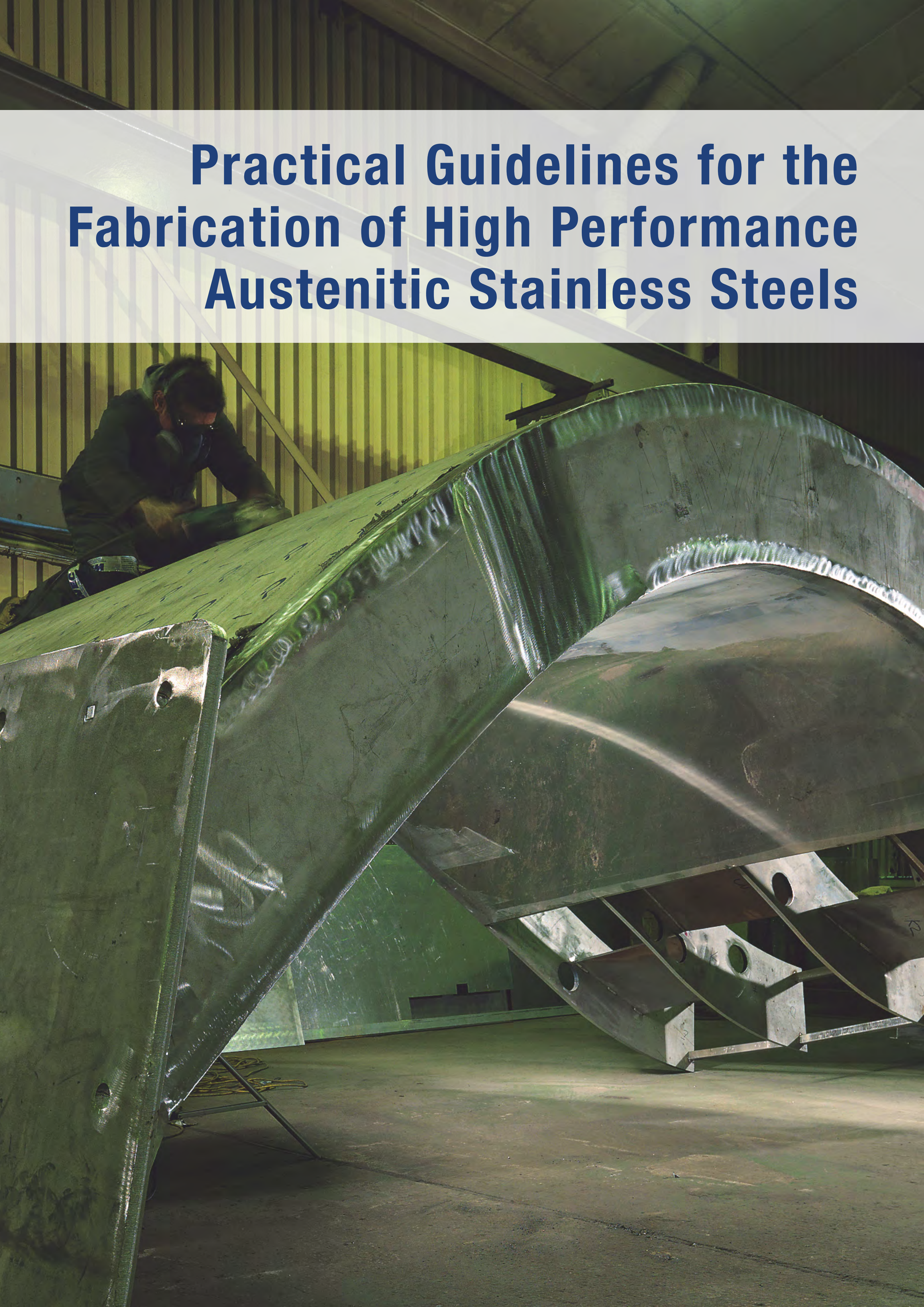
Practical Guidelines for the Fabrication of High Performance Austenitic Stainless Steels



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Practical Guidelines for the Fabrication of High Performance Austenitic Stainless Steels
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1 Introduction

In recent years, new highly corrosion-resistant austenitic stainless steels have entered the marketplace. They have demonstrated cost-effective performance in a variety of harsh and corrosive environments. They have supplied the materials engineer with alloys for demanding new energy and environmental needs. These new materials are called "High Performance Austenitic Stainless Steels" (HPASS). They obtain their performance through alloying with higher than usual amounts of molybdenum and nitrogen. They are more complex than the standard stainless steels, and demand that engineers, designers, and fabricators have thorough knowledge of their characteristics in order to specify and fabricate them successfully. This brochure provides basic information on HPASS grades and compares them to the standard grades. Its primary focus is to compare the fabrication characteristics of the two groups of steels, and to identify similarities and differences between them. This information will help those responsible for fabricating HPASS to manufacture a high-quality product that will perform successfully in the field.

HPASS in a flue gas scrubber application. (Source: Outokumpu)

2 History of Austenitic Stainless Steels

Stainless steels were introduced at the beginning of the twentieth century as a result of pioneering work in England and Germany. In the ensuing half century, manufacturers developed a large family of stainless steels that has served the chemical, energy, food, and other industries very well. The modern era of stainless steels began in the early 1970s when steelmakers introduced new refining and casting technologies. These technologies allowed steel designers and producers to both improve existing "standard grades" and develop new grades with improved performance, including the new HPASS grades.

The new steel-making technologies included argon-oxygen decarburization (AOD) and vacuum-oxygen decarburization (VOD) processes. They made it economically possible to achieve very low carbon content, high alloy recovery, and better composition control (especially precisely controlled nitrogen content). Electroslag remelting (ESR), performed as an alternative or supplemental process, provided improved composition control and a more homogenous microstructure containing fewer inclusions. Continuous casting increased efficiency, further reducing production costs.

Heat exchanger tubesheet during fabrication. (Source: Sandvik)

One of the first alloys to take advantage of the new technologies, the first member of HPASS, was 904L (N08904) developed by what is now Outokumpu Stainless. Grade 904L employs very low carbon levels to produce a weldable wrought version of an existing cast alloy having very high resistance to strong reducing acids. In 1973, ATI Allegheny Ludlum introduced the first fully seawater-resistant austenitic stainless steel, AL-6X®, containing 6% Mo and very low carbon to achieve weldable thin sheet and tubing products. By the mid-seventies, developments in the use and control of nitrogen led to improved 6% Mo alloys that were weldable in thick sections and resistant to the formation of detrimental intermetallic phases that reduce pitting resistance. Representative of these alloys are 254 SMO® (S31254) by Outokumpu Stainless and AL-6XN® (N08367) by ATI Allegheny Ludlum.

The increasing need for cost-effective, high-performance alloys in emerging environmental and energy industries pushed the required corrosion performance of these stainless steels even higher in the 1990s. Two alloys having extremely high-pitting resistance in aggressive chlorinated water were introduced. Outokumpu Stainless introduced alloy 654 SMO® (S32654), containing 7.3% Mo and 0.50% N; Industeel developed alloy B66 (S31266), containing 6% Mo, 2% W and 0.45% N. These steels approach the performance of some of the highly corrosion-resistant nickel-base alloys at significantly lower cost.

Table 1 shows the chemical composition of these new high performance stainless steels. The alloys contain chromium, nickel and molybdenum contents well above those of the standard 18% Cr-8% Ni grades. Many contain nitrogen additions as well. As market needs arise and technology improves, more alloys will certainly be added to this outstanding group of steels.

Table 1: Chemical composition* of high performance austenitic stainless steels and representative standard grades (wt. pct.)**

Grade	UNS No.	EN No.	C	N	Cr	Ni	Mo
Representative standard grades							
Type 304L	S30403	1.4307	0.03	0.10	18.0–20.0	8.0–12.0	
Type 321	S32100	1.4541	0.08	0.10	17.0–19.0	9.0–12.0	
Type 347	S34700	1.4550	0.08	0.10	17.0–19.0	9.0–13.0	
Type 316L	S31603	1.4404	0.03	0.10	16.0–18.0	10.0–14.0	2.00–3.00
Type 317L	S31703	1.4438	0.03	0.10	18.0–20.0	11.0–15.0	3.00–4.00
Type 309S	S30908	1.4833	0.08	0.10	22.0–24.0	12.0–15.0	
Type 310S	S31008	1.4845	0.08	0.10	24.0–26.0	19.0–22.0	
High performance austenitic stainless steels							
Alloy 20, 20Cb-3	N08020	2.4660	0.07		19.0–21.0	32.0–38.0	2.00–3.00
Alloy 825***	N08825	2.4858	0.05		19.5–23.5	38.0–46.0	2.50–3.50
317LM	S31725		0.03	0.10	18.0–20.0	13.2–17.5	4.00–5.00
317LMN	S31726	1.4439	0.03	0.10–0.20	17.0–20.0	13.5–17.5	4.00–5.00
904L	N08904	1.4539	0.02		19.0–23.0	23.0–28.0	4.00–5.00
155N	S31727		0.03	0.15–0.21	17.5–19.0	14.5–16.5	3.80–4.50
Alloy 28	N08028	1.4563	0.02		26.0–28.0	30.0–34.0	3.00–4.00
4565 S, Alloy 24	S34565	1.4565	0.03	0.40–0.60	23.0–26.0	16.0–19.0	3.00–5.00
20Mo-6	N08026		0.03	0.10–0.16	22.0–26.0	33.0–37.0	5.00–6.70
254N	S32053		0.03	0.17–0.22	22.0–24.0	24.0–26.0	5.00–6.00
25-6MO, 1925 hMo	N08926	1.4529	0.02	0.15–0.25	19.0–21.0	24.0–26.0	6.00–7.00
254 SMO	S31254	1.4547	0.02	0.18–0.22	19.5–20.5	17.5–18.5	6.00–6.50
AL-6XN	N08367		0.03	0.18–0.25	20.0–22.0	23.5–25.5	6.00–7.00
UR 66	S31266	1.4659	0.03	0.35–0.60	23.0–25.0	21.0–24.0	5.00–7.00
27-7MO	S31277		0.02	0.30–0.40	20.5–23.0	26.0–28.0	6.50–8.00
3127 hMo, Alloy 31	N08031	1.4562	0.02	0.15–0.25	26.0–28.0	30.0–32.0	6.00–7.00
354N	N08354		0.03	0.17–0.24	22.0–24.0	34.0–36.0	7.00–8.00
654 SMO	S32654	1.4652	0.02	0.45–0.55	24.0–26.0	21.0–23.0	7.00–8.00

Notes:

* Taken from ASTM specifications for plate, sheet and strip when available or from company data sheets. For "other" alloying elements consult these sources.

** Chemistry maximum, unless range or minimum is indicated, EN chemistry does not correspond exactly to ASTM chemistry

*** Alloy 825 is a nickel base alloy, not a stainless steel.

Registered trade names are listed on page 69.

3 Metallurgy

3.1 Types of stainless steels

Stainless steels are iron-based alloys containing at least 10.5% Cr, which are used primarily for their corrosion resistance. At this chromium level, a chromium-enriched surface oxide, called the passive layer or passive film, forms on the steel. It protects the stainless steel and keeps it from "rusting" like ordinary steel. There are many different stainless steels, but they all meet this minimum chromium requirement. Stainless steels belong to one of four major categories: austenitic, ferritic, duplex (mixed ferritic and austenitic), and martensitic. The categories are related to the steels' crystal structure (its arrangement of atoms) and their heat treatment.

As the name indicates, HPASS are in the austenitic category. They have a face-centered cubic (fcc) crystal structure, so called, because the atoms are located at corners and face centers of a cubic lattice. They usually contain nickel and chromium, are very ductile, and cannot be hardened by heat treatment. Ferritic steels have a body-centered cubic (bcc) crystal structure with atoms located at the corners and centers of a cubic lattice. They usually have low nickel content and can also not be hardened by heat treatment. Duplex steels contain roughly equal portions of the ferrite and austenite structures and offer properties between those provided by ferritic and austenitic steels. Martensitic steels are those that can be hardened by heat treatment.

3.2 Phase balance

In a metal, groups of crystals having the same crystal structure are called phases. The phase names for the three crystal structures present in stainless steels are austenite, ferrite, and martensite. The metallurgist uses a technique of polishing and etching the surface of a small sample to identify and quantify the phases present. A representative HPASS microstructure will display a collection of austenite "grains" – groups of fcc crystals – that are free of other phases (**Figure 1**).

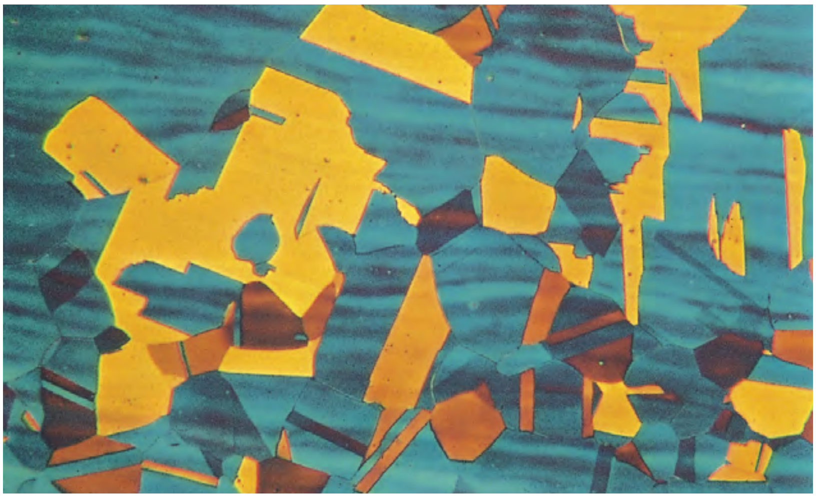


Figure 1: Microstructure of austenitic stainless steel consisting of austenite grains free of precipitates and other phases.

The metallurgist uses chemical composition and heat treatment to control the quantity and type of phases present in the steel. Ferrite-forming elements foster formation of ferrite, while austenite-forming elements promote the formation of austenite. **Table 2** lists the common ferrite and austenite forming elements.

The "phase balance" (relative amounts of different phases) of a steel determines its properties. Controlling the steel's phase balance, and therefore its properties, demands a balance of the alloying elements. The Schaeffler Diagram (**Figure 2**) is a tool that shows the relationship between the chemical composition and the phases present in a stainless steel in the as-cast condition, as might be found in a weld. It allows the user to determine the phase balance from a given specified composition. A typical HPASS containing about 20% Cr, 6% Mo, 20% Ni and 0.2% N, will be located on the diagram in the single-phase Austenite region, near the No Ferrite line at the Nickel Equivalent of about 24 and a Chromium Equivalent of about 26. Ferritic steels are designed to fall within the Ferrite region of this diagram, and duplex steels fall within the two-phase austenite + ferrite (A+F) region. The diagram shows that minor variations in carbon or silicon content can have a great effect on the phase balance.

Table 2: Alloy additions that promote formation of ferrite and austenite.

Ferrite formers	Austenite formers
Iron	Nickel
Chromium	Nitrogen
Molybdenum	Carbon
Silicon	Manganese
Niobium (Columbium)	Copper
Aluminum	Cobalt
Titanium	
Tungsten	

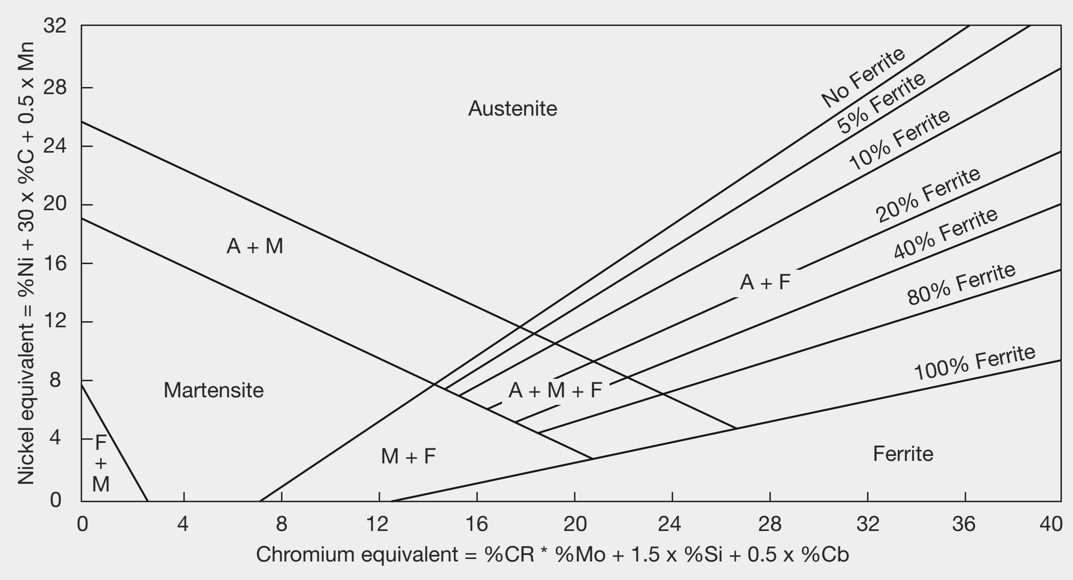


Figure 2: The Schaeffler Diagram shows the influence of chemical composition on the amount of ferrite and austenite in the microstructure of as-cast weld metal. (1)

3.3 Secondary phases – intermetallic compounds

The ideal microstructure of standard and HPASS is a homogeneous array of austenite grains without any secondary phases. However, this is in most cases not the equilibrium condition for austenitic steels. Other, secondary phases can form in the austenitic structure when stainless steels are exposed to elevated temperatures, and they are usually detrimental to properties. The producer or the fabricator must closely control annealing treatments and other fabricating parameters to avoid formation of these secondary phases. The HPASS are very susceptible to secondary phase formation because of their high alloy content. Therefore, a thorough understanding the formation and control of these phases is essential to the successful use of HPASS.

Carbides and nitrides of chromium are of concern because they tend to form in austenite grain boundaries and reduce corrosion resistance there. Two other important secondary phases are sigma and chi. These phases are called intermetallic compounds because they are more like a chemical compound than a metal. They contain very high chromium and/or molybdenum content, are brittle and can reduce corrosion resistance by depleting surrounding areas of chromium or molybdenum. The following sections discuss conditions that lead to their formation and control.

3.3.1 Temperature of secondary phase stability

At sufficiently high temperatures, up to near the melting point, a single austenite phase structure is the equilibrium condition for both the standard grades and most HPASS. At some lower temperature that depends on the steel's composition, one or more secondary phases, sometimes called precipitates, may want to form in an attempt to reach equilibrium. This lower temperature is normally the lower limit of the solution annealing temperature range for any given steel.

In the standard grades, chromium carbide, ($Cr_{23}C_6$) is the primary concern. In Type 304 for example, it starts to form below about 900°C (1650°F). With higher alloy content, the tendency to form other secondary phases increases, as does the temperature for their formation. In some of the very highly alloyed HPASS, chi phase can form at about 1095°C (2000°F). This means that HPASS must be solution annealed at much higher temperatures than standard grades, usually above 1095°C (2000°F). This requirement must be respected to anneal HPASS successfully.

3.3.2 Kinetics of secondary phase formation

The kinetics of secondary phase formation, in other words, the rate at which secondary phases form on cooling, is a very important factor to consider for the successful annealing and welding of these steels. Regardless of grade, stainless steels must be cooled rapidly enough to avoid the formation of secondary phases. To illustrate the relationship between cooling rate and grade, consider the case of standard Type 304 stainless steel and its most likely secondary phase, chromium carbide. Chromium carbide is stable and begins to form on cooling at temperatures below about 900°C (1650°F). The rate at which it forms is slow just below 900°C (1650°F), increasing rapidly with decreasing temperature until at about

700°C (1300°F), where it is very high. Therefore Type 304 must be cooled very rapidly to a temperature somewhat below 700°C (1300°F) to avoid carbide formation and obtain an acceptable annealed or welded microstructure.

If cooling is not rapid enough, chromium carbides form on the boundaries of the austenite grains. Extensive precipitation creates a continuous network of carbides along the grain boundaries. To form chromium carbides, carbon and chromium from the stainless steel matrix combine and precipitate on the grain boundary (where there is more space to form than in the grain). The area right around the carbides, along the grain boundaries, therefore has lower chromium content than the bulk material consequently a lower corrosion resistance. The phenomenon, known as "sensitization," is well known and understood. **Figure 3** illustrates a sensitized microstructure, schematically showing grain boundary precipitates and the associated chromium-depleted zone. Similar phenomena occur with other secondary phases but the temperatures and times involved are different.

The kinetics of secondary phase formation can be described by Time-Temperature-Transformation (TTT) curves for any given alloy. The curves are obtained by first heating test samples to some high temperature (the solution annealing temperature) to dissolve all secondary phases. The samples are then rapidly cooled to an intermediate temperature of interest, held there for various lengths of time, and again rapidly cooled to room temperature to "freeze" the intermediate-temperature structure. The secondary phases are quantified by metallographic or x-ray techniques, and the resulting data describing the formation and growth of the secondary phases are plotted on charts of temperature versus elapsed holding time. The samples can also be subjected to corrosion tests appropriate for the intended service conditions, and the corrosion data plotted in a similar fashion. In this case, the resulting curves are called Time-Temperature-Sensitization (TTS) curves.

Figure 4 shows TTT curves for a number of Type 304 stainless steels with a variety of carbon contents, which reveal several things. Above about 900°C (1650°F) the steels remain completely austenitic. Between about 540°C and 900°C (1,000°F and 1,650°F), the time to begin precipitation varies by more than an order of magnitude. Chromium carbide precipitation kinetics is much slower in steels with lower carbon contents. From a practical standpoint, the curves show that when annealing or welding these steels with, they must be cooled rapidly below the nose of the curves to avoid sensitization and the associated danger of localized corrosion. Lowering the carbon content extends the available time for cooling, making it easier to avoid sensitization.

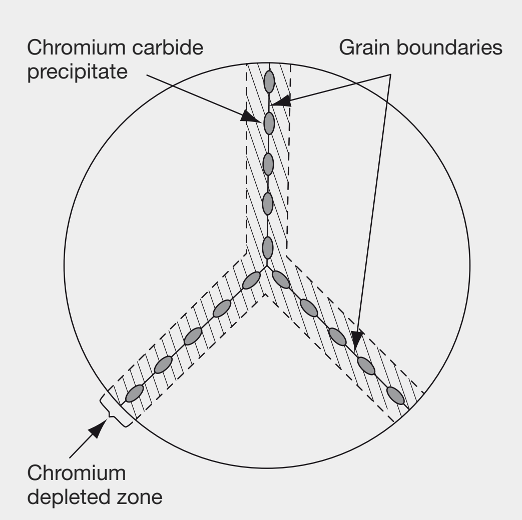


Figure 3: Schematic representation of sensitized grain boundaries in an austenitic stainless steel. (2)

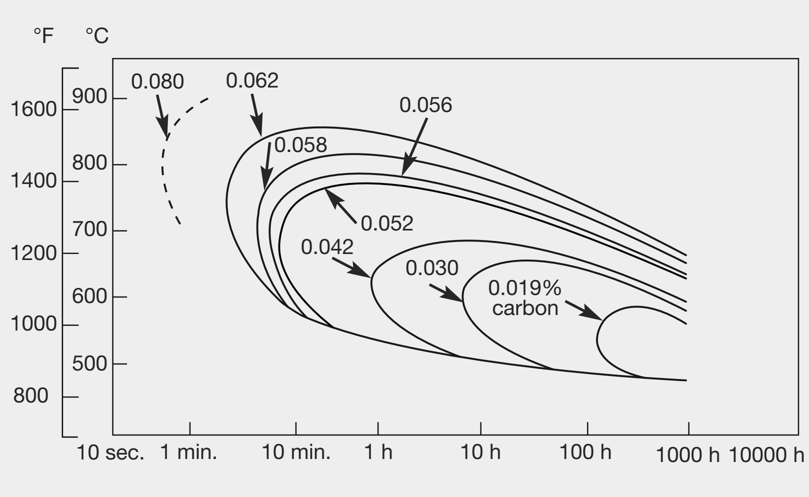


Figure 4: TTS diagram for Type 304 stainless steel with various carbon contents. (3)

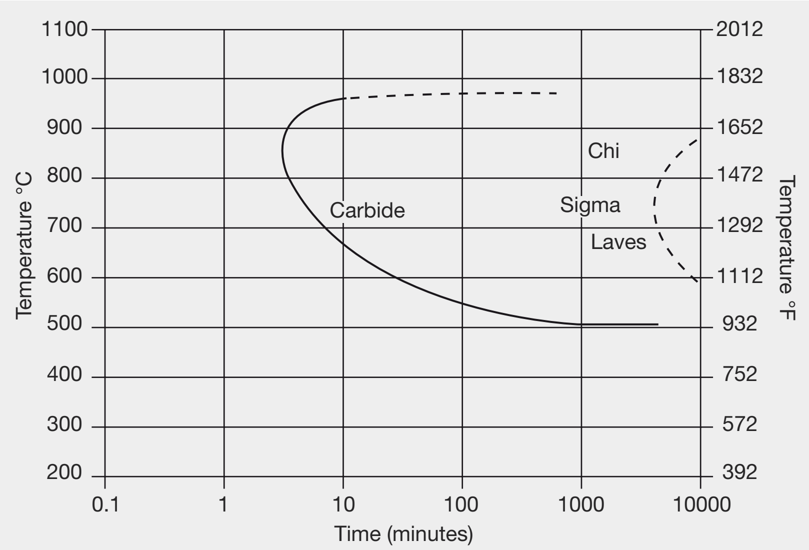


Figure 5: TTT diagram for Type 316 stainless steel. Secondary phases chi, sigma and Laves take a long time to develop in this standard grade stainless steel. (4)

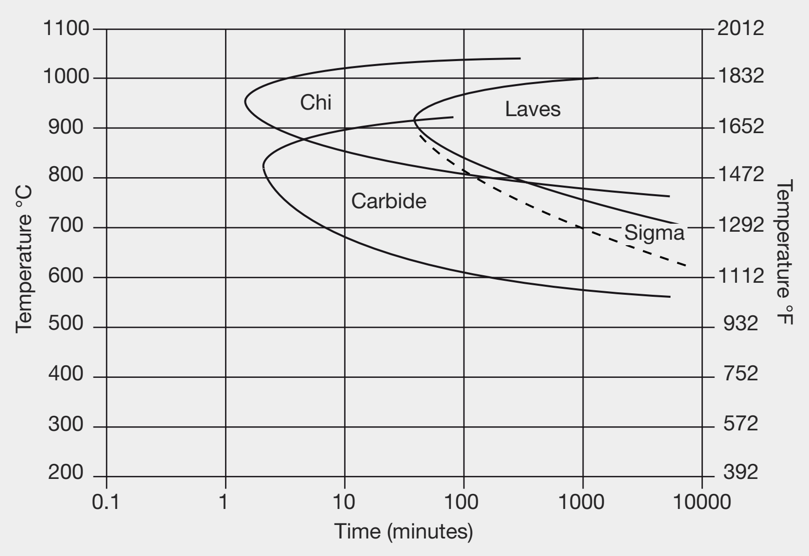


Figure 6: TTT diagram for a 0.05C-17Cr-13Ni-5Mo stainless with 0.039% N. (4)

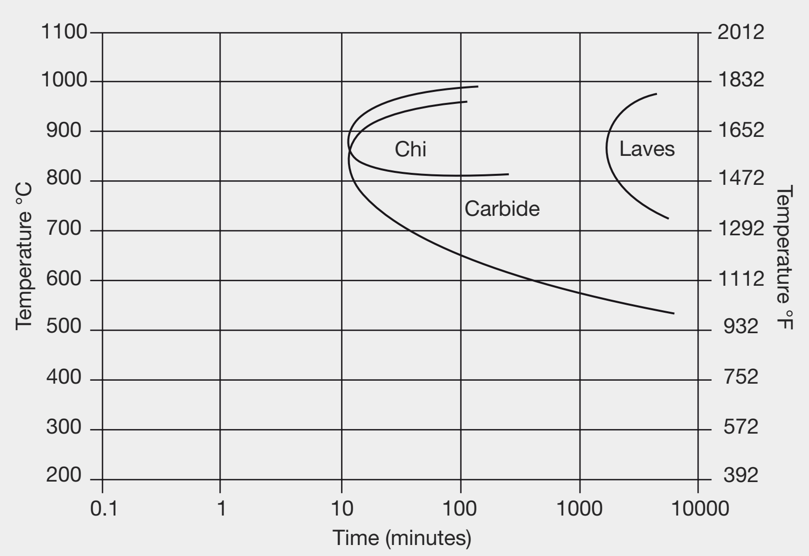


Figure 7: TTT diagram for the same alloy as in Figure 6 but with 0.145% N. (4)

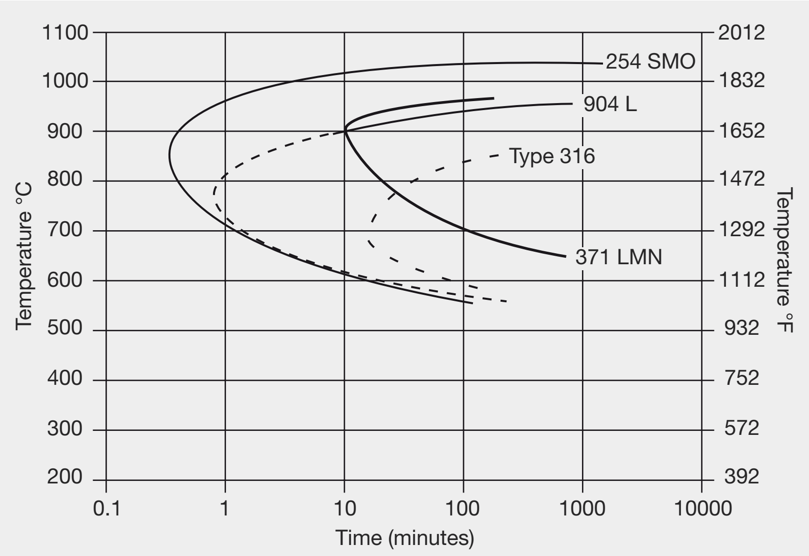


Figure 8: TTT diagram for several commercial austenitic stainless steels with different molybdenum and nitrogen contents. (4)

Chromium carbide precipitation in standard grades is well understood. Information on required cooling rates for different section sizes is available and alternative alloys exist to meet special situations. These include low carbon grades (Types 304L and 316L), stabilized grades (Types 321 and 347), and nitrogen modified standard grades that use nitrogen additions to retard the chromium carbide precipitation rate.

