY® and HAYNES® alloys. For further information, please consult the references listed throughout each section. It is also important to review any alloy-specific welding considerations prior to determining a suitable welding procedure.

The most common welding processes used to weld the HASTELLOY® and HAYNES® alloys are the gas tungsten arc welding (GTAW / “TIG”), gas metal arc welding (GMAW / “MIG”), and shielded metal arc welding (SMAW / “Stick”) processes. In addition to these common arc welding processes, other welding processes such as plasma arc welding (PAW), resistance spot welding (RSW), laser beam welding (LBW), and electron beam welding (EBW) are used. Submerged arc welding (SAW) is generally discouraged as this process is characterized by high heat input to the base metal, which promotes distortion, hot cracking, and precipitation of secondary phases that can be detrimental to material properties and performance. The introduction of flux elements to the weld also makes it difficult to achieve a proper chemical composition in the weld deposit.

While the welding characteristics of Ni-/Co-base alloys are similar in many ways to those of carbon and stainless steel, there are some important differences that necessitate the use of different welding techniques. Ni-/Co-base molten weld metal is comparatively “sluggish”, meaning it is not as fluid compared to carbon or stainless steel. In addition to the sluggish nature of the weld pool, Ni- and Co-base alloys exhibit shallow weld penetration characteristics. Therefore, weld joint design must be carefully considered, and proper welding techniques are needed to ensure that there is adequate fusion. Since the oxides that form on the surface of the metal typically melt at much higher temperatures than the Ni-/Co-base alloys being welded, it is especially important that they be removed prior to welding and between passes in multi-pass welds. These important considerations will be discussed in more detail in later sections.

Generally, it is suggested that welding heat input be controlled in the low-to-moderate range. In arc welding, heat input is directly correlated with welding current and arc voltage, and is inversely correlated to travel speed. To achieve successful welding results, it is suggested that relatively low welding currents and slow travel speeds be employed. Stringer bead welding techniques, with some electrode/torch manipulation, are preferred; wide weave beads are not recommended. Preferably, weld beads should be slightly convex, and flat or concave beads that may be acceptable with carbon and stainless steel should be avoided. Both Ni- and Co-base alloys have a tendency to crater crack, so grinding of starts and stops is recommended.

Welding and Joining Guidelines Continued

It is suggested that welding be performed on base materials that are in the annealed condition. Materials with greater than 7% cold work should be solution annealed before welding. The welding of materials with large amounts of residual cold work can lead to cracking in the weld metal and/or the weld heat-affected zone.

Chemical treatments, such as passivation, are normally not required to achieve corrosion resistance in Ni-/Co-base weldments. The solid-solution strengthened alloys can typically be put into service in the as-welded condition. In certain instances, a postweld stress relief may be desirable prior to exposure to certain service environments. Precipitation-strengthened alloys must be heat treated after welding to achieve their full properties.

As a way of achieving quality production welds, development and qualification of welding procedure specifications is suggested. Such welding procedures are usually required for code fabrication, and should take into account parameters such as base and filler metals, weld joint design/geometry, preheat/interpass temperature control, and postweld heat treatment (PWHT) requirements. Haynes International does not develop or provide specific welding procedures. The general welding guidelines and any alloy-specific welding considerations should be used to develop a specific welding procedure.

Weld Joint Design

Selection of a correct weld joint design is critical to the successful fabrication of HASTELLOY® and HAYNES® alloys. Poor joint design can negate even the most optimum welding conditions. The main consideration in weld joint design of Ni-/Co-base alloys is to provide sufficient accessibility and space for movement of the welding electrode or filler metal. Slightly different weld joint geometries are required compared to those for carbon or stainless steel; in particular, a larger included weld angle, wider root opening (gap), and reduced land (root face) thickness are typically required.

The most important characteristic that must be understood when considering weld joint design is that Ni- and Co-base molten weld metal is relatively “sluggish”, meaning that it does not flow or spread out as readily to “wet” the sidewalls of the weld joint. Therefore, care must be taken to ensure that the joint opening is wide enough to allow proper electrode manipulation and placement of the weld bead to achieve proper weld bead tie-in and fusion. The welding arc and filler metal must be manipulated in order to place the molten metal where it is needed. The joint design should allow for the first weld bead to be deposited with a convex surface. An included weld angle or root opening that is too narrow promotes the formation of a concave weld bead that places the weld surface in tension and promotes solidification cracking in the weld metal.

Additionally, weld penetration is significantly less than that of a typical carbon or stainless steel. This characteristic requires the use of reduced land thickness at the root of the joint compared to carbon and stainless steel. Since this is an inherent property of Ni-/Co-base alloys, increasing weld current will not significantly improve their shallow weld penetration characteristics.

Weld Joint Design Continued

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, as shown in Figure 1. Gas tungsten arc welding is often the preferred method for depositing the root pass for square-groove or single-V-groove joints, where there is access to only one side of the joint. 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 weld joint designs for specific situations are shown in Figure 2.

Various welding documents are available to assist in the design of welded joints. Two documents that provide detailed guidance are:

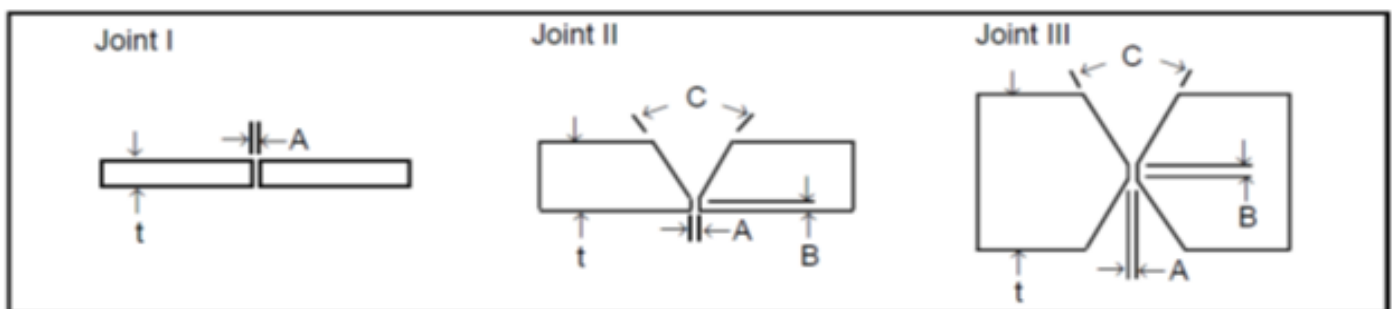
Welding Handbook, Ninth Edition, Volume 1, Welding Science and Technology, Chapter 5, Design for Welding, pg. 157-238, American Welding Society, 2001.

ASM Handbook, Volume 6, Welding, Brazing and Soldering, Welding of Nickel Alloys, pg. 740-751, ASM International, 1993.

In addition, fabrication codes such as the ASME Pressure Vessel and Piping Code may impose design requirements.

The actual number of passes required to fill the weld joint depends upon a number of factors that include the filler metal size (electrode or wire diameter), the amperage, and the travel speed. The estimated weight of weld metal required per unit length of welding is provided in Figure 1.

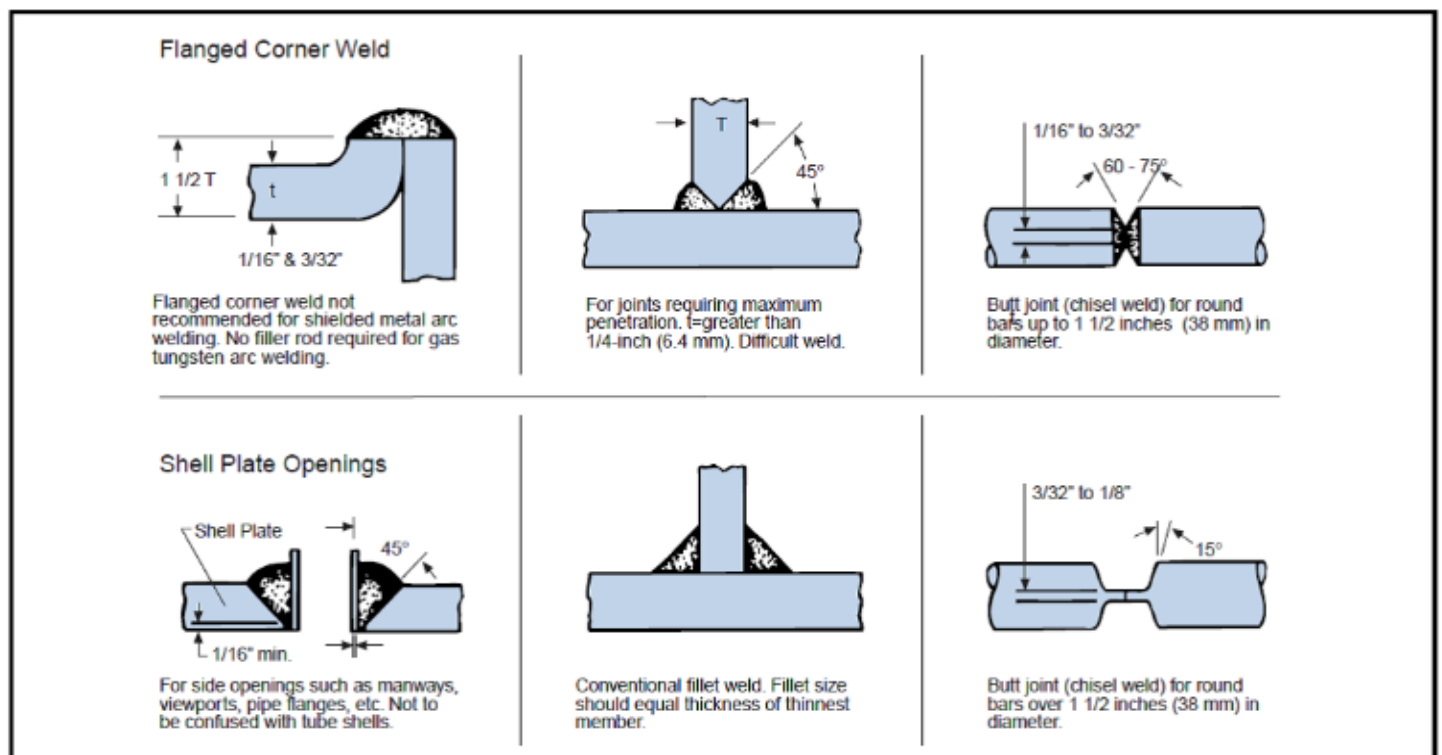
Figure 1: Typical Butt Joints for Manual Welding



Weld Joint Design Continued

Material Thickness (t)		Preferred Joint Design	Root Opening (A)		Land Thickness (B)		Included Weld Angle (C)	Approx. Weight of Weld Metal Required	
in	mm	-	in	mm	in	mm	degrees	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	1/32-3/32 (0.8-2.4)		60-75	0.3	0.45
3/8	9.5	II	1/32-5/32 (0.8-4.0)				60-75	0.6	0.89
1/2	12.7	II					60-75	0.95	1.41
1/2	12.7	III					60-75	0.6	0.89
5/8	15.9	II					60-75	1.4	2.08
5/8	15.9	III					60-75	0.82	1.22
3/4	19.1	II					60-75	1.9	2.83
3/4	19.1	III					60-75	1.2	1.79

Figure 2: Other Weld Joint Designs for Specific Situations



Weld Joint Preparation

Proper preparation of the weld joint is considered a very important part of welding HASTELLOY® and HAYNES® alloys. A variety of mechanical and thermal cutting methods are available for initial weld joint preparation. The plasma arc cutting process is commonly used to cut alloy plate into desired shapes and prepare weld angles. Waterjet cutting and laser beam cutting are also permissible. Edge preparation can be performed using machining and grinding techniques applicable to Ni- and Co-base alloys. Air carbon-arc cutting and gouging are permissible, but generally not suggested due to the very likely possibility of carbon pick-up from the carbon electrode. Not completely removing carbon contamination from the surface could lead to metallurgical issues during subsequent welding or processing. Additionally, high heat input during arc gouging could promote excessive grain growth and reduce material ductility. Thus, plasma arc cutting is generally a better alternative to air carbon-arc cutting and gouging because it does not introduce carbon contamination in the re-solidified layer and requires minimal post-cutting conditioning. The use of oxyacetylene welding and cutting is not recommended because of carbon pick-up from the flame.

It is necessary to condition all cut edges to bright and shiny metal prior to welding. In addition to the weld angle, generally a 1 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 an 80 or 120 grit flapper wheel or disk. The purpose is to have a weld joint surface that is free of oxides, scale, and foreign contaminants. Using a lower grit size abrasive may be desirable, although it should be understood that coarse abrasive scratches could make it difficult to identify fine surface cracks during inspection of the weld joint. The use of progressively higher grit sizes provides a finer surface finish. Liquid/dye penetrant inspection could be more difficult or invalid with a lower grit size surface finish since coarser scratches are more likely to trap penetrant.

Cleanliness is considered an extremely important aspect of Ni-/Co-base weld joint preparation. Prior to any welding operation, the welding surface and adjacent regions should be thoroughly cleaned with an appropriate solvent, such as acetone, or an appropriate alkaline cleaner. All greases, cutting oils, crayon marks, machining solutions, corrosion products, paints, scale, dye penetrant solutions, and other foreign matter should be completely removed. Any cleaning residue should also be removed prior to welding. Contamination of the weld region by lead, sulfur, phosphorus, and other low-melting point elements can lead to severe embrittlement or cracking.

A key difference in the welding characteristics of Ni- and Co-base alloys is the potential for copper-contamination cracking. Due to the relative insolubility of cobalt and copper, even trace amounts of copper inadvertently transferred to the surface of a Co-base alloy can result in copper-contamination cracking, a form of liquid metal embrittlement (LME), in the weld heat-affected zone. For Co-base alloys, surface contact with copper or copper-bearing materials in the weld region should be avoided. Copper jigs and fixtures, especially those typically used in sheet welding, are a possible source of copper contamination. The potential for copper transfer can be minimized by chromium or nickel plating of copper fixtures. Since nickel and copper exhibit near complete solubility, Ni-base alloys are not susceptible to LME or copper-contamination cracking.

Weld Joint Preparation Continued

Surface iron contamination resulting from contact with carbon steel can result in rust staining, but it 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 pool is not expected to significantly affect weld-metal corrosion-resistance. While such contamination is not considered a serious problem, if reasonable care is exercised to avoid the problem, no particular corrective measures should be necessary prior to service.

It is especially important that surface oxides be removed between weld passes or layers in multi-pass welds. Since the melting temperatures of the surface oxides are much higher than the base metals being welded, they are more likely to stay solid during welding and become trapped in the weld pool to form inclusions and incomplete fusion defects. Stainless steel wire brushing is often sufficient for interpass surface cleaning, although light grinding may be necessary to remove thick oxide layers. The wire brushes that are used during welding should be reserved for use on Ni- and Co-base alloys only, and should not have been used for carbon or stainless steel. There will be a stronger tendency to form surface oxides with certain alloys and welding processes, and thicker oxide layers can form during successive passes of multi-pass welds. The grinding of starts and stops is recommended for all arc welding processes. Slag removal during SMAW will require chipping and grinding followed by wire brushing.

Temperature Control and Heat-treatment of Weldments

Preheating of HASTELLOY® and HAYNES® alloys is generally not required. Ambient or room temperature is generally considered a sufficient preheat temperature. However, the alloy base material may require warming to raise the temperature above freezing or to prevent condensation of moisture. For example, condensation may occur if the alloy is brought into a warm shop from cold outdoor storage. In this case, any metal near the weld should be warmed slightly above room temperature to prevent the formation of condensate, which could cause weld metal porosity. Warming should be accomplished by indirect heating if possible, e.g. infrared heaters or natural warming 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 suggested. Care should be taken to avoid local or incipient melting as a result of the warming process.

Interpass temperature refers to the temperature of the weldment just prior to the deposition of an additional weld pass. It is suggested that the maximum interpass temperature be 200°F (93°C). Auxiliary cooling methods may be used to control the interpass temperature; water quenching and rapid air cooling are acceptable. Care must be taken to ensure that the weld zone is not contaminated with traces of oil from air lines, grease/dirt, or mineral deposits from hard water used to cool the weld joint. When attaching hardware to the outside of a thin-walled vessel, it is good practice to provide auxiliary cooling to the inside (process side) of the vessel to minimize the extent of the heat-affected zone.

