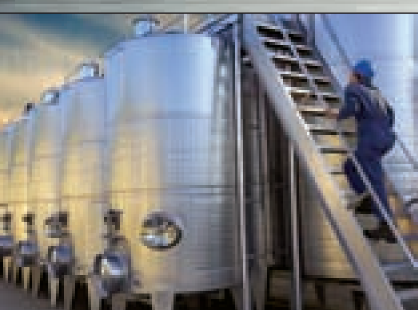
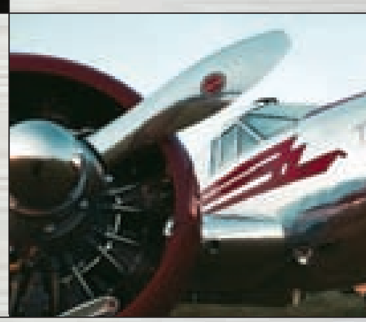
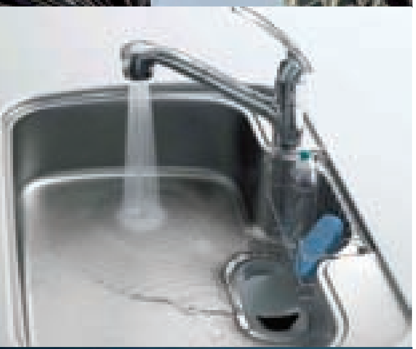
The Nickel Advantage
NICKEL IN STAINLESS STEEL

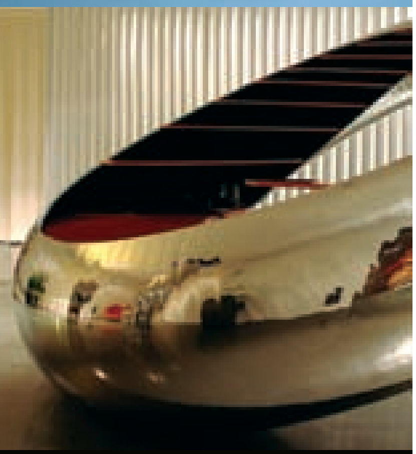




Nickel INSTITUTE

knowledge for a brighter future




With nickel you get...

…a wide range of **versatile stainless steels** in different families: the austenitic 300 and 200 series, duplex, PH grades

…stainless steels with proven **reliability** in tens of thousands of applications

…stainless steels combining **resistance to corrosion**, a wide range of mechanical properties from cryogenic to elevated temperatures and ease of fabrication

…stainless steels for **hygienic** equipment in the food, beverage and pharmaceutical industry, which can be cleaned with aggressive chemicals and ensure product purity

…stainless steels of the 18/8, 18/10 or 18/12 type associated with **high quality** in consumer goods

…stainless steels that meet the need for extreme **formability**

…stainless steels with very good **weldability** over a wide range of thicknesses

…stainless steels that are widely **available** in numerous product forms and sizes,

…stainless steels that come in a wide variety of surface finishes and even colours for **impressive** results

…stainless steels that can have **low magnetic permeability** necessary for electronic applications and even medical implants

…stainless steels that provide **long-lasting value** and at end of use they have a **high intrinsic value** as scrap

In this publication, you will find out how nickel contributes to these properties

…a wide range of other nickel alloys with **valuable engineering properties and uses**:

- nickel alloys for resistance to extreme corrosion and high temperature requirements
- copper-nickel alloys for anti-fouling resistance
- nickel-titanium alloys for shape memory
- iron-nickel alloys for low thermal expansion
- nickel plating
- nickel catalysts

Together, the above attributes mean that with nickel you get a highly versatile material

Photography from top to bottom: *Petronas Towers sourced by B-M, Cleanup Corporation, Johnsen Ultravac, Ron Arad Associates, Carl Pott*

"The Chrysler Building in New York City testifies to the long life that can be expected from nickel-containing stainless steels."

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The Other Nickel Advantage

"Nickel is produced by an industry that embraces its responsibilities…"

The Nickel Advantage isn't limited to the attributes it brings to different materials and processes.

There are the environmental and socio-economic dimensions that go beyond the technical reasons why you are using or considering the use of a nickel or nickel-containing material.

Nickel is an investment that makes possible many new and emerging products and processes important to **increased environmental efficiency**. Nickel makes many other existing products and processes **more energy efficient**, **durable and tough**.