With HPASS, precipitation of sigma and chi phases is of greater concern than chromium carbide, because the high chromium and molybdenum content in the alloys promotes rapid formation of these phases. All HPASS have low carbon content, which minimizes the rate of chromium carbide formation and reduces concern for chromium carbide sensitization. A TTT diagram for Type 316 stainless containing 2% Mo and a fairly high carbon content (**Figure 5**), shows that chromium carbide can form in as little as five minutes, but chi and sigma phases only form after 80 hours or so. In contrast, an alloy having similar chromium and nickel content, but containing 5% Mo, suffers chi formation in very short times (**Figure 6**). The time for chi formation in the 5% Mo alloy is even shorter than that for chromium carbide formation.

As briefly noted earlier, nitrogen delays the formation of these phases, and is employed for this purpose in many HPASS. This effect is demonstrated in **Figure 7**. In this figure, the 5% Mo alloy of **Figure 6** is modified with 0.145% N. The nitrogen addition pushes back the onset of both chi and chromium carbide formation to ten minutes, compared to two to four minutes for the alloy containing only 0.039% N. The 0.145% N alloy allows for slower cooling after annealing or welding without the formation of secondary phases.

As chromium and molybdenum increase to very high levels in the most highly alloyed HPASS, intermetallic phases form at even shorter times. Nitrogen additions are helpful, but even very high nitrogen contents of 0.20-0.50% N are not able to shift the onset of precipitation to times in the desired range of ten minutes or more. **Figure 8** shows representative TTT curves of several alloys to illustrate this point. Type 317LMN, (17% Cr, 14% Ni, 4.5% Mo, 0.15% N) forms secondary phases in about the same time as 316 despite its higher alloy content, due to the effect of nitrogen. Alloy 254 SMO (20% Cr, 18% Ni, 6% Mo, 0.20% N), begins to suffer precipitation in about 30 seconds, and alloy 904L (20% Cr, 25% Ni, 4.55% Mo, no nitrogen addition) suffers intermetallic phase formation in less than one minute. Clearly, alloys of this kind require limitations on section size or drastic cooling to avoid secondary phase formation.

4 Role of Alloying Elements

Chemical composition has a major influence on a steel's metallurgical structure, mechanical properties, physical properties and corrosion resistance. Both intentional alloying elements and alloying elements unintentionally introduced by the steelmaking process affect these properties.

Alloying elements other than carbon and nitrogen, for example chromium and nickel are incorporated in the crystal lattice on substitutional sites. That is, they substitute for iron on the corners and face centers of the austenitic lattice. Carbon and nitrogen, because of their small size, locate themselves in open spaces (interstitial sites) between the lattice atoms. In doing so, they create large strains in the lattice and so are potent hardening elements.

Alloying elements influence the steel's properties in different ways, sometimes beneficial, sometimes detrimental. Choosing a particular steel composition often requires the designer or materials engineer to sacrifice a measure of one property to maximize the benefit of another. The following sections describe the function of important alloying elements in austenitic stainless steels.

4.1 Chromium (Cr)

Chromium is the alloying element that makes stainless steels "stainless". At least 10.5% Cr is required to produce the unique surface passive film responsible for this characteristic. The passive film is effective in protecting the stainless steel in environments that can include aggressive waters, many acids and even highly oxidizing high-temperature gases. Corrosion resistance improves in a wide variety of environments as chromium increases above the threshold level of 10.5%. For this reason many grades have chromium levels well above that amount. Examples are the workhorse Type 304 grade with 18% Cr and the HPASS with 20–28% Cr.

4.2 Nickel (Ni)

Nickel's primary purpose is to create and stabilize austenite. Without 8% Ni, Type 304 would not be an austenitic stainless steel and would not exhibit austenite's desirable mechanical properties. Instead, it would be a ferritic stainless steel with serious limitations in strength and toughness. As more chromium or other ferrite-forming elements are added to the steel, more nickel is needed to maintain the austenitic structure. The HPASS, which have high chromium and molybdenum, require nickel contents of 20% or more to preserve the austenitic structure. Nickel also improves corrosion behavior in certain reducing acids, and increases stress corrosion resistance at levels above about 20%. It also reduces the rate of work hardening during cold deformation, so it is often found in alloys designed for deep drawing, spin forming and cold heading.

4.3 Molybdenum (Mo)

Molybdenum increases resistance to pitting and crevice corrosion in chloride-containing environments. It works synergistically with chromium and nitrogen to improve performance in these environments. This synergistic effect produces very high pitting and crevice corrosion performance in HPASS. Molybdenum also increases corrosion resistance in reducing environments like hydrochloric acid and dilute sulfuric acid. The minimum molybdenum addition to austenitic stainless steels is about 2%, as in Type 316. The most highly alloyed HPASS steels contain up to 7.5% Mo.

Molybdenum promotes ferrite formation, which affects phase balance. It participates in the formation of several detrimental secondary phases, and forms an unstable high temperature oxide, adversely affecting high temperature oxidation resistance. These factors must also be considered in using stainless steels containing molybdenum.

4.4 Carbon (C)

Carbon strengthens austenite, so it is a useful alloying element in stainless steels used in applications like boiler tubes that operate at high temperature. Carbon has no other useful function and can be detrimental to corrosion resistance under certain circumstances as noted earlier. The carbon content of most austenitic stainless steels is usually limited to the lowest practical levels.

Standard low carbon grades designed for welding (Types 304L and 316L) limit carbon to 0.030%. Some of the more highly alloyed high performance grades limit carbon even further to 0.020%.

4.5 Nitrogen (N)

Nitrogen stabilizes and strengthens austenite, and retards secondary phase formation. It is used in both standard grades and in HPASS. In low carbon standard grades, it is added in small amounts (about 0.1%) to offset the loss in strength due to the low carbon. In standard grades and HPASS, it provides strength and retards carbide sensitization and the formation of secondary phases. Nitrogen also improves resistance to chloride pitting and crevice corrosion, so some of the most corrosion resistant HPASS contain up to 0.5% N.

Type 316L stainless steel portable vessel and control panel for the bio-pharmaceutical industry. (Source DCI, Inc, St. Cloud, MN USA)

4.6 Manganese (Mn)

Steelmakers use manganese to deoxidize molten steel, so a small residual amount is found in all stainless steels. Manganese serves an alloying function because it stabilizes austenite. Additionally, it increases nitrogen solubility in the stainless steel, so it is added to many HPASS to allow higher nitrogen content and improved strength and corrosion resistance.

4.7 Copper (Cu)

Copper improves the corrosion resistance of stainless steels in reducing acids like certain sulfuric acid and phosphoric acid mixtures. It is used as an alloying element in some HPASS that have been designed specifically for service in these environments.

4.8 Silicon (Si)

Like manganese, silicon is used to deoxidize molten steel, so a small amount is always present as small oxide inclusions containing silicon, manganese and other deoxidizing elements. These inclusions can have subtle effects on the surface quality, polishability, weldability and corrosion resistance of stainless steel products.

4.9 Niobium/columbium (Nb/Cb) and titanium (Ti)

These elements are very strong carbide formers, and are used as alternatives to low carbon content to mitigate sensitization. They also confer high temperature strength. Types 347 and 321 containing Nb and Ti are often used in boiler and refinery applications where elevated temperature strength and weldability are requirements. They are also used in certain deoxidation practices, so sometimes are found as residual elements in HPASS.

4.10 Sulfur (S) and phosphorus (P)

Sulfur has both beneficial and detrimental effects on the properties of stainless steels. Its most important beneficial effect is improved machinability, while its major detrimental effect is reduced hot workability. The HPASS are intrinsically difficult to hot work, so they always contain lowest practical sulfur content, about 0.001%. Sulfur is not normally used as an alloy addition to these steels.

Phosphorous has no beneficial effect, and is detrimental to hot workability during forging and hot rolling. It also promotes hot cracking during cooling after welding. It is always limited to the lowest practical level.

5 Mechanical and Physical Properties

The HPASS retain the overall good mechanical properties of the standard grades, delivering somewhat higher strength and slightly lower ductility in the annealed condition. Cold work significantly increases their strength. Because they work harden, they have excellent formability and can absorb large amounts of energy before failure. Their strength derives from solution-hardening effects of both substitutional alloying elements and interstitial nitrogen. These alloys retain good mechanical properties at low and high temperatures.

5.1 Strength

Table 3 summarizes room temperature mechanical properties for HPASS. The higher yield and tensile strength values are due largely to nitrogen and carbon strengthening effects. **Figure 9** summarizes the effect of nitrogen on strength for a number of austenitic stainless steels. Increasing nitrogen content from the normal 0.05% to 0.20% raises yield strength from 270 MPa (39 ksi) to 340 MPa (49 ksi). This has a significant effect on specification minimums. ASTM A 240 specifies a minimum yield strength of 170 MPa (25 ksi) for Type 304L (about 0.05% N), and 240 MPa (35ksi) for Type 304N (0.15% N). A further step-up occurs for HPASS grades like S31254 (0.20% N) with a specified minimum yield strength of 310 MPa (45 ksi) and S31266 (0.50% N) with a minimum yield strength of 420 MPa (61 ksi).

Austenitic stainless steels cannot be hardened by heat treatment, so they are usually produced in the annealed condition. Cold work increases their strength, therefore, some mill products are produced in the cold rolled condition when higher strength is required. The HPASS respond to cold working as the standard grades do. Cold working processes like forming, spinning, swaging, and cold drawing can produce very high strength. Nitrogen increases the effectiveness of cold working, so even higher strength results when these alloys are cold worked (**Figure 10**) compared to standard grades. This strong work-hardening effect can cause difficulty in some shop-forming operations where a section size limitation might occur for a given machine power. High work hardening rates can also create problems during machining if the cutting tool hardens the surface of the work piece. Low speeds and large depth of cut are recommended when machining HPASS.

The yield strength of cold-worked nitrogen alloyed material can be further increased by a strain ageing process, where the steel is aged for about ten minutes at temperatures of 300 to 500°C (570 to 930°F).

The strength imparted by cold work is retained at moderate temperatures, but not at high temperatures. So, a cold-worked material does not retain its strength upon annealing or traditional fusion welding. Specialized spot welding techniques can circumvent this limitation, and are used in applications like rail cars that use cold-worked sheet.

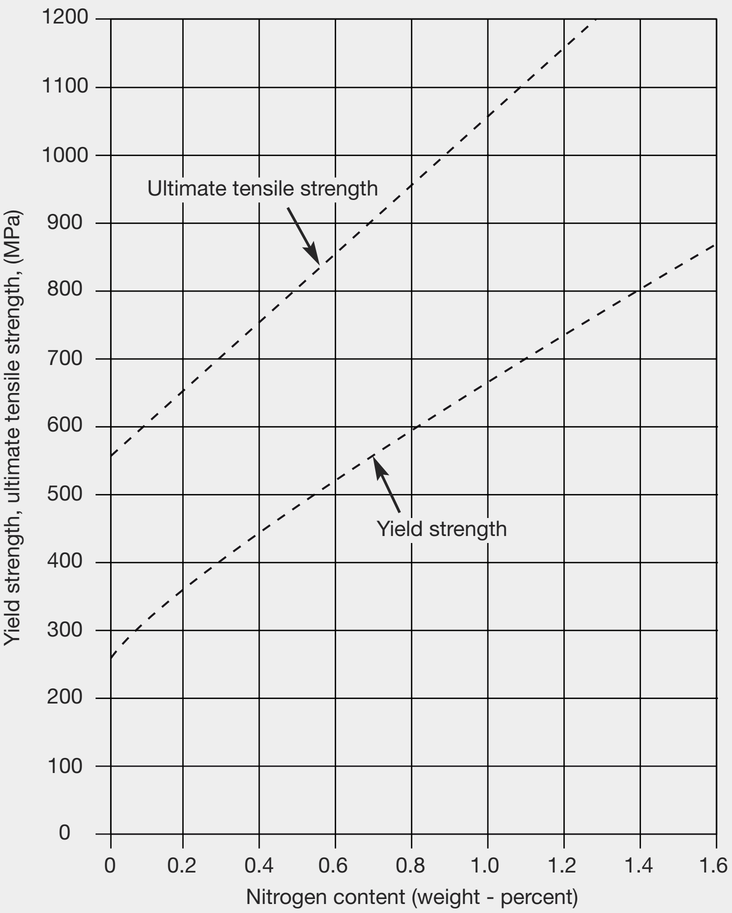


Figure 9: Effect of nitrogen on the strength of austenitic stainless steels. (5)

Table 3: Minimum mechanical properties of standard and high performance austenitic stainless steels.

Grade	UNS No.	EN No.	Yield strength 0.2%	Tensile strength	Elongation in 2”	Hardness, max	
			MPa (ksi)	MPa (ksi)	%	Brinell	Rockwell B
Chromium-nickel austenitic stainless steels							
Type 304L	S30403	1.4307	170 (25)	515 (75)	40	201	92
Type 321	S32100	1.4541	205 (30)	515 (75)	40	217	95
Type 347	S34700	1.4550	205 (30)	515 (75)	40	201	92
Type 316L	S31603	1.4404	170 (25)	515 (75)	40	217	95
Type 317L	S31703	1.4438	205 (30)	515 (75)	35	217	95
Type 309S	S30908	1.4833	205 (30)	515 (75)	40	217	95
Type 310S	S31008	1.4845	205 (30)	515 (75)	40	217	95
High performance austenitic stainless steels							
Alloy 20, 20Cb-3	N08020	2.4660	240 (35)	550 (80)	30	217	95
Alloy 825*	N08825	2.4854	310 (45)	655 (95)	30		
317LM	S31725		205 (30)	515 (75)	40	217	95
317LMN	S31726	1.4439	240 (35)	550 (80)	40	223	96
904L	N08904	1.4539	220 (31)	490 (71)	35		90
155N	S31727		245(36)	550(80)	35	217	
Alloy 28	N08028	1.4563	500 (73)	214 (31)	40		90
4565 S, Alloy 24	S34565	1.4565	415 (60)	795 (115)	35	241	100
20Mo-6	N08026		241 (35)	551 (80)	30	217	95
254N	S32053		295 (43)	640(93)	40	217	96
25-6MO, 1925 hMo	N08926	1.4529	295 (43)	650 (94)	35		
254 SMO	S31254	1.4547	310 (45)	655 (95)	35	223	96
AL-6XN	N08367		310 (45)	655 (95)	30	241	
UR 66	S31266	1.4659	420 (61)	750 (109)	35		
27-7MO	S31277		360 (52)	770(112)	40		
3127 hMo, Alloy 31	N08031	1.4562	276 (40)	650 (94)	40		
354N	N08354		295 (43)	550(80)	40	217	96
654 SMO	S32654	1.4652	430 (62)	750 (109)	40	250	

Note: These mechanical properties correspond to the grades of ASTM produced to the UNS designations shown. The grades identified by Euro Norm designation, as shown in the second column, are similar but may not be identical. Material certified as meeting the requirements of a specification within one system, e.g., ASTM, will not necessarily meet the requirements of the similar material in another specification, e.g., EN or JIS.

* Alloy 825 is a nickel base alloy, not a stainless steel.

5.2 Ductility and toughness

The HPASS have ductility similar to the standard grades, with elongation values in the range of 60% to 70%, well above specification minimums. The nitrogen used to increase strength in some of these alloys does not reduce ductility.

The face-centered-cubic crystal structure of austenite is responsible for the good ductility and high-work hardening rates of these steels, which in turn produce very good toughness at ambient temperature and below. Unlike carbon steels and some other materials, austenitic alloys do not exhibit a ductile-to-brittle transition as temperature is reduced. However, some of the most highly alloyed HPASS containing high nitrogen display a somewhat greater loss in toughness at cryogenic temperatures than lower alloyed austenitic stainless steels.

Cold work has a strong effect on ductility and toughness. It decreases ductility by depleting the ductility reservoir of the annealed starting material. Annealing erases the effects of cold working, reducing strength and restoring ductility and toughness to high values.

5.3 High-temperature strength

Austenitic stainless steels deliver good strength at elevated temperatures. Most of the standard grades have been approved for pressure vessel applications. The ASME Pressure Vessel Code gives allowable design values to temperatures up to 427°C (800°F). For furnace applications, where pressure is not a factor, standard and some special heat resistant stainless alloys are used at twice these temperatures. The HPASS are designed primarily for corrosion resistance, but they also have good high-temperature strength. Their strength advantage over standard grades at ambient temperature is retained at high temperature. For example, the ASME Code allowable stress at 427°C (800°F) for HPASS N08367 is 18 ksi (124 MPa), compared to Type 316 at 9.6 ksi (66 MPa). **Figure 11** compares high-temperature strength data for Type 316 to three HPASS.

The austenitic stainless steels retain their strength at high temperatures much better than ferritic stainless steels because of their crystal structure and their high nickel contents. They are very useful at elevated temperatures because they do not form the embrittling alpha prime phase above about 300°C (570°F), but they can form the embrittling chi and sigma phases at temperatures in the 500-1050°C (930-1925°F) range.

High strength has positive and negative effects on fabrication of these alloys. When annealing a fabricated component, high strength at temperature prevents distortion under the influence of gravity. However, if a component does distort, for example during welding, high strength makes it more difficult to straighten the component than if it had lower strength. As noted earlier, high-strength alloys may tax the available forming equipment power, limiting the section size that a given machine can form.

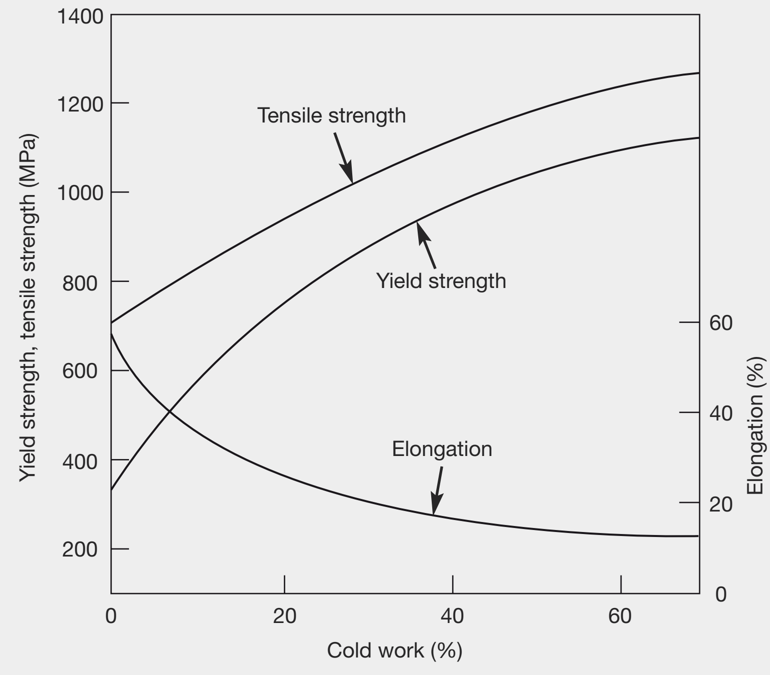


Figure 10: Effect of cold work on the strength and ductility of a 6% Mo – 0.2% N HPASS. (6)

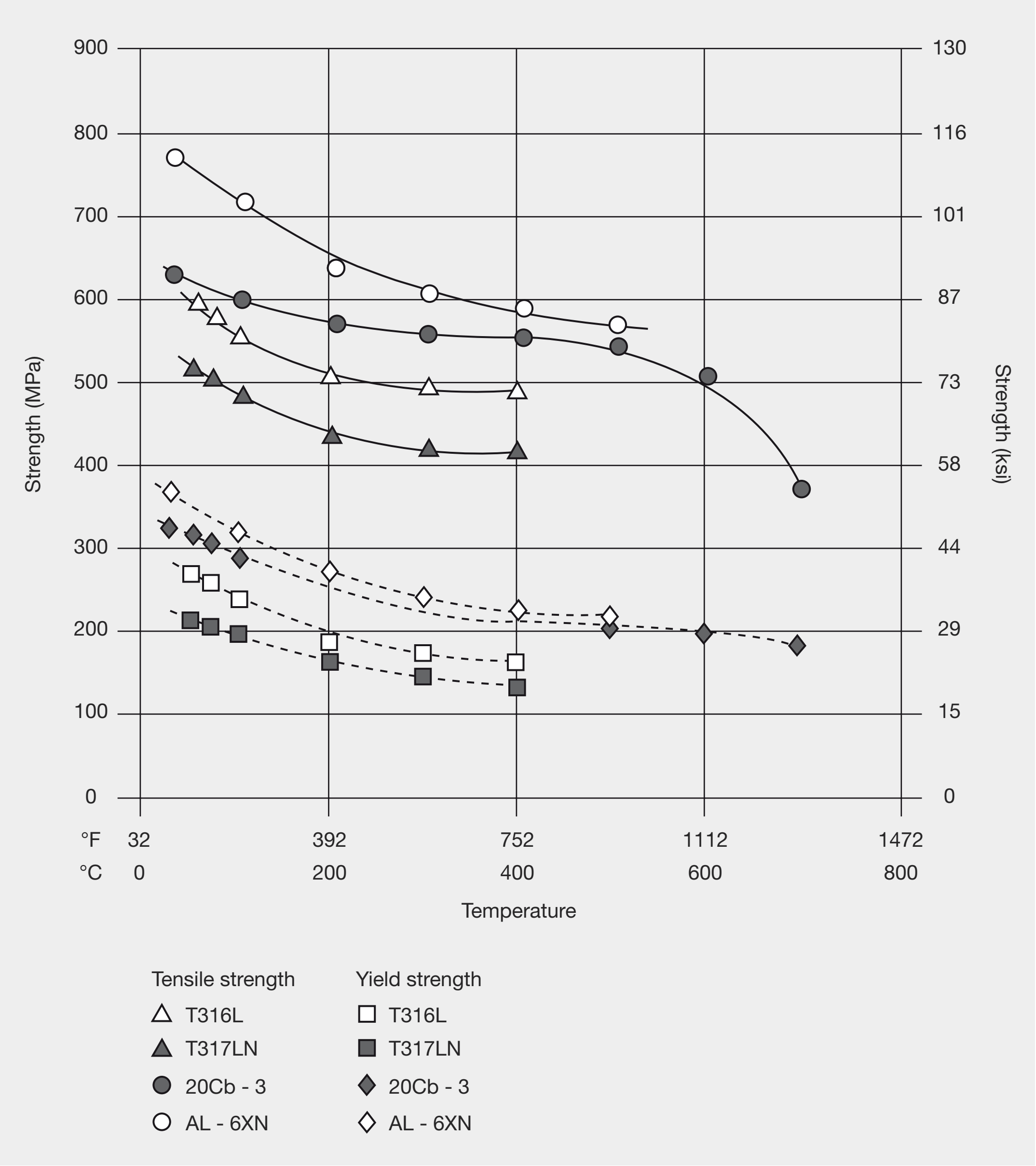


Figure 11: High temperature strength of three HPASS compared to Type 316L. (4)

5.4 Physical properties

The HPASS have physical properties similar to the standard austenitic grades when compared to carbon steels. That is, they have a slightly lower Young's modulus, higher coefficient of thermal expansion (CTE) and lower thermal conductivity. **Tables 4 and 5** summarize detailed physical property data for austenitic stainless steels.

Table 4: Ambient Temperature Physical Properties of Standard and High Performance Austenitic Stainless Steels.

Grade	UNS No.	Density		Specific heat		Electrical resistivity		Young's modulus	
		g/cm^3	lb/in^3	J/kg·K	Btu/lb/°F	Ω·mm^2/m	micro Ω in	GPa	10^6 psi
Representative standard grades									
Type 304L	S30403	8.03	0.290	500	0.120	0.72	28.3	193	28.0
Type 321	S32100	7.89	0.285	500	0.120	0.72	28.3	193	28.0
Type 347	S34700	7.97	0.288	500	0.120	0.73	28.7	200	29.0
Type 316L	S31603	7.95	0.287	469	0.112	0.74	29.1	193	28.0
Type 317L	S31703	7.95	0.287	460	0.110	0.79	31.1	200	29.0
Type 309S	S30908	7.89	0.285	500	0.120	0.78	30.7	200	29.0
Type 310S	S31008	7.86	0.284	500	0.120	0.85	33.5	200	29.0
High performance austenitic stainless steels									
Alloy 20, 20Cb-3	N08020	8.08	0.292	502	0.120	1.08	42.5	193	28.0
Alloy 825*	N08825	8.14	0.294	440	0.015	1.13	44.5	193	28.0
317LM	S31725	7.95	0.287	460	0.11	0.79	31.1	200	29.0
317LMN	S31726	8.02	0.290	502	0.112	0.85	33.5	200	29.0
904L	N08904	7.95	0.287	461	0.110	0.95	37.4	190	28.0
155N	S31727	8.02	0.290	460	0.109	0.86	33.9	203	29.4
Alloy 28	N08028	8.00	0.290	460	0.109	0.99	39.0	105	28.3
4565 S, Alloy 24	S34565	8.00	0.290	510	0.122	0.92	36.2	190	28.0
20Mo-6	N08026	8.13	0.294	461	0.110	1.08	42.5	186	27.0
254N	S32053	8.06	0.291	460	0.109	0.93	36.6	188	27.3
25-6MO, 1925 hMo	N08926	8.15	0.294	461	0.110	0.88	34.6	192	27.8
254 SMO	S31254	7.95	0.287	498	0.119	0.85	33.5	200	29.0
AL-6XN	N08367	8.06	0.291	461	0.110	0.89	35.0	195	28.2
UR 66	S31266	8.20	0.297	450	0.113	1.00	39.4	195	28.3
27-7MO	S31277	8.02	0.289	454	0.109	1.00	39.4	191	27.7
3127 hMo, Alloy 31	N08031	8.03	0.290	440	0.105	1.00	39.4	195	28.3
354N	N08354	8.16	0.295	440	0.105	1.03	40.6	193	28.0
654 SMO	S32654	8.00	0.290	510	0.122	0.78	30.7	188	27.6

* Alloy 825 is a nickel base alloy, not a stainless steel.

Table 5: Room and elevated temperature physical properties of standard and high performance austenitic stainless steels.

Grade	UNS No.	20°C (68°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (754°F)	500°C (932°F)
Young's modulus in tension GPa (10^6 psi)							
Type 304	S30400	193 (28.0)	193 (28.0)	193 (27.9)	187 (27.1)	183 (26.6)	179 (26.0)
Type 321	S32100	193 (28.0)	193 (28.0)	193 (28.0)	188 (27.3)	183 (26.5)	178 (25.8)
Type 316L	S31603	200 (29.0)	194 (28.1)	185 (26.9)	177 (25.9)	169 (24.5)	160 (23.2)
317LMN	S31726	200 (29.0)	194 (28.1)	186 (27.0)	179 (26.0)	171 (24.8)	163 (23.6)
4565 S, Alloy 24	S34565	193 (28.0)	187 (27.1)	180 (26.1)	173 (25.1)	165 (24.0)	157 (22.9)
25-6MO, 1925 hMo	N08926	193 (28.0)	186 (27.0)	179 (26.0)	173 (25.1)	168 (24.4)	162 (23.6)
254N	S32053	188 (27.3)	184 (26.7)	178 (25.8)	172 (24.9)	165 (23.9)	
AL-6XN	N08367	195 (28.3)	189 (27.4)	180 (26.1)	172 (24.9)	163 (23.7)	158 (23.0)
UR 66	S31266	195 (28.3)		180 (26.1)		165 (23.9)	
354N	N08354	198 (28.7)	194 (28.1)	189 (27.4)	183 (36.5)	177 (25.7	172 (24.8)
Mean coefficient of thermal expansion - temperature 20°C (68°F) to T - 10^{-6}/K (10^{-6}/°F)							
Type 304	S30400		16.6 (9.20)	16.9 (9.40)	17.4 (9.65)	17.6 (9.75)	18.0 (10.0)
Type 321	S32100		16.6 (9.20)				17.1 (9.50)
Type 316L	S31603		16.5 (9.16)	16.9 (9.38)	17.3 (9.61)	17.6 (9.78)	18.0 (10.00)
Alloy 20, 20Cb-3	N08020		14.9 (8.27)	15.2 (8.44)	15.5 (8.61)	15.9 (8.83)	16.1 (8.94)
317LMN	S31726		16.6 (9.22)	17.2 (9.55)	17.8 (9.89)	18.5 (10.30)	
904L	N08904		15.3 (8.50)	15.7 (8.72)	16.1 (8.94)	16.5 (9.17)	16.9 (9.39)
155N	S31727		15.9 (8.83)	16.4 (9.11)	16.7 (9.28)	17.0 (9.44)	17.2 (9.55)
4565 S, Alloy 24	S34565		14.5 (8.00)	15.5 (8.60)	16.3 (9.00)	16.8 (9.30)	17.2 (9.50)
20Mo-6	N08026		14.8 (8.22)	14.9 (8.29)	15.3 (8.52)	15.7 (8.73)	16.0 (8.89)
254N	S32053		14.5 (8.00)	15.0 (8.28)	15.4 (8.55)	15.8 (8.78)	
25-6MO, 1925 hMo	N08926		15.0 (8.33)	15.7 (8.72)	16.1 (8.94)	16.4 (9.11)	16.7 (9.28)
254 SMO	S31254		16.0 (8.89)				17.0 (9.44)
AL-6XN	N08367		15.3 (8.50)	15.5 (8.60)	15.7 (8.80)	16.0 (8.90)	16.0 (8.90)
UR 66	S31266		15.0 (8.33)		16.0 (8.90)		16.5 (9.17)
354N	N08354		14.1 (7.83)	14.6 (8.11)	14.8 (8.22)	15.1 (8.40)	15.4 (8.55)

Table 5 (continued): Room and elevated temperature physical properties of standard and high performance austenitic stainless steels.