Under the vast majority of service environments, corrosion-resistant alloys and solid-solution-strengthened high-temperature alloys are used in the as-welded condition, and post-weld heat-treatment (PWHT) of these alloys is generally not required to assure good weldability. Post-weld heat-treatment may be required, or advantageous in certain situations, such as to relieve weld residual stresses. However, stress relief heat-treatments at temperatures commonly used for carbon steels are normally ineffective for these alloys. If PWHT is conducted at these intermediate temperatures, it may result in the precipitation of secondary phases in the microstructure which can have a detrimental effect on material properties, such as corrosion resistance. For most alloys, PWHT in the 1000 to 1500°F (538 to 816°C) temperature range should be avoided. If stress relief heat treatment of attendant carbon steel components is required, contact Haynes International for guidance. In general, the only acceptable PWHT for solid-solution strengthened alloys is a full solution-anneal. The heat-treatment guidelines should be consulted to determine the appropriate solution-annealing temperature for an alloy. Annealing time is normally commensurate with weld joint thickness.

For precipitation-strengthened alloys, PWHT is normally required in order to develop appropriate material/weldment properties. In almost all cases, this involves a full solution-anneal followed by an age hardening heat treatment. Consult the heat-treatment guidelines to determine the appropriate annealing and age-hardening heat-treatment schedule for an alloy.

Welding Defects

A weld discontinuity is defined by the American Welding Society as “an interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics.” Welding defects are a type of discontinuity that compromises the usefulness of a weldment, which could render it unable to meet minimum applicable acceptance standards/specifications. Welding defects can be welding process-/procedure-related, or related to the chemical composition or metallurgy of the alloy(s) being welded.

Weld metal porosity is a cavity-type of welding defect formed by gas entrapment during solidification as a result of contamination by certain gases, such as hydrogen, oxygen, or nitrogen. Porosity caused by hydrogen pickup can be minimized by keeping the weld joint area and filler metal free of hydrocarbon contaminants and moisture. To avoid porosity caused by oxygen and nitrogen, it is important that the weld pool is properly shielded through the use of high purity shielding gases, and sufficient shielding gas flow rates are being utilized. Although porosity can occur in HASTELLOY® and HAYNES® weldments, they are not particularly susceptible to porosity since most alloys contain a significant amount of Cr, which has a natural affinity for the gases that are formed during welding.

Weld metal inclusions can form as a result of oxides that become trapped in the weld pool. This can occur from the tenacious oxide film that forms on the surface of most alloys. Since the melting temperatures of surface oxides are usually much higher than the base metal, they are more likely to stay solid during welding and become trapped in the weld pool. Thus, it is especially important that surface oxides be removed prior to welding and between passes in multi-pass welds. During GTAW, if the tungsten electrode accidentally contacts the molten weld pool or if there is excessive weld current, tungsten inclusions can be produced in the weld metal. Elements with a strong affinity for oxygen, such as aluminum or magnesium, can combine with oxygen to form oxide inclusions in the weld metal. Slag inclusions are associated with flux-based processes such as SMAW, SAW, and FCAW. These inclusions form in the weld metal when residual slag becomes entrapped in cavities or pockets that form due to inadequate weld bead overlap, excessive undercut at the weld toe, or an uneven surface profile of the preceding weld bead. Thus, an important consideration in flux-based processes is the ease with which the slag can be removed between weld passes. Inclusions must be ground out from the weld or they will act to initiate fracture prematurely, which can have a detrimental effect on mechanical properties and service performance.

Other common process-related defects that are encountered are undercut, incomplete fusion/penetration, and distortion. These defects are generally attributed to improper welding technique and/or welding parameters. Undercut is a groove that is melted into the base metal, usually at the root or toes of the weld, and can occur due to excessive welding current. This discontinuity creates a notch at the periphery of the weld and can significantly weaken the strength of the weldment. Incomplete fusion defects are promoted by the “sluggish” nature of Ni-/Co-base molten weld metal and their poor weld penetration characteristics.

Welding Defects Continued

Distortion characteristics of the HASTELLOY® and HAYNES® alloys are similar to those of carbon steel, with less tendency to distort than austenitic stainless steel weldments due to their lower coefficient of thermal expansion. Jigs, fixturing, cross supports, bracing, and weld bead placement and 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 in order to achieve final dimensions. Weld distortion for different joint designs are shown in Figure 3.

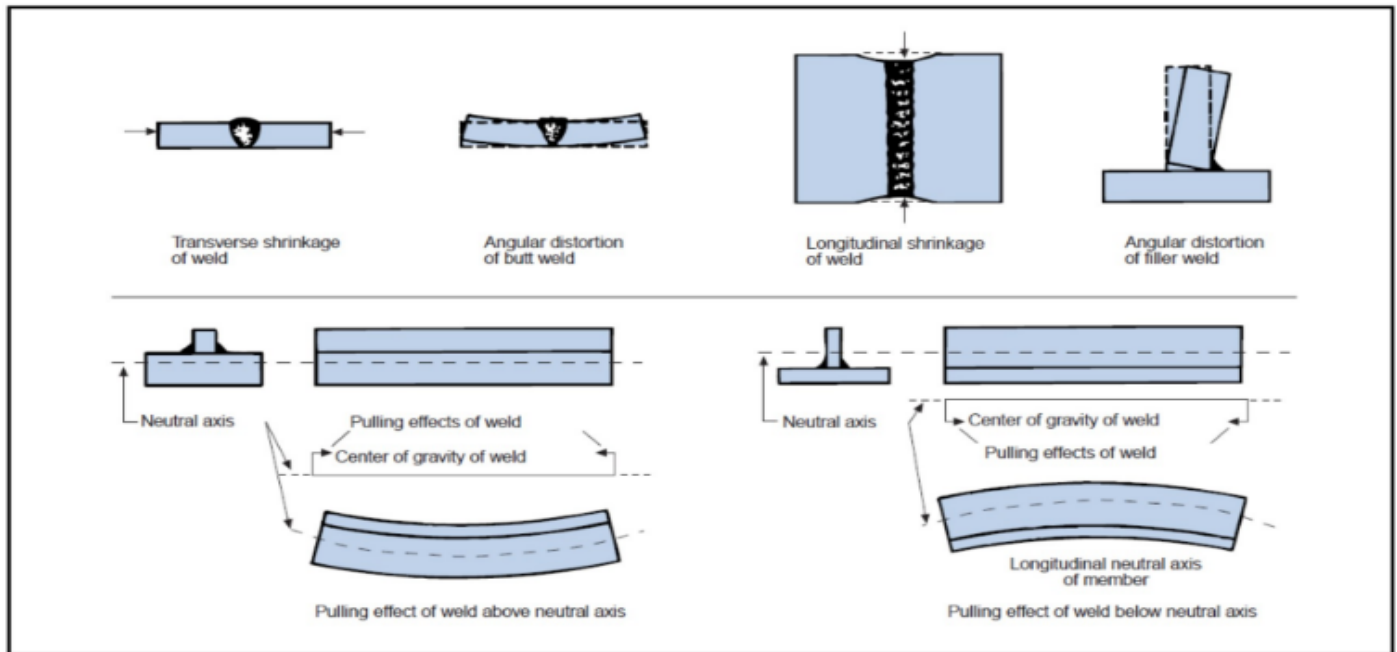
During normal fabrication of HASTELLOY® and HAYNES® alloys, weld-cracking is rare and one should expect to fabricate large, complex components with few instances of cracking. The most common type of weld-cracking encountered is hot-cracking, which is associated with the presence of liquid in the microstructure. Hot-cracking can occur in the weld metal and heat-affected zone of a weld, and usually results from liquid films along grain boundaries. These strain-intolerant microstructures temporarily occur at elevated temperatures within the melting and solidification range of all alloys. Due to their nominal chemical composition, certain alloys are more susceptible to hot-cracking than other alloys. In general, hot-cracking is a more common occurrence with high-temperature alloys due to their higher alloy content. Impurity elements, such as sulfur and phosphorus, and minor alloying additions, such as boron and zirconium, can have a strong influence on cracking susceptibility even though they are present in very low concentrations.

In addition to a susceptible microstructure, the level of tensile stress on the weld is a critical factor for hot-cracking. The development of stress is inevitable during welding because of the complex thermal stresses that are created when metal solidifies and cools. This is in part related to the inherent restraint placed on the weldment due to weld-joint geometry and thickness. In general, weldments with increased joint thickness are more susceptible to hot-cracking. Additionally, a “teardrop-shaped” weld pool created due to fast travel speed tends to increase cracking susceptibility since it produces a distinct weld centerline where elemental segregation is enhanced and transverse stresses can be high. Large concave weld beads that place the weld surface in tension tend to promote solidification cracking and should be avoided. Further information about weld-cracking mechanisms and welding metallurgy of Ni-base alloys can be found in the following textbook:

J.N. DuPont, J.C. Lippold, and S.D. Kiser, Welding Metallurgy and Weldability of Nickel-Base Alloys, John Wiley & Sons, Inc., 2009.

Welding Defects Continued

Figure 3: Weld Distortion for Different Joint Designs



Post-weld Inspection and Repair

In order to determine the suitability of the weldment for its intended purpose, some degree of nondestructive examination/testing (NDE/NDT) should be conducted as part of sound fabrication practice and quality assurance. For non-code fabrication, NDE may be as simple as visual or liquid/dye penetrant inspection. For code fabrication, certain mandatory inspections may be required. These NDE methods should be considered for both intermediate inspections during multi-pass welding, as well as for final acceptance of the weldment.

NDE methods are similar to those used for carbon and stainless steels. Liquid/dye penetrant inspection is commonly used to reveal surface defects, such as hot-cracking. Radiographic and ultrasonic testing can be used to detect for subsurface defects and thoroughly check the soundness of the weldment; however, the results can be difficult to interpret and these methods are generally not well suited for inspection of fillet welds. Magnetic particle inspection is not an effective NDE method for Ni-/Co-base alloys since they are non-magnetic. If further information is required, it is suggested that the fabricator consult with an outside laboratory that is experienced with NDE of Ni-/Co-base alloy welds.

Welding defects that are believed to affect quality or mechanical integrity should be removed and repaired. Removal techniques include grinding, plasma arc gouging, and air carbon-arc gouging. As explained previously in the weld joint preparation section, extreme care must be exercised during air carbon-arc gouging to insure that carbon contamination of the weld joint area does not occur. It is suggested that the prepared cavity is liquid/dye penetrant inspected to insure that all objectionable defects have been removed. The repair cavity should then be thoroughly cleaned prior to any welding repair. Since Ni-/Co-base alloys have low weld penetration characteristics, the ground cavity must be broad enough and have sufficient sidewall clearance in the weld groove to allow for weld electrode/bead manipulation. The technique of "healing" or "washing out" cracks and defects by autogenously re-melting weld beads, or by depositing additional filler metal over the defect, is not recommended.

Gas Tungsten Arc Welding (GTAW / “TIG”)

The gas tungsten arc welding (GTAW) process is a very versatile, all-position welding process that is widely used to join Ni-/Co-base alloys. In GTAW, the heat for welding is generated from an electric arc established between a non-consumable tungsten electrode and the workpiece. GTAW can be performed manually or adapted to automatic equipment, and can be used in production as well as repair welding situations. It is a process that offers precise control of welding heat, and is therefore routinely used for welding thin base metal and depositing root passes of thicker section welds. The major drawback of the GTAW process is productivity, as weld metal deposition rates during manual welding are low.

Two percent thoriated tungsten electrodes (AWS A5.12 EWTh-2) have been traditionally used for GTAW of Ni-/Co-base alloys, but now other compositions are becoming more common due to possible health concerns associated with EWTh-2 and other thoriated tungsten electrodes. The thorium oxide contained in the EWTh-2 electrode is a low-level radioactive material that presents a small external radiation hazard and an internal hazard from ingestion or inhalation. The greatest risk for a welder is associated with the inhalation of radioactive dust while grinding the tungsten electrode tip to maintain the desired conical shape. Consequently, it is necessary to use local exhaust ventilation to control the dust at the source, complemented if necessary by respiratory protective equipment, and precautions must be taken in order to control any risks of exposure during the disposal of dust from grinding devices. As a result of these health concerns, thoriated tungsten electrodes are being phased out by certain governing bodies and organizations. Fortunately, there are alternatives that provide comparable performance to EWTh-2, including two percent ceriated (AWS A5.12 EWCe-2) and lanthanated (AWS A5.12 EWLa-2) electrodes. For further information on the different types of tungsten electrodes, the reader is referred to: AWS A5.12/A5.12M, Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting, American Welding Society.

The diameter of the tungsten electrode should be selected according to weld joint thickness and filler wire diameter. It is suggested that the electrode be ground to a cone shape (included angle of 30 to 60 degrees) with a small flat of 0.040 to 0.060 in (1.0 to 1.5 mm) ground at the point. See Figure 4 for the suggested tungsten electrode geometry.

Welding-grade argon shielding gas with a 99.996% minimum purity is suggested for most welding situations. Helium, or mixtures of argon/helium or argon/hydrogen may be advantageous in certain situations, such as high travel speed, highly mechanized welding operations, in order to increase weld penetration. Shielding gas flow rates are critical; too low of a rate will not provide adequate protection of the weld pool, while too high of a rate can increase turbulence and aspirate air. Typically, flow rates for 100%Ar shielding gas are in the 20 to 30 cubic feet per hour (CFH) (9 to 14 L/min) range. Generally, the shielding gas cup should be as large as practical so that the shielding gas can be delivered at lower velocity. It is also recommended that the welding torch be equipped with a gas lens in order to stabilize the gas flow and provide optimum shielding gas coverage. While welding-grade shielding gases are of a very high purity, even a small amount of air can compromise the protective shielding and cause weld metal oxidation/discoloration and porosity. This can be caused by air movement from fans, cooling systems, drafts, etc., or from leakage of air into the shielding due to a loose gas cup or other welding torch components. When proper shielding is achieved, the as-deposited weld metal should typically have a bright-shiny appearance and require only minor wire brushing between passes.

Gas Tungsten Arc Welding (GTAW / “TIG”) Continued

In addition to welding torch shielding gas, a back-purge at the root side of the weld joint with welding-grade argon is suggested. The flow rates are normally in the range of 5 to 10 CFH (2 to 5 L/min). Copper backing bars are often used to assist in weld bead shape on the root side of the weld. 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 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. Under these open-butt welding conditions, the torch flow rates are reduced to approximately 10 CFH (5 L/min) and the back purge flow rates are increased to about 40 CFH (19 L/min). Detailed information concerning back-purging during pipe welding is available from Haynes International upon request.

It is recommended that the welding torch be held essentially perpendicular to the work-piece, with the work angle at 90° from the horizontal and only a slight travel angle of 0° to 5°. If a large drag angle is utilized, air may be drawn into the shielding gas and contaminate the weld. The arc length should be maintained as short as possible, especially during autogenous welding. Stringer bead techniques, or narrow weave techniques, using only enough current to melt the base material and allow proper fusion of the filler, are recommended. Filler metal should be added carefully at the leading edge of the weld pool to avoid contact with the tungsten electrode. During welding, the tip of the welding filler metal should always be held under the shielding gas to prevent oxidation. Pausing or “puddling” the weld pool adds to the weld heat input and is not recommended.

Electrical polarity for the GTAW process should be direct current electrode negative (DCEN / “straight polarity”). Typical manual GTAW parameters for welding HASTELLOY® and HAYNES® alloys are provided in Table 1. The parameters should be viewed as approximate values that are ultimately dependent on many other factors, including the particular welding power source, weld joint geometry, and welder skill level. Thus, it is suggested that the parameters be used as a guideline for developing a specific welding procedure. Smaller diameter filler wire is suggested for depositing root passes. A power source equipped with high-frequency start, pre-purge/post-purge and up-slope/down-slope (or foot pedal) controls is highly recommended. Weld travel speed has a significant influence on the quality of Ni-/Co-base welds, and is typically lower than for carbon and stainless steel. The suggested travel speed for manual GTAW is 4 to 6 inches per minute (ipm) / 100 to 150 mm/min.