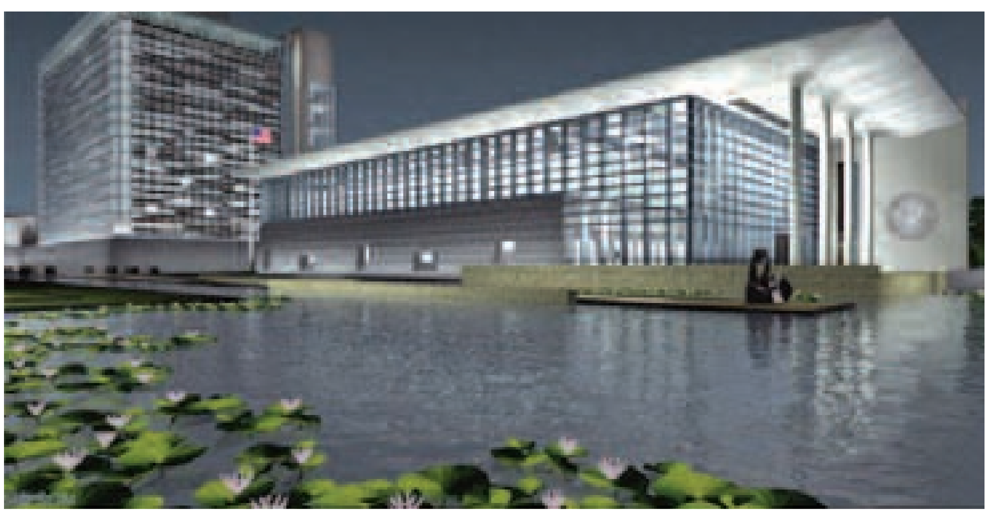
The value of nickel ensures that it is **used efficiently and highly recycled**.

The attributes of nickel-containing materials are wholly supportive of **eco-efficiency**.

The production, use and recycling of nickel is a **value-added economic activity** that supports communities and governments.

Nickel is produced by an industry that **embraces its responsibilities** to workers, communities, shareholders and the environment.

Nickel makes **significant contributions to sustainability** and is responsibly managed through its life cycle by the nickel value chain, starting with the primary nickel industry itself.



U.S. Embassy, Beijing

Photo courtesy of: Nickel Institute

Introduction

Overview of nickel-containing stainless steels

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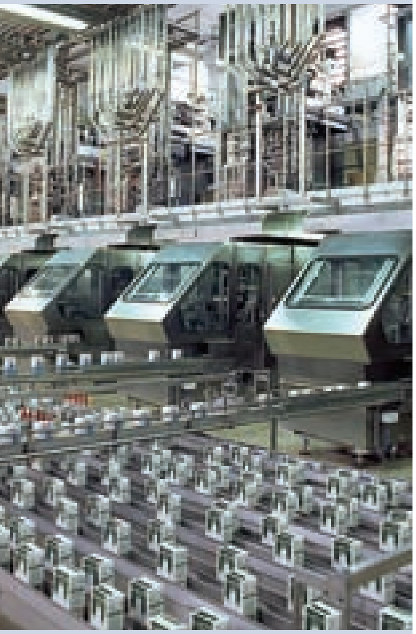
Overview of nickel-containing stainless steels

Stainless steel is not a single material: there are five families, each of which contains many grades. Nickel is an important alloying addition in nearly two-thirds of the stainless steel produced today.

Chromium is the key alloying element that makes stainless steels "stainless." More than 10.5% needs to be added to steel to allow the protective oxide film to form which provides corrosion resistance and the bright, silvery appearance. In general, the more chromium that is added, the greater the corrosion resistance. That discovery was made about a century ago, yet even some of the early stainless steels contained nickel. Nickel-containing grades have been in use ever since. Today about two-thirds of the tonnage of stainless steel produced each year contains nickel, even though nickel may be seen as a relatively high cost alloying addition. What is the role of nickel and why is it used so extensively?



304 used extensively in a milk packaging plant.

Photo courtesy of: Tetra Pak

The primary function of the nickel is to stabilize the austenitic structure of the steel at room temperature and below. This austenitic (i.e., face-centred cubic crystal) structure is particularly tough and ductile. Those and other properties are responsible for the versatility of these grades of stainless steel. Aluminum, copper, and nickel itself are good examples of metals with the austenitic structure.