Grade	UNS No.	20°C (68°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (752°F)	500°C (932°F)
Thermal conductivity - W/m·K (Btu in/hr ft^2 °F)							
Type 304	S30400	14.6 (100)	16.2 (112)	17.0 (117)	19.6 (135)	20.3 (140)	21.4 (148)
Type 316L	S31603	14.0 (97)	14.9 (103)	16.0 (111)	17.3 (120)	18.6 (129)	19.9 (138)
317LMN	S31726	14.0 (97)	14.4 (100)				
Alloy 20, 20Cb-3	N08020	11.6 (81)	13.1 (91)	15.0 (104)	16.6 (115)	18.2 (126)	19.6 (136)
904L	N08904	11.5 (80)	13.1 (91)	15.1 (105)			
155N	S31727	12.5 (87)	14.1 (98)	16.2 (112)	18.2 (126)	19.9 (138)	21.8 (151)
4565 S, Alloy 24	S34565	14.5 (101)	14.5 (101)				
20Mo-6	N08026	11.6 (81)	13.1 (91)	15.0 (104)	16.6 (115)	18.2 (126)	19.6(136)
254N	S32053	11.6 (81)	12.5 (87)	14.4 (100)	16.1 (112)	17.6 (122)	
25-6MO, 1925 hMo	N08926	12.0 (83)	12.9 (89)	14.4 (100)	16.5 (114)	18.5 (128)	20.1 (139)
254 SMO	S31254	13.4 (92)	14.5 (100)	15.9 (110)	17.3 (119)	18.7 (129)	20.2 (139)
AL-6XN	N08367	11.5 (80)	13.0 (90)	15.1 (105)	17.2 (120)	19.3 (134)	21.2 (147)
UR 66	S31266	12.0 (83)		13.0 (90)		14.0 (97)	
354N	N08354	11.3 78)	13.2 (91)	15.3 (106)	17.6 (122)	19.1 (132)	20.8 (144)
654 SMO	S32654	8.6 (59)	9.8 (68)	11.3 (78)	12.6 (87)	14.5 (100)	

6 Corrosion Resistance

The HPASS provide the highest corrosion resistance obtainable with stainless steels. While each alloy has different attributes, they all are outstanding in one or more of the three main areas of corrosion performance: general corrosion, pitting and crevice corrosion, and stress corrosion cracking.

The passive film on HPASS is strengthened with molybdenum. Even so, it can break down under adverse environmental conditions, allowing corrosion to begin. Widespread film breakdown results in corrosion across the entire surface (general corrosion). Localized film breakdown produces pitting corrosion. Because of molybdenum's presence, the film on HPASS is more resistant to breakdown than it is for the standard grades.

The materials engineer must select the most cost-effective grade of stainless steel that will maintain the passive film in the environment of interest. The fabricator and user must understand the factors that reduce the alloy's basic resistance through poor fabrication or operating conditions. This section presents some basic principles related to stainless steel corrosion resistance. Detailed information on the corrosion performance of stainless steels can be found in resources cited in the Appendix.

6.1 General corrosion

General corrosion is a uniform metal loss from the surface that produces a uniform thinning of the cross-section. With stainless steels it usually occurs in strong, warm acids. General corrosion usually indicates that the environment is too aggressive for the grade selected. If the environment is oxidizing, a grade having more chromium will often give better performance. If the environment is reducing, grades with higher chromium, nickel, molybdenum, and copper will perform better. Small amounts of contamination can substantially change the aggressiveness of service environments, affecting their relative oxidizing or reducing powers. Such changes can correspondingly affect the stainless steel's corrosion performance.

6.2 Localized corrosion

6.2.1 Pitting and crevice corrosion

Pitting and crevice corrosion occur in a localized area on the surface of a metal. There are many ways that the passive film can be disrupted locally, so these forms of corrosion are the most likely to occur. By definition, pitting occurs on a relatively clean, unblemished surface. Crevice corrosion occurs in a crevice – for example, underneath a bolt or scale. These kinds of corrosion are particularly threatening because they often occur in a seemingly benign environment and, once initiated, can penetrate very rapidly.

Resistance to localized attack increases with higher Cr, Mo and N content, which accounts for the large amounts of these alloying additions in HPASS. Environmental conditions that promote pitting and crevice corrosion include halide ions (especially chloride), oxidants like manganese, high temperatures, and acid conditions not aggressive enough to produce general attack. Detrimental design or operating conditions include built-in crevices like bolted joints, and deposits related to poor system cleanliness like scaled surfaces. Careless fabrication practices can also promote localized corrosion by creating dirty or blemished surfaces that initiate corrosion. Occasionally, poor internal steel cleanliness and certain undesirable nonmetallic inclusions or intermetallic phases can nucleate localized corrosion.

The HPASS deliver the highest possible pitting and crevice corrosion resistance for a given set of cost and fabricability requirements. Laboratory pitting and crevice corrosion tests in highly corrosive solutions are used to rank different alloys for relative resistance and to assist in the development of improved alloys. Most of these tests use temperature as the ranking criterion for a given set of test environment conditions. The ranking is expressed in terms of the critical pitting temperature (CPT) or critical crevice temperature (CCT). The critical temperature is the temperature at which corrosion will begin to occur as temperature increases (thus a higher critical temperature is better than a lower one). A given alloy's CCT is always lower than its CPT because crevice corrosion initiates more easily than pitting corrosion. **Figure 12** shows critical crevice and pitting temperatures measured in a ferric chloride solution for a number of stainless steels. Note the superior performance of HPASS compared to standard Type 316 stainless.

The ranking tests and resultant critical temperatures do not predict in detail how an alloy will perform in a given environment, but alloys with higher CCT or CPT generally have better corrosion resistance over a range of real environments. Field experience allows some general correlations between the critical temperatures and field performance. Type 316L, with an ASTM G48 CPT of 10°C (50°F), is not suitable for steam condenser tube service in seawater. HPASS alloy 254 SMO, with a CPT of 75°C (167°F), gives satisfactory service in this environment.

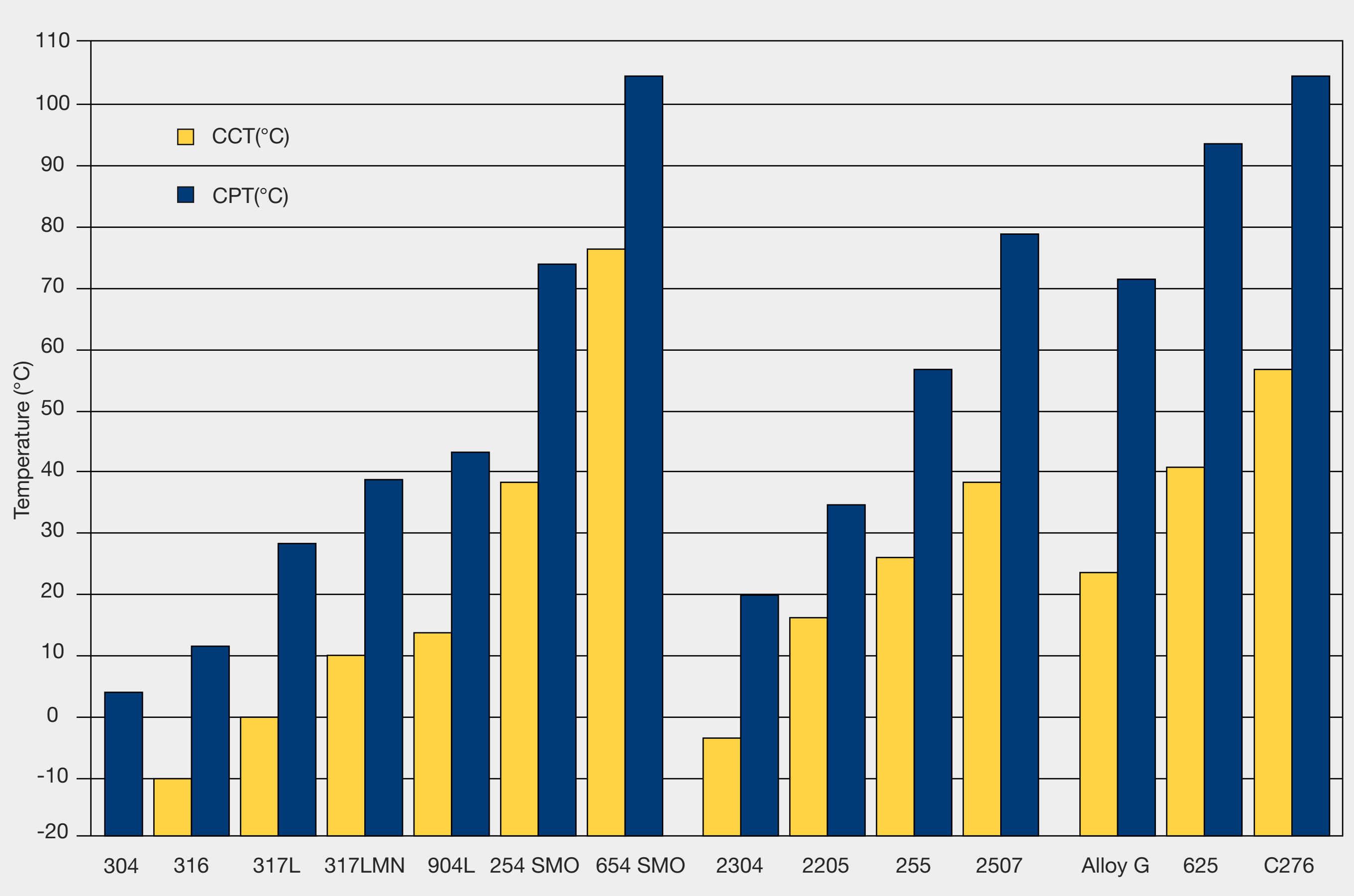


Figure 12: Critical pitting and crevice corrosion temperatures for stainless steels and nickel alloys. (4)

6.2.2 Effect of secondary phases on localized corrosion

While austenitic stainless steels are single-phase alloys, they always contain other minor phases that are the normal result of steelmaking. The phases present include oxide and sulfide inclusions from the steel refining practice in the melt shop, ferrite resulting from phase separation during solidification, and carbide, chi and sigma phases that can form during annealing or welding. These phases represent discontinuities on the steel surface, and they can facilitate pitting or crevice corrosion because they disrupt the passive film. Pickling and passivation treatments often remove them from the surface and minimize their effect.

When sigma and chi phases form however, they can present problems in certain circumstances. They result from alloy element segregation during initial solidification of the steel, and can also form during subsequent thermal treatments like annealing or welding as discussed in Section 3.3. Since they contain large amounts of chromium and molybdenum, they deplete the surrounding area in alloying elements and reduce corrosion resistance. If they form during steelmaking they usually are not detrimental, subsequent rolling and annealing processes homogenize the structure and dissolve the intermetallic phases. However, if they form during shop welding or annealing, they can be very detrimental.

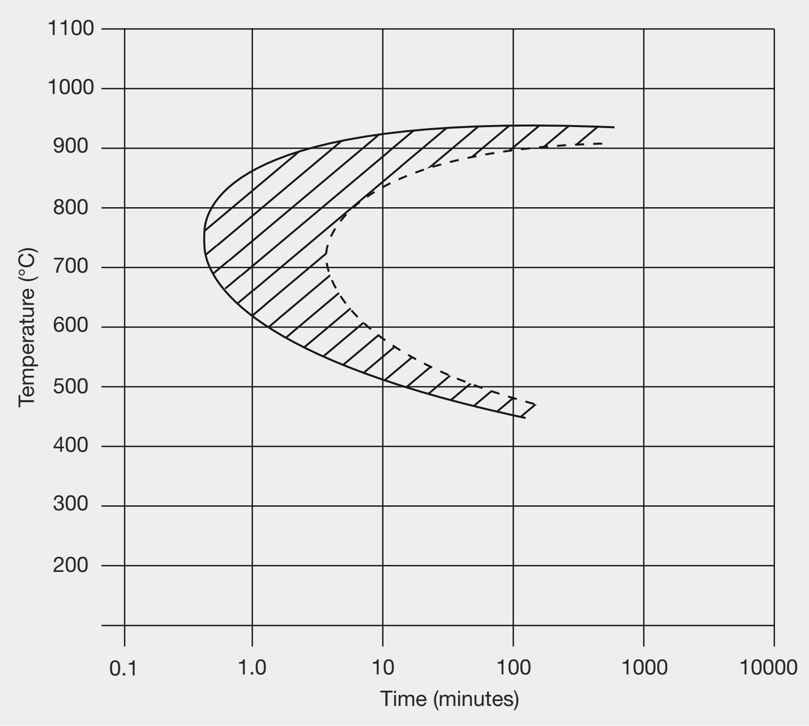


Figure 13: Effect of temperature on the time to start corrosion in a 6% Mo austenitic stainless steels as evaluated by critical pitting temperature.

Figure 13 illustrates the temperatures and times over which precipitation of sigma and chi will begin to occur in a 6% Mo HPASS. In this figure the formation of secondary phases is detected by determining the critical pitting temperature for samples treated isothermally for various time/temperature combinations. Using the criterion that a CPT<85°C (185°F) is unacceptable, only very short times at 700°C (1290°F) can be tolerated before pitting resistance is degraded. Thus, annealing and welding cycles must be controlled carefully to avoid secondary phase precipitation that degrades corrosion resistance. A small amount of precipitate can be tolerated if a lower CPT is allowed. If these phases have formed, they can be eliminated by a full solution annealing treatment that dissolves them and restores the alloy's corrosion resistance.

6.2.3 Stress corrosion cracking

In most alloys, a combination of stress and specific environment will cause a kind of corrosion known as stress corrosion cracking (SCC). This form of corrosion usually occurs as narrow branching cracks that penetrate across grain boundaries (**Figure 14**). With stainless steels, this usually takes place in chloride-containing environments, and is called chloride stress corrosion cracking (CSCC).

In order for SCC to occur, some form of tensile stress must be present along with the specific corrosive environment. The source of stress can be service stresses or residual stress due to fabrication processes. Since residual stresses frequently are quite high, they often are a factor in SCC. The standard austenitic stainless steels, including Types 304 and 316, are very susceptible to this form of corrosion. The HPASS are quite resistant to it.

6.2.3.1 Chloride stress corrosion cracking (CSCC)

When CSCC occurs in an annealed austenitic stainless steel, it exhibits transgranular cracks with a morphology determined by the stress pattern. Sensitization increases SCC susceptibility and promotes intergranular cracking. High stress, high temperature, high chloride, and low pH all increase the likelihood of stress corrosion cracking. **Figure 15** presents a summary of available CSSC data for Types 304 and 316. In neutral waters, the chloride content required to produce cracking in these alloys at temperatures near boiling or higher is less than 1 ppm. At lower temperatures, near ambient, stress corrosion failures will still occur but at somewhat higher chloride levels – in the range of 1–10 ppm and above. Conditions that concentrate chlorides, like alternate wet/dry surfaces under insulation, can cause CSCC even when the nominal environment contains only a few ppm chloride.

The austenitic stainless steels that contain nickel above the 8-12% range of Types 304 and 316 all deliver substantially better CSCC performance. The HPASS, which benefit from their greater chromium and molybdenum contents as well as higher nickel, are particularly resistant to CSCC. For example, in alloy UNS N08367 (AL-6XN) (**Figure 15**), cracking does not begin until much higher temperature and chloride levels. The temperature thresholds are well

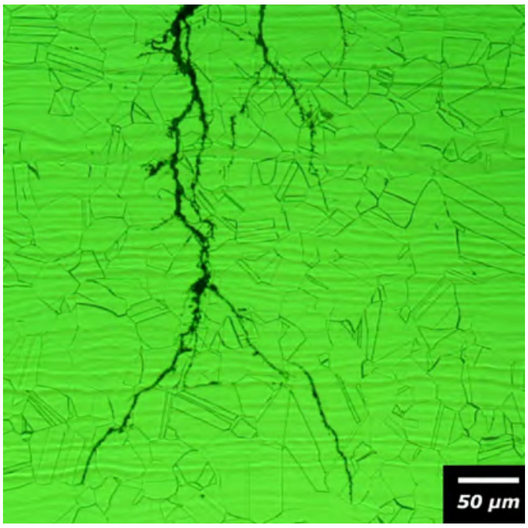


Figure 14: Branching transgranular stress corrosion cracks in an austenitic stainless steel.

above 100°C (212° F), indicating that boiling neutral chloride solutions at atmospheric pressure are unlikely to produce cracking in the 6% Mo and similar HPASS, a substantial improvement over Types 304 and 316.

6.2.3.2 Stress corrosion cracking in other environments

Strong caustic environments produce a type of stress corrosion in stainless steels called caustic cracking. Types 304 and 316, and other similar standard grades, are susceptible at temperatures of approximately 100°C (212°F) or higher. Increasing nickel improves caustic cracking resistance, so all HPASS perform better than the standard grades. However, for applications like caustic evaporators, that operate in very aggressive environments approaching 150°C (300°F), only Ni base alloys provide adequate service.

Environments having high hydrogen activity can produce a form of cracking termed “hydrogen embrittlement”. Such environments include high-pressure hydrogen gas, strong acids, acid solutions containing a catalyst such as hydrogen sulfide, and electroplating solutions. All standard austenitic and HPASS grades are highly resistant to this form of cracking except for the metastable grades like Type 301 that can contain martensite. However, any grade that has been heavily cold worked to increase strength and hardness is vulnerable. NACE Standard MR0175 and ISO 15156 provide detailed information on approved grades and acceptable hardness.

Polythionic acid ($H_2S_40_6$) can also produce SCC in sensitized austenitic stainless steel. Using Types 304 and 316 subjected to appropriate thermal treatments, or sensitization-resistant grades like Types 321 and 347 will avoid this danger. However, even these grades can become sensitized and susceptible upon long-term exposure in the sensitizing range. The HPASS perform somewhat better than the standard grades in polythionic acid.

6.3 Intergranular corrosion (IGA)/ sensitization corrosion

Intergranular corrosion occurs rapidly in or near grain boundaries with little or no attack of the grains. For standard austenitic stainless steels, this mode of attack is usually associated with sensitization that occurs during welding or heat treatment (see Section 3.3). Depending on the degree of sensitization and on the corrosivity of the environment, the corrosion can take more than one form. Pitting attack is likely if the sensitization is moderate. If a continuous network of chromium carbides exists along the grain boundaries, corrosion will occur intergranularly and the corrosion will look similar to general corrosion with grains dropping from the surface. An SCC-like corrosion can occur if a tensile stress is present.

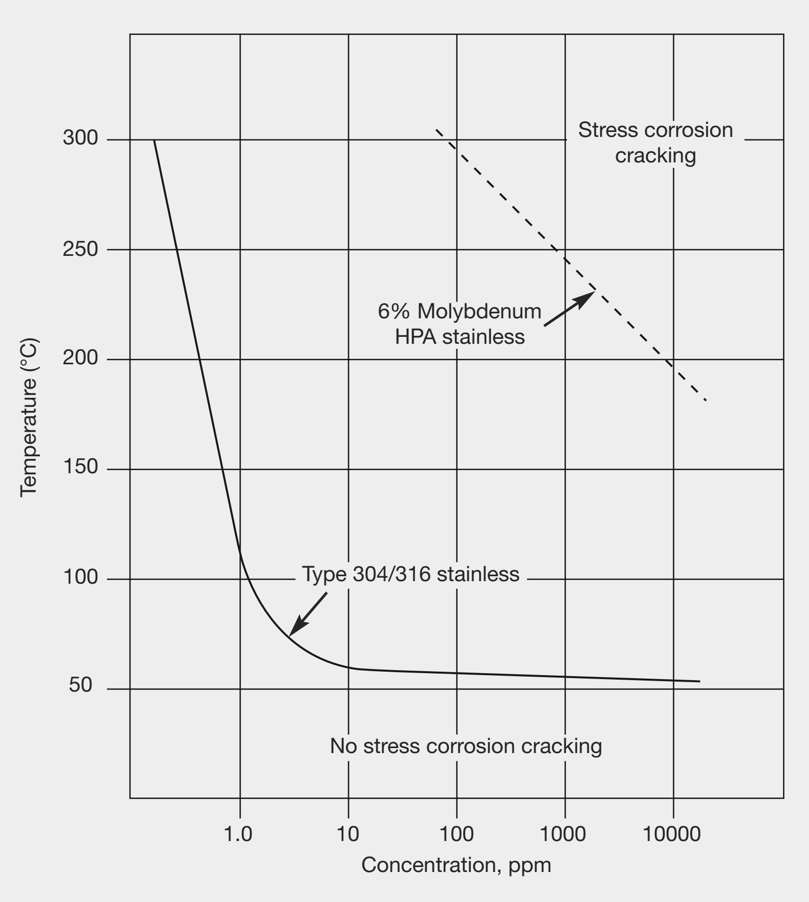


Figure 15: Chloride stress corrosion cracking thresholds in near neutral chloride waters for Types 304 and 316 stainless steels compared to a 6% Mo HPASS.

Designers and fabricators have three options to minimize sensitization and consequent intergranular attack:

- Employ a low carbon grade (e.g., Types 304L, 316L, or 317L). Low carbon content prolongs the time available before chromium carbide precipitation begins during cooling (Figure 3-3). This makes it possible to use hot fabrication techniques, welding, and heavy annealed sections. Using L grades does not mean that the steel will resist sensitization during long-term service exposure in the critical sensitization temperature range.

- Use a stabilized austenitic grade in which a stabilizing additive ties up carbon. The two common additives are titanium (Ti) and niobium/columbium (Nb/Cb). These grades require a suitable stabilizing thermal treatment, which preferentially forms titanium or niobium/columbium carbide instead of chromium carbide.

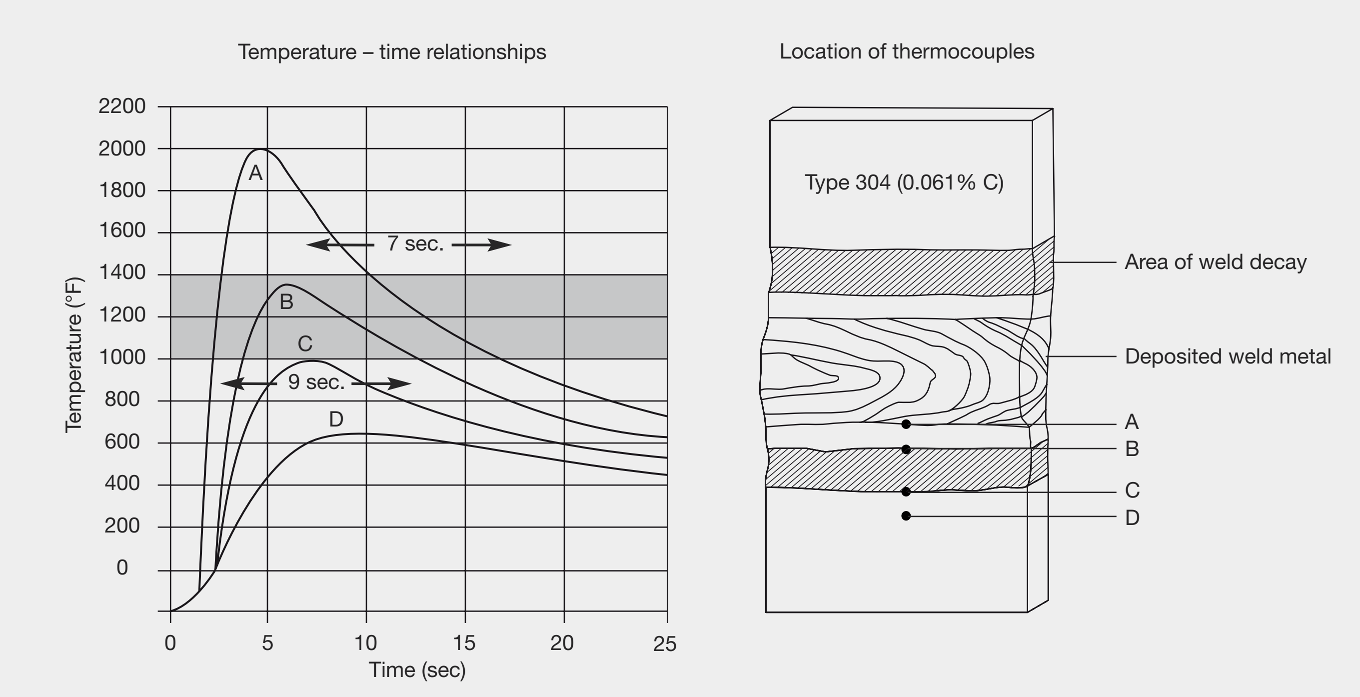


Figure 16: Time-temperature profile during electric arc welding of Type 304 stainless steel and the resulting regions of sensitization and weld decay. (7)

- Solution anneal previously sensitized material to restore its corrosion resistance. Recommended solution annealing temperatures are in the range of 1030–1175°C (1900–2150°F). The solution annealing treatment must be the last thermal treatment seen by the component. It does not remove the danger of long-term sensitization for components exposed to elevated temperatures in service.

The HPASS are low carbon alloys that generally contain sufficient nitrogen to insure that chromium carbide sensitization is not a concern. However, as previously discussed, intermetallic phases can form in these alloys under thermal conditions similar to those that produce sensitization in the standard grades. If this happens, accelerated pitting corrosion is the likely corrosion result when the steel is exposed to an aggressive environment.

6.3.1 Weld sensitization/weld decay

Welding causes metal to be in the sensitization temperature range in and near the weld for some period of time. Whether welding sensitizes the steel depends on the alloy, section thickness, and heat input. **Figure 16** schematically illustrates a typical weld thermal cycle and the associated region which is susceptible to weld decay. The figure shows a band of sensitized material that has formed on either side of the weld. Weld decay is minimized by controlling welding conditions and using one or more of the three previously discussed approaches to sensitization control. For the reasons noted in 6.3, HPASS usually do not suffer chromium carbide sensitization during welding. However, welding thermal cycles can promote formation of the intermetallic compounds that degrade pitting resistance. Welding parameters must minimize the time in the critical temperature range, and multiple welding passes should be avoided.

6.3.2 Knife-line attack

Knife-line attack is a unique form of sensitization that occurs only in the stabilized grades Types 321 and 347. If the welding process dissolves TiC or NbC/CbC, chromium carbide may form during a subsequent thermal treatment. This phenomenon produces a very narrow sensitized region adjacent to the weld, hence its name. Most austenitic stainless steels, and HPASS, are not susceptible to this knife-line attack because they are not stabilized.

6.4 Relations between fabrication and corrosion resistance

This chapter has dealt primarily with metallurgical and environmental factors affecting corrosion. However, it is safe to say that simple fabrication slip-ups are often the cause of many field corrosion problems. Stainless steel depends on a good, strong passive film to provide corrosion resistance. Unfortunately, many standard fabrication operations can adversely affect the passive film. It is critical to remember that anything that damages the surface protective film degrades corrosion resistance. Two broad damage categories can be defined: surface condition and surface contamination. Surface condition includes roughness, residual stress, and surface alloy depletion, all of which are intrinsic to the component. Surface contamination is foreign material introduced to the surface, and is extrinsic to the component. The list of contaminants is long, but some common ones are chloride-containing marking crayons or solvents, iron contamination from tools, and annealing or weld scale. Sections 7 and 14 provide further discussion of these topics and recommendations for fabricators to eliminate or minimize their effects.

Fortunately, corrosion associated with fabrication problems can be avoided by understanding their causes and by taking careful steps to eliminate them. This usually means good housekeeping combined with good cleaning procedures. **Table 6** summarizes causes and effects of corrosion related to shop fabrication problems.

Table 6: Potential influence of fabrication processes on the mode of corrosion (actual effect is dependent on many factors).