Gas Tungsten Arc Welding (GTAW / “TIG”) Continued

Figure 4: Tungsten Electrode Geometry

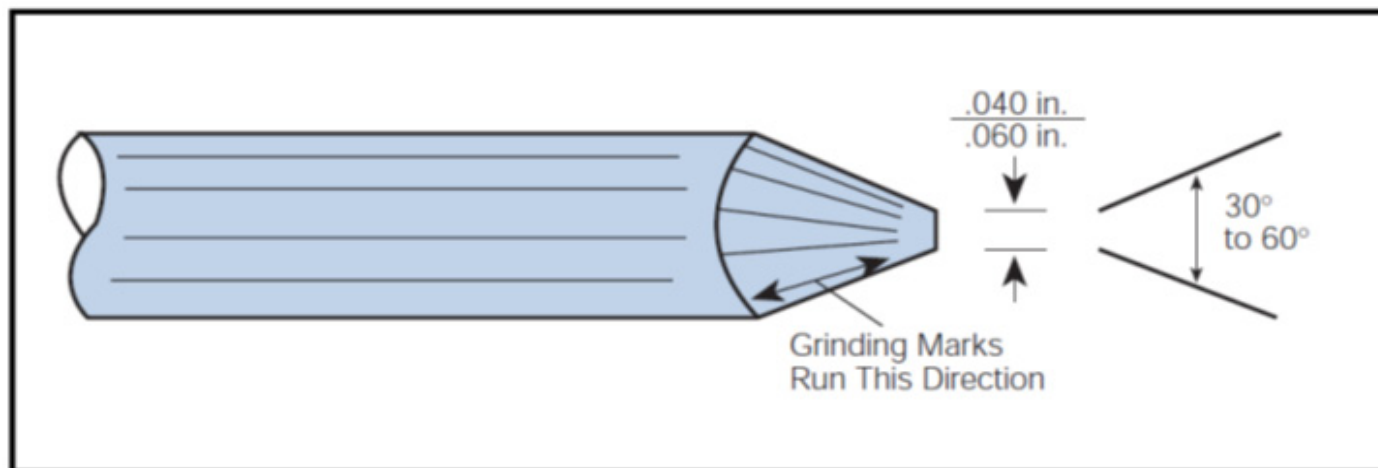


Table 1: Typical Manual Gas Tungsten Arc Welding Parameters (Flat Position)

Joint Thickness		Tungsten Electrode Diameter		Filler Wire Diameter		Welding Current	Arc Voltage
in	mm	in	mm	in	mm	Amps	Volts
0.030-0.062	0.8-1.6	0.062	1.6	0.062	1.6	15-75	9-15
0.062-0.125	1.6-3.2	0.062/0.093	1.6/2.4	0.062/0.093	1.6/2.4	50-125	9-15
0.125-0.250	3.2-6.4	0.093/0.125	2.4/3.2	0.093/0.125	2.4/3.2	100-175	12-18
> 0.250	>6.4	0.093/0.125	2.4/3.2	0.093/0.125	2.4/3.2	125-200	12-18

Gas Metal Arc Welding (GMAW / “MIG”)

The gas metal arc welding (GMAW / “MIG”) process utilizes an electric arc established between a consumable wire electrode and the workpiece. GMAW can be implemented as a manual, semi-automatic, or automatic process, and the flexibility offered by the various process variations is advantageous in many applications. GMAW provides a considerable increase in weld metal deposition rates compared to GTAW or SMAW, and when implemented as a semi-automatic process, less welder skill is typically required. However, GMAW equipment is more complex, less portable, and generally requires more routine maintenance than for the GTAW and SMAW processes. GMAW is the most common process for welding corrosion-resistant alloys and for performing thick-section welds.

In GMAW, the mechanism by which the molten metal at the end of the wire electrode is transferred to the workpiece has a significant effect on the weld characteristics. Three modes of metal transfer are possible with GMAW: short-circuiting transfer, globular transfer, and spray transfer. In addition, there is a variation of the spray transfer mode called pulsed spray.

Electrical polarity for GMAW of HASTELLOY® and HAYNES® alloys should be direct current electrode positive (DCEP / “reverse polarity”). Typical parameters for different GMAW transfer modes are provided in Table 2 for flat position welding. Since different GMAW power sources vary greatly in design, operation, and control systems, the parameters should be viewed as an estimated range for achieving proper welding characteristics with specific welding equipment. GMAW travel speeds are typically 6 to 10 inches per minute (ipm) / 150 to 250 mm/min.

Gas Metal Arc Welding (GMAW / “MIG”) Continued

Short-circuiting transfer occurs at the lowest current and voltage ranges, which results in low weld heat input. It is typically used with smaller diameter filler wire, and produces a relatively small and easily controlled weld pool that is well-suited for out-of-position welding and joining thin sections. However, the low heat input makes short-circuiting transfer susceptible to incomplete fusion (cold lap) defects, especially when welding thick sections or during multipass welds.

Globular transfer occurs at higher current and voltage levels than short-circuiting, and is characterized by large, irregular drops of molten metal. The globular transfer mode can theoretically be used to weld Ni-/Co-base alloys, but is seldom used because it creates inconsistent penetration and uneven weld bead contour that promotes the formation of defects. Since the force of gravity is critical for drop detachment and transfer, globular transfer is generally limited to flat position welding.

Spray transfer occurs at the highest current and voltage levels, and is characterized by a highly directed stream of small metal droplets. It is a high heat input process with relatively high deposition rates that is most effective for welding thick sections of material. However, it is mainly useful only in the flat position, and its high heat input promotes weld hot-cracking and the formation of secondary phases in the microstructure that can compromise service performance.

Pulsed spray transfer is a highly controlled variant of spray transfer, in which the welding current alternates between a high peak current, where spray transfer occurs, and a lower background current. This results in a stable, low-spatter process at an average welding current significantly below that for spray transfer. Pulsed spray offers lower heat input compared to spray transfer, but is less susceptible to the incomplete fusion defects that are common to short-circuiting transfer. It is useful in all welding positions and for a wide range of material thickness. In most situations, Haynes International highly encourages the use of pulsed spray transfer for GMAW of HASTELLOY® and HAYNES® alloys. The use of a modern power source with synergic control and the provision for waveform adjustment (“adaptive pulse”) is highly beneficial for pulsed spray transfer. These advanced technologies have facilitated the use of pulsed spray transfer, in which pulse parameters such as pulse current, pulse duration, background current, and pulse frequency are included in the control system and linked to the wire feed speed.

Gas Metal Arc Welding (GMAW / “MIG”) Continued

Shielding gas selection is critical to GMAW procedure development. For Ni-/Co-base alloys, the protective shielding gas atmosphere is usually provided by argon or argon mixed with helium. The relatively low ionization energy of argon facilitates better arc starting/stability and its low thermal conductivity provides a deeper finger-like penetration profile. If used alone, helium creates an unsteady arc, excessive spatter, and a weld pool that can become excessively fluid, but when added to argon, it provides a more fluid weld pool that enhances wetting and produces a flatter weld bead. Additions of oxygen or carbon dioxide, while commonly used with other metals, is to be avoided when welding Ni-/Co-base alloys. These additions produce a highly oxidized surface and promote weld metal porosity, irregular bead surfaces, and incomplete fusion defects. The optimum shielding gas mixture is dependent on many factors, including weld joint design/geometry, welding position, and desired penetration profile. In most instances, a mixture of 75% Ar and 25% He is suggested; good results have been obtained with helium contents of 15 to 30%. During short-circuiting transfer, the addition of helium to argon helps to avoid overly convex weld beads that can lead to incomplete fusion defects. For spray transfer, good results can be obtained with pure argon or argon-helium mixtures. The addition of helium is generally required for pulsed spray transfer as it greatly enhances wetting.

Since argon and helium are inert gases, the as-deposited weld surface is expected to be bright and shiny with minimal oxidation. In this case, it is not mandatory to grind between passes during multipass welding. However, some oxidation or "soot" may be noted on the weld surface. If so, heavy wire brushing and/or light grinding/conditioning (80 grit) between weld passes is suggested in order to remove the oxidized surface and ensure the sound deposit of subsequent weld beads. Shielding gas flow rates should generally be in the 25 to 45 CFH (12 to 21 L/min) range. A flow rate that is too low does not provide adequate shielding of the weld, while excessively high flow rates can interfere with the stability of the arc. As with GTAW, back-purge shielding is recommended to ensure the root side of the weld joint does not become heavily oxidized. If back-purge shielding is not possible, the root side of the weld joint should be ground after welding to remove all oxidized weld metal and any welding defects. The weld joint can then be filled from both sides as needed.

During GMAW, the welding gun should be held perpendicular to the work-piece at both a work angle and travel angle of approximately 0°. A very slight deviation from perpendicular may be necessary for visibility. If the gun is positioned too far from perpendicular, oxygen from the atmosphere may be drawn into the weld zone and contaminate the molten weld pool. A water-cooled welding gun is always recommended for spray transfer welding and anytime higher welding currents are being utilized.

It should be recognized that some parts of the GMAW equipment, such as the contact tip and filler wire conduit/liner, experience high wear and should be replaced periodically. A worn or dirty liner can cause erratic wire feed that will result in arc instability, or cause the filler wire to become jammed, a situation known as a “bird nest”. It is recommended that sharp bends in the gun cable be minimized. If possible, the wire feeder should be positioned so that the gun cable is nearly straight during welding.

Gas Metal Arc Welding (GMAW / “MIG”) Continued

Table 2: Typical Gas Metal Arc Welding Parameters (Flat Position)

Wire Diameter		Wire Feed Speed		Welding Current	Average Arc Voltage	Shielding Gas
in	mm	ipm	mm/s	Amps	Volts	-
Short-Circuiting Transfer Mode						
0.035	0.9	150-200	63-85	70-90	18-20	75Ar-25He
0.045	1.1	175-225	74-95	100-160	19-22	75Ar-25He
Spray Transfer Mode						
0.045	1.1	250-350	106-148	190-250	28-32	100Ar
0.062	1.6	150-250	63-106	250-350	29-33	100Ar
Pulsed Spray Transfer Mode*						
0.035	0.9	300-450	127-190	75-150 Avg.	30-34	75Ar-25He
0.045	1.1	200-350	85-148	100-175 Avg.	32-36	75Ar-25He

*Detailed pulsed spray parameters are available upon request

Shielded Metal Arc Welding (SMAW / “Stick”)

The shielded metal arc welding (SMAW / “Stick”) process generates an arc between a flux-coated consumable electrode and the work-piece. SMAW is well known for its versatility because it can be used in all welding positions, and in both production and repair welding situations. It is one of the simplest welding processes in terms of equipment requirements and can be easily operated in remote locations. However, it is strictly a manual welding process that generally requires a high welder skill level. In addition, it is typically restricted to material thickness greater than approximately 0.062 in (1.6 mm).

HASTELLOY® and HAYNES® coated electrodes for SMAW undergo a number of qualification tests to determine the usability of the electrode, the chemical composition of the weld deposit, and the soundness and mechanical properties of the weld metal. Coated electrodes are generally formulated to produce a weld deposit with a chemical composition that corresponds to that of the matching base metal. The coating formulations are generally classified as slightly basic to slightly acidic depending on the particular alloy. For further information on the requirements for the classification of Ni-base coated electrodes, the reader is referred to: AWS A5.11/A5.11M, Specification for Nickel and Nickel-Alloy Welding Electrodes for Shielded Metal Arc Welding, American Welding Society.

Prior to their use, coated electrodes should remain sealed in a moisture-proof canister. After the canister has been opened, all coated electrodes should be stored in an electrode storage oven. It is recommended that the electrode storage oven be maintained at 250 to 400°F (121 to 204°C). If coated electrodes are exposed to an uncontrolled atmosphere, they can be reconditioned by heating in a furnace at 600 to 700°F (316 to 371°C) for 2 to 3 hours.

Shielded Metal Arc Welding (SMAW / “Stick”) Continued

Typical SMAW parameters are presented in Table 3 for flat position welding. While the coated electrodes are classified as AC/DC, in almost all situations electrical polarity should be direct current electrode positive (DCEP / “reverse polarity”). For maximum arc stability and control of the molten pool, it is important to maintain a short arc length. The electrode is generally directed back toward the molten pool (backhand welding) with about a 20° to 40° drag angle. Even though stringer bead welding techniques are generally preferred, some electrode manipulation and weaving may be required to place the molten weld metal where it is needed. The amount of weave is dependent on weld joint geometry, welding position, and type of coated electrode. A rule of thumb is that the maximum weave width should be about three times the electrode core wire diameter. Once deposited, weld beads should preferably exhibit a slightly convex surface contour. Appropriate welding current is based on the diameter of the coated electrode. When operated within the suggested current ranges, the electrodes should exhibit good arcing characteristics with minimum spatter. The use of excessive current can lead to overheating of the electrode, reduced arc stability, spalling of the electrode coating, and weld metal porosity. Excessive spatter is an indication that arc length is too long, welding current is too high, polarity is not reversed, or there has been absorption of moisture by the electrode coating. The suggested travel speed for SMAW is 3 to 6 inches per minute (ipm) / 75 to 150 mm/min.

SMAW of Ni-base alloys is not well suited for out-of-position welding and generally only feasible with 0.093 in (2.4 mm) and 0.125 in (3.2 mm) diameter electrodes. During out-of-position welding, the amperage should be reduced to the low end of the suggested range in Table 3. In order to keep the bead profile relatively flat during vertical welding, a weave bead technique is necessary. Using 0.093 in (2.4 mm) electrodes will reduce the weave width that is required and produce flatter beads. In vertical welding, a range of electrode positions is possible from forehand (up to 20° push angle) to backhand welding (up to 20° drag angle). In overhead welding, backhand welding (drag angle of 0° to 20°) 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 certain alloys, such as HASTELLOY® B-3® alloy. 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 weld 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 weld starts and stops be ground to sound weld metal.

The slag formed on the weld surface should be completely removed. This can be accomplished by first chipping with a welding/chipping hammer, then brushing the surface with a stainless steel wire brush. In multi-pass welds, it is essential that all slag is removed from the last deposited weld bead before the subsequent bead is deposited. Any remaining weld slag can compromise the corrosion resistance of the weldment.

Shielded Metal Arc Welding (SMAW / “Stick”) Continued

Table 3: Typical Shielded Metal Arc Welding Parameters (Flat Position)

Electrode Diameter		Arc	Welding
		Voltage	Current
in	mm	Volts	Amps
0.093	2.4	22-25	45-75
0.125	3.2	22-25	75-110
0.156	4	23-26	110-150
0.187	4.7	24-27	150-180

Plasma Arc Welding (PAW)

The plasma arc welding (PAW) process is a gas-shielded process that utilizes a constricted arc between a non-consumable tungsten electrode and the workpiece. The transferred arc possesses high energy density and plasma jet velocity. Two distinct operating modes are possible, referred to as melt-in-mode and keyhole mode. The melt-in-mode utilizes lower welding current and generates a weld pool similar to that formed in GTAW, whereby a portion of the workpiece material under the arc is melted. In the keyhole mode, higher welding current is utilized so that the arc fully penetrates the workpiece material to form a concentric hole through the joint thickness. The molten weld metal solidifies behind the keyhole as the torch traverses the workpiece. Shielding of the weld pool is provided by the ionized plasma gas that is issued from the torch orifice, which is supplemented by an auxiliary source of shielding gas. The PAW process can be utilized with or without a filler metal addition.

Since the constricted arc of PAW allows for greater depth of fusion compared to GTAW, PAW is potentially advantageous for autogenous welding (i.e. without the use of filler metal) of Ni-/Co-base material in the thickness range of approximately 0.125 to 0.3 in (3.2 to 7.6 mm). In comparison, filler metal is typically required for GTAW of material greater than about 0.125 in (3.2 mm) thickness. Square-groove weld joints can be utilized up to about 0.3 in (7.6 mm) thickness. While it is possible to weld a wide range of thicknesses with PAW, better results can usually be achieved with other welding processes for thicknesses outside of the 0.125 to 0.3 in (3.2 to 7.6 mm) range. For joint thicknesses greater than 0.3 in (7.6 mm), autogenous keyhole welding can be utilized for the first pass, followed by non-keyhole (melt-in) PAW with filler metal. Another welding process, such as GTAW, could also be utilized for the second and succeeding passes.