The minimum amount of nickel that can stabilize the austenitic structure at room temperature is around 8%, and so that is the percentage present in the most widely used grade of stainless steel, namely Type 304*. Type 304 contains 18% chromium and 8% nickel (often referred to as 18/8). That composition was one of the first to be developed in the history of stainless steel, in the early twentieth century. It was used for chemical plants and to clad the iconic Chrysler Building in New York City, which was completed in 1929.

Manganese was first used as an addition to stainless steel in the 1930s. The 200-series of low-nickel, austenitic grades was developed further, in the 1950s, when nickel was scarce. More recent improvements in melting practices have allowed the controlled addition of increased amounts of nitrogen, a potent austenite former. This might suggest that all the nickel can be replaced with the structure remaining austenitic. However, it is not as simple as that, and all the high-manganese austenitic grades commercially available today still contain some deliberate additions of nickel. Many also have a somewhat reduced chromium content, so as to maintain the austenitic structure. As we will see below, this side effect reduces the corrosion resistance of these alloys compared with the standard 300-series nickel grades.

"The primary function of the nickel is to stabilize the austenitic structure."

As the total content of austenite formers is reduced, the structure of the stainless steel changes from 100% austenite to a mixture of austenite and ferrite (body-centred cubic). These are the duplex stainless steels. The nickel continues to stabilize the structure of the austenite phase. All the commercially important duplex grades, even the "lean duplexes", contain about 1% or more nickel as a deliberate addition. Most duplex stainless steels have a higher chromium content than the standard austenitic grades: the higher the mean chromium level, the higher the minimum nickel content must be. This is similar to the case for the 200-series noted above.

*Compositions and approximate equivalents of grades are listed in the Appendix (page 50)

The two-phase structure of the duplex grades makes them inherently stronger than common austenitic grades. Their slightly higher chromium content also gives them slightly higher corrosion resistance compared to standard grades. While there are other characteristics to take into consideration, the duplex grades have found some valuable niche applications.

Reduction of the nickel content further – even to zero – gives grades with no austenite at all. These have a completely ferritic structure. Iron and mild steels also have a ferritic structure at ambient temperatures.

Not all the ferritic grades are completely nickel-free. Nickel is known to lower the ductile-to-brittle transition temperature (DBTT), that is, the temperature below which the alloy becomes brittle. The DBTT is also a function of other factors such as grain size and other alloying additions. Nevertheless, some of the highly alloyed super-ferritic grades contain an intentional addition of nickel to improve the DBTT, especially of welds.

Unlike the austenitic grades, the martensitic grades are hardenable by heat treatment. Some do contain nickel though, which not only improves toughness but also enables the steel to have a higher chromium content, and this in turn gives increased corrosion resistance. The hardening heat treatment involves heating to a certain temperature and then quenching the material, followed by a tempering operation.

Finally, the precipitation-hardening (PH) grades can also develop high strength by heat treatment. There are various families of PH grades, but all are nickel-containing. The heat treatment does not involve a quenching step, unlike the case with the martensitic family.

Formability The characteristics of the austenitic structure give these stainless steels good tensile ductility and good formability, as reflected in comparative forming limit diagrams. The common 18% chromium/8% nickel grade shows particularly good stretch forming characteristics but has a somewhat lower limiting drawing ratio than some ferritic grades. Slightly higher nickel contents increase the stability of the austenite further and reduce the work hardening tendency, thereby increasing suitability to deep drawing. Unlike traditional low-nickel, high-manganese grades, these are not prone to delayed cold cracking. This good formability has led to the widespread use of 300-series austenitic grades for items that demand good formability, such as kitchen sinks, pots and pans.

Weldability Many pieces of equipment have to be fabricated by welding. In general, the nickel austenitic grades have better weldability than other grades, and Types 304 and 316 are the most widely fabricated stainless steels in the world. They are not prone to embrittlement as a result of high-temperature grain growth and the welds have good bend and impact properties. They are also more weldable in thick sections of, say, above 2 mm.

The duplex grades are far more weldable than the ferritic grades for equivalent alloy content, but even the standard and more highly alloyed super-duplex alloys require more attention to the details of the welding procedure than the equivalent austenitic grades. The 200-series alloys have welding characteristics similar to the 300 series.