Fabrication process	Common stainless steel grades			
	304, 316	304L, 316L	321, 347, 316Ti	High-Mo grades
Hot forming	IGC	IGC	IGC	IGC, P, CC
Cold forming	SCC	SCC	SCC	SCC
Machining	SCC	SCC	SCC	SCC
Welding				
Thermal effects	IGC		KLA	P, CC
Stress effects	SCC	SCC	SCC	SCC
Heat tint	P, CC	P, CC	P, CC	P, CC
Mechanical joining (bolting, riveting, lock seams)	CC	CC	CC	CC
Surface iron contamination (from various fabrication processes)	P, CC	P, CC	P, CC	P, CC

Note: IGC = intergranular corrosion; P = pitting; CC = crevice corrosion; SCC = stress corrosion cracking;
KLA = knife-line-attack.

7 Care in the Shop – Keeping the Surface Smooth and Clean

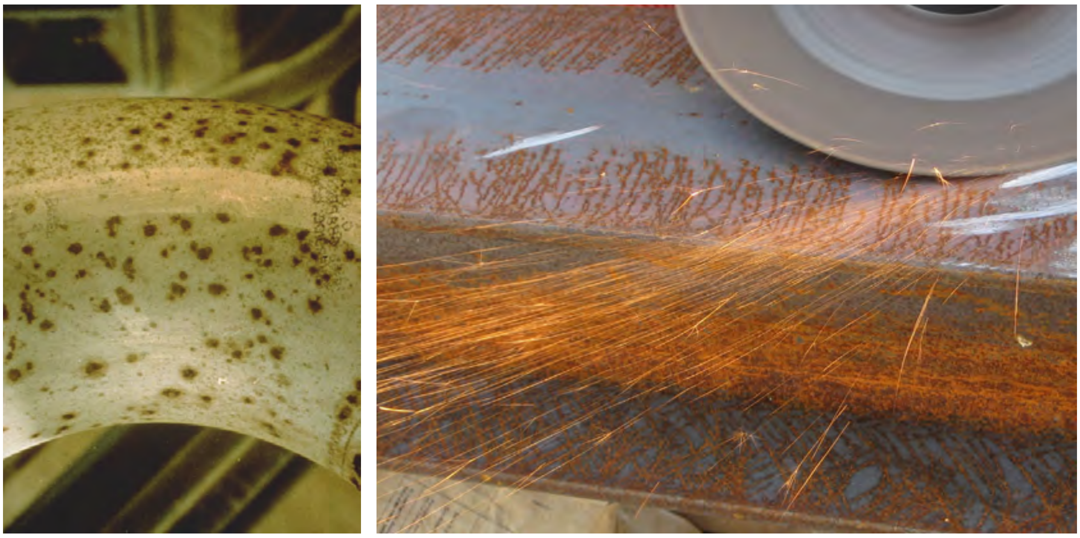
The most important shop rule to follow when working with HPASS is to keep the surface smooth and clean, just as it is for standard stainless steels. Careless handling and fabrication can disrupt the steel's passive film, and may reduce its corrosion resistance. Surface contaminants, especially carbon steel particles and steel scale, and rough or scratched surfaces introduced in the shop are common causes of film disruption.

Walking on stainless steel should not be allowed. Cover surfaces with paper, cardboard or plastic if workers must walk on the material.

Shops should institute procedures that preserve the steel's surface condition as it moves through the shop. Procedures should cover initial receipt and storage, all handling and fabrication operations, as well as final storage and shipment. They should also cover grade and other product identification and traceability, since there are many different grades of stainless steel.

7.1 Surface protection – initial delivery and storage

Fabricators should order stainless steels with protective wrapping, delivered in waterproof trucks whenever possible. Steel delivered on open trucks, should be inspected and its wrappings opened to dry if there is any chance that water has penetrated the wrapping. This is very important in the winter when exposure to deicing salt is likely. Wrapped and packaged stainless should be stored indoors in a clean, low humidity environment. Plate, pipe and other large product forms can be stored outdoors, if necessary, in properly designed storage areas. Storage areas should be free from deicing salts and airborne contaminants like acid fumes and grinding dust. Racks should not be made of carbon steel, and should prevent contact with ground water. Oils, paints, or other shop coatings should not be used to protect stainless steel during storage or fabrication.



Grinding of carbon steel near an area where stainless steel is being stored or fabricated can lead to contamination of the stainless as shown by the corroded pipe bend on the left.

Stainless steel should be stored separately from carbon steel in a clean area, removed from any carbon steel fabricating operations. This is extremely important, because a stainless steel surface contaminated by carbon steel particles can easily develop a rusted surface with poor appearance.

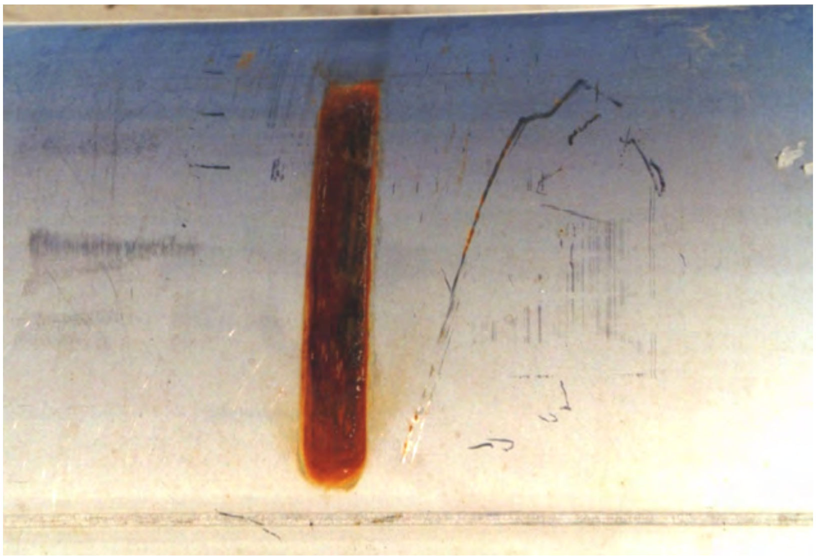
Sheet should be stored flat in wooden boxes to maintain flatness and prevent edge damage, and should be interleaved with paper or plastic to maintain surface quality. Boxes should be covered to prevent airborne contamination. Plate should be stored vertically on racks in a covered dry location, to minimize airborne contamination and avoid the possibility of footprints contaminating plate surfaces.

Stainless steel must not be stored in contact with, or in the same area, as galvanized steel. Surface contamination by copper, zinc, or similar low-melting metals can embrittle stainless steel during welding or heat treatment.

Stainless steel can be ordered with a protective plastic film, a useful option when surface appearance is critical, as in architectural components and appliances. These strippable films remain in place during storage and fabrication. They are then removed after installation. They minimize light scratches and minor mechanical damage, and they prevent contamination by carbon steel and other particles.

Film-protected stainless steel should also be stored under controlled low humidity conditions, because moisture can penetrate the film at perforations or edges and lead to crevice corrosion. Film-protected stainless steel should not be stored in direct sunlight or heated because the strippable film may become difficult to remove. Protective film should be removed for long-term storage, because the film has a shelf life, after which it loses its protective properties.

Carbon steel wire brushes used to clean stainless steel welds can produce discoloration and rust. (Source: Outokumpu Stainless)



Carbon steel strapping has produced rust marks on a stainless steel pipe.

7.2 Fabrication

Contact with carbon steel should be avoided during fabrication and handling. Transport clamps, hooks, and other devices should either be stainless steel or be protected with plastic or cardboard to prevent carbon steel contamination. Special tool sets should be dedicated for use only on stainless steel. Color-coding tools to differentiate those used on carbon steel from those used on stainless steel is helpful.

Only clean grinding wheels, sanding belts, and blast media (glass beads, sand, and shot) should be used on stainless steel. None of these may be used previously on carbon steel. Contaminated media will transfer carbon steel to the stainless steel surface, which will produce rust. Steel shot must not be used on stainless steel because it will embed carbon steel into the stainless steel surface. For the same reason, only stainless steel wire brushes and wool should be used. They cannot be used previously on carbon steel. The figure on the left illustrates problems created by using incorrect brushes.

Rolls, presses, and dies used for stainless steel fabrication should be cleaned thoroughly to remove steel particles or scale if they have been used to process carbon steel. Protective paper or plastic film can prevent contamination by carbon steel particles from the forming tools.

8 Hot and Cold Forming

8.1 Hot forming

Austenitic stainless steels have excellent forming characteristics in hot rolling, forging, and extrusion operations. Standard austenitic grades have higher hot strength than carbon steels, and HPASS have much higher hot strength than the standard grades. Thus, reductions per pass will be less than for carbon steels and may be limited by equipment capability with HPASS. It is important that stainless steels be heated throughout when being hot worked. This means longer reheating times than for carbon steel because of their lower thermal conductivity. On the other hand, the high molybdenum content grades scale very rapidly; therefore, the operator has to minimize holding times during preheating.

The upper temperature limit of the stainless steel hot working range is well below the melting temperature, because these alloys undergo a rapid loss in ductility at very high temperatures for various reasons. Delta ferrite formation causes this ductility loss in standard austenitic grades. With HPASS, the loss is related to low-melting sulfide or phosphide phases in the microstructure. The lower temperature limit of the hot working range is given by the steel's ability to recrystallize and soften while being worked. Working at too low a temperature can lead to equipment failure because the material work hardens rapidly, or the workpiece fractures due to ductility loss. This latter phenomenon is a very real possibility with HPASS.

Table 7 gives hot forming temperature ranges for various austenitic stainless steel categories. All grades have an upper temperature limit in the range of 1175–1200°C (2150–2200°F), but the lower limit depends strongly on the grade. It is quite low for the standard grades, and is considerably higher for the more highly alloyed grades, a consequence of their high strength. This grade dependence of the lower limit means that the window for hot working the more highly alloyed grades is smaller, with HPASS having the smallest window in which to work.

It is important to maintain uniform workpiece temperature during hot forming. Lower temperature regions of the workpiece (e.g., edges readily seen as darker than the bulk of the work piece or even black relative to a red-hot surface) can be much stronger than hotter sections because of the temperature dependence of the alloy's strength. Cooler regions may tear or crack because they have insufficient ductility to withstand further deformation.

The workpiece should be solution annealed after hot forming to insure a uniform microstructure free of sensitization, detrimental second phases, and residual stress. Failing to achieve a fully annealed structure increases the risk of sensitization during later welding or high temperature service, and the risk of corrosion associated with chi and sigma phases. It also assures the removal of residual stresses that can lead to dimensional instability in service.

If the material temperature never falls below the solution annealing temperature during the forming operation, it may be possible to consider a "process anneal" where the temperature of the hot forming is used to perform the solution anneal. However, it is difficult to ensure that a process anneal is achieved throughout the entire work piece because of non-uniform cooling during hot work.

Austenitic stainless steels require rapid cooling after hot working. The appropriate cooling rate depends on section thickness and composition (particularly the carbon content in standard grades). In the more highly alloyed grades, the chromium, molybdenum,

Table 7: Hot forming ranges for austenitic stainless steels.

Grades	Hot forming temperature range		Solution annealing temperature	
	°C	°F	°C	°F
Standard grades Types 304, 316, 321	870 to 1200	1600 to 2200	1040 min.	1900 min.
High temperature grades Types 309, 310	980 to 1175	1800 to 2150	1050 min.	1925 min.
6% Mo-0.2% N grades S31254, S31266, N08367, N08926	980 to 1200	1800 to 2190	1150 min.	2100 min.
7% Mo-0.5% N S32654	1100 to 1200	2000 to 2200	1150 min.	2100 min.

Hot pressing of petals for a vessel head. (Source: Antonius Vesselheads BV)

and nitrogen content are particularly important because they participate in intermetallic phase formation. Unstabilized grades with greater than 0.030% C should be water quenched to prevent sensitization. Standard grades with less than 0.030% C, or stabilized grades like Types 321, 347, or 316Ti, can be air-cooled. Grades with more than 3% Mo should be water quenched to prevent formation of intermetallic phases. Increasing section size increases the cooling rate necessary to avoid secondary phases.

8.2 Warm forming

Heavy section austenitic stainless steel plate is often warm formed to take advantage of reduced strength at elevated temperature. Unlike the ferritic and duplex grades, the austenitic grades do not form secondary phases at temperatures up to about 480°C (900°F). This defines an upper limit for warm forming of austenitic grades. The limit may be higher for low-carbon or stabilized grades or for material that is solution annealed after warm forming.

8.3 Cold forming

Austenitic stainless steels have very high ductility at ambient temperatures, which translates into excellent formability in cold-forming processes ranging from simple bending to complex deep drawing and stretch drawing. Differences among grades relate to differences in strength and work-hardening behavior. High strength grades like HPASS require greater press power or have section size limitations. High work-hardening grades, such as Type 301, lend themselves best to stretch type operations.

Variations in yield strength and work hardening produce variability in springback and final dimensions. Austenite instability (as in Type 301) and nitrogen alloying (as in HPASS) increase yield strength and work-hardening rate. These high strength steels need higher forming forces and show more elastic springback, so overbending is necessary to achieve a specific profile. Nitrogen variations within specified composition ranges can introduce significant variations in formability, even in the standard grades having 0.10% N maximum.

Figure 17 compares springback of annealed 2 mm duplex stainless steel sheet with that of Type 316L. Austenitic stainless steels with higher nitrogen contents, and those rolled to increase yield strength (see ASTM A666), have springback more like the duplex grades in the figure than the annealed standard austenitic grades. When springback is accounted for properly, the nitrogen-alloyed and cold-worked grades permit thickness reductions, saving material weight and cost.

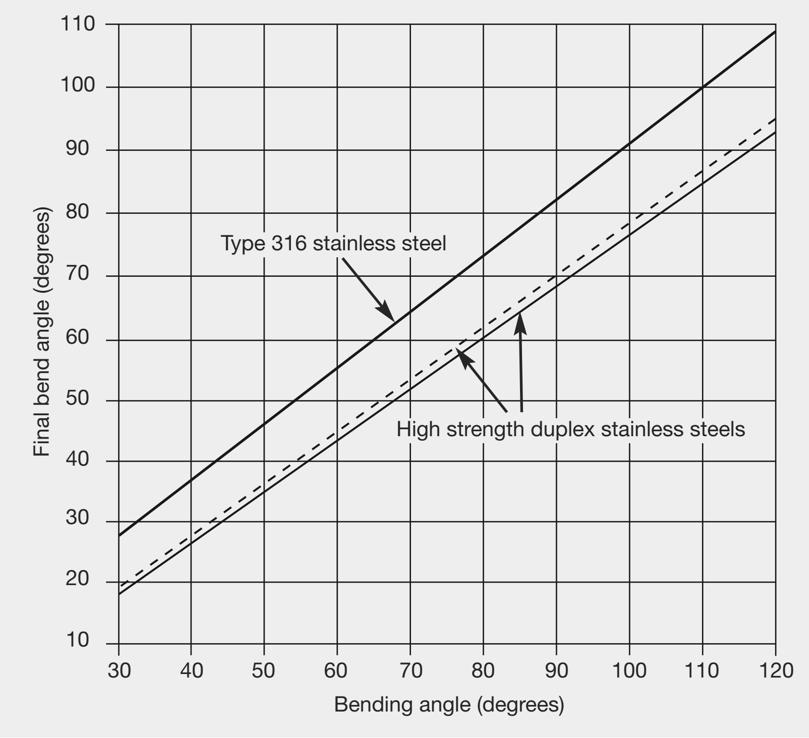


Figure 17: HPASS have spring-back in forming higher than standard grades, and similar to the high-strength duplex grades shown here. (7)

8.3.1 Bending

Austenitic stainless steels can be formed to small radius bends in the annealed condition. A 180° bend over a radius of half the material thickness (1/2 t 180° bend), independent of the rolling direction, is a common acceptance criterion. This criterion has to be relaxed slightly for a higher strength or temper rolled material.

Even highly work-hardened sheet still has substantial ductility. Types 301, 304, and 316 can produce 1/2 t 180° bends in the quarter-hard condition (minimum yield approximately 2.5X that of annealed material), and 1t 180° bends in the half-hard condition (minimum yield approximately 3.6X that of annealed material). This reserve ductility allows bending or forming of work hardened sheet, and provides crashworthiness (impact absorption) for rail vehicles.

A complex sink that requires drawing and stretching can be made from austenitic stainless steel. (Source: Thyssen Krupp Stainless)

8.3.2 Roll forming

Roll forming is a highly efficient and economical method to produce long open shapes like angles and channels. It is also a good way to stiffen panels by imposing character lines like ridges or grooves, reducing the required thickness in architectural or transportation applications. Austenitic steels are readily roll formed, but wide material variations in strength and work hardening rate introduce variability in the dimensional tolerances of the roll formed product. Steelmakers minimize variability by restricting within-grade variations in nickel, carbon, and nitrogen content.

Large reactor head in austenitic stainless that has been weld fabricated from cold formed sections. (Source: Antonius Vesselheads BV)

8.4 Drawing and stretching

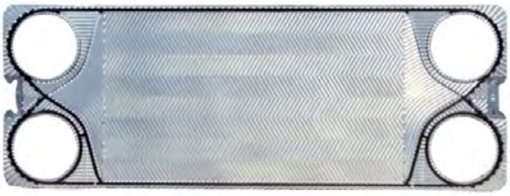
The wide range of ductility and work-hardening properties among austenitic stainless steels allows a wide range of drawing and stretch forming operations, or combinations of the two. Material for drawing should have enough ductility to flow through a die with minimal edge clamping, which favors materials with high ductility and a low work-hardening rate. Stretch forming uses hard clamping of the blank edge, and deformation occurs by stretching within the die and corresponding sheet thinning. A high work-hardening rate enables the blank to stretch without fracture, allowing greater formed depth.

Most forming operations use a combination of drawing and stretching, so the properties of the blank need to match the degree of draw or stretch involved with the given part design. The different grades of austenitic stainless steels offer a wide range of forming properties, facilitating a wide range in part designs. The sophisticated technology of sheet forming has spawned specialized steel compositions within standard grade ranges. For example, a complex sink requires both material draw and stretch capability (See figure on the left.). To meet these needs, Type 304 compositions that blend ductility and work hardening are available.

Certain grades have compositions balanced to encourage deformation martensite formation, which augments stretching. For example, Type 301 with higher carbon and lower nickel content has a very high work hardening rate that strengthens areas thinned by forming. This shifts strain to adjacent areas so that deformation can continue without fracture. The figure at top right shows a heat exchanger formed with a great deal of stretch. The length of the profile after forming is far greater than the starting length. Only the excellent work-hardening behavior of the austenitic grade enables the steel to form the channels without fracturing at the bends.

8.5 Spin forming

Spin forming requires high ductility and low work hardening rates, so the high work-hardening rates of some standard austenitic grades limit their use in this process. Compositional modifications can solve this problem. Types 305, 309, 310, and 904L contain high nickel content (and sometimes small copper additions) which reduces the effective work-hardening rate, producing alloys that are more easily deep drawn and spin formed. Even with their high ductility, these steels may require intermediate annealing steps to enable further spin forming.



A stretch-formed plate for a flat-plate heat exchanger uses the stretch form capabilities of austenitic stainless steel. (Source: Paul Mueller Company)

Spin forming of an austenitic stainless steel vessel head takes advantage of the steel's high ductility and low work hardening characteristics. (Source: Antonius Vesselheads BV)

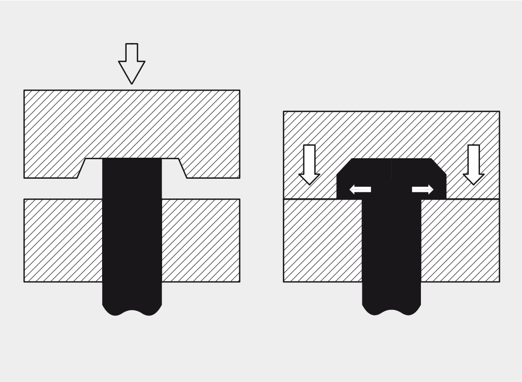


Figure 18: Cold heading of a stainless bolt requires good metal flow within a die. (Source: Forging Industry Association)

8.6 Cold heading

Stainless bolts and other fasteners are easily manufactured by cold heading (axial stamping within a die). Some work hardening is desirable to increase the strength of the bolt head, but high ductility and low work hardening rates make the process easier to accomplish. Type 304 with increased nickel (Type 305) or copper (S30433, sometimes called as "302HQ") provide excellent flow characteristics minimizing the risk of edge cracking. **Figure 18** illustrates a cold heading process.

9 Cutting

Austenitic stainless steels are readily sawed, sheared, punched, and cut by plasma or laser techniques. These methods can cut plate and other large components with dimensional precision and surface quality that sometimes meet final requirements. The same methods can cut HPASS, keeping in mind that the requirement for positive cut is more important because of their high work hardening rates. Stainless steels cannot be cut with an oxyacetylene torch.

9.1 Saw cutting

Cutting stainless steel with band saws and hacksaws requires a sharp saw blade, positive feed rate, and good alignment. A strong coolant/lubricant flow should be directed at the point of cutting. Synthetic emulsions are ideal for this purpose. Positive feed and minimal blade "wander" are important factors in cutting austenitic stainless steels because of their high work-hardening rates. The saw needs sufficient power to drive the feed of the blade to cut beneath the previously hardened cut layer (**Figure 19**). If the blade smears the surface instead of cutting it, the surface will be hardened and resist further cutting, leading to rapid blade wear and loss of cutting ability.

The more highly alloyed grades, both those with nitrogen additions and those with molybdenum and nitrogen additions, may resist sawing with any but very high power machines because of their combination of high strength and high work-hardening rate. If the saw cannot maintain positive feed, another cutting method may be required.

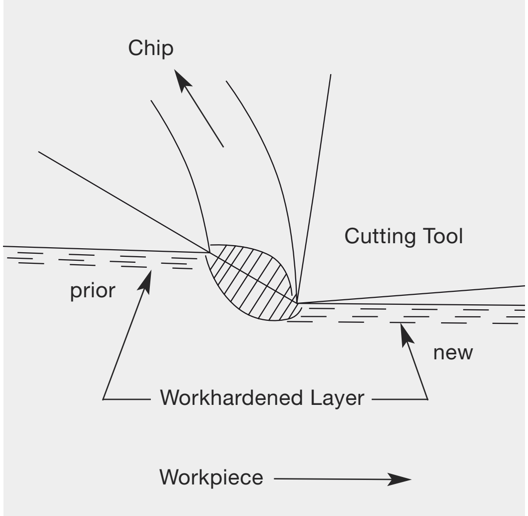


Figure 19: A positive cut removes material below the previous work-hardened layer. Image based on reference 8.

9.2 Shearing

Shearing is a fast, accurate, and highly effective method of cutting austenitic stainless steels. The high ductility and work-hardening rate of austenitic stainless steels cause them to require machines that are more powerful than those used for carbon steel. They also require more careful setups. The differences between carbon steel and HPASS are even more pronounced. Proper setup requires rigid machines, sharp blades, and smaller blade

Saw cutting

Blanking, one of many shearing processes.

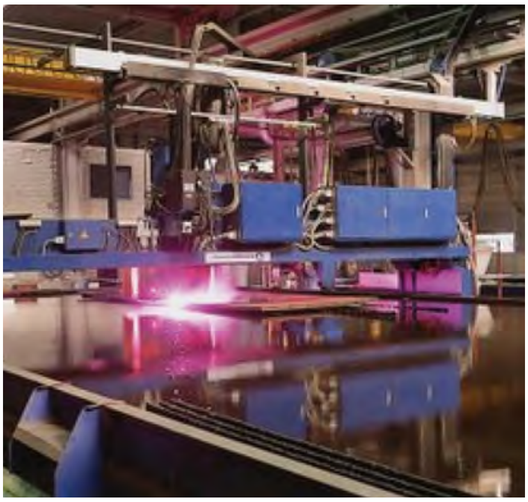
clearance than required for carbon steel. Modern high strength shears commonly provide excellent shape and dimensional accuracy for standard austenitic stainless steel plate of up to 25 mm (1 inch) thickness. In order to shear the higher strength grades, the thickness rating of the shear must be reduced in proportion to their increased strength relative to Type 304. The shear strength of stainless steels may be estimated as 0.6 times the ultimate tensile strength, giving an indication of the thickness limitations for the larger shears.

9.3 Punching

Punching is a variation of shearing that uses a punch and die to shear the material instead of straight-edged shear blades. Sharp cutting edges and close clearances are also required to punch stainless steel. Again, the grades with higher strength or work-hardening rates require more power and more attention to set up than the standard austenitic stainless steels.

9.4 Plasma cutting

Plasma cutting is the most common method for cutting all grades of austenitic stainless plate 25 mm (1 inch) thick and heavier. The evolution of plasma torch design has dramatically improved accuracy and edge quality, making the technology ideal for cutting shapes as well as straight lines. In some cases, the plasma-cut edge is good enough to use in service or in a weld joint without further preparation. Portable plasma units are available for cutting formed parts and test pieces. Underwater plasma cutting reduces fumes.



Plasma cutting

9.5 Laser cutting

In laser cutting, the laser beam melts the material while a nitrogen jet blows the molten metal out of the kerf. The nitrogen gas prevents oxidation and loss of corrosion resistance. The nitrogen pressure used in laser cutting stainless steel is higher than the oxygen pressure used when cutting carbon steel, and must be increased as material thickness increases to remove the melted metal effectively. Thin sections of HPASS and standard austenitic steels are often cut to final dimensions using lasers, eliminating the need for additional machining. There is little difference between the laser-cutting characteristics of HPASS and standard grades.

Plasma cutting stainless steel demands high purity nitrogen. A minute amount of oxygen contamination will oxidize chromium in the alloy, deplete the surface of chromium, and decrease corrosion resistance. A slight discoloration of the cut surface indicates chromium oxidation. If significant discoloration occurs, subsequent acid pickling or edge milling is required to restore corrosion resistance. Nitrogen assist gas should have a certified purity of at least 99.95% with a maximum oxygen content of 200 ppm.

Laser cutting

10 Machining

The high strength and ductility of austenitic stainless steels dictate the use of high power machine tools and creates significant abrasion at the tool-chip interface. The heat generated by deformation and abrasion is not removed efficiently through the work piece, because of the steel's low thermal conductivity. These factors make austenitic stainless steels more difficult to machine than carbon steels. The higher strength of HPASS presents an even greater challenge. However, all these steels can be machined successfully when basic stainless machining principles (powerful machines, rigid setups, and positive feeds beneath the prior work-hardened layer) are employed.

Austenitic stainless steels can be divided into four general categories with respect to machinability:

- Standard grades, including Types 304 and 316 in plate and sheet product forms.
- Standard grades with optimized machinability, typical of bar products.
- Free-machining grades, usually in bar-product form.
- Higher alloyed grades and higher strength grades including HPASS.

The standard grades in plate and sheet are designed for weldability and surface finish instead of machinability. The optimized alloys still meet all specification requirements of the standard grades, but employ special processing and controls, often proprietary, to get the best possible machinability. Optimized processing typically involves tight control of composition and microstructure, especially the size, shape, and distribution of non-metallic inclusions like sulfides and oxides.

Free-machining grades are designed for maximum machinability. The most machinable grade is Type 303, which is Type 304 with a sulfur addition and other modifications. Type 303 contains as much as 0.3–0.4% S compared to the 0.015% S typical of Type 304. The sulfur produces sulfide inclusions that reduce cutting forces and aid chip formation. Sulfide inclusions can substantially degrade corrosion resistance, toughness, ductility, and weldability, limiting the ability of Type 303 to qualify for some pressure vessel and other applications.

The HPASS are more difficult to machine than the standard grades for a number of reasons. Most importantly, they contain very low sulfur (0.001% S or less) to improve hot workability and corrosion resistance. Their high molybdenum content produces more tooling wear. Finally, nitrogen is especially detrimental for machinability because it significantly increases strength, work hardening rate, and toughness.

10.1 General guidelines

The following machining guidelines are applicable to all stainless steels:

- Use powerful, rigid machines with extremely strong, rigid tooling and work piece setups. This produces positive cuts and minimizes vibration. These requirements are essential for machining the higher alloyed grades.
- Because of the extra loading imposed by the high work-hardening rate of austenitic stainless steels, the tool's nose radius should be no larger than necessary for adequate tool life.
- The cutting edge should be as sharp as possible consistent with adequate tool life. Highly aggressive geometries are possible for the optimized-machining and free-machining grades, but sharp edges may not provide sufficient strength to the tool when cutting the higher alloyed grades.
- The feed rate should be high enough to cut below the work-hardened layer left by the previous cut, typically at least 0.076 mm (0.003 inch).
- The cutting speed should be well below the limit for the tooling in terms of rigidity and vibration, to avoid formation of a work-hardened layer.
- Tools should be changed or sharpened at regular intervals before they become dull. A dull edge leads to the formation of a work-hardened layer.
- Generous coolant/lubricant flow directed at the point of cutting is essential. Emulsions with extreme pressure (EP) additives are particularly beneficial.
- Coated carbide inserts, especially those with positive chip breaker geometry, produce good results when machining both the standard stainless steels and the more difficult higher alloyed grades.
- High-speed steel tooling should be of premium grade quality.