Plasma Arc Welding (PAW) Continued

Electrical polarity for the PAW process should be direct current electrode negative (DCEN / “straight polarity”). A proper balance must be achieved between welding current, gas flow, and travel speed to provide consistent keyhole welding. An unstable keyhole can result in turbulence in the weld pool. Argon or argon-hydrogen mixtures are normally utilized for the orifice gas and shielding gas. The orifice gas has a strong effect on the penetration depth and profile. Small amounts of hydrogen (~5%) are typically sufficient to increase the arc energy for autogenous keyhole welding, and higher amounts can lead to porosity in the weld metal. For greater joint thicknesses, increased orifice gas flow and upslope of the welding current may be required to initiate the keyhole. To fill the keyhole cavity at the end of the weld, decreased orifice gas flow and downslope of the welding current may be required. Higher travel speeds require higher welding currents to obtain keyhole welding. Excessive travel speeds can produce undercut, which is a groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal. The welding torch should be held essentially perpendicular to the work piece in both the longitudinal and transverse directions, and maintained on the centerline of the weld joint. Even a slight deviation from this condition can cause incomplete fusion defects in the weld metal.

Electron Beam Welding (EBW) and Laser Beam Welding (LBW)

The electron beam welding (EBW) and laser beam welding (LBW) processes are high-energy density welding processes that offer several possible advantages, including low welding heat input, high weld depth-to-width ratio, narrow heat-affected zone (HAZ), and reduced distortion. To impinge on the weld joint and produce coalescence, EBW utilizes a moving concentrated beam of high-velocity electrons, while LBW utilizes the heat from a high-density coherent laser beam.

Most Ni-/Co-base alloys that can be joined with conventional arc welding processes can also be successfully joined via EBW and LBW. These beam welding processes are even considered more suitable for alloys that are difficult to arc weld and can provide better overall weld properties compared to arc welding. The low welding heat input results in a shorter time spent in the solidification temperature range and relatively fast cooling rates, which suppresses precipitation of secondary phases during weld solidification.

Electron Beam Welding (EBW) and Laser Beam Welding (LBW) Continued

Weld joint preparation and fit-up are especially important for the EBW and LBW processes. In most cases, a square butt joint design is utilized. Although filler metal is not normally added to the weld pool, it can be added via bare wire. EBW generally needs to be performed in a vacuum environment without the use of shielding gas, which provides excellent protection against atmospheric contamination. LBW is normally performed with argon or helium shielding gases to prevent oxidation of the molten weld pool. Porosity can be a weldability issue due to the rapid solidification rates and deep weld pools that do not readily allow for dissolved gases to escape; this effect is exacerbated by high weld travel speeds. Oscillation or agitation of the weld pool by weaving the beam may provide the time necessary to help gases escape the weld pool and reduce porosity. Susceptibility to liquation cracking in the 'nail-head' region of the HAZ is promoted by the stress/strain state in this region. Slower weld travel speeds produce a shallower temperature gradient in the HAZ and are beneficial towards reducing liquation cracking susceptibility.

For detailed information on EBW, please refer to: AWS C7.1M/C7.1, Recommended Practices for Electron Beam Welding and Allied Processes.

For detailed information on LBW, please refer to: AWS C7.2M, Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes.

Brazing and Soldering

Brazing

Brazing refers to a group of joining processes that produces the coalescence of materials by heating them to the brazing temperature in the presence of a brazing filler metal having a liquidus above 840°F (450°C) and below the solidus of the base metal, i.e. without melting of the base metal. The liquidus, or melting point, is the lowest temperature at which a metal or an alloy is completely liquid, and the solidus is the highest temperature at which a metal or an alloy is completely solid. Brazing is characterized by the distribution of a brazing filler metal between the closely fitted faying surfaces of the joint. With the application of heat, the brazing filler metal flows by capillary action, and is melted and re-solidified to form a metallurgical bond between the surfaces at the joint. Furnace brazing is the usual method of brazing Ni-/Co-base alloys, especially when high-temperature brazing filler metals are employed, and the information that follows will focus on furnace brazing.

The keys to successful brazing of Ni-/Co-base alloys are:

- Thorough cleaning and preparation of base metal surfaces
- Proper filler metal selection for the intended application
- Proper fit-up and freedom from restraint during brazing
- Proper atmospheric protection during brazing
- Minimal thermal exposure to avoid secondary precipitation in the base metal

Brazing and Soldering Continued

Base Metal Surface Preparation

All forms of contamination such as dust, paint, ink, chemical residues, oxides, and scale must be removed from part surfaces prior to brazing. Otherwise, the molten brazing material will have difficulty "wetting" and flowing along the surface of the base metal. Surfaces must be cleaned by solvent scrubbing or degreasing and then by mechanical cleaning or pickling. Tenacious surface oxides and scales may require grinding. Once cleaned, the parts should be assembled as soon as possible using clean gloves to prevent subsequent contamination. It is important to note that proper cleaning techniques should be used on the entire component assembly prior to brazing, not just the surfaces being brazed.

Some high-temperature alloys may benefit from the application of a thin nickel flashing layer before brazing, particularly those alloys containing higher aluminum and titanium contents. This layer is normally applied by electroplating; electroless nickel deposits using nickel-phosphorus alloys are not recommended. Flashing layer thicknesses of up to about 0.001 in (0.025 mm) maximum are normally employed, depending upon the specific base metal alloy and the specific joint geometry.

Brazing Filler Metal Selection

Proper selection of a brazing filler metal for the intended application depends upon a number of factors, including component design, base metal alloy(s), and service environment. Brazing filler metals are typically classified according to chemical composition. HASTELLOY® and HAYNES® alloys may be successfully brazed using a variety of nickel-, cobalt-, silver-, copper-, and gold-based filler metals; some of the possible brazing filler metals are listed in Table 4. The exact alloying content of the brazing filler metal determines the temperature range between the liquidus and solidus, i.e. the melting temperature range. The magnitude of the melting temperature range indicates the potential filling capability, and a brazing filler metal with a larger melting range is generally more capable of filling a larger joint clearance. If the brazing filler metal melts at a specific temperature, it is referred to as a eutectic filler metal. As a result, eutectic filler metals have less filling capability and require tight joint clearances. Examples of eutectic filler metals are the AWS A5.8 BAg-8, BAu-4, and BCu-1 classifications.

Filler metals are commonly applied as a powder mixed with a liquid binder. The brazing filler metal powder can also be mixed with a water-based gel suspension agent to produce a paste. Filler metals are also available as foil and tape. Every effort should be made to confine the brazing filler metal to the joint area as any spatter upon non-joint surfaces could severely degrade the environmental resistance at that location, particularly if it is exposed to service temperatures above the melting point of the brazing filler metal. Since most brazing filler metals do not possess the same level of corrosion resistance as Ni-base corrosion-resistant alloys, it is preferable that brazing is used for joining only when the brazed joint will be isolated from the corrosive environment.

Brazing and Soldering Continued

Brazing Filler Metal Selection Continued

Nickel-based brazing filler metals can be utilized for high-temperature service applications up to 2000°F (1093°C). They generally have additions of boron, silicon, and manganese to depress the melting range and accommodate brazing at various temperatures. The boron-containing brazing filler metals are used for aerospace and other applications subject to high temperature and stress conditions. However, they are susceptible to the formation of brittle borides. These brazing filler metals may also contain chromium to provide for more oxidation-resistant joints.

Cobalt-based brazing filler metals are typically useful for achieving compatibility with Co-base alloys, and obtaining good high-temperature strength and oxidation resistance. Silver-based brazing filler metals have been successfully used for brazing Ni-base corrosion-resistant alloys intended for service applications below approximately 400°F (204°C). They are known for excellent flow characteristics and ease of usage. Filler metals containing low-temperature constituents, such as zinc and tin, are difficult for furnace brazing since they will evaporate prior to reaching the brazing temperature. Most furnace brazing with silver-based filler metals should be conducted in an argon atmosphere. It should be cautioned that most Ni-base alloys are subject to stress-corrosion cracking when exposed to molten silver-rich compositions, so it is imperative that the base metal be stress-free during brazing when utilizing silver-based filler metals. This liquid metal embrittlement form of cracking occurs catastrophically at the brazing temperature.

Copper-based brazing filler metals tend to alloy rapidly with Ni-base alloys, raising the liquidus and reducing fluidity. Therefore, they should be placed as close to the joint as possible, and the assembly should be heated rapidly to the brazing temperature. Copper-based brazing filler metals are only suggested for joining components to be used at service temperatures below 950°F (510°C). Copper-based brazing filler metals that contain significant amounts of phosphorus should be used with caution since they tend to form nickel phosphides at the bond line that promote brittle fracture. Copper-based filler metals should not be used for brazing Co-base alloys.

Gold-based brazing filler metals are mostly used when joining thin base metals due to their low interaction with the base metal. They are also useful when good joint ductility and/or resistance to oxidation and corrosion are primary concerns.

For more detailed information on different brazing filler metal classifications, please refer to: *AWS A5.8M/A5.8, Specification for Filler Metals for Brazing and Braze Welding, American Welding Society*. There are also numerous proprietary brazing filler metals and alloy compositions that are commercially available. It is suggested that brazing filler metal manufacturers be consulted when selecting a filler metal for a specific base metal alloy or application.

Brazing and Soldering Continued

Table 4: Some Possible Brazing Filler Metals for HASTELLOY® and HAYNES® Alloys

Designation/Specification			Nominal Composition (wt.%)	Liquidus - Solidus	Brazing Temperature Range
AWS A5.8	ISO 17672	AMS			
BAG-1	Ag 345	4769	45Ag-15Cu-16Zn-24Cd	1125-1145°F (607-618°C)	1145-1400°F (620-760°C)
BAG-2	Ag 335	4768	35Ag-26Cu-21Zn-18Cd	1125-1295°F (607-702°C)	1295-1550°F (700-840°C)
BAG-3	Ag 351	4771	50Ag-15.5Cu-15.5Zn-16Cd-3Ni	1170-1270°F (632-688°C)	1270-1500°F (690-815°C)
BAG-4	Ag 440	----	40Ag-30Cu-28Zn-2Ni	1240-1435°F (671-779°C)	1435-1650°F (780-900°C)
BAG-8	Ag 272	----	72Ag-28Cu	1435°F (779°C)	1435-1650°F (780-900°C)
BAu-4	Au 827	4787	Au-18Ni	1740°F (949°C)	1740-1840°F (950-1005°C)
BAu-5	Au 300	4785	Au-36Ni-34Pd	2075-2130°F (1135-1166°C)	2130-2250°F (1165-1230°C)
BAu-6	Au 700	4786	Au-22Ni-8Pd	1845-1915°F (1007-1046°C)	1915-2050°F (1045-1120°C)
BCu-1	Cu 141	----	Cu-0.075P-0.02Pb	1981°F (1083°C)	2000-2100°F (1095-1150°C)
BNi-1	Ni 600	4775	Ni-14Cr-3.1B-4.5Si-4.5Fe-0.75C	1790-1900°F (977-1038°C)	1950-2200°F (1065-1205°C)
BNi-1a	Ni 610	4776	Ni-14Cr-3.1B-4.5Si-4.5Fe-0.06C	1790-1970°F (977-1077°C)	1970-2200°F (1080-1205°C)
BNi-2	Ni 620	4777	Ni-7Cr-3.1B-4.5Si-3Fe-0.06C	1780-1830°F (971-999°C)	1850-2150°F (1010-1180°C)
BNi-3	Ni 630	4778	Ni-3.1B-4.5Si-0.5Fe-0.06C	1800-1900°F (982-1038°C)	1850-2150°F (1010-1180°C)
BNi-4	Ni 631	4779	Ni-1.9B-3.5Si-1.5Fe-0.06C	1800-1950°F (982-1066°C)	1850-2150°F (1010-1180°C)
BNi-5	Ni 650	4782	Ni-19Cr-0.03B-10.1Si-0.06C	1975-2075°F (1079-1135°C)	2100-2200°F (1150-1205°C)
BNi-6	Ni 700	----	Ni-11P-0.06C	1610°F (877°C)	1700-2000°F (930-1095°C)
BNi-7	Ni 710	----	Ni-14Cr-0.02B-0.1Si-0.2Fe-0.06C-10P	1630°F (888°C)	1700-2000°F (930-1095°C)
BCo-1	Co 1	4783	Co-19Cr-17Ni-0.8B-8Si-1Fe-4W-0.4C	2050-2100°F (1120-1149°C)	2100-2250°F (1150-1230°C)

Brazing and Soldering Continued

Fit-Up and Fixturing

Since most brazing alloys flow under the force of capillary action, proper fit-up of the parts being brazed is crucially important. To facilitate uniform flow of the molten brazing filler metal through the joint area, joint gap clearances on the order of 0.001 to 0.005 in (0.025 to 0.125 mm) must be maintained at the brazing temperature. Excessive external stresses or strains imposed on the brazed joint during brazing may cause cracking, especially when brazing fluxes are involved. If possible, components should be brazed in the annealed condition (i.e., not cold worked).

Making use of appropriate joint fixturing is also helpful. Fixtures used in furnace brazing must have good dimensional stability and generally low thermal mass to facilitate rapid cooling. Metallic fixtures are limited in their ability to maintain close tolerances through repeated thermal cycles, and are relatively high in thermal mass. Accordingly, graphite and ceramic fixtures are normally better suited for use in high-temperature furnace brazing applications. Graphite has been widely used in vacuum and inert gas furnace brazing, and provides excellent results. However, graphite should not be used for fixturing in hydrogen furnace brazing without a suitable protective coating, as it will react with the hydrogen and possibly produce carburization of the parts being brazed. Ceramics are also used, but typically for smaller fixtures.

Brazing and Soldering Continued

Protective Atmospheres and Fluxes

In addition to proper cleaning procedures prior to brazing, control of furnace environment and purity of the brazing atmosphere is vitally important to ensure proper flow characteristics of the brazing filler metal. Since most Ni-/Co-base alloys are designed to form tenacious oxide films, these same oxide films will cause problems during brazing if atmospheres are not rigorously controlled. Exclusion of oxygen, oxidizing gas species, and reducible oxide compounds from the furnace environment is required as oxygen derived from any source within the furnace can produce surface contamination in the joint area. Ni-based brazing filler metals, for instance, are commonly used in conjunction with vacuum, high purity argon, or hydrogen (reducing) furnace atmospheres. The interior of the furnace and fixtures should be kept clean and free of any type of reducible oxide deposits, and outside atmospheric leak rates should be kept as low as possible. A high atmospheric leak rate through a vacuum furnace could easily cause a thin oxide film to form on the base metal surfaces being brazed. The presence of a surface oxide film impedes the flow of the brazing filler metal, and often results in a poor brazed joint. Flux-based brazing operations can be carried out by using an induction coil heating source, or in a furnace with a reducing atmosphere.

Brazing fluxes are utilized to protect and assist in wetting of base metal surfaces. Fluxes are usually mixtures of fluorides and borates that melt below the melting temperature of the brazing filler metal. Standard brazing fluxes can be used with most Ni-/Co-base alloys. Specialized formulations may be necessary for use with certain brazing filler metals or for base metal alloys containing aluminum and titanium. There are many variables that influence the choice of the most appropriate flux, including base metal, filler metal, brazing time, and joint design. To be effective, a brazing flux must remain active throughout the brazing temperature range. Recommendations from a brazing flux supplier should be sought when considering the use of a specific flux for the first time. Flux removal after brazing is necessary, and particularly important on brazed components that will experience corrosive or high-temperature environments. Grinding or abrasive blasting may be required to remove any tenacious flux residue.

Effect of Brazing Thermal Cycles

The thermal cycles associated with brazing can have deleterious effects upon the microstructure and properties of HAYNES® and HASTELLOY® alloys. Thermal cycle exposure during brazing includes both the time at the selected brazing temperature, and the time taken to heat and cool from elevated temperature. Care should be taken to ensure that the respective brazing thermal cycle does not produce deleterious precipitation of secondary phases in the component. Thus, thermal cycles associated with the brazing operation should be controlled to minimize exposure to temperatures in the approximate range of 1000 to 1800°F (538 to 982°C) where most Ni-/Co-base alloys tend to precipitate secondary phases. For corrosion-resistant alloys, such secondary precipitation could strongly influence their corrosion resistance in service. Normal cooling rates from the brazing temperature, particularly in vacuum furnace brazing, are usually too slow to prevent carbide precipitation in most Ni-/Co-base alloys. Cooling rates in a vacuum environment can be increased by backfilling the furnace with argon or helium. Where brazing is performed in the solution annealing temperature range of the base metal alloy, there is the possibility for both normal and abnormal grain growth, which could be deleterious to service performance.