Toughness Toughness – the ability of a material to absorb energy without breaking – is essential in many engineering applications. Most stainless steels have good toughness at room temperature, but, with decreasing temperature, the ferritic structure becomes progressively more brittle so that ferritic stainless steels are not suitable for use at cryogenic temperatures. In contrast, the common austenitic stainless steels retain good toughness

Innovative use of stainless steel.

Photos courtesy of:
Top: *Experience Music Project, Seattle*
Bottom: *Eero Hyrkäs*

"Types 304 and 316 are the most widely fabricated stainless steels in the world."

Photo courtesy of: Nickel Instiute/ Hyatt Chicago

even to liquid helium temperatures; therefore, grades such as Type 304 are widely used for cryogenic applications.

High-Temperature Properties The addition of nickel gives the austenitic grades significantly better high-temperature strength than other grades (particularly the ability to resist creep). These grades are also much less prone to the formation of deleterious phases as a result of exposure at intermediate and high temperatures. Nickel also promotes the stability of the protective oxide film and reduces spalling during thermal cycling. Consequently, the austenitic grades are used for high-temperature applications and where fire resistance is needed.

It is worth noting that there is a continuum in composition between the austenitic stainless steels and the nickel-based superalloys that are used for the most demanding high-temperature applications such as gas turbines.

Corrosion Resistance As noted, it is the formation of the chromium-rich oxide layer that accounts chiefly for the corrosion resistance of stainless steels. However, this layer is susceptible to damage, particularly in the presence of chlorides, and such damage can lead to the onset of localized corrosion such as pitting and crevice corrosion. Both molybdenum and nitrogen increase resistance to pit initiation in the presence of chlorides. Nickel does not influence the initiation phase but is important in reducing the rate at which both pitting and crevice corrosion propagate (see Figure 9). This is critical in determining how serious corrosion will be.

Nickel also influences the resistance of stainless steels to another form of localized corrosion, namely chloride stress corrosion cracking. In such cases, however, there is a minimum in resistance at nickel contents of around 8%. Stress corrosion cracking resistance increases markedly at nickel levels that are both lower and higher than this.

In general, increasing the nickel content of stainless steels, including ferritic grades, also increases their resistance to reducing acids such as sulphuric acid. Other elements such as molybdenum and particularly copper also have a strong influence in this regard. However, there are potential drawbacks to using nickel in this way in the ferritic grades. These drawbacks are related to stress corrosion cracking resistance and the formation of intermetallic phases.

Lustre and Finish At first sight, all stainless steel grades look similar. However, side-by-side comparisons of identically polished surface finishes do show differences in colour and lustre. Appearance and aesthetic qualities will always be a matter of taste; still, the 200-series grades generally appear darker and the ferritic grades, cooler-looking, than the nickel austenitic grades. In some architectural applications, a greyer colour might be preferred, but consumers generally prefer a brighter, whiter metal, as witnessed by the popularity of the 300-series. The 200- and 300-series stainless steels are also more scratch–resistant, owing to their inherent work hardening properties.

Various surface finishes are available on all the stainless grades, from mill finishes to mechanically polished (rough to mirror-finished), brushed, bead-blasted, and patterned (and many more). All of which indicates the versatility of the nickel stainless steels in achieving a wide range of aesthetic appearances. One caution, however, is that a rougher finish will generally have poorer corrosion resistance, especially in outdoor architectural applications. Marine environments and the presence of de-icing salts require more corrosion-resistant materials, such as Type 316L.

Sustainability Taking into account the Brundtland Report's definition of sustainable development – "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" – it is clear that stainless steels in general, and the nickel-containing ones in particular, have a major role to play in the areas of environmental protection, economic growth, and social equality. Examples are given below.

To appreciate the contribution a material makes toward sustainability, it is important to look at that material's whole life cycle, from extraction to recycling or disposal at the end of the product's life.

Most nickel-containing materials are fully recyclable at the end of a product's useful life. Their high value encourages this. Recycling lessens the environmental impact by reducing both the need for virgin raw materials and the use of energy. For example, the amount of stainless steel scrap being used today reduces the energy required for the manufacture of stainless steel to about 33% less than if 100% virgin materials were to be used (Yale[1]). Nearly half that reduction comes from end-of-life scrap (using IISF data[2]). Only lack of availability of more scrap, owing to the long useful life and considerable growth in the use of stainless steel products, prevents a greater reduction.