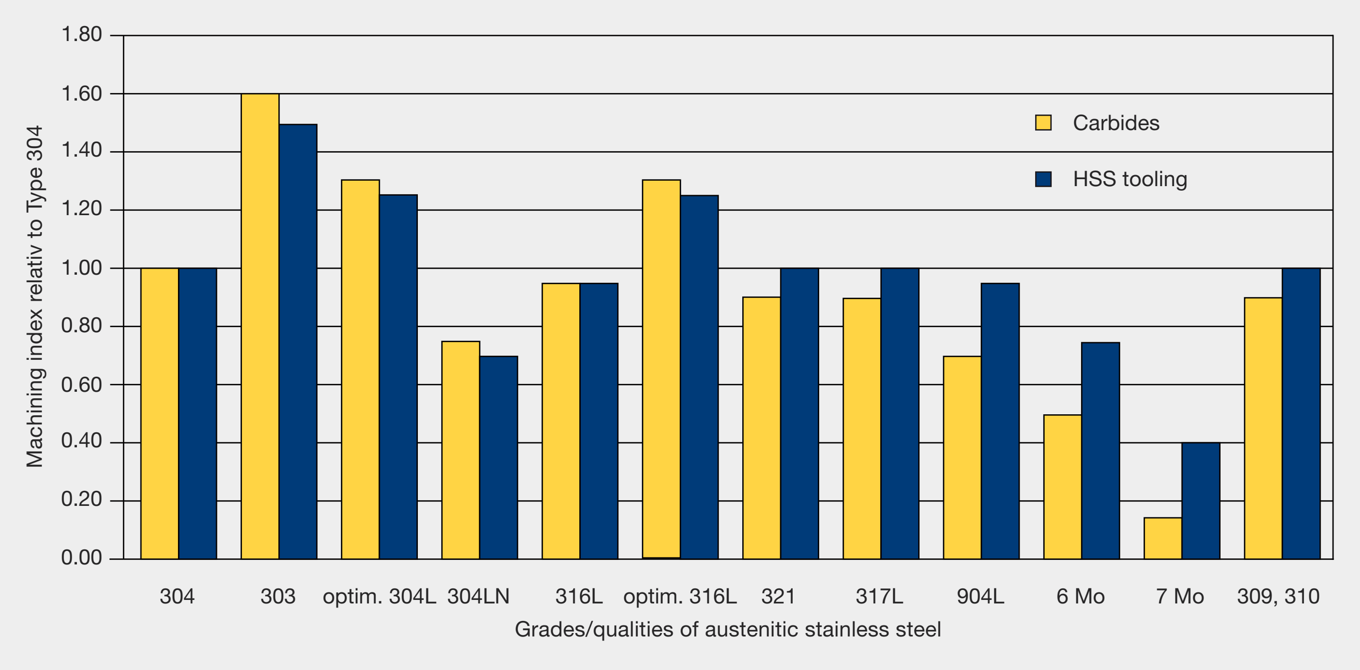


Figure 20: Machining index for different austenitic stainless steel grades compared to standard Type 304. The relative machinability is similar for both carbide and high speed steel tooling. (9)

10.2 Machinability index for different stainless steel grades

Stainless steels exhibit a wide range of machinability as a function of the properties of each grade and the range of possible machining conditions. No single machining index can fully represent all grades or conditions, but indices have value when comparing different grades. They can help to establish starting conditions when working with a new grade. **Figure 20** compares several stainless steel grades using a machinability index.

10.3 Turning

Turning austenitic stainless steels requires maximum rigidity and minimum vibration. Chip breakers are often required. Guidelines for turning austenitic stainless steels are provided in **Table 8**.

10.4 Face milling with cemented carbides

Following these guidelines will give the best results when milling with cemented carbides:

- Use coated inserts or tough grades of uncoated inserts for roughing, and a depth of cut exceeding 0.5 mm (0.020 inch). When a fine surface is desired, a harder uncoated insert, higher speeds, and lower feed rate should be used.

- When climb milling, use a feed rate of 0.10–0.25 mm (0.004–0.010 inch) per tooth, a highly positive axial rake, and a slightly negative radial rake with the width of cut being 1/2 to 3/4 of the diameter of the milling tool being used.

- The most important requirement for interrupted cuts is to eject the chip from the tool instead of carrying it around to be cut again. This is achieved by using sufficient speed to obtain the appropriate temperature at the chip/insert interface so the chip does not stick to the insert edge or face. When roughing, it is best to use no coolant to achieve this condition. For fine finishing, coolant will help eject the chip clear of the tool, but a much higher speed and lower feed are required to assure that the chip does not stick to the tool.

- Guidelines for face milling parameters are provided in **Table 9.**

Table 8: Guidelines for turning austenitic stainless steels.

Guideline	Carbides				High-speed steel tools	
	Roughing		Finishing			
Standard grades						
Speed, m/min (sfm)	120–150	(395–490)	150–210	(490–690)	20–25	(65–82)
Feed, mm (in/turn)	0.3–0.6	(0.012–0.024)	0.05–0.30	(0.002–0.012)	0.05–0.20	(0.002–0.008)
Depth of cut, mm (in)	2–5	(0.080–0.20)	0.5–2.0	(0.020–0.080)	0.5–2.0	(0.020–0.080)
ISO grade	P20–P35		P10–P15			
Optimized grades						
Speed, m/min (sfm)	170–180	(560–590)	230–250	(750–820)	25–35	(82–115)
Feed, mm (in/turn)	0.3–0.5	(0.012–0.020)	0.1–0.3	(0.004–0.012)	0.3–0.5	(0.012–0.020)
Depth of cut, mm (in)	2–5	(0.080–0.20)	< 2	(< 0.080)	2–5	(0.080–0.20)
ISO grade	P20		P10			
HPASS grades						
Speed, m/min (sfm)	60–80	(195–262)	80–100	(262–307)	4–6	(12–19)
Feed mm, (in/turn)	0.3–0.6	(0.012–0.024)	0.05–0.30	(0.002–0.012)	0.05–0.20	(0.002–0.008)
Depth of cut, mm (in)	2–5	(0.080–0.20)	0.5–2.0	(0.020–0.080)	0.5–2.0	(0.020–0.080)
ISO grade	P30–P50		P25–P35			

Table 9: Guidelines for face milling austenitic stainless steels.

Guideline	Carbides				High-speed steel tools	
	Roughing		Finishing			
Standard grades						
Speed, m/min (sfm)	160–190	(525–625)	190–220	(625–720)	15–20	(50–65)
Feed, mm (in/tooth)	0.2–0.4	(0.008–0.016)	0.1–0.2	(0.004–0.008)	0.10	(0.004)
Depth of cut, mm (in)	2–5	(0.080–0.20)	1–2	(0.040–0.080)	0.1 x tool diameter	
Optimized grades						
Speed, m/min (sfm)	180–210	(600–700)	305–350	(1000–1150)	25–30	(80–100)
Feed, mm (in/tooth)	0.2–0.4	(0.008–0.016)	0.1–0.2	(0.004–0.008)	0.10	(0.004)
Depth of cut, mm (in)	2–5	(0.080–0.20)	1–2	(0.040–0.080)	0.1 x tool diameter	
HPASS grades						
Speed, m/min (sfm)	40–60	(130–195)	60–80	(195–262)	6–8	(20–25)
Feed, mm (in/tooth)	0.2–0.4	(0.008–0.016)	0.1–0.2	(0.004–0.008)	0.10	(0.004)
Depth of cut, mm (in)	2–5	(0.080–0.20)	1–2	(0.040–0.080)	0.1 x tool diameter	

10.5 Twist drilling with high-speed steel drills

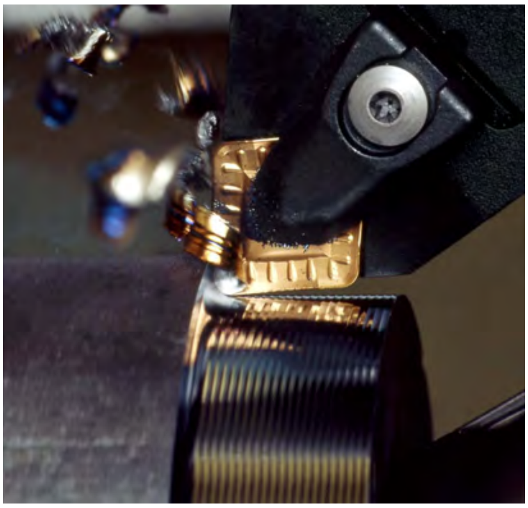
When using high-speed steel tooling, it is very important to prevent overheating of the cutting tip. The poor thermal conductivity of austenitic stainless steel promotes overheating, which leads to drill softening, loss of cutting edge, rapid further heating and catastrophic tool failure. Getting the coolant to the drill tip is critical. Through-drill coolant flow and pecking (withdrawing the drill periodically to allow coolant into the hole) are effective ways to achieve this.

High feed rates are necessary for drilling stainless steel, but they impose high axial loading and can test the buckling limits of a drill. Maintaining a stable alignment of the drill perpendicular to the work piece helps to avoid vibration and buckling. Use drills with a length no greater than necessary for the operation for good stability.

Side milling using carbide cutters. (Source: Seco Tools)

Guidelines for twist drilling stainless steel:

- Use a top angle of 130° for best chip breaking. A sharper top angle, perhaps 109°, produces a smoother wall but longer chips.
- Use self-centering drill point geometry and web thinning for larger diameter drills.
- Both cooling and lubrication are required. Use a 10% emulsion coolant with ample flow to the drill point. For solid drills, the drill should be withdrawn periodically and the hole flooded with coolant when the depth exceeds twice the drill diameter. Through-drill coolant eliminates the need to peck except for chip management.
- Speeds may be increased by 10% for TiN-coated drills and 10–20% with through-drill coolant flow.



Turning stainless steel using carbide with a built-in chip breaker. (Source: Seco Tools)

Face milling austenitic stainless steel with a carbide insert cutter. (Source: Seco Tools)

Table 10a: Guidelines for twist drilling austenitic stainless steels with high speed steel drills (metric units).

Speed/Feed, m/min (mm/rev)			
Drill diameter (mm)	**Standard austenitic**	**Optimized austenitic**	**High alloy austenitic**
1–3	6–10 (0.05)	10–12 (0.10)	5–8 (0.04)
5	10–12 (0.10)	12–14 (0.20)	8–10 (0.08)
10	10–12 (0.20)	12–15 (0.30)	8–10 (0.15)
15	10–12 (0.25)	12–15 (0.40)	8–10 (0.20)
20	10–12 (0.30)	12–15 (0.45)	8–10 (0.25)
30	10–12 (0.35)	12–15 (0.55)	8–10 (0.30)
40	10–12 (0.40)	12–15 (0.60)	8–10 (0.35)

Table 10b: Guidelines for twist drilling austenitic stainless steels with high speed steel drills (English units).

Speed/Feed, sfm (in/rev)			
Drill diameter (inch)	**Standard austenitic**	**Optimized austenitic**	**High alloy austenitic**
0.040–0.120	20–33 (0.002)	33–40 (0.004)	16–26 (0.0015)
0.20	33–40 (0.004)	40–46 (0,008)	26–33 (0.003)
0.40	33–40 (0.008)	40–49 (0.012)	26–33 (0.006)
0.60	33–40 (0.010)	40–49 (0.016)	26–33 (0.008)
0.80	33–40 (0.012)	40–49 (0.018)	26–33 (0.010)
1.20	33–40 (0.014)	40–49 (0.022)	26–33 (0.012)
1.60	33–40 (0.016)	40–49 (0.024)	26–33 (0.014)

11 Heat Treatment – Annealing and Stress Relieving

Austenitic stainless steels cannot be hardened by heat treatment. Heat treatment of these alloys is only used to remove the effects of cold work, re-dissolve unwanted secondary phases, and reduce residual stresses to acceptable levels.

Solution annealing softens material after cold working and dissolves secondary phases that can precipitate during hot working or welding. The term “full anneal” often means that the material is in its optimum metallurgical condition, with secondary phases completely dissolved and homogenized. This condition produces the best corrosion resistance and ductility. Because it is conducted at high temperatures, annealing in air produces a surface oxide scale that must be removed by descaling and pickling to restore surface corrosion resistance.

Stress relief treatments reduce residual stresses that can develop during forming and welding, and lower the risk of distortion or stress corrosion cracking. Stress relief is performed at temperatures below those used for annealing, and may not require the descaling and pickling needed after full annealing.

Table 11: Minimum solution annealing temperature for stainless steels.

UNS No.	Grade	Annealing temperature	
		° C	° F
S20101	Type 201	1040	1900
S30400/S30403	Type 304/304L	1040	1900
S30409	Type 304H	1040	1900
S31600/S31603	Type 316/316L	1040	1900
S34700	Type 347	1040	1900
N08020	Alloy 20, 20Cb-3	1150	2100
N08904	904L	1095	2000
N08367	AL-6XN	1105	2025
S31254	254 SMO	1150	2100

11.1 Solution annealing

11.1.1 Preparation

All grease, oil, cutting fluids, forming lubricants, crayon marks and other contaminant must be removed from the surface before annealing. Annealing can burn contaminants into the surface, which cannot be removed easily except by grinding. Carbon-containing contaminants can carburize and sensitize the surface, making it susceptible to intergranular corrosion in service. Section 14 discusses cleaning methods appropriate to stainless steels.

Surface contamination with low-melting-point metals like lead, copper, and zinc is very dangerous. It can lead to grain boundary penetration during annealing and resulting so called liquid-metal-embrittlement. These contaminants must therefore be removed from the surface prior to annealing or welding.

11.1.2 Temperature

The minimum annealing temperature is the lowest temperature that will dissolve carbides and intermetallic precipitates. Annealing must be performed above this temperature to insure complete precipitate dissolution and to restore corrosion resistance. The upper limit of the annealing temperature range is determined by heating rate and section size considerations, and the need to avoid excessive scale that can be difficult to remove. **Table 11** provides annealing temperature guidelines for some austenitic stainless steels. HPASS tend to form intermetallic compounds (chi and sigma) that require higher temperatures to dissolve than carbides, so they have a higher annealing temperature than other alloys.

11.1.3 Annealing time

Holding time at temperature of two to three minutes per millimeter thickness (three minutes per 0.1 inch) is sufficient to dissolve small amounts of carbide and other secondary phases, and to soften cold-formed material. If large amounts of precipitate are present, especially chi and sigma phases, longer holding times are necessary.

Solution annealing for too long a time or at too high a temperature can cause excessive scaling that is difficult and costly to remove. The high-molybdenum HPASS scale rapidly in an air furnace. Molybdenum trioxide normally volatilizes and leaves the surface as a gas. If volatilization is inhibited, liquid molybdenum trioxide can accumulate on the surface and accelerate the oxidation process. Precautions to minimize oxidation of high molybdenum steels are:

- Avoid conditions that inhibit volatilization (tightly packed loads and excessively tight furnaces).
- Do not reanneal heavily scaled material.
- Avoid long exposures above the minimum annealing temperature.
- Use the lowest practicable annealing temperature.

11.1.4 Atmospheres

Air and oxidizing combustion gases are satisfactory atmospheres for the annealing of stainless steels. Air annealing produces oxide scale that must be removed to restore corrosion resistance. Protective atmospheres like argon, helium, hydrogen, cracked ammonia, hydrogen/nitrogen mixtures, and vacuum, prevent scale formation. Bright annealing is typically performed in either hydrogen or cracked ammonia having a dew point of -40°C (-40°F) or less. When properly performed, protective atmosphere annealing produces no scale, and no post-anneal cleaning is required.

11.1.5 Cooling

Austenitic stainless steels may require rapid cooling after annealing to avoid precipitation of chromium carbides or other intermetallic phases. The need for rapid cooling and choice of method depends on section size and grade.

Degreasing of austenitic stainless steel. (Source: Sandvik)

In most situations, thin sections of Types 304L and 316L can be air-cooled. As section size, carbon content, and alloy content increase, the need for rapid cooling increases. The HPASS require rapid cooling in all section sizes. Common methods are fan-air cooling and water spray or quench cooling. In vacuum annealing, inert gas quenching can cool without scale formation.

If a material will be subjected to further hot processing after annealing, for example welding, it is best to provide maximum cooling, e.g., water quench, following the anneal. This increases the material's tolerance for the detrimental effects of further thermal cycles. The possibility of distortion should be considered when choosing a cooling method.

11.1.6 Post anneal cleanup

Metal immediately beneath the annealing scale is low in chromium and has poor corrosion resistance because the scale is rich in chromium. Both the scale and the chromium-depleted metal must be removed to restore corrosion resistance.

The most common cleaning method is to shot blast the scale, then acid pickle to remove the chromium-depleted metal. Immersion pickling is the most common technique used to pickle stainless steel, but pickling is also performed with sprays, gels, and pastes.

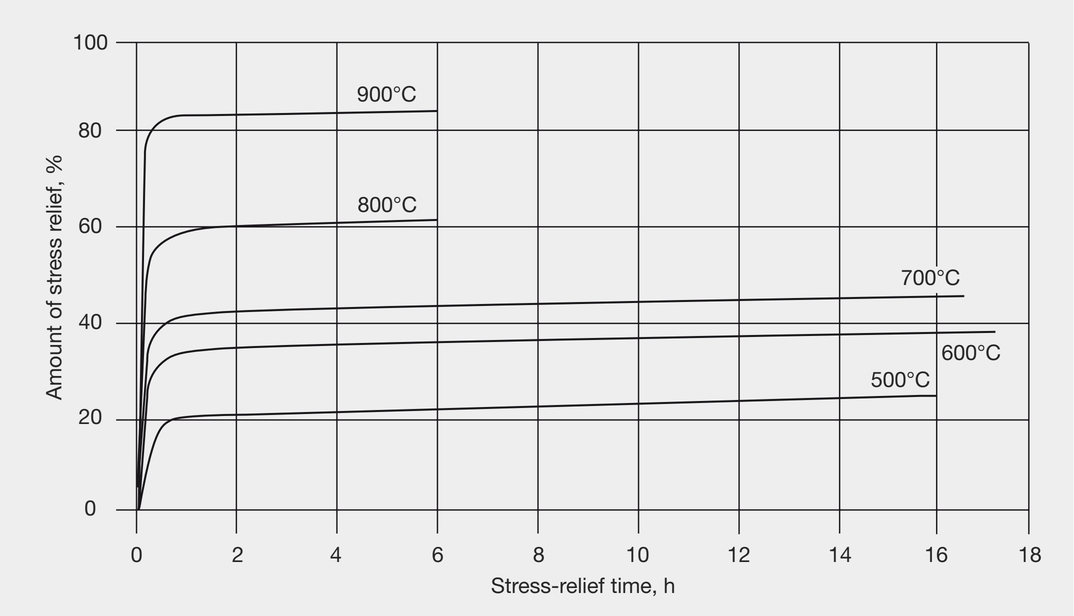


Figure 21: Residual stress relief in Type 347 stainless steel as a function of temperature and time. Residual stress before annealing was 230 MPa (33 ksi). (10)

Pickling acids are very hazardous, and it is extremely important to comply with all safety guidelines when using them (ventilation, gloves, goggles, protective clothing, etc.). The work piece must be neutralized and thoroughly rinsed with ample amounts of clean low-chloride water after pickling. Spent fluids must be collected separately and disposed of in accordance with applicable hazardous waste regulations.

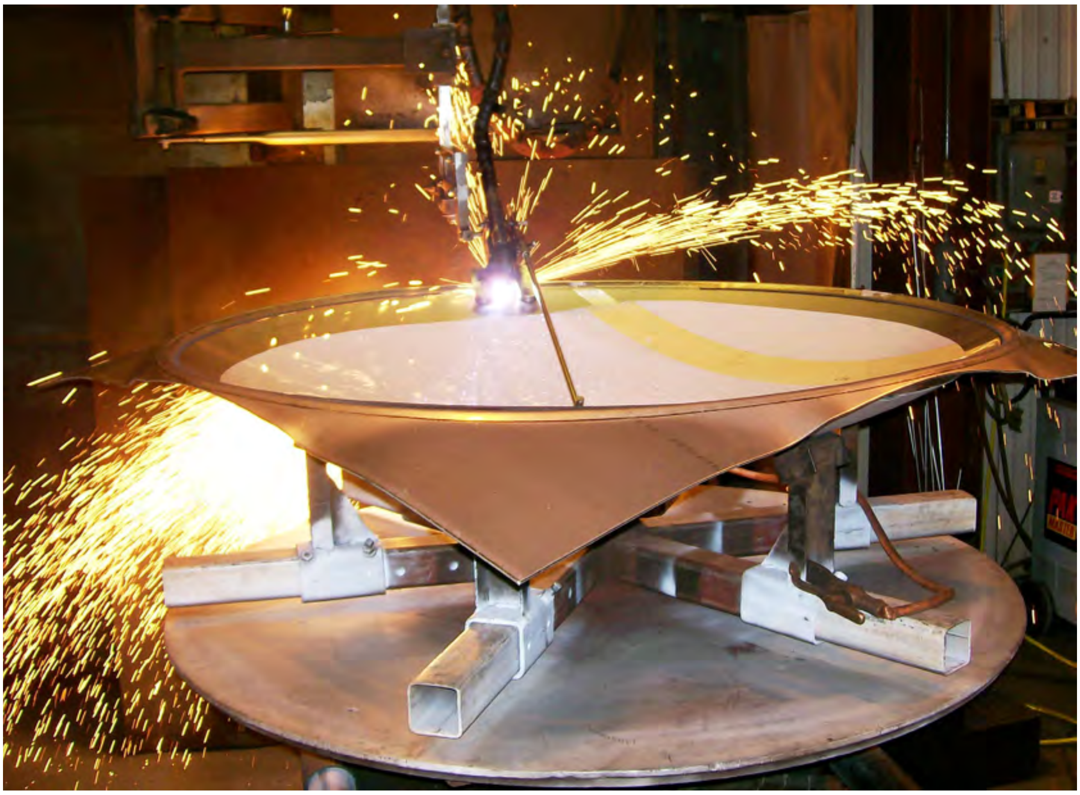
Section 14-2 provides detailed information about cleaning methods. The reader is urged to read this section carefully before undertaking any cleaning operation.

11.2 Stress relieving

Stress relieving temperatures are lower than annealing temperatures, and are not high enough to dissolve precipitates or produce softening. Stress relief removes some, but not all, residual stresses. The stress relief process is slow, so stress-relief times are in the range of hours, compared to minutes for annealing. Stress relief temperatures often fall in the low end of the temperature range where secondary phase precipitation occurs. At these temperatures, annealing times must be chosen carefully to avoid precipitation that degrades corrosion resistance. This restriction often limits the amount of stress relief possible. The potential stress relief benefit must be weighed against the sensitization risk when deciding whether to use a low temperature stress relief, an intermediate temperature stress relief, or a full solution anneal.

There are many cases where mixed constructions involving stainless steel and carbon or alloy steels require the carbon steel to be stress relieved. In these cases, the code or specification for the carbon steel controls the annealing time and temperature. The engineer must determine if the required thermal cycle will negatively affect the stainless steel. If so, a different stainless grade may be required.

A low temperature stress relief is one conducted in the “safe” region, up to about 540°C (1000°F). **Figure 21** shows that this treatment reduces stress by less than 40% of its initial value. A major advantage of the low temperature treatment is that there is no danger of producing sensitization. The figure also shows that an intermediate temperature treatment produces more stress relief, but temperatures are in the precipitation range of 540 to 900°C (1000 to 1650°F). In this case, holding time must be severely restricted. Fortunately, most stress relief comes within the first half hour of reaching temperature in this temperature range.



Plasma trimming of a GTA welded and hydro-formed austenitic stainless steel vessel head for sanitary applications. (Source: DCI, Inc, St. Cloud, MN USA)

When employing intermediate temperatures for stress relief, the cumulative effect of all thermal cycles must be considered. The stress relief cycle includes heating up, time at temperature, and cooling. The heat-affected zone (HAZ) of multi-pass welds may already have seen significant time at temperature before the stress relief. Adding more thermal exposure by stress relieving in the critical TTS range can cause unexpected precipitation of secondary phases that deteriorate the corrosion resistance and mechanical properties of the HAZ. Most of the high chromium or high molybdenum HPASS form intermetallic phases in relatively short times, so they are candidates for only low temperature stress relief treatments.

The determination of how to cool the part after stress relief requires careful consideration. A high cooling rate, as with water cooling, can re-introduce stresses due to differences in thermal contraction. It can be very difficult to cool large complex components having variable cross-sections without introducing new stresses. For treatments in the TTS range, a fan cool to the bottom of the range followed by a still air cool is an attractive option. A still air cool is usually satisfactory for use with low-temperature stress relief treatments.

Stainless steel surface preparation prior to stress relief is identical to that for solution annealing, and consists of a thorough cleaning to remove contamination. Low-temperature stress relief treatments will not produce the heavy scale typical of solution annealing, but they can cause surface oxidation. If the surface appears gold or blue after the treatment, it should be pickled to obtain maximum corrosion resistance.

12 Welding, Brazing and Soldering

Welding, brazing, and soldering are widely used to join stainless steels. It is more complicated to join stainless steels than to join carbon steels because the process must maintain both the corrosion properties and the mechanical properties of the base metal. Property differences between the joint and base metal can be minimized with proper joint preparation, joining practice and final cleanup. This section offers general guidance on the welding and joining of stainless steels. The HPASS require somewhat different techniques than the standard austenitic grades.

12.1 Welding

12.1.1 Physical property effects on welding

Thermal expansion, electrical resistivity, and thermal conductivity are important physical properties that affect welding behavior. **Table 12** summarizes several of these parameters for carbon steel and for a standard stainless steel. Note that stainless steel physical properties have quite different values from those of carbon steel.

A larger CTE increases austenitic stainless steels' tendency to distort. Tack welds should be spaced more closely than in carbon steel to control distortion.

A higher electrical resistivity reduces the electrical current necessary to generate the same heat in austenitic stainless steel. This, coupled with a lower melting point, means that lower welding current is required to weld austenitic stainless steels.

Low thermal conductivity concentrates heat near the weld in austenitic stainless steels, producing a steeper temperature gradient and an increased tendency for shrinkage stresses and distortion as compared to carbon steel. Sluggish heat removal due to low conductivity keeps the weld metal and heat-affected zone hot longer, allowing more time for precipitation of carbides or intermetallic phases.

12.1.2 Edge considerations when welding

- Edge design and fit-up: Molten stainless weld metal is less fluid than that of carbon steel, so weld penetration is not as great for the same welding parameters. To compensate, stainless steel joints have a wider bevel, thinner root face, and a wider root gap than carbon steel joints. Bearing these facts in mind when designing and preparing joints helps avoid burn-through and facilitates production of a full-penetration weld. Many different weld joint designs result in acceptable welds. A good collection of detail drawings for various weld joints is given in Nickel Institute publication No. 11007. (3)

- Edge preparation: Careful edge preparation is important for successful welding of austenitic stainless steels. Straight, clean, and burr-free edges make joint alignment easier, assist with arc stability, and produce welds with consistent penetration. Good edge preparation makes it easier for the welder to make a good weld. Machined edges are ideal, but grinding is an acceptable preparation technique if burrs are removed and the grinding produces a uniform gap.

12.1.2.1 Edge cleanliness

- Oxides: Stainless steels form a high melting point oxide slag during plasma or laser cutting. If these are not removed from cut edges before welding, they can be incorporated into the weld metal, creating internal stress raisers and sites for corrosion initiation. All oxides must be removed by machining or fine grinding to expose bare base metal before welding. Wire brushing, even when performed with a stainless steel wire brush, does not always remove tightly adhering oxides.

Table 12: Physical properties of austenitic stainless steel and carbon steel.

Physical property	Carbon steel	Austenitic stainless steel 19 Cr–9 Ni	Comment
Linear coefficient of thermal expansion	11.7 6.5	17.6 9.8	20–628°C (20–500°C for stainless) : [x 10^{-6}/K] 68-1162°F (68-932°F for stainless) : [x 10^{-6}/°F]
Ratio of thermal conductivity	100 100	28 66	Pct of carbon steel at 100°C (212°F) Pct of carbon steel at 650°C (1200°F)
Electrical resistivity	0.125 1.25	0.72 1.26	At 20°C (68°F) $\Omega \cdot mm^2/m$ At 885°C (1625°F) $\Omega \cdot mm^2/m$
Approx. melting point	1540 2800	1425 2600	°C °F

- Organic contamination: Organic contamination can cause weld cracks or porosity if not removed. Carbon from organic contamination can dissolve in the stainless steel and lead to sensitization. Organic contaminants like oils, cutting fluids, or crayon marks must be removed with appropriate solvents.

- Metallic contamination: Copper, lead and zinc melted by welding heat can penetrate grain boundaries and embrittle stainless steel. Contamination with these metals is typically the result of contact with tooling or backing bars, or contact during storage or handling. These metals must be removed before welding. Grinding and pickling work best for removing metallic contamination.

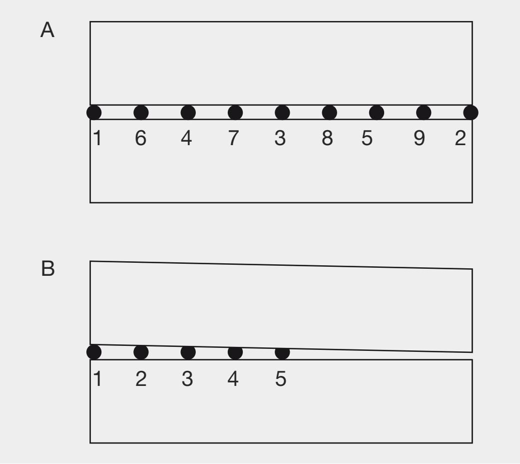


Figure 22: Proper tacking sequence to avoid closing of the gap during welding. A: Correct, B: Incorrect. (3)

12.1.2.2 Fit-up, tacking, and clamping

Proper fit-up prior to welding is critical in the fully austenitic HPASS, which require minimum heat input to avoid hot cracking. The welder should not have to "weave" in order to bridge a large or irregular root gap. Good fit-up provides a uniform gap width and alignment along the length of the weld. This can be achieved with precise edge preparation, and clamping or tacking of the weld.