Brazing and Soldering Continued

Soldering

Soldering refers to a group of joining processes that produces the coalescence of materials by heating them to the soldering temperature in the presence of a soldering filler metal having a liquidus below 840°F (450°C) and below the solidus of the base metal, i.e. without melting of the base metal. Ni/Co-base alloys can be successfully soldered, although alloys containing higher levels of chromium, aluminum, and titanium can be more difficult to solder. Many of the considerations for soldering are similar to those previously outlined for brazing of HASTELLOY® and HAYNES® alloys.

Common soldering filler metals are composed of mixtures of lead and tin. Most of the common types of filler metals can be used to solder Ni-/Co-base alloys. Soldering filler metals with a relatively high tin content provide the best wettability, such as the 60 wt. % tin-40% wt. % lead or 50 wt. % tin-50 wt. % lead compositions. If color matching is a priority, certain filler metals, such as the 95 wt. % tin-5 wt. % antimony composition, may be best. However, the soldered joint may eventually oxidize and become noticeable if there is exposure to elevated temperatures.

The soldering filler metal can be used to seal the joint, but should not be expected to provide a mechanically strong joint or carry the structural load. Mechanical strength needs to be provided for by another means of reinforcement, such as lock seaming, riveting, spot welding, or bolting. For precipitation-strengthened alloys, soldering should be performed after the alloy has gone through its age hardening heat treatment. The relatively low temperatures involved in soldering should not soften or weaken the precipitation-strengthened alloy. Any welding, brazing, or other heating treating operations should also take place before soldering. Ni-/Co-base alloys are susceptible to liquid metal embrittlement when in contact with lead and other metals with low melting points. While this will not occur at normal soldering temperatures, overheating of the soldered joint should be avoided.

Fluxes containing hydrochloric acid are typically required for soldering most Ni/Co-base alloys that contain chromium. Rosin-base fluxes are generally ineffective. Since most flux residues absorb moisture and can become highly corrosive, they should be thoroughly removed from the workpiece after soldering. Rinsing in water or aqueous alkaline solutions should be effective for removing most residues; however, in the presence of oil or grease, the material must be degreased before rinsing.

Joint designs that will be inaccessible for cleaning after soldering, such as long lap joints, should be coated with soldering filler metal prior to assembly. This is generally performed with the same filler metal alloy to be used for soldering. The workpieces may be immersed in a molten bath of the soldering filler metal or the surfaces may be coated with flux and heated to allow the soldering filler metal to coat the joint. Pre-coating may also be accomplished by tin plating.

Visual inspection is usually sufficient for evaluating the quality of a soldered joint. The soldered metal should be smooth and continuous; lumps or other visual discontinuities are indicative of insufficient heat. Holes are most likely caused by contamination or overheating, and can result in leaks. Soldered joints with leak-tight requirements should be pressure tested.

Heat Treatment

Recommended Procedures and Temperatures Applicable to:
Corrosion-resistant Alloys
High-temperature Alloys
Wear & Corrosion-resistant Alloy

The heat treatment of the HAYNES® and HASTELLOY® alloys is a very important topic. In the production of these wrought materials, there are many hot- and cold-reduction steps, between which intermediate heat treatments are necessary, to restore the optimum properties, in particular ductility. In the case of the corrosion-resistant alloys, these intermediate heat treatments are generally solution-annealing treatments. In the case of the high-temperature alloys, this is not necessarily so.

Once the materials have reached their final sizes, they are given a final anneal. This is usually a solution-anneal; however, a few high-temperature alloys (HTA) are final annealed at an adjusted temperature, to control grain size, or some other microstructural feature.

Subsequent fabrication of these as-supplied materials can again involve hot- or cold-working, as discussed in the Hot-working and Cold-working sections of this guide. Again, working often involves steps, with intermediate annealing (normally solution-annealing for the CRA materials) treatments to restore ductility. Beyond that, fabricated components will require a final anneal (normally a solution-anneal for the CRA materials), to restore optimum properties prior to use, or (in the case of the age-hardenable alloys) to prepare them for age-hardening.

Heat Treatment Continued

Applicable to: Corrosion-resistant Alloys

The compositions of the corrosion-resistant alloys (CRA) comprise a nickel base, substantial additions of chromium and/or molybdenum (in some cases partially replaced by tungsten), small additions such as copper (to enhance resistance to certain media) and iron (to allow the use of less expensive raw materials), and minor additions such as aluminum and manganese, which help remove deleterious elements such as oxygen and sulfur, during melting. As-supplied, they generally exhibit single phase (face-centered cubic, or gamma) wrought microstructures.

In most cases, the presence of a single phase microstructure in as-supplied (CRA) materials is due to a high temperature, solution-annealing treatment, followed by quenching (rapid cooling), to “lock-in” the high-temperature structure. Left to cool slowly, most of these alloys would contain second phases (albeit in small amounts), commonly within the structural grain boundaries, as a result of the fact that the combined contents of the alloying additions exceed their solubility limits.

This is exacerbated by the fact that, despite sophisticated melting techniques and procedures, traces of unwanted elements (with very low solubility), such as carbon and silicon, can be present. Fortunately, solution-annealing, followed by quenching (by water or cold gas), solves this problem also.

The corrosion-resistant alloys are usually supplied in the solution-annealed condition, and their normal solution-annealing temperatures are given in the table below. They represent temperatures at which phases other than gamma (and, in rare cases, primary carbides and/or nitrides) dissolve, yet provide grain sizes within the range known to impart good mechanical properties. Primary carbides and/or nitrides are seen in C-4 alloy, due to the presence of titanium.

In the case of the corrosion-resistant alloys (CRA), the terms solution-annealed and mill-annealed (MA) are generally synonymous; however, the temperatures used in continuous hydrogen-annealing furnaces (in sheet production) are adjusted to compensate for the line speeds (hence time at temperature).

Heat Treatment Continued

Solution-annealing Temperatures of the Corrosion-resistant Alloys (CRA)

Alloy	Solution-annealing Temperature*		Type of Quench
	°F	°C	-
B-3®	1950	1066	WQ or RAC
C-4	1950	1066	WQ or RAC
C-22®	2050	1121	WQ or RAC
C-22HS®	1975	1079	WQ or RAC
C-276	2050	1121	WQ or RAC
C-2000®	2100	1149	WQ or RAC
G-30®	2150	1177	WQ or RAC
G-35®	2050	1121	WQ or RAC
HYBRID-BC1®	2100	1149	WQ or RAC

*Plus or Minus 25°F (14°C)

WQ = Water Quench (Preferred); RAC = Rapid Air Cool

There are no specific rules regarding the times required to heat up, then anneal, the corrosion-resistant alloys (CRA), since there are many types of furnace, involving different modes of loading, unloading, and operation. There are only general guidelines.

The temperature of the work-piece being annealed should be measured with an attached thermocouple, and recording of the annealing time should begin only when the entire section of the work-piece has reached the recommended annealing temperature. It should be remembered that the center of the section takes longer to reach the annealing temperature than the surface.

Heat Treatment Continued

The general guidelines regarding time are:

Normally, once the whole of the workpiece is at the annealing temperature, the annealing time should be between 10 and 30 minutes, depending upon the section thickness.

The shorter times within this range should be used for thin sheet components.

The longer times should be used for thick (heavier) sections.

Rapid cooling is essential after annealing, to prevent the nucleation and growth of deleterious second phase precipitates in the microstructure, particularly at the grain boundaries. Water quenching is preferred, and highly recommended for materials thicker than 3/8 in (9.5 mm). Rapid air cooling has been used for thin sections. The time between removal from the furnace and the start of quenching must be as short as possible (and certainly less than three minutes).

Special precautions are necessary with B-3[®] alloy. Although more stable than other nickel-molybdenum alloys (particularly its predecessor, B-2[®] alloy), it is still prone to significant, deleterious, microstructural changes in the temperature range 1100-1500°F (593-816°C), especially after being cold-worked. Thus, care must be taken to avoid exposing B-3[®] alloy to temperatures within this range for any length of time. B-3[®] alloy should be annealed in furnaces pre-heated to the annealing temperature (1950°F/1066°C), and with sufficient thermal capacity to ensure rapid recovery of the temperature after loading of the furnace with the B-3[®] work-piece.

One of the potential problems associated with these microstructural changes (which can occur during heating to the annealing temperature) in the nickel-molybdenum (B-type) alloys is cracking due to residual stresses, in cold-worked material. Shot peening of the knuckle radius and straight flange regions of cold-formed heads, to lower residual tensile stress patterns, has been found to be very beneficial in avoidance of such problems.

Heat Treatment Continued

Applicable To:

High-temperature Alloys

The high-temperature alloys (HTA), whether based on nickel, cobalt, or a mixture of nickel, cobalt, and iron, are compositionally much more complicated. However, as in the CRA alloys, chromium is an important alloying element, enabling the formation of protective, surface films (particularly oxides) in hot gases.

Large atoms such as molybdenum and tungsten are used to provide solid-solution strength to many of the high-temperature alloys. Those relying on age-hardening for strength include significant quantities of elements such as aluminum, titanium, and niobium (columbium), which can form extremely fine precipitates of second phases (“gamma prime” and “gamma double prime”) known to be very effective strengtheners.

Aluminum can play another role in the high temperature alloys, and that is to modify the protective films (oxides, in particular) that form on the surfaces of these materials at high-temperatures, in the presence of oxygen, etc. Indeed, aluminum oxide is very adherent, stable, and protective.

Unlike the CRA materials, in which carbon is generally a negative actor, the high-temperature HAYNES® and HASTELLOY® (HTA) alloys rely upon deliberate carbon additions, or rather the carbides they induce in the microstructures, to provide the necessary levels of strength (particularly creep strength) for high-temperature service. In some cases, these carbides form during solidification of the materials (primary carbides). In other cases, they form during high-temperature exposure, in the solid state (secondary carbides).

As a consequence of the need for specific carbide types and morphologies in the HTA materials, annealing is a much more complicated subject, especially between steps in the manufacturing and fabrication processes.

Heat Treatment Continued

The high-temperature HAYNES® and HASTELLOY® alloys are normally supplied in the solution-annealed condition, which is attained by heat treatment at the following temperatures (or within the specified ranges):

Solution-annealing Temperatures of the High-temperature Alloys (HTA)

Alloy	Solution-annealing Temperature/Range		Type of Quench
	°F	°C	-
25	2150-2250	1177-1232	WQ or RAC
75	1925*	1052*	WQ or RAC
188	2125-2175	1163-1191	WQ or RAC
214®	2000	1093	WQ or RAC
230®	2125-2275	1163-1246	WQ or RAC
242®	1900-2050	1038-1121	WQ or RAC
244®	2000-2100	1093-1149	WQ or RAC
263	2100 + 25	1149 + 14	WQ or RAC
282®	2050-2100	1121-1149	WQ or RAC
556®	2125-2175	1163-1191	WQ or RAC
625	2000-2200	1093-1204	WQ or RAC
718	1700-1850**	927-1010**	WQ or RAC
HR-120®	2150-2250	1177-1232	WQ or RAC
HR-160®	2025-2075	1107-1135	WQ or RAC
HR-224®	-	-	WQ or RAC
HR-235®	2075-2125	1135-1163	WQ or RAC
MULTIMET®	2150	1177	WQ or RAC
N	2150	1177	WQ or RAC
R-41	2050	1121	WQ or RAC
S	1925-2075	1052-1135	WQ or RAC
W	2165	1185	WQ or RAC
WASPALLOY	1975	1079	WQ or RAC
X	2125-2175	1163-1191	WQ or RAC
X-750	1900*	1038*	WQ or RAC

WQ = Water Quench (Preferred); RAC = Rapid Air Cool

*Bright (Hydrogen) Annealing Temperature

**Not Strictly a Solution-annealing Temperature Range (More a Preparatory Annealing Temperature Range)

Heat Treatment Continued

In the solution-annealed condition, the microstructures of the high-temperature alloys (HTA) generally consist of primary carbides dispersed in a gamma phase (face-centered cubic) matrix, with essentially clean (precipitate-free) grain boundaries. For the solid-solution strengthened alloys, this is usually the optimum condition for both high-temperature service, and for room temperature fabricability.

Although the HAYNES® and HASTELLOY® alloys should not be subjected to stress relief treatments at the sort of temperatures used for the steels and stainless steels, for fear of causing the precipitation of undesirable second phases (particularly in the alloy grain boundaries), some lower annealing temperatures have been used for the high-temperature alloys (HTA) between processing steps, to restore the ductility of partially-fabricated workpieces. These so-called intermediate annealing temperatures should be used with caution, since they too are likely to result in the aforementioned grain boundary precipitation. Some minimum, intermediate annealing temperatures are given in the following table (for selected solid-solution strengthened HTA materials):

Minimum Intermediate Annealing Temperatures (HTA)

Alloy	Minimum Intermediate Annealing Temperature	
	°F	°C
25	2050	1121
188	2050	1121
230®	2050	1121
556®	1900	1038
625	1700	927
HR-120®	1950	1066
HR-160®	1950	1066
S	1750	954
X	1850	1010

Whether an intermediate annealing temperature (rather than a solution-annealing temperature) is appropriate between processing steps will depend upon the alloy and the effects of the lower temperature upon microstructure, and upon the nature of the subsequent operation. These issues must be studied carefully, and advice sought.

Heat Treatment Continued

Annealing During Cold (or Warm) Forming

Applicable To: **High-temperature Alloys**

The response of the HAYNES® and HASTELLOY® high-temperature alloys (HTA) to heat treatment is very dependent upon the condition of the material prior to the treatment. When the material is not in a cold- or warm-worked condition, the principal response is usually a change in the amount and morphology of the secondary carbide phases. Other minor effects might occur, but the grain structure normally remains the same (in the absence of prior cold or warm work).

When these alloys have been subjected to cold- or warm-work, the application of a solution or intermediate anneal will almost always alter the grain structure. Moreover, the amount of prior cold- or warm-work will significantly affect the grain structure, and consequently the mechanical properties of the material.

The following table indicates the effects of heat-treatments (of 5 minutes duration) at various temperatures upon the grain sizes of sheets of several high temperature alloys, subjected to different levels of cold-work.

Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on Grain Size

Cold-work	Heat Treatment Temperature		ASTM Grain Size Produced			
	°F	°C	25	230®	556®	X
0	None		3.5-4	5-6	5-6	4-5
10	1850	1010	NA	NA	NR	NR
	1950	1066	NR	NR	NR	NR
	2050	1121	NR	NFR	5-5.5	5-7
	2150	1177	4-4.5	4-7	5-5.5	NA
	2250	1232	3-4.5	6.5-7	NA	NA
15	1950	1066	7	NA	NA	NA
	2050	1121	6-7	NA	NA	NA
	2150	1177	5-7	NA	NA	NA
	2250	1232	3-4.5	NA	NA	NA
20	1850	1010	NA	NA	NR	NFR
	1950	1066	7-8	NFR	NR	NFR
	2050	1121	7-8	8-8.5	7.5-8.5	7-8
	2150	1177	4.5-7	7.5-8	6-6.5	NA
	2250	1232	2.5-4.5	7-7.5	NA	NA
25	1950	1066	7.5-8	NA	NA	NA
	2050	1121	7.5-8	NA	NA	NA
	2150	1177	4	NA	NA	NA
	2250	1232	3.5	NA	NA	NA
30	1850	1010	NA	NA	NFR	NFR
	1950	1066	NA	8-9	7.5-9.5	8-10
	2050	1121	NA	9-10	7-7.5	7.5-9.5
	2150	1177	NA	8.5-9	4.5-6.5	NA
	2250	1232	NA	6-7	NA	NA
40	1850	1010	NA	NA	7.5-9.5	8-9
	1950	1066	NA	9.5-10	8-9.5	8-10
	2050	1121	NA	9-10	7-9	9.5-10
	2150	1177	NA	8.5-9	4.5-6.5	NA
	2250	1232	NA	4-7	NA	NA
50	1850	1010	NA	NA	9-10	8.5-10
	1950	1066	NA	9-10	8.5-10	8.5-10
	2050	1121	NA	9-10	8-9.5	8.5-10
	2150	1177	NA	9-9.5	5.5-6	NA
	2250	1232	NA	5.5-6.5	NA	NA

NA=Not Available

NR= No Recrystallization Observed

NFR=Not Fully Recrystallized

Heat Treatment Continued

The effects of cold-work plus heat treatment at various temperatures upon the mechanical properties of several solid solution strengthened, high temperature HAYNES® and HASTELLOY® alloys are shown in the following tables and figures.