Table 13 shows appropriate spacing of tack welds in austenitic stainless steel, and **Figure 22** illustrates the proper tacking sequence for a straight weld. Tack welds in pipe or tubing that will be incorporated into the final weld should not be full penetration welds, and must be free of oxidation. It is very important that tack welds in heavy section weldments, not contribute to defects in the final weld. High-contour

Table 13: Recommended tack weld spacing as a function of thickness. (11)

Sheet thickness		Tack weld spacing	
mm	inch	mm	inch
1–1.5	0.04–0.06	30–60	1.2–2.4
2–3	0.08–0.12	70–120	2.8–4.7
4–6	0.16–0.24	120–160	4.7–6.3
Over 6	Over 0.24	150–200	5.9–7.9

Table 14: Suggested filler metals for welding of some more common stainless steels.

Wrought Alloys	Metal	Covered welding electrode (AWS)	Bare welding electrodes and rods (AWS)
Grade	UNS No.	A5.4 (stainless) A5.11 (nickel alloys)	A5.9 (stainless) A5.14 (nickel alloys)
304	S30400	E 308/E 308L(1)	ER 308/ER 308L(1)
304L	S30403	E 308L	ER 308L
309S	S30908	E 309/E 309L(1)	ER 309/ER 309L(1)
310S	S31008	E 310	ER 310
316L	S31603	E 316L	ER 316L
317L	S31703	E 317L	ER 317L
317LM	S31725	See filler metals for 6% Mo SS	See filler metals for 6% Mo SS
317LMN	S31726	See filler metals for 6% Mo SS	See filler metals for 6% Mo SS
904L	N08904	E 385 or see filler metals for 6% Mo SS	ER 385 or see filler metals for 6%Mo SS
Alloy 20, 20Cb-3 (2)	N08020	E 320 or E 320L	ER 320 or ER 320L
Alloy 825	N08825	See filler metals for 6% Mo SS	See filler metals for 6% Mo SS
Alloy 28	N08028	E 383	ER 383

Table 14 (continued): Suggested filler metals for welding of some more common stainless steels.

Wrought Alloys	Metal	Covered welding electrode (AWS)	Bare welding electrodes and rods (AWS)
Grade	UNS No.	A5.4 (stainless) A5.11 (nickel alloys)	A5.9 (stainless) A5.14 (nickel alloys)
6% Mo Stainless Steels			
254 SMO (2,3)	S31254	E NiCrMo-3, E NiCrMo-4, E NiCrMo-10, E NiCrMo-12, E NiCrMo-13, E NiCrMo-14.	ER NiCrMo-3, ER NiCrMo-4, ER NiCrMo-10, ER NiCrMo-13, ER NiCrMo-14.
AL-6XN (2,3)	N08367		
25-6MO, 1925 hMo (2,3)	N08926		
20Mo-6 (2,3)	N08026		
254N (2,3)	S32053		
Castings	**Metal**	**Covered welding electrode (AWS)**	**Bare welding electrodes and rods (AWS)**
ACI grade	**UNS No.**	**A5.4 (stainless) A5.11 (nickel alloys)**	**A5.9 (stainless) A5.14 (nickel alloys)**
CF-8	J92600	E 308(1)	ER 308(1)
CF-3	J92500	E 308L	ER 308L
CF-8M	J92900	E 316(1)	ER 316(1)
CF-3M	J92800	E 316L	ER 316L
CN-7M	J95150	E 320 or E 320L	ER 320 or ER 320L
CK-3MCuN (3)	J93254	E NiCrMo-3, E NiCrMo-4, E NiCrMo-10, E NiCrMo-12, E NiCrMo-13, E NiCrMo-14.	ER NiCrMo-3, ER NiCrMo-4, ER NiCrMo-10, ER NiCrMo-13, ER NiCrMo-14.
CN3MN (3)	J94651		

Notes:

(1) The "L" or low carbon grade or a stabilized grade is always used for welded fabrication except in a few instances where the slightly higher strength of the regular grade is more important than best corrosion resistance.

(2) Trade name.

(3) Any of these filler metals, which contain a minimum of 9% Mo, are suitable.

tacks or tacks with abrupt starts and stops should be contour ground. Welders should avoid striking or extinguishing the arc on a tack weld.

12.1.3 Filler metals

Table 14 lists filler metals commonly used to weld austenitic stainless steels. The table should be used only as a guide since alternates or proprietary filler metals are often available.

For the alloys higher alloyed than the 6% Mo grades, it is especially important to consult the alloy manufacturers' data sheets and also determine that the filler metal is suitable from both a corrosion and mechanical properties viewpoint.

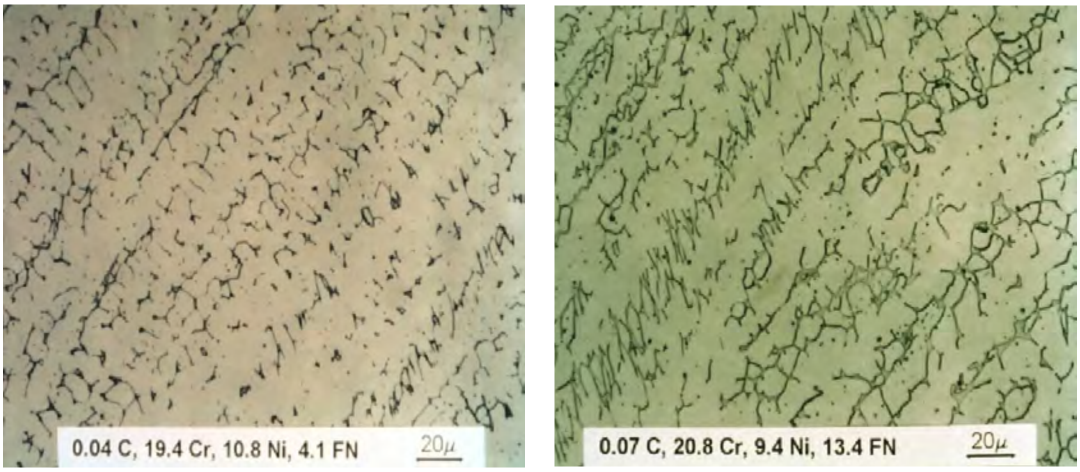


Figure 23: Austenitic stainless steel weld metal with different ferrite contents. (Source: Lincoln Electric)

12.1.4 Weld defects

12.1.4.1 Microfissures and hot cracks

Microfissures are tiny, short fissures or cracks that may occur in austenitic stainless steel welds. They rarely propagate and cause a weld structural failure, but in some environments, they may initiate pitting corrosion. Hot cracking, or more correctly weld solidification cracking, meanwhile, is a serious weld defect that must be avoided.

The compositions of the most commonly used filler metals, Types 308(L) and 316(L), are adjusted to obtain ferrite contents of typically 5 to 10 percent, which greatly improves resistance to microfissuring and hot cracking. Ferrite absorbs shrinkage stress and has higher solubility for sulfur, phosphorus, and certain other impurities that embrittle austenite. Microfissures and hot cracks do not normally occur in standard grade welds containing the required amount of ferrite, but they can occur under conditions of very high heat input, high weld restraint stress, or concave weld contours. The American Welding Society (AWS A5.4) defines a Ferrite Number to express the amount of ferrite in a weld. The FN corresponds roughly to the volume percent of ferrite present in the weld for austenitic stainless steels. **Figure 23** shows weld metal with two different ferrite contents.

The filler metals intended for welding HPASS do not produce welds containing ferrite, so welds in these grades are prone to microfissures and hot cracking. HPASS filler metals contain extremely low phosphorous and sulfur to minimize these problems. Strict control of heat input and other weld parameters is also necessary for good results when welding HPASS. A common limit on heat input is 1.5 KJ/mm.

Any practice that increases the size of the molten weld pool (e.g. excessive weaving) should be avoided when welding austenitic stainless steels. A large weld pool creates greater solidification shrinkage stresses. Large weld pools can also lead to larger grain size in the weld and HAZ. Large grain material has less grain boundary area than fine grain material.

This leads to higher impurity concentrations at grain boundaries, and a possible reduction of corrosion resistance. Excessive shrinkage stresses and excessive concentration of trace elements in grain boundaries promote hot cracking.

12.1.4.2 Sensitization

Standard grades with elevated carbon content can be sensitized by relatively short exposure to temperatures between 480 and 900°C (900 and 1650°F) (see Figure 3-4), which can result in susceptibility to intergranular corrosion in aqueous or acidic environments (see section 6). However, modern standard grades are often “L-grades”, and if not typically contain only slightly more than 0.04% carbon, and resist sensitization during normal fabrication welding provided there is no subsequent thermal processing. For example, it takes approximately one hour to sensitize a Type 304 stainless steel with 0.042% carbon at its fastest sensitization temperature (see Figure 3-4). This is far longer than the time at temperature during welding. Even so, exposure in the critical temperature range during welding should be limited for heavy sections.

Using low carbon grades helps to avoid sensitization in welded heavy sections and in components subjected to post-weld heat treatment. Type 304L tolerates a long time at temperature, which permits safe cooling even for heavy sections (Figure 3-4). Even stress relieving a mixed stainless steel – carbon steel construction might be possible when using L grades.

High temperature grades often contain a minimum of 0.04% carbon (Type 304H) for improved elevated temperature strength. Fortunately, aqueous corrosion due to sensitization is not normally a concern in elevated temperature applications. These grades generally require a high-carbon filler metal to provide adequate high-temperature weld strength.

The stabilized grades Type 321 and 347 may be vulnerable to narrow knife-line attack if they are exposed to temperatures in the 480 to 900°C (900 to 1650°F) temperature range during welding. If knife-line attack is a concern, a post weld solution anneal followed by a stabilizing heat treatment should be specified. See Section 6.3.2 for a discussion of the mechanism of knife-line attack.

Most of the HPASS have an even lower maximum carbon content than the standard “L-grades”, as they would sensitize faster than the standard grades for the same carbon content. However, the formation of secondary phases is generally far more of a concern in HPASS than sensitization with heat from welding.

12.1.4.3 Secondary phases

Sigma and chi phases can form in the temperature range of 500 to 1050°C (930 to 1925°F). Stainless steels containing sigma and chi have substantially lower corrosion resistance and toughness. About 5% sigma phase cuts the impact toughness in half.

The extent of secondary phase formation depends on the presence of ferrite, the steel chemistry, and unfavorable thermal conditions. Steels containing ferrite are more susceptible because secondary phases form more readily in ferrite. Chromium and molybdenum strongly promote secondary phase formation. The standard grades usually require some ferrite. However, sigma precipitation does not occur in these grades until after about 100 hours of high-temperature exposure, so in these steels secondary phase formation is a service problem, not a fabrication problem. It may be necessary to use fully austenitic filler metal when sigma phase is likely to form during service.

Sigma and chi can form in HPASS in less than a minute in the critical temperature range. Therefore, welding parameters for these materials must specify low-heat input (below 1.5 kJ/mm [38 kJ/in]) and an interpass temperature not to exceed 100°C (212°F) to minimize the time in the critical temperature range. The interpass temperature should be measured on the weld bead at the end of the pass, with an electronic thermocouple for accuracy. Do not use temperature-sensitive crayons, which can contaminate the weld.

12.1.4.4 Weld segregation

Molybdenum microsegregation in HPASS weld metal is pronounced in welds that contain high molybdenum. Microsegregation occurs during solidification because the first metal to solidify contains less molybdenum than metal that solidifies later, creating microscopic gradients in molybdenum content. In a 6% Mo stainless steel, low-molybdenum regions may contain as little as 4% Mo, creating an area with significantly lower corrosion resistance.

HPASS, therefore, require welding with an over-alloyed filler metal to compensate for microsegregation. The recommended nickel-base filler material for 6% Mo stainless steels contains a minimum of 9% Mo, which assures a minimum molybdenum content of 6% in the regions that solidify first, preserving good weld metal corrosion resistance.

High performance stainless steel fabrications that cannot be post-weld annealed should not be welded autogenously (without a filler metal), because of the microsegregation problem. Autogenous welds are acceptable only if the welded construction is subsequently solution annealed to homogenize the weld and reduce microsegregation, which restores corrosion resistance.

12.1.5 Welding processes

12.1.5.1 Gas shielding

Stainless steel should be shielded during welding to prevent oxidation of the weld and the heat-affected zone. Oxidation during welding can reduce both, corrosion resistance and mechanical properties. One way to provide shielding to the material is to use an inert gas to protect the weld and HAZ during welding. Shielding gas also helps to stabilize the arc, and can affect penetration and bead contour. **Table 15** lists shielding gases for different welding processes.

The backside of the weld should also be shielded to maximize corrosion resistance in the as-welded condition. Argon, nitrogen, and a 90% N–10% H_2 mixture, are used as backing gases. Nitrogen dissolves in the weld pool, increasing the weld's nitrogen content. Nitrogen increases the weld's strength without impairing its corrosion properties.

A copper backing bar is often used when welding sheet material. The backing bar cools the weld, prevents burn-through, and helps contain the shielding gas to protect the back of the weld. It is important to avoid rubbing the stainless steel against the copper, which can transfer copper to the stainless surface and can cause cracking by liquid metal embrittlement if melted.

12.1.5.2 Gas tungsten arc welding (GTAW, also called TIG)

Gas tungsten arc welding is used primarily for sheet and tube welding and for the root pass on pipe welds. It is relatively slow but produces a clean, high quality weld that is free of slag and weld spatter. It can be used in all positions.

GTAW uses a non-consumable tungsten electrode to produce an electric arc that melts the base metal. The technique can be performed autogenously (without filler metal), or with a bare filler wire fed manually in straight pieces or automatically from a coil. An inert shielding gas, introduced through the torch, protects the molten weld metal and tungsten electrode. Autogenous GTAW can be used to weld thin gauge leaner alloy stainless steel sheet, or to make the root pass in other welds. Autogenous welding should not be

Table 15: Shielding gases for various welding processes. (11)

Process	Shielding gas	Advantage / disadvantage
GTAW manual	99.95% Ar	Good penetration, low gas flow rate, low burn-through danger, produces high quality welds, expensive
	99.9% Ar	Same as above
GTAW automated	He	Higher heat input, deeper penetration
	Ar + He	Improved bead contour and wettability
	Ar + H	Improved penetration and welding speed
	Ar + He + H	Improved penetration and welding speed
	Ar + N_2	Limits loss of nitrogen in N-alloyed grades, improved corrosion resistance / might deteriorate tungsten electrode
GMAW spray arc	99.95% Ar	For 6% molybdenum stainless steel
	Ar + 1–2% O_2	Improved arc stability, wetting compared to pure Ar
	Ar + 2% O_2	Improved weldability for out of position welding
GMAW short arc and pulsed arc	99.95% Ar	For 6% molybdenum stainless steel
	Ar + 7.5% He + 2.5% CO_2	Preferred in Europe
	Ar + 30% He + 1% O_2	For 904L and 6% molybdenum stainless steel
	He + 7.5% Ar + 2.5% CO_2	Preferred in North America
	He + 30% Ar	For 904L
FCAW	Ar + 20–25% CO_2	Preferred for horizontal welding
	100% CO_2	Preferred for vertical welding

Table 16: Typical welding parameters for GTAW (11)

Tungsten electrode dia.		Current	Voltage	Typical section thickness	
mm	inch	A	V	mm	inch
1.6	0.063	50–120	10–12	<1	<0.040
2.4	0.095	100–230	16–18	1.0–3.0	0.040–0.120
3.2	0.12	100–200	15–18	>2.0	>0.80

used with high performance stainless steels unless they are post-weld solution annealed because of a possible loss in corrosion resistance due to molybdenum microsegregation.

GTAW is best performed with a constant current power supply and a high frequency arc-starting feature. Welding should be performed with a direct current straight polarity (DCSP) electrode negative procedure because reverse polarity (DCRP) causes electrode deterioration.

A commonly used electrode is a 2% thoriated tungsten electrode (AWS A5.12, Classification EWTh-2; EN ISO 6848). Arc control is aided by grinding the electrode to a conical point with a vertex angle of 20 degrees for thin material to 65 degrees for thicker material, and a small, rounded tip. The "correct" electrode end preparation depends on operator preference. For automated GTAW, a few tests under production conditions can determine the ideal geometry to achieve the desired penetration.

A gas lens or a nozzle cap improves shielding gas coverage, prevents turbulence, and minimizes air aspiration into the shielding gas. Gas flow should be initiated several seconds ahead of striking the arc and maintained for several seconds after the arc extinguishes to avoid oxygen contamination. **Table 16** summarizes typical weld parameters for GTAW.

12.1.5.3 Gas metal arc welding (GMAW, also called Metal Inert Gas, or MIG)

Gas metal arc welding enables fast deposition of large amounts of weld metal. It provides higher welding speed and lower costs than GTAW or shielded metal arc welding (SMAW).

In GMAW, the consumable bare wire is also the electrode, and is fed automatically from a coil through the torch. The process is usually semi-automatic where the welder guides the torch manually, but it can be automated for simple weld geometries. The shielding gas flows through the gun and protects the weld pool.

GMAW requires specialized equipment, including a constant voltage supply with variable slope and variable inductance control or pulsed arc current capability. GMAW should be performed with direct current reverse polarity (DCRP), electrode positive. There are three GMAW arc transfer modes:

- Short-circuiting transfer: This mode requires separate slope and secondary inductance controls, and is useful for material up to approximately 3 mm (1/8 inch) thick. Metal transfer from the consumable electrode occurs by repeated short-circuits resulting in a relatively low deposition rate. This mode gives the lowest heat input, and is especially useful for thin sections where there is a risk of distortion. It can be used for out-of-position welding.

- Pulsed-circuiting transfer: This mode requires a special power source that pulses the welding current and voltage. This combination provides the benefit of higher metal deposition rates than the short-circuiting transfer, while still using modest heat input. It can also be used for out-of-position welding.

- Spray transfer: This mode provides a high deposition rate with a stable arc, but it has high heat input. The metal is transferred in the form of a fine mist of droplets. The mode is limited to flat position welding, and is used for sheet and plate 3 mm (0.120 inches) or thicker. It is economical when making long, straight welding runs in moderate to heavy welds.

GMAW, like any welding process using gas shielding, may not be suitable for field or outdoor welding, or for welding where drafts can disturb the gas shield and contaminate the weld with oxygen. **Table 17** lists typical welding parameters for the different welding transfer processes for pure argon gas shielding. These parameters will vary with different gas mixtures, so it is best to consult the gas supplier to obtain parameters for a particular gas mixture.

12.1.5.4. Flux-cored arc welding (FCAW)

Flux cored arc welding can provide even higher deposition rates than GMAW. It is suitable for a wide range of metal thicknesses and can be used for out-of-position welding.

In FCAW, the flux-filled wire is fed automatically through the torch with the same equipment used for GMAW. The flux inside the wire provides a slag that protects the weld from the atmosphere. This slag supplements the gas shielding provided through the torch to protect the HAZ. In the case of self-shielding FCAW electrodes, the flux also generates a shielding gas, although this type is never used for demanding corrosion-resisting applications. As in GMAW, the process is either semi-automatic or fully automatic. Stainless FCAW consumables are covered by AWS A5.22. Very few FCAW wires are available suitable for HPASS. The two major gases used for stainless FCAW are argon with 15–25% carbon dioxide which gives best weldability or 100% carbon dioxide which gives better penetration. Gas flow rates are typically 20–25 litres/min. (0.7–0.9 cfm). Typical welding parameters for FCAW are given in **Table 18**.

Table 17: Typical welding parameters for GMAW as function of welding wire diameter and welding process. (11)

Process	Wire diameter		Current	Voltage
	mm	inch	A	V
GMAW short arc	0.8	0.031	90–120	19–22
	1.0	0.039	110–140	19–22
GMAW spray arc	0.8	0.031	150–170	24–27
	1.0	0.039	170–200	25–28
	1.2	0.045	200–270	26–29
	1.6	0.063	250–330	27–30
GMAW pulsed arc	1.2	0.047	75–300	24–30

Table 18: Typical welding parameters for FCAW. (11)

Process	Wire diameter		Current	Voltage
	mm	inch	A	V
FCAW horizontal	0.9	0.035	80–160	22–28
	1.2	0.047	150–280	24–32
	1.6	0.063	200–320	26–34
FCAW vertical up	0.9	0.035	80–130	22–26
	1.2	0.047	140–170	23–28
FCAW overhead	0.9	0.035	80–150	22–27
	1.2	0.047	150–200	24–29

12.1.5.5 Shielded metal arc welding (SMAW, also called stick welding)

SMAW uses straight length “sticks” of metal wire coated with flux, that function as consumable electrodes. The flux shields the weld from oxygen and the slag that forms absorbs contaminants. This process is often used for repair welding of equipment in service, and for welds where it is difficult to clean the surrounding area. It is useful for field welding because no shielding or purging gas is necessary. A flux process is less susceptible to air contamination from drafts, making SMAW a good process for outdoor welding. SMAW requires a constant current power supply, and is normally carried out with DCRP electrode positive.

SMAW is a versatile process; it can weld complex geometries in difficult positions and in difficult locations. It is not economical for long straight welds that are candidates for automation or higher-efficiency processes.

The electrode covering, which contains gas-forming components, is based on a slag-forming flux. The specific flux chemistry affects arc stability, weld-bead contour, and weld cleanliness. Flux chemistry also determines how successful the technique is in out-of-position applications. Electrodes are available with a variety of flux formulations designed for specific welding positions, including out-of-position welding, vertical-down welding, and others.

The covering may also incorporate alloying elements into the weld. In this case, the bare wire in the center may be a standard grade stainless steel. The coating on SMAW electrodes should never be stripped and the wire used as GTAW bare-wire electrode, since the core wire may lack essential alloying elements incorporated into the coating. Slag must be removed completely before the next pass, and before fabricated equipment is put in service.

Welding rods are sold in airtight containers and, once opened, must be stored in a dry, low humidity location. If exposed to high humidity for any length of time, they should be dried in an electrode oven at 250–280°C (480-535°F) prior to use, to remove

Table 19: Typical parameters for SMAW for basic and rutile electrodes for different welding positions. (11)

Electrode				Current		
Type	Diameter		Voltage	Horizontal welding	Vertical, up-welding	Overhead
	mm	inch	V	A	A	A
Rutile	1.6	0.063	22–24	30–40	30–35	30–40
	2.0	0.078	22–24	35–55	35–40	40–50
	2.5	0.098	22–24	50–75	50–60	60–70
	3.25	0.128	22–24	70–110	70–80	95–105
	4.0	0.157	22–24	100–150	100–120	120–135
	5.0	0.197	22–24	140–190		
Basic	2.0	0.078	24–27	35–55	35–40	35–45
	2.5	0.098	24–27	50–75	50–60	55–65
	3.25	0.128	24–27	70–100	70–80	90–100
	4	0.157	24–27	100–140	100–115	125–135
	5	0.197	24–27	140–190		

moisture that can produce weld porosity. Recommended welding parameters differ from producer to producer and with the alloy. **Table 19** provides general guidelines, but it is best to use the voltage and current suggested on the electrode container. For most HPASS alloys, lower currents than shown below should be used.

12.1.5.6 Submerged arc welding (SAW)

In SAW, the consumable electrode is a bare wire, usually having the same composition used for GMAW. Flux powder is applied to the weld site. The flux powder melts and forms a blanket when the arc is struck. The melted flux powder forms a protective slag over the weld metal, and the unmelted powder is usually recycled. The arc is not visible through the flux covering, so SAW must be automated.

SAW deposition rates are considerably higher than those of other welding processes. The process is well suited for components like heavy wall vessels and piping. It is used for butt and fillet welding in the flat position or for horizontal-vertical fillet welding. It produces excellent as-welded surfaces, and requires a minimum of post-weld surface conditioning.

There are no specifications for stainless steel SAW fluxes, but a number of proprietary fluxes are available. Fluxes can be metallurgically neutral, acid, or basic in their effect on weld metal. The fabricator should consult with the flux manufacturer in selecting the correct wire-flux combination for the particular type of welding intended. HPASS fluxes tend to fall into strongly basic category, whereas for standard alloys they may be neutral to slightly basic.

Attractive as high deposition rates may be, the high-heat input, large weld beads and low cooling and solidification rates of SAW can bring problems. In butt-welding applications, the standard grades of Type 304L and 316L (low carbon grades are preferred for high heat input rates) are easiest to weld. When SAW is used on HPASS, heat input and interpass temperature must be well controlled. See the guidelines in Section 12.1.4.3. As indicated in Table 12-3, these alloys are normally welded with Ni-Cr-Mo filler metal. SAW is particularly well suited for applying stainless steel weld overlays on carbon steel substrates in the flat position. Procedures specifying the correct filler metal/flux combinations to meet required weld composition limits are available. **Table 20** provides some typical welding parameters.

Table 20: Typical welding parameters for SAW of standard stainless alloys using a neutral or slightly basic flux. (11)

Wire diameter		Current	Voltage	Welding speed	
mm	inch	A	V	cm/min.	in/min.
2.4	0.094	200–350	27–33	30–60	12–24
3.2	0.125	300–600	30–36	30–60	12–24
4.0	0.157	400–700	30–36	30–60	12–24

12.1.6 Weld quality considerations

Stainless steel welds must be both corrosion resistant and structurally sound. Weld defects can impair corrosion resistance and strength, and must be avoided. If they occur, they must be repaired. The following provides guidelines to minimize common defects.

- Incomplete joint penetration: Incomplete joint penetration occurs most often in tube or pipe butt welds, or other butt welds that are not double-welded. It creates a crevice that can initiate corrosion and trap dirt and contaminants, allowing them to accumulate. The crevice lowers the strength and corrosion resistance of the weld, and is very difficult to sanitize (clean). High quality butt welds demand full penetration joints. Otherwise, the joint's mechanical strength and fatigue resistance may be substantially reduced. To avoid these problems, it is important to use a suitable weld joint design or back gouge and weld the reverse side when possible.

- Porosity: Surface porosity offers a haven for dirt, and other contamination that can initiate corrosion. Surface porosity is difficult to properly clean and sanitize because it traps dirt and bacteria. Moisture usually causes weld porosity. It can come from electrode flux, shielding gas, or the work piece surface. Careful attention to electrode drying, gas chemistry, and cleaning practices minimize surface porosity. It also important to establish porosity acceptance levels to guide visual inspection of welded surfaces.

- Surface oxides: Heat tint on the interior surface of tube or pipe welds can be a concern for many applications. There are a number of methods to eliminate or minimize the heat tint oxide. One is to use good internal inert gas purging techniques. When making butt joints using orbital GTAW, good joint fit-up and inert gas purge is necessary in order to achieve welds essentially free of heat tint. With manual GTAW root-pass welding, some degree of heat tint often occurs. Depending on the amount of heat tint and the intended service, it may be necessary to remove the oxide by pickling or mechanical polishing.

Heat tint reduces crevice corrosion resistance substantially, especially in standard austenitic stainless steels. In crevices formed under deposits, the resistance to microbiologically influenced corrosion (MIC) is reduced. MIC of heat-tinted areas has occurred in untreated water service, particularly under low flow or stagnant conditions. Failing to drain and dry systems after hydrostatic testing with ordinary water can also induce MIC.

There are two challenges to establishing an acceptance criterion for heat tint on welds where it cannot be removed. One challenge is to quantify the degree of heat tint. A number of industries use heat tint color photograph charts to convey acceptance levels for heat tint clearly. One such chart is available in AWS D18.1 and D18.2. Another challenge is to establish an acceptable amount of heat tint for a specific service.

Reduced corrosion resistance from heat tint is more pronounced in the standard alloyed stainless steels (e.g. 304L and 316L) than in the higher alloyed grades (e.g. HPASS). When it may be extremely difficult or costly to remove heat tint, designers should consider a more corrosion-resistant grade to better accommodate its effects.

- Arc strikes and weld spatter: Arc strikes and weld spatter act as crevices and can initiate crevice corrosion. To minimize these defects, the welder should strike the arc in the weld joint instead of next to the weld. If these are present, they should be removed by fine grinding.

12.1.7 Dissimilar metal welding (DMW)

Austenitic stainless steels can be easily welded to different austenitic grades, to duplex stainless steels, and to carbon and low-alloy steel. Welding dissimilar metals requires that both, the properties of the metals to be joined and the filler metal be considered, because welding creates a new alloy made from the base metals and the filler metal. Detailed information on dissimilar metal welding can be found in Nickel Institute Publication No. 14 018 (12), but the following discussion provides some background information.

When welding stainless steel to carbon or low-alloy steel, the mixed weld composition should not form significant martensite. Martensite causes low weld ductility, and is prone to hydrogen-related defects. After dilution, the weld should contain austenite and a minimum of 5% ferrite to provide good resistance to hot cracking. The weld composition can be estimated by assuming an alloy dilution factor of about 30%. The Schaeffler Diagram (Figure 3-2) can then predict the phases present in the weld. Stainless steel filler with higher ferrite content (E309L, E309MoL, or Type 312) is a good choice. With a leaner filler metal alloy like Type 308 and dilution from ordinary steel, martensite that forms may embrittle the weld.

Dissimilar metal welds must meet the mechanical property and corrosion resistance requirements of the service environment. The weld metal should be equal to or stronger than the weaker of the two base metals. Its corrosion resistance should equal or exceed that of the least resistant base metal. If the service environment involves thermal cycles, the thermal expansion of the weld and base metals should be as similar as possible to minimize thermal fatigue failures. However, in welds between carbon or low-alloy steels and austenitic stainless steels, the difference in thermal expansion is not considered significant when the service temperature is 425°C (800°F) or lower.

When welding different grades of molybdenum-containing austenitic stainless steel, a filler metal with a molybdenum content, equal to the higher molybdenum-alloyed base metals, is typically chosen when welding different grades of austenitic stainless steel, or when joining austenitic grades to duplex stainless steels.

12.2 Brazing and soldering

Brazing and soldering join base metal components with a fusible filler alloy having a melting point well below that of the base metal. With these techniques, the base metal always remains in the solid state. The difference between soldering and brazing is primarily the processing temperature. The American Welding Society defines soldering as metal coalescence below 427°C (800°F). Although methods above 427°C (800°F) are technically brazing operations, the term "hard soldering" has been applied to silver brazing, which typically requires temperatures in the range of 595 to 705°C (1100 to 1300°F).

All stainless steels can be soldered and brazed. Requirements for good soldering and brazing of stainless steels are similar for nearly all grades. Surfaces should be clean, a non-corrosive flux should be used, and care must be taken to avoid sensitization if the process takes place in the sensitization temperature range. Differences among grades relate primarily to their oxidation resistance. The more oxidation resistant grades often require fluxes that are more aggressive.

12.2.1 Brazing

Most stainless steels are brazed with filler alloys that fall into the following categories:

- silver alloys – BAg group
- nickel alloys – BNi group
- copper alloys – BCu group
- gold alloys – BAu group

The alloy is selected based on the mechanical properties, corrosion resistance, and high-temperature properties required by the service environment.

Silver alloys (Ag-Cu-Zn and Ag-Cu-Zn-Cd) are the most widely used and are applicable to all austenitic grades. Cadmium-containing alloys are prohibited in the dairy and food industries because of cadmium's toxicity. Cadmium-free alloys should be used whenever possible from a health and safety standpoint.

Brazing temperatures for most silver alloys are in the sensitizing temperature range, so the process can result in chromium carbide precipitation and sensitization. For this reason, Type 347 or the low carbon grades are preferred when silver brazing. Because most silver alloys contain copper and/or zinc, overheating for extended times must be avoided to avoid liquid metal embrittlement of the stainless steel.

Nickel alloys are usually chosen for their excellent corrosion resistance and good strength at higher temperatures. These alloys consist primarily of Ni-Cr-B-Si alloys. Most nickel-alloy alloys require high brazing temperatures (927 to 1204°C, 1700 to 2200°F). Although this temperature range is above the sensitization temperature, the metallurgical impact of brazing temperature and cooling cycle on the base metal must be evaluated.

Copper alloys consist predominately of pure Cu, and have high brazing temperatures with better flow characteristics than the Ni fillers, permitting a tighter joint fit. Unfortunately, the copper alloys have lower corrosion and oxidation resistance, which limits their applicability.

Table 21: Advantages and limitations of soldered joints.

Advantages	Limitations
Produces a liquid- and gas-tight joint at low temperatures	Possible reduced corrosion resistance at the joint
Avoids high temperature metallurgical effects	Rapid loss of strength with increased temperature
Minimum thermal distortion	Low strength compared to the stainless steel base metal and welded joints
Lower costs relative to other methods	Appearance may be sacrificed
Seals crevices and round corners	Slow compared to welding methods

Gold alloys are used in special applications where corrosion resistance and joint ductility requirements preclude the use of other alloys. The gold alloys consist primarily of Au-Cu and Au-Pd-Ni alloys. Their high cost restricts their use to niche applications like aerospace equipment.

Stainless steel assemblies are usually brazed in a furnace with a controlled inert atmosphere or vacuum. In strongly reducing or inert atmospheres, a flux is not required. Torch brazing always requires a flux. Induction and resistance brazing require flux when not performed under protective atmosphere or in vacuum.

Many special flux compositions are available for use with stainless steels. Fluxes like AWS 3A and 3B are suitable. These fluxes contain boric acid, borates, fluorides, fluoborates, and a wetting agent. The flux must be removed completely after brazing to avoid corrosion by flux residue.

12.2.2 Soldering

Stainless steels are typically soldered with tin-lead or tin-silver solder compositions, although the industry is moving to eliminate lead-containing solders. Soldering is primarily a joining technique, but it also eliminates crevices and sharp corners. Most standard austenitic stainless steels have good solderability, with the exceptions of Ti stabilized grades like Type 321 and the oxidation resistant grades. The high chromium, content of HPASS places them among the oxidation-resistant grades that present more difficulty. Standard soldering fluxes cannot remove the tenacious oxides of HPASS, which impede surface wetting by the solder. Strong fluxes are required to solder these alloys successfully.

The flux must remove the stainless steel's passive film to ensure wetting of the work piece by the solder. Acid-based fluxes are most commonly used, and commercial fluxes designed specifically for stainless steels are available. Phosphoric acid and hydrochloric acid fluxes have produced good results in the standard grades. The more oxidation resistant stainless steel grades with high Cr, Mo, Al, or Ti contents require fluxes that contain hydrofluoric acid. It is important to clean the surface thoroughly after soldering to prevent future corrosion problems by highly corrosive flux residue. The hydrofluoric acid in these fluxes requires special practices to ensure their safe handling and application.

Surface finish also plays a role in wetting. Pickled finishes (No. 1 or 2D) provide better solderability than smoother finishes such as 2B or BA (bright annealed) finishes.

The soldered joint introduces a dissimilar metal that can limit the corrosion resistance of the joint. Because the solders are low melting “soft” materials, the joint strength is that of the solder. Joints that incorporate laps and sleeves have higher strength than simple butt joints because of their larger bond area. **Table 21** summarizes advantages and limitations of soldering stainless steels.

13 Mechanical Joining Methods

All common mechanical joining methods can be used with stainless steels. These methods are nearly all ambient-temperature processes. With the exception of hot riveting, there is little concern for oxidation, precipitation, or residual stresses that may occur with high temperature joining processes. However, mechanical joining does raise some concerns. One is crevice corrosion associated with mechanical joints. Another is galvanic corrosion in joints made from dissimilar metals. Mechanical joints also tend to have lower strength than welded joints.

13.1 Joining methods

13.1.1 Bolting and screwing

Bolts and screws are readily available in the standard grades but are not as available in HPASS. Austenitic stainless fasteners in the annealed condition are prone to galling, so cold worked or high strength HPASS fasteners are preferred. Important mechanical issues with bolted joints include the position of bolt holes and the tension and shear capacity of the connection. The strength of a bolted joint is usually less than that of a welded joint. Guidelines for the design of bolted connections are available in Reference 13.

13.1.2 Riveting

Standard grade stainless steel rivets are available in most common head designs and shank diameters. Rivets should be loaded in shear, not tension, so the mating surfaces must be clean and free of burrs, and the rivet holes matched precisely to assure proper fit-up. The driving and shaping of a rivet involves plastic deformation of the rivet material. Austenitic stainless steels, with their higher work-hardening rates than carbon steel require riveting equipment with higher power.

Riveting can be performed cold or hot. Cold riveting avoids scaling and the expense of heating. Hot riveting provides additional compressive tightening as the rivet shank cools and contracts. Austenitic stainless steel rivets are generally heated to 1065 to 1150°C (1950 to 2100°F) prior to hot riveting. Riveting should be performed before the temperature drops below 930°C (1700°F).

13.1.3 Clinching

Clinching is a periodic deformation that serves to crimp the material together. It is an alternative to riveting or spot welding, and can be applied to any thin, ductile material. Clinching and adhesive bonding are often combined to form a hermetically sealed joint that prevents fluid from entering the crevice area.

13.1.4 Lock seaming

Lock seaming bends the edges of two sheets through an angle of 180° to produce a tight seam (**Figure 24**). This technique is most commonly used with stainless steel sheet and strip of 1.6 mm (0.062 in) thickness or less. It is widely used in stainless steel roofing applications and in the manufacture of household appliances. Seam adhesive applied to the joint surfaces enhances sealing of the seams. Joints of this type have tight crevices that make cleaning more difficult and increase the risk of crevice corrosion. If the service environment permits, they may be filled with solder to avoid crevice corrosion problems.

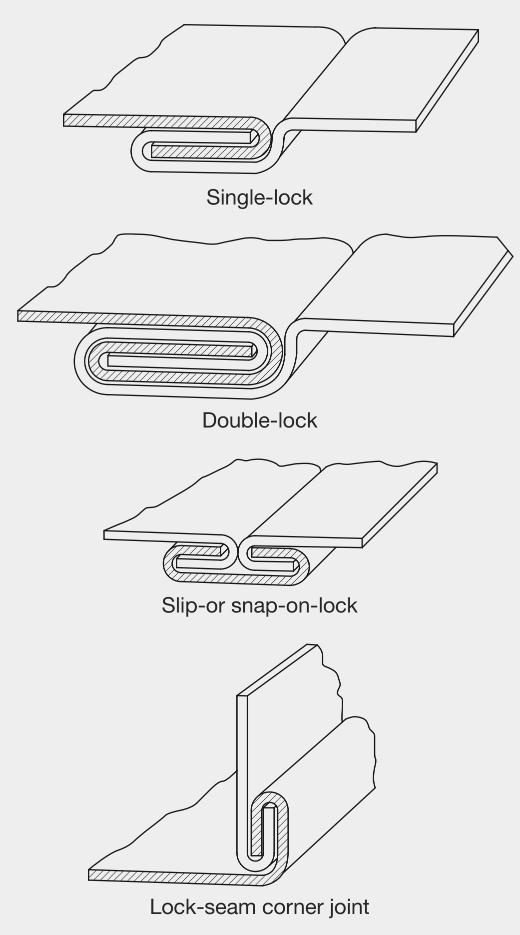


Figure 24: Typical lock joint designs. (13)

13.1.5 Adhesive joining

Adhesive joining can be used with mechanical techniques to produce a higher strength connection, or can be used exclusively to join thin stainless steel sheets and strips. Because it is a low temperature process, adhesive joining does not change the stainless steel's microstructure or surface appearance. Adhesives save significant amounts of weight, which is particularly beneficial for transportation applications. On the other hand, adhesive-bonded joints usually have lower strength than welded or brazed joints, and require lap joints to provide sufficient strength.

13.2 Corrosion considerations with mechanical joints

13.2.1 Crevice corrosion

The natural crevices beneath the bolt head, washer, and nut of bolted joints are susceptible to crevice corrosion. In a moist environment some fluid will penetrate even the tightest joint, and the chemical make-up of the trapped fluid will change compared to the external fluid chemistry, due to reaction with the joint surfaces. This produces a battery-like effect that drives further corrosion. It occurs with similar metals if the corrosivity of the crevice environment exceeds the metals' corrosion resistance. It also occurs in joints with dissimilar metals, where the least resistant metal suffers the most attack.

The likelihood of crevice corrosion increases with increased crevice tightness, certain gasket materials, and severity of the corrosive environment. Normal atmospheric environments usually are not a threat to bolted joints of Type 304. On the other hand, an HPASS bolted joint in a warm seawater environment could present a problem. It is difficult to design against crevice corrosion if the aggressiveness of the environment is close to the joint materials' corrosion resistance. **Figure 25** shows a bolted joint that uses insulating washers to protect against galvanic corrosion. All the various interfaces in this joint (bolt head/washer, washer/gasket, gasket/plate, washer/nut, insulating bush/bolt shank, between-plate crevice) are potential sites for crevice corrosion.

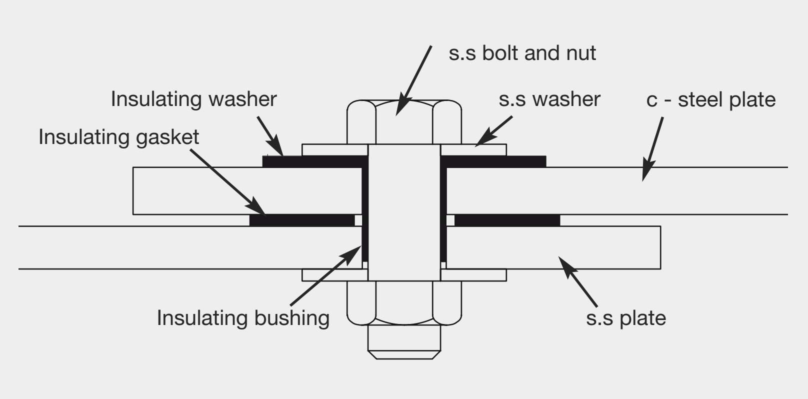


Figure 25: Insulating washers used to prevent galvanic corrosion in a bolted joint. (14)

13.2.2 Galvanic corrosion

Galvanic corrosion can occur whenever two different metals are electrically connected in a corrosive environment. One will corrode at an accelerated rate, while the other will not corrode. The tendency for one or the other metal to corrode is described by the so-called "Galvanic Series." A metal that is above and far apart from another metal on the series is more likely to corrode. There are four ways to deal with the galvanic problem:

- Do not use different stainless grades or any dissimilar metals in a mechanical joint.
- Use insulators to separate the dissimilar metals making up the joint (see Figure 23).
- Select dissimilar metals that are close together in the galvanic series.
- Adjust surface areas of dissimilar metals so that the metal most likely to corrode has the largest exposed surface area.

The HPASS are relatively noble (corrosion resistant), so they will cause carbon steel, aluminum, many copper alloys, and most stainless steels to corrode if used improperly in a joint. They are useful as fasteners to join less noble material (e.g. bolts in Type 316 sheet), because in this case the less noble metal has a much larger surface area than the fastener. The design brochures on the Reading List in the Appendix provide approaches to avoid galvanic corrosion through optimum joint design.

14 Post-fabrication Clean-up

Stainless steel surfaces should be clean, smooth, and free from heavy surface oxides and contaminants. Fabrication can alter the surface and degrade corrosion resistance. It can contaminate the surface with free iron and other deposits; it can damage the passive film through chromium depletion; and it can impart mechanical damage such as rough grinding marks. **Figure 26** shows examples of some of these surface imperfections.

After fabrication, components must be cleaned and corrosion resistance restored by appropriate techniques. The following sections discuss surface damage and techniques to remove it.

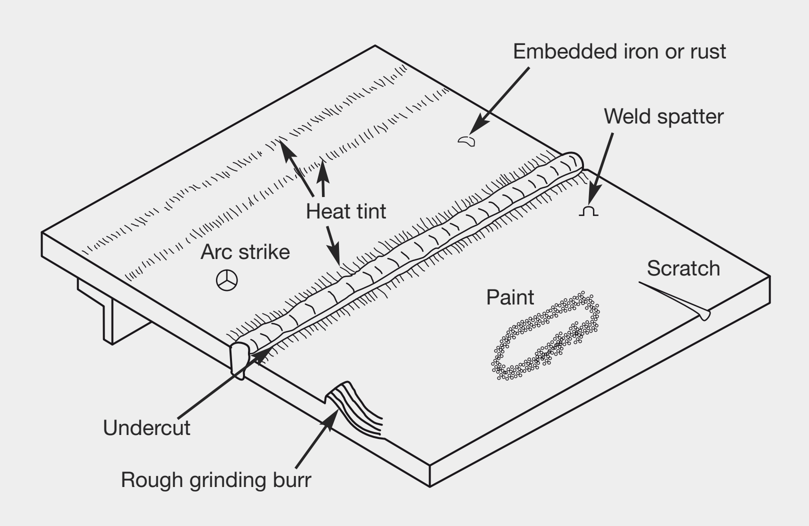


Figure 26: Surface damage and contamination can occur in fabrication. (3)

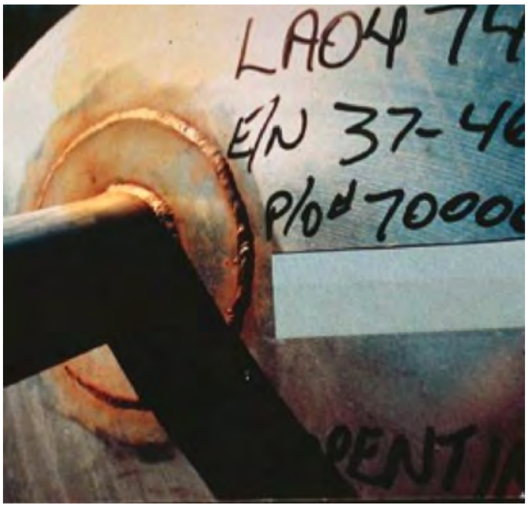
14.1 Typical kinds of damage and surface contamination

14.1.1 Iron contamination

Iron contamination is possible whenever stainless comes in contact with carbon steel. It is a common concern because all fabrication shops use carbon steel tools and fixtures. Iron contamination will corrode and form rust stains on the stainless steel surface in a moist environment (**The figure at bottom right**). The iron rust can also cause corrosion of the stainless if it is only marginally corrosion resistant in the application environment. HPASS alloys are not immune to this effect, although it is not as severe as for standard grades. **Figure 27** illustrates this point, comparing the effect of several kinds of iron contamination on corrosion of Type 316 and a 6% Mo stainless steel.

Common sources of iron contamination in the fabricating shop are:

- Carbon steel dust from grinding near stainless steel
- Touching or dragging carbon steel on stainless steel
- Carbon steel tools, or tools previously used on carbon steel
- Grinding wheels previously used on carbon steel
- Steel shot blast media
- Grit blast abrasive previously used on carbon steel
- Carbon steel clamps and transport hooks
- Forming rolls, presses, and dies used to fabricate carbon steel
- Steel brushes and steel wool



Carbon steel wire brushes used to clean stainless steel welds can produce discoloration and rust.
(Source: Outokumpu Stainless)

14.1.2 Organic compound contamination

Organic compounds include forming lubricants, coolants, crayon marks, and dirt. They can act as crevices and initiate crevice corrosion in some service environments. They can cover embedded iron or weld oxide and prevent pickling or passivation acids from reaching the metal surface to clean and passify it. They carburize the surface upon subsequent heating.

14.1.3 Oxide scale formed during annealing and welding

Stainless steels form an oxide scale when annealed, stress relieved or welded in the presence of oxygen. The oxide forms in the air and in oxidizing furnace atmospheres, and is much thicker than the normal protective passive layer that forms on a clean stainless surface.

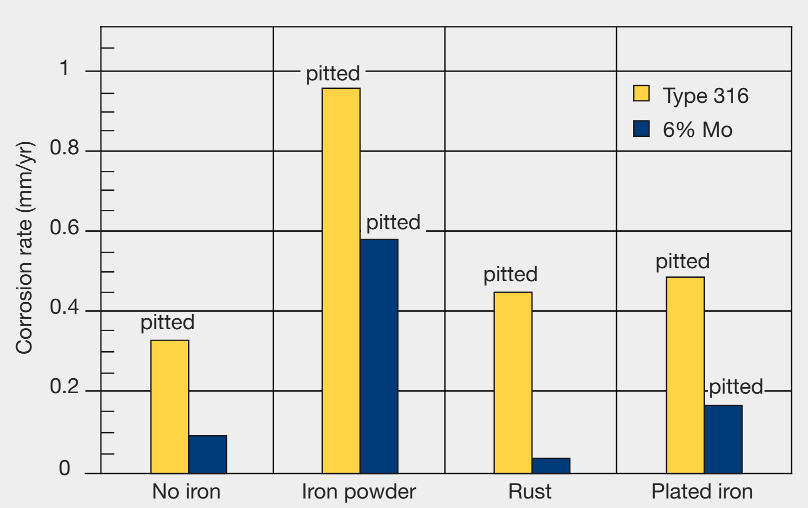


Figure 27: Effect of various types of iron contamination on the pitting resistance of Type 316 and a 6% Mo stainless steel. Samples exposed for 24 hours to an aqueous solution containing 3% $CaCl_2$, 3% NaCl, 0.5% $FeCl_3$, and aerated with 80% air / 20% SO_2. (15)

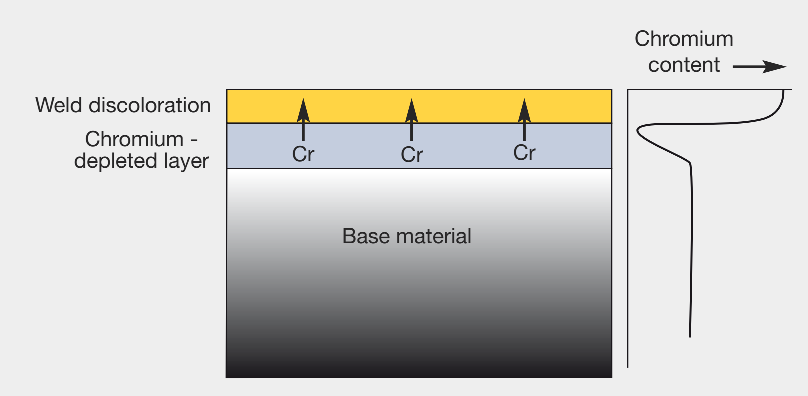


Figure 28: Schematic of the chromium concentration across an oxide scaled surface.

Moving from thinner to thicker layers, oxide color ranges from a transparent light straw to deep blue and opaque black. Scale color and thickness depend on exposure temperature and time, with higher temperature and longer time promoting layer growth. (For example, welding scale is normally thinner and lighter in color than annealing scale.) Oxidation can be minimized by welding with a gas shield or annealing in protective atmospheres, but even with the best of care, it is difficult to avoid all discoloration. Any visual evidence of oxide formation usually indicates cleaning is necessary.

The stainless steel underneath an oxide scale layer has lower corrosion resistance than the base material because chromium enters the oxide from the metal during its formation and growth, depleting the metal below in chromium. **Figure 28** shows a schematic chromium composition profile across a scale layer and its associated base metal. The low point of chromium content can easily be less than the 10.5% minimum required to make stainless steel, so both, the scale and the chromium-depleted metal must be removed during post-fabrication cleanup to restore corrosion resistance.

14.1.4 Other defects

Welding defects (undercuts, spatter, and craters) can deplete the stainless steel in chromium and cause crevices that lead to corrosion. Scratches, gouges, and extreme roughness can initiate corrosion because they create an “active” surface. Low-melting metals like copper can cause intergranular attack upon subsequent heating.

14.2 Post-fabrication cleanup methods

Many mechanical and chemical methods are available for post-fabrication cleanup. Often methods are used, depending on the nature and severity of the contamination and intended use of the stainless steel. The best possible method always involves a final chemical treatment that restores passivity and corrosion resistance. **Table 22** summarizes common methods and provides a short discussion of each.

14.2.1 Sandblasting

Sandblasting can clean large, heavily scaled areas cost-effectively. The sand should be clean, and it cannot have been previously used on carbon steel. It can easily embed contaminants like dirt or iron particles. A final passivation after sand blasting is necessary to impart optimum corrosion resistance.

Table 22: Post fabrication cleanup methods.

Defect or contamination	Cleaning method	Comment
Oil, cutting fluid, organic compounds	Solvent Hot steam High pressure water	Remove organic compounds before pickling or passivating.
Iron and steel	Passivation	Passivation must be aggressive enough to remove.
	Pickling Electropolishing Grinding Brushing	Iron contamination. If pickling is planned, passivation is normally not necessary. Pickling may be necessary if large quantities of embedded iron are present.
Paint	Glass bead blasting or solvent	Use clean grit.
Annealing scale	Sand or glass bead blasting followed by pickling	Use clean grit.
Undercuts Rough grinding marks Scratches Weld spatter	Grinding	Use only clean, uncontaminated media. Do not use coarse grinding as a finishing technique; finish with fine grit to smooth the surface.
Weld discoloration	Grinding/polishing Pickling Blasting Brushing Electropolishing	A combination of grinding and pickling is the most effective method to restore corrosion resistance.

14.2.2 Glass bead blasting

Glass bead blasting is preferred to sand blasting because it leaves a relatively smooth surface. Initial cleanliness is important in this process. It also requires a final passivation step.

14.2.3 Grinding and polishing

Coarse grit grinding removes deep defects like weld undercut and deep scratches. The grinding wheel or belt must be new, or used only on stainless steel. Grinding should not heat the surface so hot that a yellow oxide layer forms. Follow coarse grinding with successively finer grit, finishing in the 180–220 grit range to produce a smooth surface having good corrosion resistance. Post-grind passivation provides even better corrosion resistance.

14.2.4 Stainless steel wire brush/stainless steel wool

A stainless steel wire brush or stainless steel wool can remove superficial heat tint, surface contamination, and dirt. They will not remove a chromium-depleted layer. Acid pickling is required to restore full corrosion resistance for a lightly oxidized surface cleaned by brushing or steel wool.

14.2.5 Degreasing

Organic contaminants like cutting oils, drawing lubricants, or crayon marks can be corrosive. They will prevent a stainless steel surface from being wetted during chemical cleaning with acids. These contaminants must be removed with a non-chlorinated solvent prior to customer use or before chemical cleaning treatment.

14.2.6 Acid pickling

Pickling creates the most corrosion-resistant surface of all cleaning methods. It uses strong acids that remove oxide scale and the underlying chromium-depleted layer. Since pickling dissolves the stainless steel surface, it must be carefully controlled. It produces clean surfaces with a dull grey, matte finish that passivates spontaneously upon air exposure.

There are many pickling acid solutions. They usually contain dilute nitric, hydrofluoric, and sulfuric acids, either individually or in various mixtures. The optimum solution chemistry, bath temperature and immersion time depends on the scale thickness, degree of pretreatment by blasting or other techniques, and stainless steel grade.

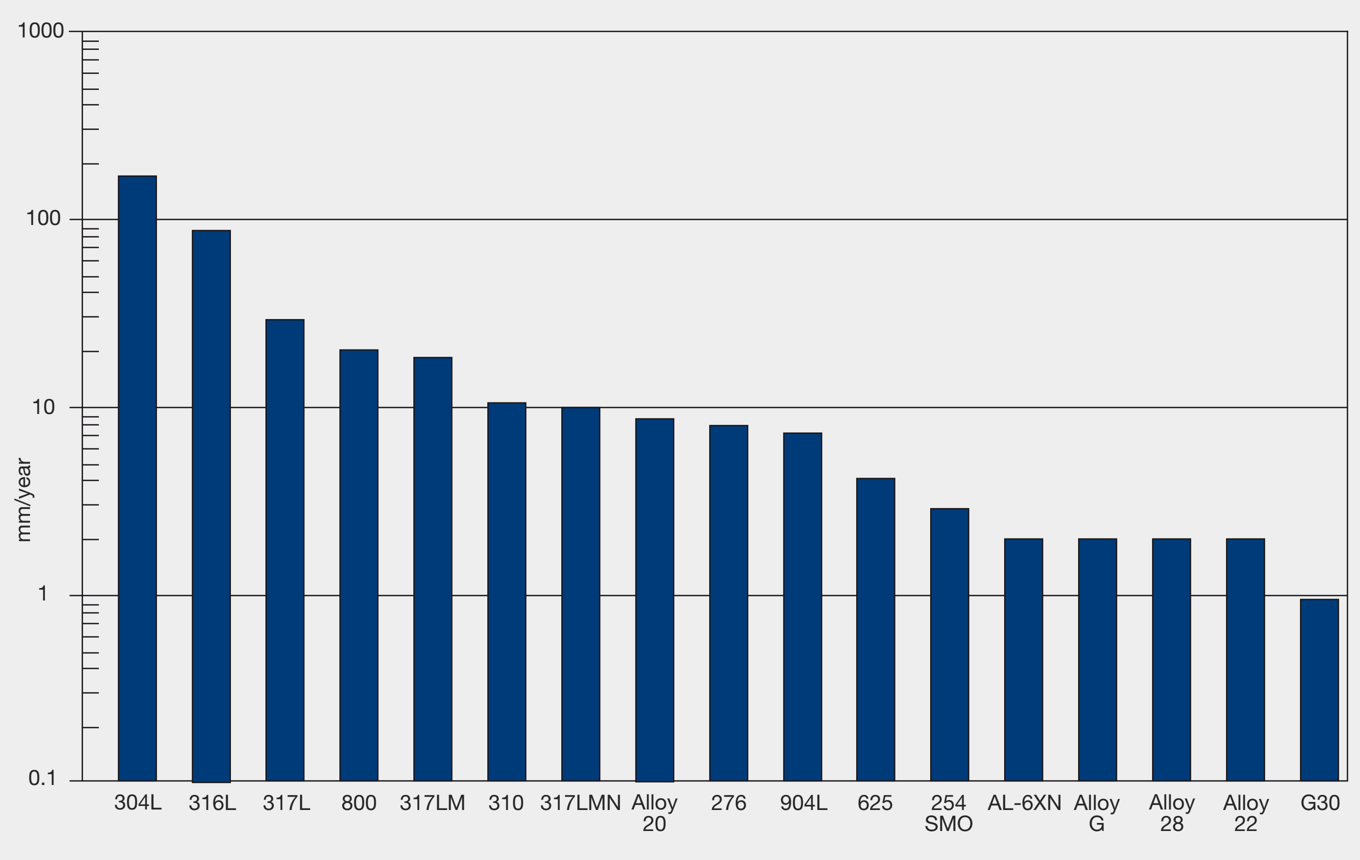


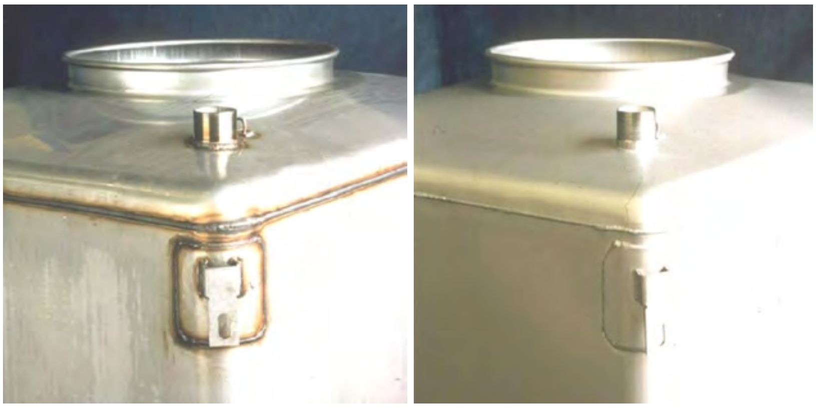
Figure 29: Metal removal rates of stainless steels and nickel base alloys in a simulated pickling solution, (10% HNO_3 + 3% HF) at 21°C (70°F). (16)

Pickling rates vary greatly depending upon the alloy. Conditions used on Types 304 and 316 stainless steels will not be adequate for more corrosion-resistant alloys like 6% Mo HPASS. **Figure 29** shows that pickling can take very long times with the more corrosion-resistant steels (note the logarithmic time scale). Grit blasting reduces pickling time in most instances, but salt bath descaling might be required in extreme cases.