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 25 Sheet

Cold-work	Heat Treatment*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	%	°F °C	ksi	MPa	ksi	MPa	%	HRC
No Cold-work	No Heat Treatment		68	469	144	993	58	24
10	No Heat Treatment		124	855	182	1255	37	36
15	No Heat Treatment		149	1027	178	1227	28	40
20	No Heat Treatment		151	1041	193	1331	18	42
25	No Heat Treatment		184	1269	232	1600	15	44
10	1950	1066	98	676	163	1124	39	32
15	1950	1066	91	627	167	1151	44	30
20	1950	1066	96	662	171	1179	41	32
25	1950	1066	89	614	169	1165	44	32
10	2050	1121	74	510	157	1082	53	27
15	2050	1121	79	545	161	1110	52	28
20	2050	1121	82	565	165	1138	48	31
25	2050	1121	83	572	166	1145	48	30
10	2150	1177	67	462	148	1020	63	21
15	2150	1177	74	510	156	1076	55	26
20	2150	1177	72	496	154	1062	59	26
25	2150	1177	69	476	149	1027	62	25
10	2250	1232	69	476	144	993	64	95
15	2250	1232	64	441	142	979	68	97
20	2250	1232	62	427	135	931	69	97
25	2250	1232	61	421	138	951	70	96

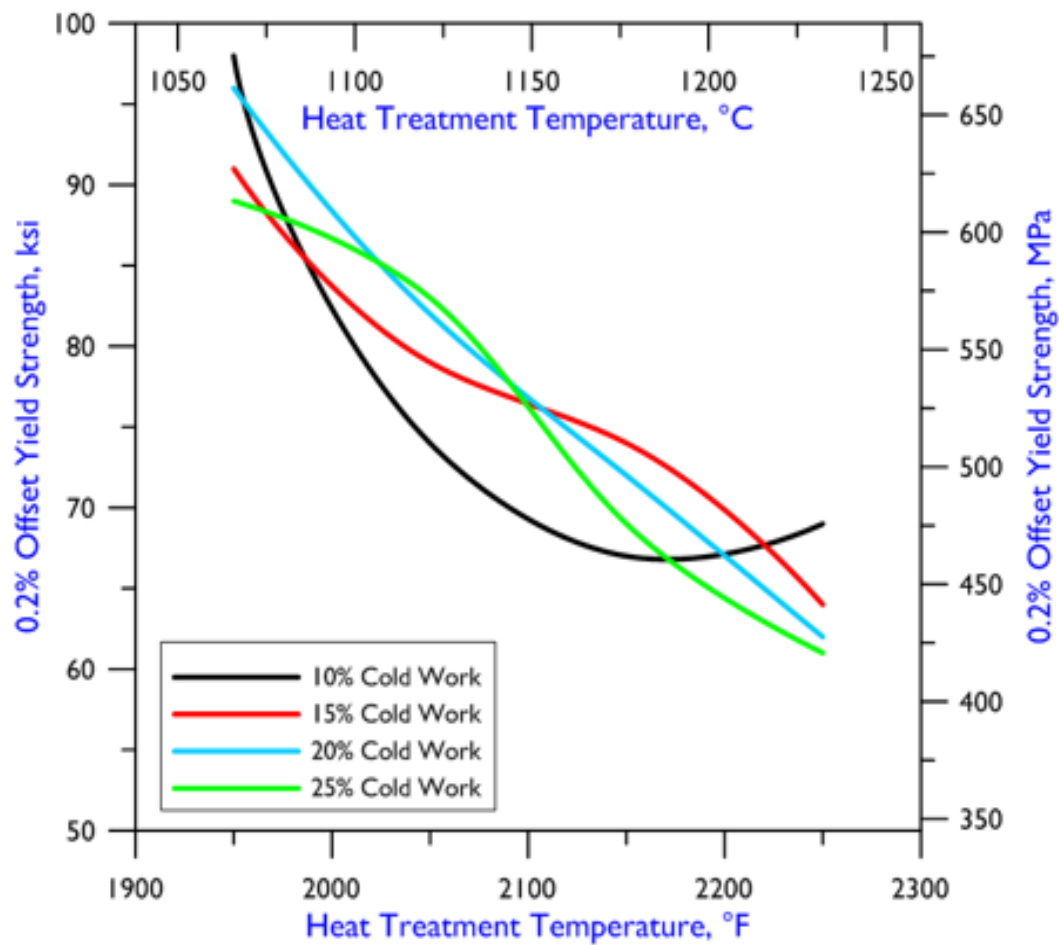
*5 Minutes Duration + Rapid Air Cool

Tensile Results are Averages of 2 or More Tests

HRC= Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES[®] 25 Sheet



Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 188 Sheet

Cold-work	Heat Treatment*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	%	°F °C	ksi	MPa	ksi	MPa	%	HR BW/C
No Cold-work	No Heat Treatment		67	462	137	945	54	98 HRBW
10	No Heat Treatment		106	731	151	1041	45	32 HRC
20	No Heat Treatment		133	917	166	1145	28	37 HRC
30	No Heat Treatment		167	1151	195	1344	13	41 HRC
40	No Heat Treatment		177	1220	215	1482	10	44 HRC
10	1950	1066	91	627	149	1027	41	30 HRC
20	1950	1066	88	607	153	1055	41	28 HRC
30	1950	1066	84	579	158	1089	41	30 HRC
40	1950	1066	91	627	163	1124	40	31 HRC
10	2050	1121	65	448	143	986	50	22 HRC
20	2050	1121	71	490	149	1027	47	25 HRC
30	2050	1121	80	552	155	1069	44	28 HRC
40	2050	1121	87	600	159	1096	43	30 HRC
10	2150	1177	62	427	140	965	55	96 HRBW
20	2150	1177	65	448	141	972	53	97 HRBW
30	2150	1177	67	462	143	986	52	99 HRBW
40	2150	1177	64	441	141	972	56	97 HRBW
10	2250	1232	59	407	132	910	59	95 HRBW
20	2250	1232	58	400	130	896	63	94 HRBW
30	2250	1232	58	400	131	903	63	93 HRBW
40	2250	1232	58	400	132	910	62	93 HRBW

*5 Minutes Duration + Rapid Air Cool

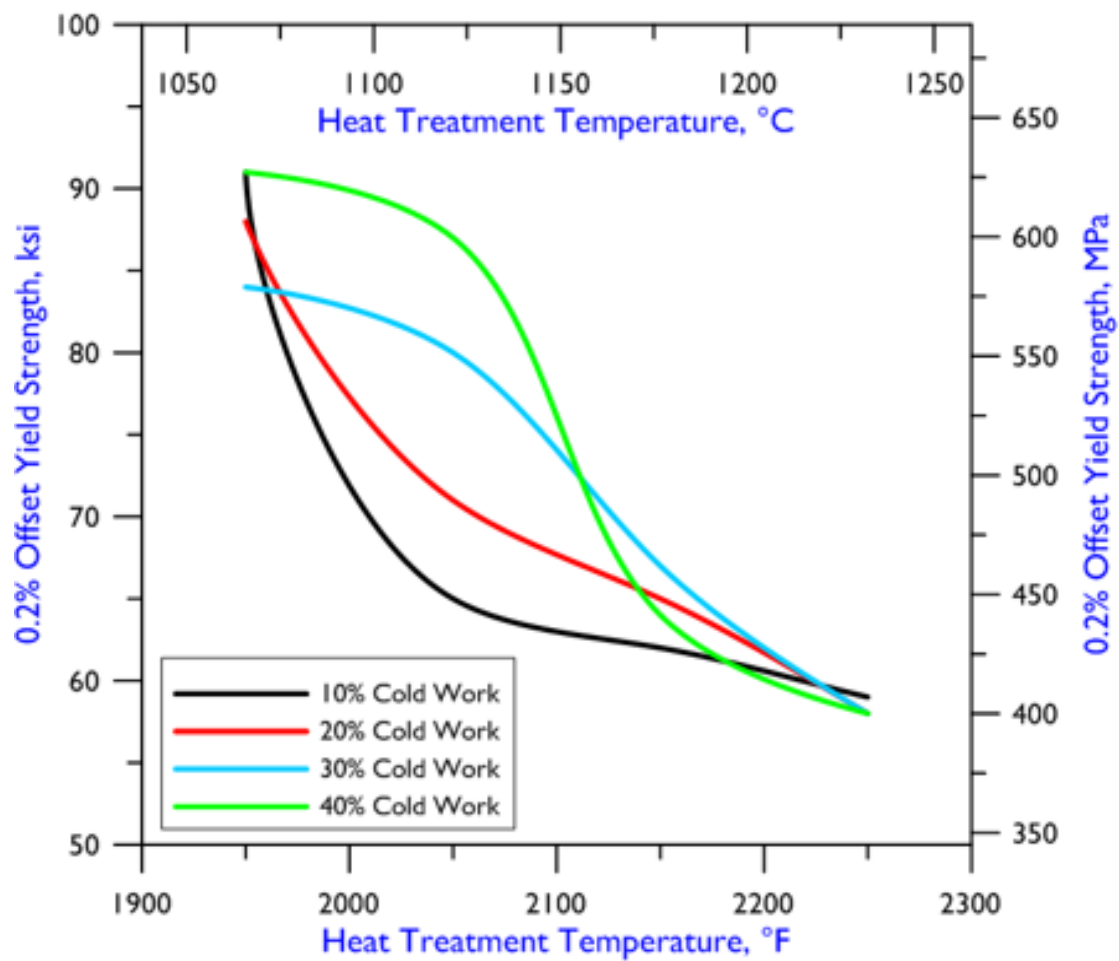
Tensile Results are Averages of 2 or More Tests

HRBW = Hardness Rockwell "B", Tungsten Indentor

HRC = Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES® 188 Sheet



Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 230® Sheet

Cold-work	Heat Treatment*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	°F	°C	ksi	MPa	ksi	MPa		
No Cold-work	No Heat Treatment		62	427	128	883	47	95 HRB
10	No Heat Treatment		104	717	145	1000	32	28 HRC
20	No Heat Treatment		133	917	164	1131	17	35 HRC
30	No Heat Treatment		160	1103	188	1296	10	39 HRC
40	No Heat Treatment		172	1186	202	1393	8	40 HRC
50	No Heat Treatment		185	1276	215	1482	6	42 HRC
10	1950	1066	92	634	144	993	33	24 HRC
20	1950	1066	81	558	142	979	36	26 HRC
30	1950	1066	76	524	142	979	36	99 HRBW
40	1950	1066	81	558	146	1007	32	23 HRC
50	1950	1066	86	593	148	1020	35	24 HRC
10	2050	1121	81	558	139	958	37	98 HRBW
20	2050	1121	65	448	136	938	39	97 HRBW
30	2050	1121	72	496	140	965	38	99 HRBW
40	2050	1121	76	524	142	979	36	99 HRBW
50	2050	1121	81	558	144	993	36	23 HRC
10	2150	1177	56	386	130	896	44	92 HRBW
20	2150	1177	64	441	134	924	40	96 HRBW
30	2150	1177	70	483	138	951	39	98 HRBW
40	2150	1177	73	503	139	958	38	98 HRBW
50	2150	1177	72	496	138	951	39	98 HRBW
10	2250	1232	52	359	125	862	47	92 HRBW
20	2250	1232	57	393	128	883	45	92 HRBW
30	2250	1232	54	372	126	869	48	92 HRBW
40	2250	1232	53	365	126	869	47	91 HRBW
50	2250	1232	55	379	128	883	46	89 HRBW

*5 Minutes Duration + Rapid Air Cool

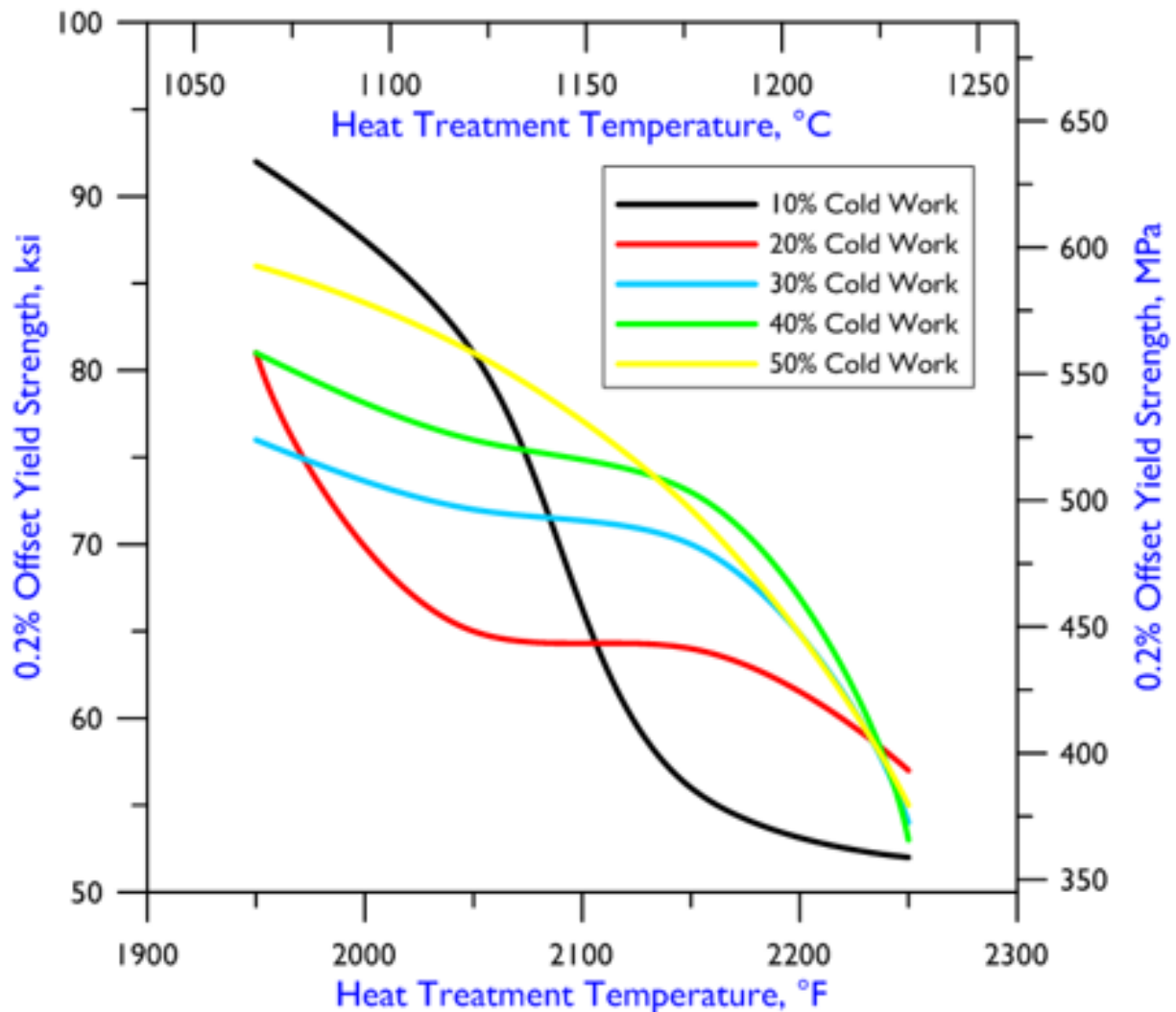
Tensile Results are Averages of 2 or More Tests

HRBW = Hardness Rockwell "B", Tungsten Indentor

HRC = Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES® 230® Sheet



Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 625 Sheet

Cold-work	Heat Treatment* Temperature		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
%	°F	°C	ksi	MPa	ksi	MPa	%	HR BW/C
No Cold-work	No Heat Treatment		70	483	133	917	46	97 HRBW
10	No Heat Treatment		113	779	151	1041	30	32 HRC
20	No Heat Treatment		140	965	169	1165	16	37 HRC
30	No Heat Treatment		162	1117	191	1317	11	40 HRC
40	No Heat Treatment		178	1227	209	1441	8	42 HRC
50	No Heat Treatment		184	1269	223	1538	5	45 HRC
10	1850	1010	63	434	134	924	46	NA
20	1850	1010	71	490	138	951	44	NA
30	1850	1010	78	538	141	972	44	NA
40	1850	1010	82	565	141	972	42	NA
50	1850	1010	82	565	141	972	42	NA
10	1950	1066	61	421	133	917	46	NA
20	1950	1066	71	490	137	945	45	NA
30	1950	1066	77	531	140	965	44	NA
40	1950	1066	83	572	142	979	42	NA
50	1950	1066	82	565	141	972	42	NA
10	2050	1121	58	400	128	883	50	NA
20	2050	1121	67	462	135	931	46	NA
30	2050	1121	58	400	127	876	52	NA
40	2050	1121	72	496	137	945	44	NA
50	2050	1121	61	421	130	896	50	NA
10	2150	1177	52	359	122	841	55	NA
20	2150	1177	54	372	124	855	55	NA
30	2150	1177	53	365	122	841	56	NA
40	2150	1177	52	359	122	841	55	NA
50	2150	1177	51	352	119	820	58	NA

*5 Minutes Duration + Rapid Air Cool

Tensile Results are Averages of 2 or More Tests

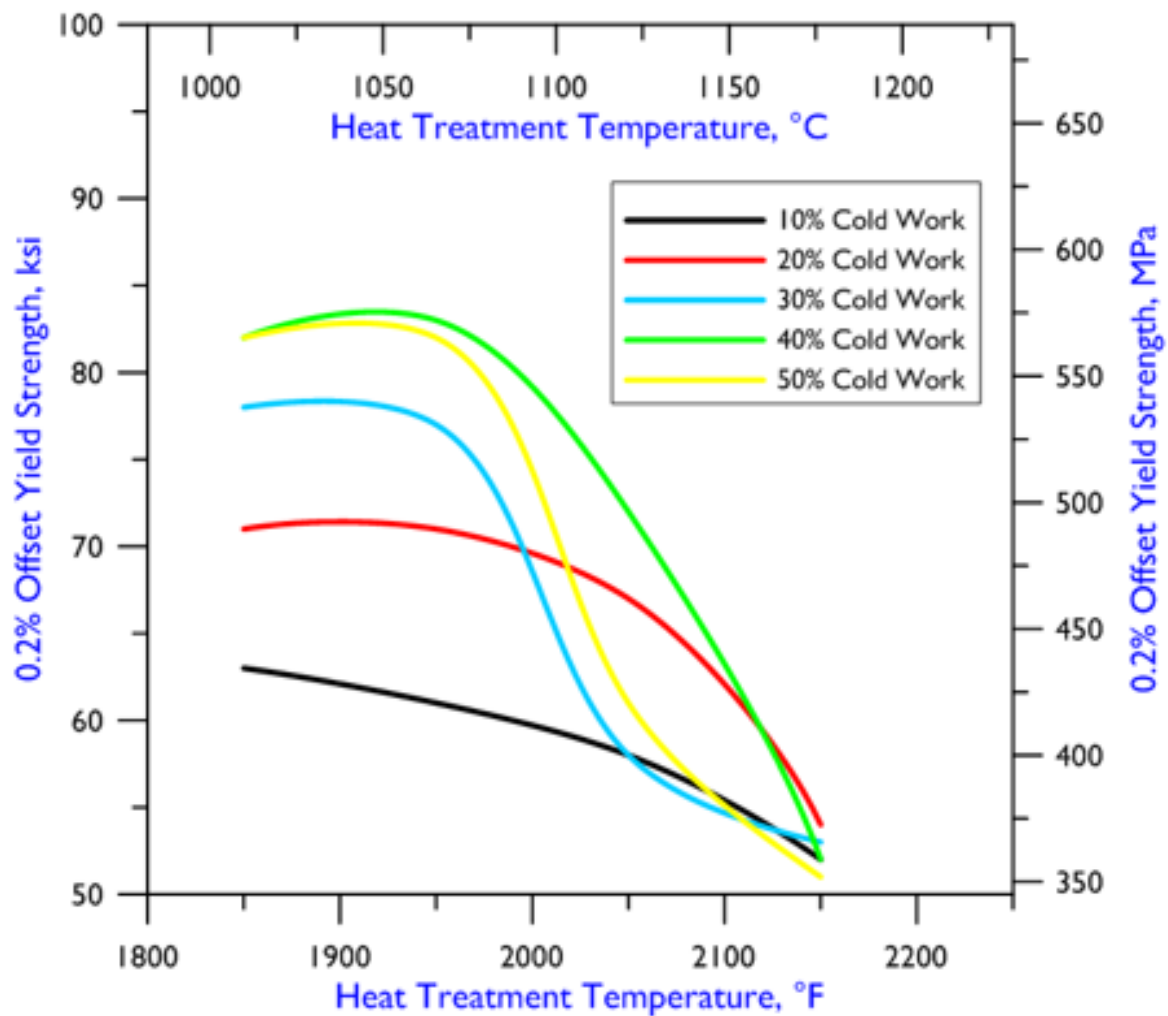
NA=Not Available

HRBW = Hardness Rockwell "B", Tungsten Indentor

HRC = Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES® 625 Sheet



Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES HR-120® Sheet

Cold-work	Heat-treatment*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	%	°F °C	ksi	MPa	ksi	MPa	%	
No Cold-work	No Heat Treatment		60	414	113	779	39	93 HRBW
10	No Heat Treatment		103	710	126	869	26	27 HRC
20	No Heat Treatment		129	889	144	993	11	32 HRC
30	No Heat Treatment		143	986	157	1082	6	34 HRC
40	No Heat Treatment		159	1096	179	1234	6	35 HRC
50	No Heat Treatment		166	1145	186	1282	5	36 HRC
10	1950	1066	52	359	109	752	38	89 HRBW
20	1950	1066	55	379	111	765	38	92 HRBW
30	1950	1066	60	414	115	793	38	93 HRBW
40	1950	1066	65	448	117	807	37	93 HRBW
50	1950	1066	67	462	118	814	34	93 HRBW
10	2050	1121	49	338	108	745	47	88 HRBW
20	2050	1121	53	365	117	807	41	90 HRBW
30	2050	1121	55	379	112	772	40	91 HRBW
40	2050	1121	58	400	114	786	37	91 HRBW
50	2050	1121	59	407	114	786	37	89 HRBW
10	2150	1177	49	338	109	752	43	86 HRBW
20	2150	1177	50	345	109	752	42	87 HRBW
30	2150	1177	51	352	110	758	43	88 HRBW
40	2150	1177	50	345	111	765	38	86 HRBW
50	2150	1177	50	345	110	758	39	82 HRBW
10	2250	1232	46	317	106	731	46	84 HRBW
20	2250	1232	44	303	104	717	47	80 HRBW
30	2250	1232	44	303	103	710	48	80 HRBW
40	2250	1232	44	303	104	717	45	81 HRBW
50	2250	1232	44	303	104	717	43	83 HRBW

*5 Minutes Duration + Rapid Air Cool

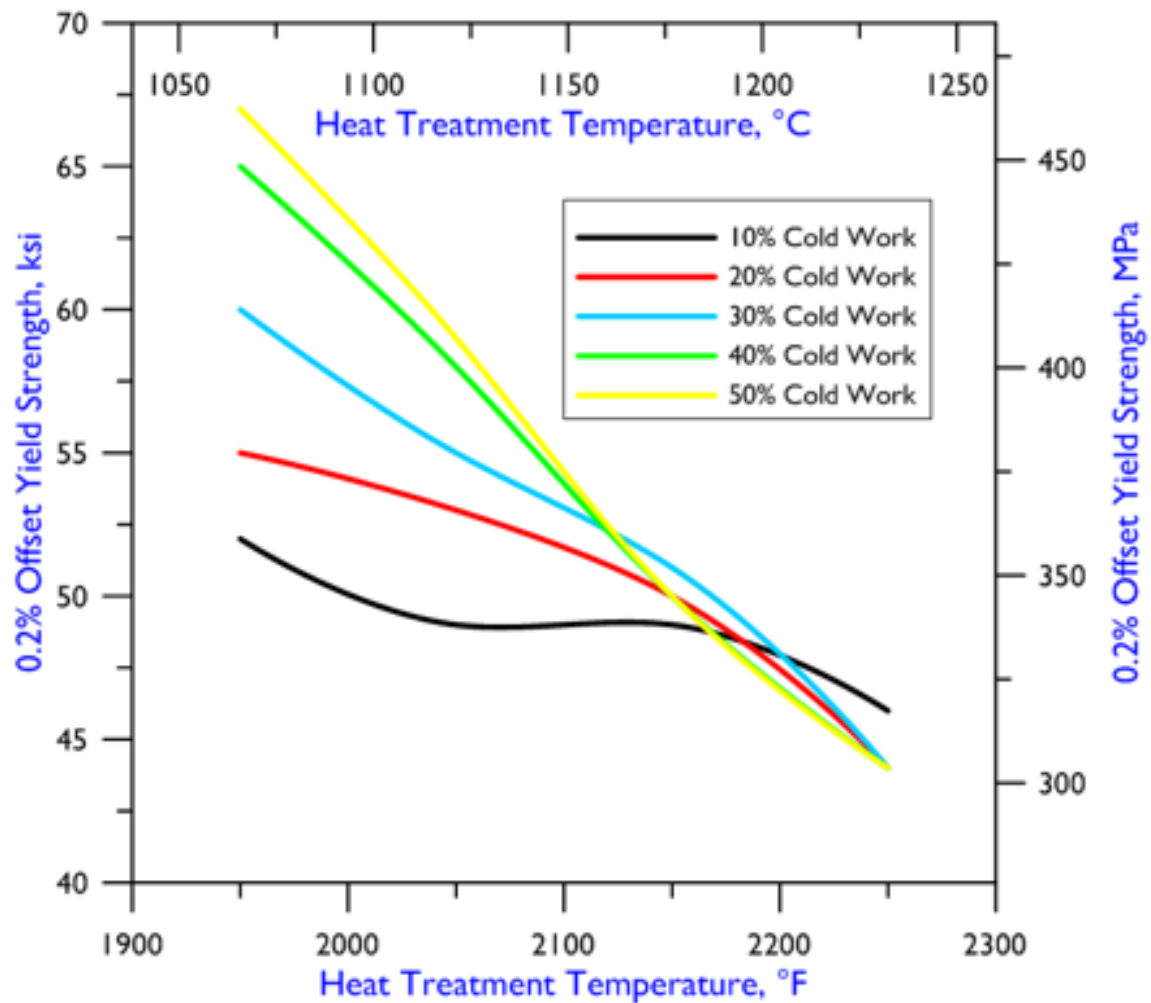
Tensile Results are Averages of 2 or More Tests

HRBW = Hardness Rockwell "B", Tungsten Indentor

HRC = Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES® HR-120® Sheet



Heat Treatment Continued

Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HASTELLOY® X Sheet

Cold-work	Heat Treatment*		0.2% Offset		Ultimate Tensile		Elongation	Hardness
	Temperature		Yield Strength		Strength			
%	°F	°C	ksi	MPa	ksi	MPa	%	HR BW/C
No Cold-work	No Heat Treatment		57	393	114	786	46	89 HRBW
10	No Heat Treatment		96	662	129	889	29	25 HRC
20	No Heat Treatment		122	841	147	1014	15	31 HRC
30	No Heat Treatment		142	979	169	1165	10	35 HRC
40	No Heat Treatment		159	1096	186	1282	8	37 HRC
50	No Heat Treatment		171	1179	200	1379	7	39 HRC
10	1850	1010	76	524	125	862	32	98 HRBW
20	1850	1010	91	627	132	910	27	23 HRC
30	1850	1010	87	600	135	931	28	99 HRBW
40	1850	1010	77	531	133	917	32	98 HRBW
50	1850	1010	81	558	135	931	33	99 HRBW
10	1950	1066	74	510	122	841	34	93 HRBW
20	1950	1066	66	455	124	855	35	96 HRBW
30	1950	1066	63	434	126	869	36	96 HRBW
40	1950	1066	70	483	129	889	35	96 HRBW
50	1950	1066	74	510	129	889	34	97 HRBW
10	2050	1121	53	365	119	820	42	89 HRBW
20	2050	1121	56	386	121	834	40	91 HRBW
30	2050	1121	61	421	123	848	39	94 HRBW
40	2050	1121	65	448	125	862	37	94 HRBW
50	2050	1121	67	462	125	862	38	94 HRBW
10	2150	1177	45	310	109	752	49	94 HRBW
20	2150	1177	47	324	111	765	47	87 HRBW
30	2150	1177	49	338	113	779	46	86 HRBW
40	2150	1177	46	317	110	758	48	85 HRBW
50	2150	1177	46	317	110	758	48	84 HRBW

*5 Minutes Duration + Rapid Air Cool

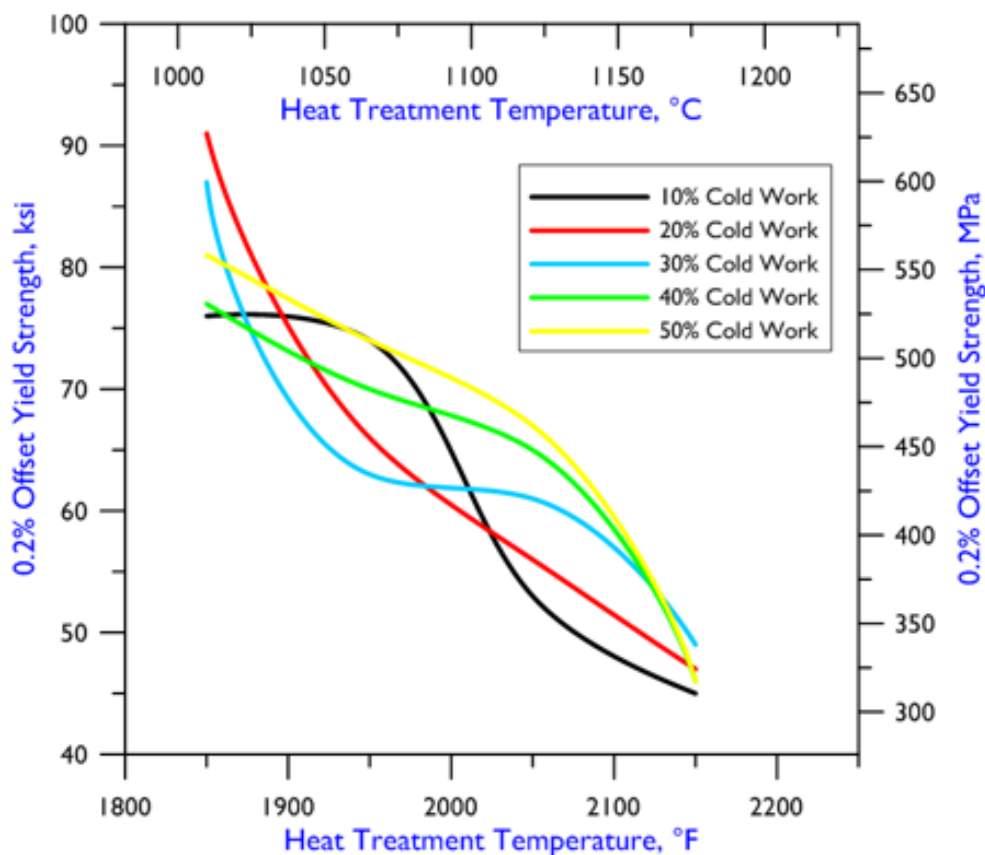
Tensile Results are Averages of 2 or More Tests

HRBW = Hardness Rockwell "B", Tungsten Indentor

HRC = Hardness Rockwell "C"

Heat Treatment Continued

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HASTELLOY® X Sheet



Age-hardening Treatments for Age-hardenable Alloys

Applicable to:

Corrosion-resistant Alloys

High-temperature Alloys

Alloy	No. of Steps	Treatment
C-22HS®	2	16 hours at 1300°F (704°C), furnace cool to 1125°F (607°C), hold at 1125°F for 32 hours, air cool
242®	1	48 hours* at 1200°F (649°C), air cool
244®	2	16 hours at 1400°F (760°C), furnace cool to 1200°F (649°C), hold at 1200°F for 32 hours, air cool
263	1	8 hours at 1472°F (800°C), air cool
282®	2	2 hours at 1850°F (1010°C), rapid air cool or air cool, followed by 8 hours at 1450°F (788°C), air cool
718	2	8 hours at 1325°F (718°C), furnace cool to 1150°F (621°C), hold at 1150°F for 8 hours, air cool
R-41	1	16 hours at 1400°F (760°C), air cool
WASPALLOY	3	2 hours at 1825°F (996°C), air cool, followed by 4 hours at 1550°F (843°C), air cool,
		followed by 16 hours at 1400°F (760°C), air cool
X-750	2	8 hours at 1350°F (732°C), furnace cool to 1150°F (621°C), hold at 1150°F for 8 hours, air cool

*Minimum

Heat Treatment Continued

To harden/strengthen those materials capable of age hardening, the following treatments are usually applied, assuming the starting material is in the solution-annealed condition. Alternate hardening/strengthening treatments are possible for some of these alloys, depending upon the intended applications and the required strength levels. Please contact Haynes International for details.