Pickling can be performed by immersing the part in a bath or by spraying the pickling solution on the part while passing it through a spray box. Proprietary pickling products can also be applied locally in spray, gel, or paste forms. Pickling pastes can be used on an entire part or on a limited area – for example, only on the weld heat tint.

After pickling, the component must be thoroughly rinsed in a solution that neutralizes trapped and entrained pickling acid, and rinsed in clean, low-chloride water. After rinsing, it can be air-dried. Tests are available to determine if the surface is free of acid and chloride ion after final rinsing.

Spent pickling and rinse solutions should be disposed of according to applicable waste disposal requirements. It is important to read and comply with all safety instructions (e.g. use of safety goggles, gloves and other protective gear and others). Hydrofluoric acid presents special dangers because of its ability to penetrate the skin and remain in the body. It can cause severe long-term damage and even death. Proper safety and environmental precautions for pickling cannot be overemphasized.



Pickling effectively removes weld oxide in stainless steel fabrications.

Table 23: Summary of post-fabrication cleaning treatments.

	Chemical treatments				Mechanical treatments		
	Degrease	Pickle	Electropolish	Passivation	Blasting	Wire brush	Grinding/polishing
Grease and oil	E	N	N	N	N	N	N
Weld heat tint	N	E	E	N	E	E	E
Weld chromium-depleted zone	N	E	(E)[3]	N	N	N	(E)[3]
Weld slag	N	E	(E)	N	(E)[1]	(E)	E
Light surface iron contamination	N	E	E	E	(E)[2]	(E)[2]	(E)[2]
Embedded iron contamination	N	E	(E)	(E)	(E)[2]	N	(E)[2]
Weld defects, mechanical scratches	N	N	N	N	N	N	E

E = Effective (E) = May be effective N = Not effective
1 = Difficult in tight corners, etc.
2 = Iron contamination tends to smear
3 = Since this zone is not visible, it is not easy to know if the zone has been removed

14.2.7 Passivation

Passivation is used to remove iron contamination from the surface of stainless steel. Unlike pickling, it does not remove scale or the chromium-depleted layer. When complete it allows the surface to form a passive film spontaneously upon exposure to air. It is a very effective way to assure the complete cleaning of stainless that has not been pickled. It helps assure the complete removal of iron from blasted, ground, or wire brushed surfaces.

ASTM standards A 967 and A 380 provide information on passivation treatments for a variety of stainless steels. Some commercial passivation products are also available. Passivation treatments generally utilize an aqueous solution of 20 to 45 volume percent nitric acid. The parts are immersed for about 30 minutes at temperatures of 21°C to 32°C (70°F to 90°F), then rinsed in water. Surfaces must first be degreased to assure that the passivation agent can reach the stainless steel surface and remove iron.

14.2.8 Electropolishing

Electropolishing is an electrochemical process that removes embedded iron, welding heat tint, and nonmetallic inclusions. It smoothes the surface and leaves a shiny appearance. It is often a finishing operation in applications where extreme cleanliness is important. An electropolished surface is easier to inspect and more easily cleaned because contaminants do not readily attach to the smooth surface. These attributes make it a preferred finishing process for components used in pharmaceutical, semiconductor gas handling, and dairy applications.

14.3 Effect of cleaning method on corrosion resistance

The choice of a post-fabrication cleaning method can have a significant effect on the resulting corrosion resistance. Abrasive pad cleaning, stainless steel wire brushing, and rough grinding are least effective in restoring the corrosion resistance (17). A combination of mechanical cleaning followed by pickling provides maximum corrosion resistance. **Table 23** summarizes the effectiveness of several post-fabrication cleaning methods. **Figure 30** shows the relative effectiveness of several cleaning methods on CPT, when applied to weld, HAZ, and base metal surrounding welds.

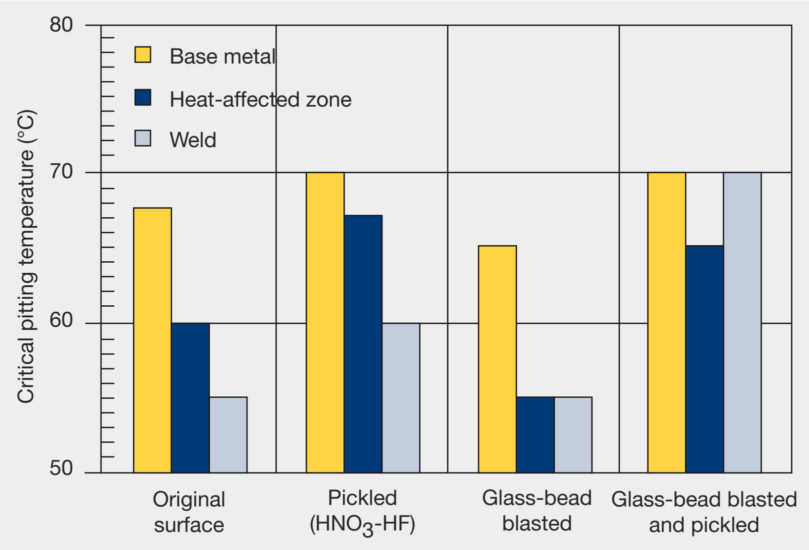


Figure 30: Effectiveness of various cleaning methods on pitting resistance of a 6% Mo stainless steel, as measured by CPT. (18)

15 Surface finishes

Surface finish is an important characteristic because it affects corrosion resistance, cleanability, and appearance. Smooth finishes generally give better corrosion resistance and cleanability but are typically more expensive to produce. The finish of a completed piece reflects its manufacturing history through the steel mill and the fabrication shop. The end user often specifies a surface finish that meets his design criteria, which can dictate specific surface finishing processes.

The HPASS are produced with the same surface finish characteristics as other stainless grades, but achieving a given finish is somewhat more expensive because of their greater resistance to acid pickling, grinding, and polishing.

15.1 Finish and performance

A rough finish normally has poorer corrosion resistance than a smooth finish because it contains microscopic crevices that can initiate corrosion or trap corrosion-causing contaminants. HPASS are inherently less susceptible to this problem, but they are usually used in more corrosive environments that might nullify this advantage. Users should specify a smooth finish for maximum corrosion resistance.

Many applications in the food, pharmaceutical, medical, gas handling and other industries require an easily cleaned finish that does not attract contaminants. Specific finishes are often specified for these applications. The HPASS offer an advantage in some critical applications requiring high smoothness and corrosion resistance. Examples are equipment to handle high-purity corrosive gases, and some medical applications requiring cleanliness and resistance to corrosion by body fluids.

Appearance is important in many decorative and architectural applications. Many finishes, bright and dull, rough and smooth, are available to meet the needs of designers. They are available in most grades including HPASS. It is advisable to use product samples in addition to standards or descriptive words to specify a surface finish.

Mills and fabricating shops use a variety of techniques to produce different surface finishes. Hot rolled, annealed, and pickled stainless steel plate has a rougher surface than cold finished sheet rolled with smooth polished rolls. Polishing modifies the mill finish with abrasives. It can be conducted by either the stainless steel producer or a polishing house. Specifications defining finish categories establish two broad classes: mill finishes and polished finishes. Many proprietary finishes such as embossed and colored finishes are also available. (19)

15.2 Steel mill supplied finishes

15.2.1 Plate

Plate is a flat-rolled or forged product at least 4.76 mm (3/16 inch) thick and wider than 254 mm (10 inches). It is produced as hot rolled or forged slabs or ingots that are then annealed and descaled. The standard plate finish is a dull, rough finish. For select applications, cold rolling or a temper pass after annealing and descaling provides a smother finish. Stainless steel plates can also have finishes similar to the polished sheet finishes given in **Table 26. Table 24** summarizes available plate finishes.

Table 24: Plate surface finishes. (20)

Condition and finish	Description and remarks
Hot rolled	Scale not removed; not heat-treated; plate not recommended for final use in this condition.
Hot or cold rolled and annealed	Scale not removed; use of plate in this condition generally confined to heat-resisting applications; scale impairs corrosion resistance.
Hot or cold rolled, annealed	Condition and finish commonly preferred for corrosion-resisting descaled. And most heat-resisting applications.
Hot or cold rolled, annealed, descaled and temper passed	Smoother finish for specialized applications.
Hot or cold rolled, annealed descaled and polished	Polished finishes similar to the polished finishes on sheet product.

15.2.2 Sheet and strip

Sheet and strip are thinner than plate. They are produced by various process sequences that include hot rolling with or without subsequent cold rolling, annealing, and final finishing and cleaning. They can be delivered in coil form or as individual pieces of cut sheet. There are specific process sequences designed to produce both standard finishes and special finishes. **Table 25** describes standard mill finishes. Finish designations used in Japan and Europe are cross-referenced in **Table 26**.

The most common sheet or strip finish is 2B. It is produced by hot rolling, followed by cold rolling, annealing, and pickling. The sheet is then brightened with a final pass through polished rolls to give a slightly reflective finish.

Table 25: Classification of sheet and strip standard mill finishes. (20)

	Description	Standard mill surface finishes	Corresponding finishing operation
Sheet	Coils and cut lengths under 4.76 mm (3/16 inch) thick and over 610 mm (24 inch) wide.	No. 1 – Rough, dull surface.	→ Hot rolling followed by annealing and descaling.
		No. 2D – Cold rolled finish with dull gray matte to reflective surface depending on the grade.	→ Cold rolling followed by annealing and descaling, may also receive final light roll through unpolished rolls.
		No. 2B – Bright cold rolled finish.	→ Same processing as 2D with a final, light pass through polished rolls.
		BA – Bright annealed finish – a bright, cold rolled finish retained by final annealing in a controlled atmosphere furnace.	→ Cold rolling followed by inert gas annealing, then cold rolled using highly polished rolls.
Strip	Cold finished coils and cut lengths between 0.127 and 4.76 mm (0.005 and 3/16 inch) thick and under 610 mm (24 inch) wide.	No. 1 – Approximates a No. 2D sheet finish. Dull gray matte to reflective surface depending on the grade.	→ Cold rolling followed by annealing and descaling, may also receive final, light roll through unpolished rolls.
		No. 2 – Approximates a No. 2B sheet finish. Bright, cold rolled finish.	→ Same process as No. 1 with the addition of a final, light cold roll pass through polished rolls.
		BA – Bright annealed finish – a bright, cold rolled finish retained by final annealing in a controlled atmosphere furnace.	→ Cold rolling followed by inert gas annealing, then cold rolled using highly polished rolls.
		Mill-buffed finish – highly reflective, cold rolled finish.	→ Applied to a No. 2 or BA strip using a continuous buffing pass.

Table 26: International cross-reference of surface finishes. (21)

Finish Type	USA (ASTM A 480)	Japan (JSSA)	European Standard EN 10088
Mill	No. 1	No. 1	1D
	No. 2D	2D	2D
	No. 2B	2B	2B
	Bright annealed (BA)	BA	2R
Polished	No. 3	No. 3	1G or 2G
	No. 4	No. 4	1J or 2J
	–	No. 240	1K or 2K
	No. 7	No. 7	1P or 2P
	No. 8	–	1P or 2P

Note: In the European Standard, 1 indicates a hot rolled product and 2 a cold rolled product.

Table 27: Polished sheet and strip surface finish descriptions. (20)

Condition and finish	Description and remarks
No. 3	An intermediate polished surface, obtained by finishing with a 100-grit abrasive. General used when a semi-finished, polished surface is required. A No. 3 finish usually receives additional polishing during fabrication.
No. 4	A polished surface, obtained by finishing with 120–150 grit abrasive. This is a general-purpose, bright finish with a visible grain that prevents mirror reflection.
No. 6	A dull satin finish with lower reflectivity than the No. 4 finish. It is produced by Tampico brushing the No. 4 finish in a medium of abrasive and oil. It is used for architectural and ornamental applications where high luster is undesirable and contrast with brighter finishes is desired.
No. 7	A highly reflective finish, produced by buffing finely ground surfaces, but not to the extent of completely removing the grit lines. It is used chiefly for architectural and ornamental applications.
No. 8	The most reflective polished surface, obtained by polishing with successively finer abrasives and buffing extensively until all grit lines from previous grinding operations are removed. It is used for applications like mirrors and reflectors.

15.3 Polished finishes

Polished finishes are obtained by a final polishing or buffing using abrasives. The final abrasive grit number and other variables of the polishing process determine the surface finish and appearance. **Table 27** summarizes common polished finishes.

Standard mill finishes have both characteristic roughness (a quantitative measurement) and characteristic appearance (a subjective description). One might expect surfaces to become smoother as reflectivity increases, but this is not always the case. When roughness is important to product performance, it should be specified instead of appearance. **Figure 31** summarizes typical surface roughness ranges for polished and mill finishes.

If a uniform surface finish is desired, and the production of the part involves steps that affect the surface finish like welding or bending, it is best to specify an initial polished finish. Welded areas can then be blended with the base material so that they become nearly invisible. The sheet can be fabricated with most of the surface finish protected by an adhesive sheet. The areas affected by fabrication can be blended with the initial finish by successive grinding and polishing during installation.

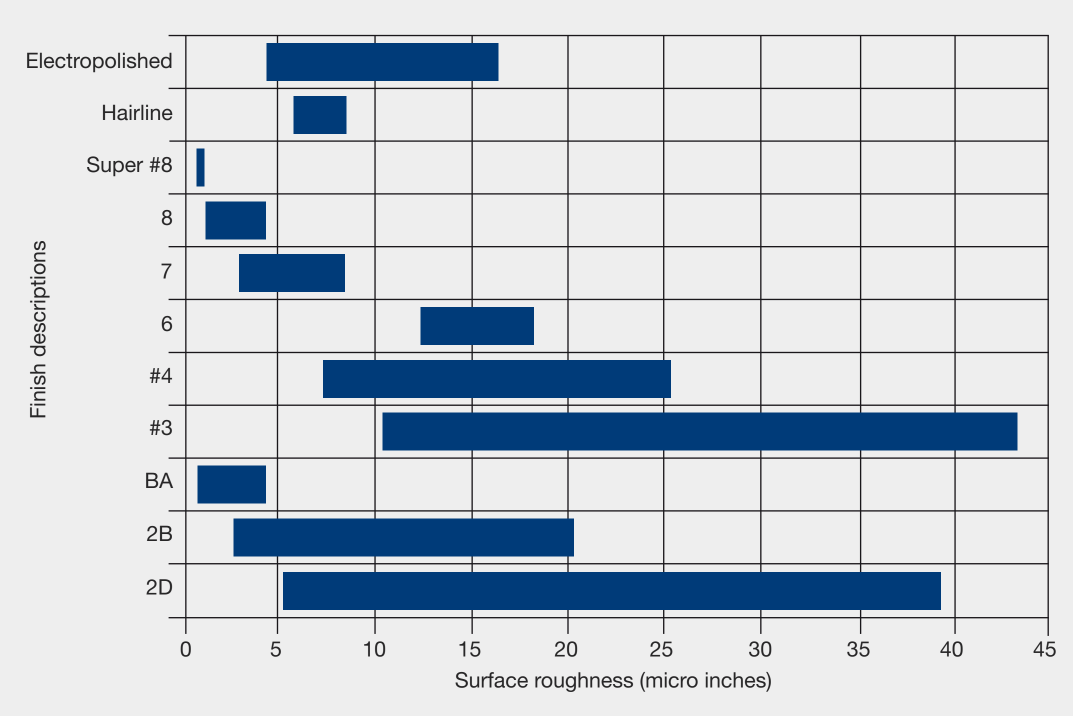


Figure 31: Typical surface roughness ranges for stainless steel sheet and strip from North American suppliers (21).

15.4 Surface finishing with abrasives

Stainless steels deliver many beautiful and functional finishes. It is often practical to produce these finishes by polishing or buffing in the final fabricating or manufacturing operation. Polishing can reduce initial roughness and remove defects and blemishes. Buffing does not remove metal and defects; it merely changes surface appearance. The process designer must consider the finishing options available and the surface condition of the starting material. This requires knowledge of abrasives and how they interact with the material surface.

Polishing starts with coarser abrasives to remove rough scratches and imperfections, and continues with progressively finer abrasives to create a smooth surface. The type of abrasive used determines cutting efficiency and cost. It is very important to work with the correct speed for each grit number and abrasive type. Excessive speed can produce heat buildup that may cause distortion and a yellowing of the finished surface due to oxidation. Abrasive producers publish tables and charts that can help the user to determine the correct abrasives and speeds for specific jobs. The following sections give an overview of the available abrasive types.

15.4.1 Coated abrasives

Coated abrasives employ abrasive particles embedded in a sheet of paper, cloth, or some other material. Common abrasives are oxides of aluminum (alumina) or zirconium (zirconia). Alumina is brown, whereas zirconia is blue or green.

Coated abrasive products come in various sizes, shapes, and grit numbers. The term “grit” expresses the roughness of the abrasive, and is related to the particle size of the abrasive used in the sheet. Larger particles remove material more aggressively than smaller particles. Grit numbers vary from no. 36 up to 400, with particle size decreasing as the grit number increases. When polishing to a progressively finer surface finish, one does not have to move progressively through every grit number. The rule of thumb is to move to a grit number no more than twice the previous number. For example, when working with grit 40, one should not go higher than grit 80 for the next pass.

Discs, belts, and wheels are available for the abrasive finishing of stainless steels. (Source: Magic Disc)

It is good practice to alternate the polishing direction when changing grit numbers, so that each pass is perpendicular to the previous one. This way, the abrasive will not cut deeper and deeper but the differences between the peaks and valleys on the surface become shallower. This technique also allows the operator to know when all of the grinding marks from the previous operation have been removed. If this is not accomplished, marks can remain after polishing and cause appearance problems.

15.4.2 Non-woven products

Non-woven products are made of nylon fibers soaked with an abrasive whose grit number determines the “roughness” of the product. Unlike coated abrasives, non-woven products do not remove much material from the work piece. They merely smooth the peaks and valleys in the surface. Consequently, their nomenclature is not like that of coated abrasives where grit numbers are used. Instead, the fineness is expressed as “coarse”, “medium”, “fine”, “very fine”, or “super fine”. These products are known under the trade name Scotch Brite™.

15.4.3 Buffing pastes

Buffing does not remove appreciable amounts of metal from the surface, but merely smoothes the surface and makes it lustrous and reflective. Buffing is done after the surface is already smooth from grinding and polishing or from an appropriate mill finish. It uses pastes or liquids containing submicron abrasive particles that are typically applied to cotton wheels. The process produces the so-called mirror finish.

Buffing adds luster to a stainless steel surface. (Source: Magic Disc)

15.5 Restoring and protecting the finish after fabrication

Most fabrication operations and even simple handling can scratch and mar the surface finish of stainless steel. Blending can remove these discontinuities and produce a uniform overall look. The blending of a weld or other surface defect is analogous to producing a polished surface. First, the weld bead and discoloration are removed. This can be done with a grinding disc, a flap disc, or an abrasive belt, according to the geometry or the work piece. Then, the relatively rough ground surface is ground with successively finer grit until it is smooth and matches the appearance of the surrounding area.

Stainless steel can be ordered with a protective adhesive film, which can be left on the surface during most fabrication operations. If localized heating is involved, the film can be removed from the heated area. Only when the piece is ready to install, or after it has been installed, should the whole film be removed. In this way, most of the surface finish is protected and the work piece requires less finishing.

Suggested additional reading

Specifications

Specifying Stainless Steel Surface Treatments, Nickel Institute Publication No. 10068

Metallurgy

High Performance Stainless Steels, Nickel Institute Publication No 11021, Nickel Institute, Toronto, Canada

Corrosion

Outokumpu Corrosion Handbook, Tenth Edition, Outokumpu Oyi, Espoo, Finland, 2009

Experience Survey – Stress Corrosion Cracking of Austenitic Stainless Steels in Water, MTI Publication No. 27, Materials Technology Institute of the Chemical Industry

Fabrication

Fabrication of Chromium-Nickel Stainless Steels (300 series), Nickel Institute Publication No. 428, Nickel Institute, Toronto, Canada

Fabrication and Post-Fabrication Cleanup of Stainless Steels, Nickel Institute Publication No. 10004, Nickel Institute, Toronto, Canada

Practical guide to Using 6Mo Austenitic Stainless Steel, Nickel Institute Publication No. 10032, Nickel Institute, Toronto, Canada

Fabrication Options for Nickel Containing Alloys in FGD Service: Guidelines for Users, Nickel Institute Publication No 14029, Nickel Institute, Toronto, Canada

Practical Guidelines for the Fabrication of Duplex Stainless Steels, Second Edition, International Molybdenum Association Publication, London, UK, 2009

Pickling and Passivating Stainless Steel (Materials and Applications Series, Volume 4), Euro Inox, Brussels, Belgium, 2004

Stainless Steel in Contact with Other Metallic Materials, (Materials and Application Series, Volume 10), Euro Inox, Brussels, Belgium, 2009

Electropolishing Stainless Steels, (Materials and Application Series, Volume 11), Euro Inox, Brussels, Belgium, 2010

Welding

Welding of Stainless Steels, Materials and Applications Series, Volume 3, Euro Inox, Brussels, Belgium, 2001

Handbook for the Welding of Stainless Steels, Information 9815, Avesta Welding, Avesta, Sweden

How to Weld 904L, Information 9724:2, Avesta Welding, Avesta, Sweden

How to Weld 254 SMO Stainless Steel, ASI-2 9/99, Outokumpu Stainless Inc., Schaumburg, Illinois, USA

Weld Fabrication of a 6% Molybdenum Alloy to Avoid Corrosion in Bleach Plant Service, Nickel Institute Publication No. 14020, Nickel Institute, Toronto, Canada

Welding Recommendations for Welding Metallic Materials, Part 3, Arc Welding of Stainless Steel, (EN 1011-3)

Guidelines for Welding Dissimilar Metals, Nickel Institute Reprint Series No 14018, Nickel Institute, Toronto, Canada.

Guidelines on the Welded Fabrication of Stainless Steels (Materials and Application Series, Volume 9), Euro Inox, Brussels, Belgium, 2007

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Producer registered trademarks and trade names

- 20Cb-3® Stainless, 20Mo-6® Stainless: CRS Holdings Inc., a subsidiary of Carpenter Technology Corporation
- INCOLOY® alloy 825, INCOLOY® alloy 25-6MO, INCOLOY® alloy 27-7MO: Special Metals Corporation
- NAS 155N, NAS 254N, NAS 354N: Nippon Yakin Kogyo Co.
- Sandvik® Sanicro® 28: Sandvik AB
- NIROSTA® 4565 S: ThyssenKrupp Nirosta
- Cronifer® 1925 hMo, Nicrofer® 3127 hMo: ThyssenKrupp VDM
- URANUS® 66 (UR 66): ArcelorMittal Industeel
- 254 SMO®, 654 SMO®: Outokumpu Stainless
- AL-6XN® Alloy: ATI Properties, Inc.

Appendix: List of ASTM and EN specifications for stainless steel products

ASTM specifications

Flat-rolled stainless steel products	
A 480/A 480M*	General requirements for flat-rolled stainless and heat-resisting steel plate, sheet, and strip
A 240/A 240M*	Chromium and chromium-nickel stainless steel plate, sheet, and strip for pressure vessels and for general applications
A 167	Stainless and heat-resisting chromium-nickel steel plate, sheet, and strip
A 666	Annealed or cold-worked austenitic stainless steel sheet, strip, plate, and flat bar
Long-rolled or forged stainless steel products	
A 484/A 484M*	General requirements for stainless steel bars, billets, and forgings
A 555/A 555M	General requirements for stainless steel wire and wire rods
A 276	Stainless steel bars and shapes
A 479/A 479M*	Stainless steel bars and shapes for use in boilers and other pressure vessels
A 564/A 564M	Hot-rolled and cold-finished age-hardening stainless steel bars and shapes
A314	Stainless steel billets and bars for forging
A473	Stainless steel forgings
A 313/A 313M	Stainless steel spring wire
A 368	Stainless and heat-resisting steel wire strand
A 492	Stainless steel wire rope
A 580/A 580M	Stainless and heat-resisting steel wire
Tubular stainless steel products	
A 999/A 999M*	General requirements for alloy and stainless steel pipe
A 1016/A 1016M*	General requirements for ferritic alloy steel, austenitic alloy steel, and stainless steel tubes
A 312/A 312M*	Seamless and welded austenitic stainless steel pipe
A 358/A 358M*	Electric-fusion-welded austenitic chromium-nickel alloy steel pipe for high-temperature service
A 409/A 409M	Welded large diameter austenitic steel pipe for corrosive or high-temperature service
A 778	Welded, unannealed austenitic stainless steel tubular products
A 813/A 813M	Single- or double-welded austenitic stainless steel pipe
A 814/A 814M	Cold-worked welded austenitic stainless steel pipe
A 249/A 249M*	Welded austenitic steel boiler, superheater, heat-exchanger, and condenser tubes
A 269	Seamless and welded austenitic stainless steel for general service
A 270	Seamless and welded austenitic stainless steel sanitary tubing
A 688/A 688M	Welded austenitic stainless steel feedwater heater tubes
A 851	High-frequency induction welded, unannealed austenitic steel condenser tubes

Note: For each category of stainless steel products, the general requirements specification is shown first in the Table, followed by specifications for particular products. The general requirements are referenced by each of the individual product specifications so it is not necessary to specify anything other than the product specification. For example ordering A 240 sheet will automatically apply all requirements of A 480.

* A specification having a corresponding “SA-“ specification of the same number in section II of the ASME Boiler and Pressure Vessel Code.

ASTM specifications (continued)

Fittings, bolting, and forgings	
A 960	Common requirements for wrought steel pipe fittings
A 962	Common requirements for steel fasteners or fastener materials, or both, intended for use at any temperature from cryogenic to the creep range
A 182/A 182M	Forged or rolled alloy-steel pipe flanges, forged fittings, and valves and parts for high-temperature service
A 193/A 193M	Alloy-steel and stainless steel bolting materials for high-temperature service
A 194/A 194M	Carbon, and alloy steel nuts for bolts for high pressure and high-temperature service
A 403/A 403M	Wrought austenitic stainless steel fittings
A 744/A 744M	As-welded wrought austenitic stainless steel fittings for general corrosive service at low and moderate temperatures

EN specifications

EN 1600:1997	Welding consumables. Covered electrodes for manual metal arc welding of stainless and heat resisting steels.
EN 10028-7:2000	Specification for flat products made of steels for pressure purposes. Stainless steels
EN 10088-1:2005	List of stainless steels
EN 10088-2:2005	Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes. Stainless steels.
EN 10088-3:2005	Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes. Stainless steels.
EN 10151:2002	Stainless steel strip for springs. Technical delivery conditions
EN 10213:2007/AC:2008	Steel castings for pressure purposes.
EN 10222-5:1999/AC:2000	Steel forgings for pressure purposes. Martensitic, austenitic and austenitic-ferritic stainless steels
EN 10250-4:1999	Open steel die forgings for general engineering purposes. Stainless steels
EN ISO 9445-1:2010	Cold-rolled stainless steel narrow strip and cut lengths. Tolerances on dimensions and shape
EN ISO 9445-2:2010	Cold-rolled stainless and heat resisting steel wide strip and plate/sheet. Tolerances on dimensions and shape
EN 10269:1999/A1:2006/AC:2008	Steels and nickel alloys for fasteners with specified elevated and/or low temperature properties
EN 10270-3:2001	Steel wire for mechanical springs. Stainless spring steel wire
EN 10272:2007	Stainless steel bars for pressure purposes
EN 10283:2010	Corrosion resistant steel castings
EN 10312:2002/A1:2005	Welded stainless steel tubes for the conveyance of aqueous liquids including water for human consumption. Technical delivery conditions
EN ISO 14343:2009	Welding consumables. Wire electrodes, wires and rods for arc welding of stainless and heat-resisting steels. Classification
EN 10217-7:2005	Welded steel tubes for pressure purposes. Technical delivery conditions. Stainless steel tubes

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