Heating and Cooling Rates

Applicable to:

Corrosion-resistant Alloys

High-temperature Alloys

Wear & Corrosion-resistant Alloy

Heating and cooling of the HAYNES® and HASTELLOY® alloys should generally be as rapid as possible. This is to minimize the precipitation of second phase particles (notably carbides, in the case of the high-temperature alloys) in their microstructures at intermediate temperatures. Rapid heating also preserves stored energy from cold- or warm-work, which can be important to re-crystallization and/or grain growth at the annealing temperature. Indeed, slow heating can result in a finer than desirable grain size, particularly in thin-section components, given limited time at the annealing temperature.

Rapid cooling after solution-annealing is critical, again to prevent the precipitation of second phases, particularly in the microstructural grain boundaries in the approximate temperature range 1000°F to 1800°F (538°C to 982°C). Where practical, and where it is unlikely to cause distortion, a water quench is preferred. It will be noted that cooling from age-hardening treatments (in the case of the age-hardenable, high-temperature alloy components) usually involves air cooling.

The sensitivity of individual alloys to slow cooling varies, but as an example of the effect of cooling rate upon properties, the following table shows the creep life of HAYNES® 188 alloy as a function of the cooling process.

Effect of Cooling Rate upon the Creep Life of HAYNES® 188 Sheet

Cooling Process after Solution-annealing at 2150°F (1177°C)	Time to 0.5% Creep for 1600°F/7 ksi (871°C/48 MPa) Test
Water Quench	148 h
Air Cool	97 h
Furnace Cool to 1200°F (649°C), then Air Cool	48 h

Heat Treatment Continued

Holding Time

The times at temperature required for annealing are governed by the need to ensure that all metallurgical reactions are complete, uniformly and throughout the component. As mentioned earlier, the general rules for holding time are at least 30 minutes per inch of thickness in the case of massive workpieces and components, and 10 to 30 minutes (once the entire piece is uniformly at the required annealing temperature) for less massive workpieces and components, depending upon section thickness. Extremely long holding times (such as overnight) are not recommended, since they can be harmful to alloy microstructures and properties.

For continuous annealing of strip or wire, several minutes at temperature will usually suffice.

Time in the furnace will depend on the furnace type and capacity, and the work-piece/component thickness and geometry. To determine when the entire work-piece has reached the required annealing temperature, measurements should be taken using thermocouples attached to the work-piece, where possible.

Use of a Protective Atmosphere

Most of the HAYNES® and HASTELLOY® alloys can be annealed in oxidizing environments, but will form adherent oxide scales which should normally be removed prior to further processing. For details on scale removal, please refer to the the section on Descaling and Pickling.

Some HAYNES® and HASTELLOY® alloys contain low chromium contents, and require annealing in neutral or slightly reducing atmospheres.

When a bright finish (free from oxide scales) is required, a protective atmosphere, such as low dew point hydrogen, is necessary. Atmospheres of argon and helium have been used, although pronounced tinting is possible with these alternate gases, due to oxygen or water vapor contamination. Annealing in nitrogen or cracked ammonia is not usually recommended, but may be acceptable in certain cases.

Vacuum annealing is generally acceptable, but again some tinting is possible, depending on the vacuum pressure and temperature. Selection of the gas used for forced gas cooling is important: Helium is normally preferred, followed by argon and nitrogen (for some alloys).

Selection of Heat-Treating Equipment

Most types of industrial furnace are suitable for heat treating the HAYNES® and HASTELLOY® alloys. However, induction heating is not normally recommended, due to inadequate control of the temperature and lack of uniform heating. Heating by torches, welding equipment, and the like is unacceptable. Flame impingement of any type during heat treatment should be avoided.

Machining

Recommended Tools and Machining Parameters Applicable to: Corrosion-resistant Alloys High-temperature Alloys

Be aware that the cobalt-base alloys in these categories (25 and 188) can require different feeds and speeds (as noted in the table) than the nickel- and iron-based alloys.

Operations	Tool Types	Tool Geometry and Set-Up	Speed	Feed	Depth of Cut	Lubricant
-	-	-	surface ft./min*	in**	in**	-
Roughing with severe interruptions; Turning or Facing	Carbide: C-2 or C-3 grade	Negative rake square or trigon insert, 45° SCEA 1, 1/16 in nose radius Tool holder: 5° negative back rake, 5° negative side rake	30-50	0.004-0.008 per revolution	0.15	Dry ² , oil ³ , or water-based ^{4,5}
Normal roughing; Turning or Facing	As above	As above	90 (80 for cobalt alloys) ⁶	0.01 per revolution	<0.15	Dry, oil, or water-based
Finishing; Turning or Facing	As above	Positive rake square or trigon insert, if possible, 45° SCEA ¹ , 1/32 in nose radius Tool holder: 5° positive back rake, 5° positive side rake	95-110 (90 for cobalt alloys)	0.005-0.007 per revolution	0.04	Dry or water-based

Machining Continued

Operations	Tool Types	Tool Geometry and Set-Up	Speed	Feed	Depth of Cut	Lubricant
-	-	-	surface ft./min*	in**	in**	-
Rough Boring	As Above	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° positive side rake, 1/32 in nose radius and largest possible SCEA	70 (60 for co-balt alloys)	0.005-0.008 per revolution	0.125	Dry, oil, or water-based
Finish Boring	As Above	Use standard positive rake tools on insert-type bars Grind brazed bars as for finish turning, except back rake may be best at 0°	95-110 (90 for co-balt alloys)	0.002-0.004 per revolution	0.04	Water-based
	High Speed Steel: M-2, M-7, or M-40 series7	Radial and axial rake 0° to 10° positive, 45° corner angle, 10° relief angle	20-30 (20-25 for cobalt alloys)	0.003-0.005 per tooth	-	Oil or water-based
	Carbide: C-2 grade (marginal performance)	Use positive axial and radial rake, 45° corner angle, 10° relief angle	50-60 (35-40 for cobalt alloys)	0.005-0.008 per tooth (0.005 per tooth for cobalt alloys)	-	Oil or water-based
End Milling	High Speed Steel: M-40 series or T-15	If possible, use short mills with four or more flutes for rigidity	20-25 (15-20 for cobalt alloys)	Feed per tooth: ¼ in dia. 0.002 ½ in dia. 0.002 ¾ in dia. 0.003 1 in dia. 0.004 (cobalt alloys: ¼ in dia. 0.001 ½ in dia. 0.0015 ¾ in dia. 0.002 1 in dia. 0.003)	-	Oil or water-based
	Carbide: C-2 grade	Use sharp tools with 4 or more flutes and variable lead, if possible	50-60 (40-50 for cobalt alloys)	As above	-	Oil or water-based

Machining Continued

Operations	Tool Types	Tool Geometry and Set-Up	Speed	Feed	Depth of Cut	Lubricant
-	-	-	surface ft./min*	in**	in**	-
Drilling	High Speed Steel: M-33, M-40 series, or T-15	Use short, heavy-web drills with 135° crank shaft point; thinning of web at point may reduce thrust and aid chip control	10-15 (7-10 for cobalt alloys) Maximum of 200 rpm for ¼ in dia. drills or smaller	Feed per rev.: ⅛ in dia. 0.001 ¼ in dia. 0.002 ½ in dia. 0.003 ¾ in dia. 0.005 1 in dia. 0.007 (same for cobalt alloys)	-	Oil or water-based Use coolant feed drills if possible
	Carbide: C-2 grade	Not recommended, but tipped drills may be successful on rigid set-ups if depth is not great. The web must be thinned to reduce thrust; use 135° included angle on point Gun drill can be used	50 (40 for cobalt alloys)	As above	-	Oil or water-based Coolant-fed, carbide-tipped drills may be economical in some set-ups
Reaming	High Speed Steel: M-33, M-40 series, or T-15	Use 45° corner angle, narrow primary land, and 10° relief angle	10-15 (8 for cobalt alloys)	Feed per rev.: ½ in dia. 0.003 2 in dia. 0.008 (same for cobalt alloys)	-	Oil or water-based
	Carbide: C-2 or C-3 grade	Tipped reamers recommended; solid reamers require very good set-up Tool geometry same as above	40 (20 for cobalt alloys)	As above	-	Oil or water-based

Machining Continued

Operations	Tool Types	Tool Geometry and Set-Up	Speed	Feed	Depth of Cut	Lubricant
-	-	-	surface ft./min*	in**	in**	-
Tapping	High Speed Steel: M-1, M-7, or M-10	Use two flute, spiral point, plug tap 0° to 10° hook angles Nitrided surface may be helpful by increasing wear resistance, but may result in chipping or breakage Tap drill for 60-65% thread if possible, to increase tool life	7 (same for cobalt alloys)	-	-	Use best possible tapping compound; sulfo-chlorinated oil-base preferred
	Carbide: not recommended	-	-	-	-	-
Electrical Discharge Machining	HAYNES® and HASTELLOY® alloys can be readily cut using any conventional Electrical discharge machining (EDM) system, or by wire EDM					

General note: Use high pressure coolant systems and through the tool coolant, when possible.

*To convert to surface m/min, multiply by 0.305

**To convert from in to mm, multiply by 25.4

¹SCEA = side cutting edge angle, or lead angle of the tool

²At any point where dry cutting is recommended, an air jet directed at the tool may provide a substantial increase in tool life

³Oil coolants should be premium quality, sulfo-chlorinated oils, with extreme pressure additives; a viscosity of 50 to 125 SSU at 100°F (38°C) is standard

⁴Water-based coolants should consist of a 15:1 mixture of water and either a premium quality, sulfo-chlorinated, water-soluble oil or a chemical emulsion, with extreme pressure additives

⁵Water-based coolants may cause chipping or rapid failure of carbide tools in interrupted cuts

⁶Depending upon the rigidity of the set-up

⁷M-40 series high speed steels include M-41 through M-46 at time of writing; others may be added and should be equally suitable

Machining Continued

Applicable to:

Wear & Corrosion-resistant Alloy

ULTIMET® alloy can be successfully turned, drilled, and milled if appropriate tooling and parameters are employed. However, the alloy possesses high strength and work hardens rapidly. Machining guidelines specific to ULTIMET® alloy are as follows:

Turning (ULTIMET® alloy)

Carbide (not high speed steel) tools are recommended.

Surface speed: 60-70 surface ft./min (0.30-0.35 m/s).

Feed rate: 0.005-0.010 in (0.13-0.25 mm).

Depth of cut for roughing: 0.05-0.10 in (1.3-2.5 mm).

Depth of cut for finishing: 0.010-0.015 in (0.25-0.38 mm).

Drilling (ULTIMET® alloy)

Carbide tipped or high speed steel drills are recommended.

Surface speed: 30-35 surface ft./min (0.15-0.18 m/s) for carbide tipped drills; 8-10 surface ft/min (0.04-0.05 m/s) for high speed steel drills.

Feed rate: 0.004 in (0.1 mm) per revolution for 0.25 in (6.4 mm) diameter and greater.

135° included angle on point.

Milling (ULTIMET® alloy)

Carbide (not high speed steel) end mills are recommended.

Surface speed: 25-30 surface ft/min (0.13-0.15 m/s).

Feed per tooth: 0.002 in (0.05 mm) for cutter diameters below 0.75 in (19 mm); 0.003 in (0.08 mm) for cutter diameters above 0.75 in (19 mm).

Grinding

Recommended Wheels and Coolants Applicable to: Corrosion-resistant Alloys High-temperature Alloys

Type of Grinding	Wheels*	Manufacturer	Type of Work	Coolant
Cylinder grinding				
Straight or tapered O.D.	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-sized holes, large holes, small counter-bores	Heavy-duty soluble coolant 25:1 mix >CASTROL 709
Surface grinding				
Straight wheel	32A46-H8VBE 38A46-I-V	Norton	-	Dry or any heavy-duty soluble coolant 25:1 mix CASTROL 653
Double-opposed disk type	87A46-G12-BV 87A46-J11-BW	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 Sunn	-	VANTOL 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 surface ft./min

Descaling and Pickling

Applicable to:

Corrosion-resistant Alloys

High-temperature Alloys

Wear & Corrosion-resistant Alloy

As a result of their inherent resistance to corrosion, the HAYNES® and HASTELLOY® alloys are generally inert to cold acid pickling solutions. Also, the oxide films that form on these alloys during heat treatment are more adherent than those that form on the stainless steels.

The most effective descaling methods for the HAYNES® and HASTELLOY® alloys are immersion in molten caustic baths, followed by acid pickling at elevated temperatures.

Three descaling methods have been used successfully with the HAYNES® and HASTELLOY® alloys, namely:

1. The VIRGO descaling salt bath process.
2. The sodium hydride reducing salt bath process.
3. The DGS oxidizing salt bath process.

The procedures associated with these methods are shown in the table below.

Descaling and Pickling Procedures

	VIRGO Descaling Salt Bath	Sodium Hydride Reducing Salt Bath	DGS Oxidizing Salt Bath
Descaling Bath	VIRGO Salt	Sodium Hydride	DGS Salt
Bath Temperature	970°F (521°C)	750°F-800°F (399°C-427°C)	850°F-950°F (454°C-510°C)
Descaling Time	1 to 3 minutes	15 minutes	2 to 10 minutes
Water Rinse Time	1 to 2 minutes	1 to 2 minutes	1 to 5 minutes
Pickling Step 1	15-17% Sulfuric Acid + 0.5-1% Hydrochloric Acid at 165°F (74°C) for 3 minutes*	4-6% Potassium Permanganate + 1-2% Sodium Hydroxide at 135°F-155°F (57°C-68°C) for 15 minutes*	15-25% Nitric Acid + 3-5% Hydrofluoric Acid at 130°F-150°F (54°C-66°C) for 10 to 20 minutes
Pickling Step 2	7-8% Nitric Acid + 3-4% Hydrofluoric Acid at 125°F-160°F (52°C-71°C) for 25 minutes	8-12% Nitric Acid + 2-3% Hydrofluoric Acid at 125°F-160°F (52°C-71°C) for 15 minutes	No Second Step
Final Water Rinse	3 minutes or Steam Spray	Dip	Dip and Steam Spray

*Followed by a water rinse

Descaling and Pickling Continued

Sand, shot, or vapor blasting are acceptable for removing scales, under certain conditions. The blasting materials should be such that they provide a rapid cutting action, rather than smearing the surface. Also, sand should not be re-used, especially if contaminated with iron. After blasting, it is desirable to pickle the work-piece in acid, to remove any embedded iron or other impurities.

Extreme care should be taken when blasting thin-sectioned components with sand, because of the dangers of distortion and/or embedding sand or scale in the metal surface. Sand blasting also tends to work harden the surfaces, which may cause subsequent forming problems for certain alloys.

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