The key contributions of nickel-containing stainless steels are that, when properly applied, they maintain and improve the quality of life of citizens and allow businesses and other institutions to deliver sustainable solutions. These sustainable solutions depend on the attributes and services provided by nickel: corrosion protection, durability, cleanability, temperature resistance and recyclability.

Application Case History: *Monumental Strength*

The Air Force Memorial recently unveiled in Washington, D.C. ranks as one of the world's largest structural applications of stainless steel, along with the Dublin Spire in Ireland and America's largest memorial, the Gateway Arch.

Consisting of three stainless steel spires reaching 64 metres into the air, the new memorial honours the millions of men and women who have contributed to the United States Air Force and its predecessors over the years, including 54,000 who died in combat.

Each spire has a 19-millimetre-thick skin of low sulphur (0.005% max) S31600 stainless steel, containing 11% nickel covering a core of reinforced concrete.

Engineers involved in the design chose S31600 to prevent corrosion and allow the structure's appearance to be retained over decades without the need for manual cleaning. Though Washington is not coastal, nor particularly polluted, the memorial is surrounded by three highways that use de-icing salt that could threaten a lesser material.

S31600 also provides structural integrity to help withstand the tendency for the spires, which are curved, to sway in windy conditions.

Photo: Catherine Houska for Nickel Institute, U.S. Air Force Memorial in Washington, D.C.

"Most nickel-containing materials are fully recyclable."

[1] Johnson, J. et al, The energy benefit of stainless steel recycling, Energy Policy. Vol. 36, Issue 1, Jan. 2008, p181ff.
[2] www.worldstainless.org

The most visible examples of the durability of stainless steels are in buildings. The restorations of St Paul's Cathedral and the Savoy Hotel canopy in London, U.K. (1925 and 1929, respectively), the Chrysler Building in New York City (1930), the Progreso Pier in Mexico's Yucatan state (circa 1940), the Thyssen Building in Düsseldorf, Germany (1960), and the Gateway Arch in St Louis, U.S.A. (1965) all testify to the long life that can be expected from nickel-containing stainless steel.

Ease of production This is not something immediately apparent to the final user. However, the long experience of manufacturing the common austenitic grades, their widespread use, their versatility, and the scale of their production mean that they have become commodity grades of a high quality. These grades are economically available in all forms and in all parts of the world.

Stainless steel in use The picture that emerges is of the common nickel-containing austenitic grades being good all-round performers. They are widely available, well-understood, versatile and easy to use. They also demonstrate good performance and are extensively recycled. All of which means they often offer the most practical, lowest-risk solution.

"They are widely available. well-understood, versatile and easy to use… the most practical, lowest risk solution."

Because they have been in use for so long, the 300 series grades are often already approved for use in situations that involve contact with food or drinking water. In addition, all product forms needed are usually readily available.

300 series stainless steels are used extensively for water and waste water applications
Photo courtesy of Robert Lowell for Nickel Institute

Chapter 1
Physical and Mechanical Properties

Chapter 1

Physical and Mechanical Properties

Physical properties The physical properties of the stainless steels can be categorized broadly in terms of the families to which they belong, as shown in Table 1.

“...higher mechanical strength... may more than offset the lower thermal conductivity.”

Table 1
Typical physical properties for the families of stainless steel as illustrated by the sample grades

Family	Grade	Density,		Thermal conductivity, 100 °C,		Electrical resistivity	Specific heat		Thermal expansion 0-100 °C,		Magnetic permeability
		g/cm³	lb/in³	W/m.K	Btu/ft.hr. °F	nΩ.m	J/kg.K	Btu/lb. °F	10^{-6}/°C	10^{-6}/°F	
Ferritic	430	7.8	0.28	26.1	15.1	600	460	0.11	10.4	5.8	600-1,000
Martensitic	410	7.8	0.28	24.9	14.4	570	460	0.11	9.9	5.5	700-1,000
Austenitic	304	8.0	0.29	16.2	9.4	720	500	0.12	17.2	9.6	1.02
Austenitic (high Mn)	201	7.8	0.28	16.2	9.4	690	500	0.12	15.7	8.7	1.02
Superaustenitic	S31254	8.0	0.29	14	8.1	850	500	0.12	16.5	9.2	c.1
Duplex	2205	7.8	0.28	16	9.3	800	500	0.12	13.0	7.2	>>1
PH	17-4PH	7.8	0.28	18.3	10.6	800	460	0.11	10.8	6.0	95

Reference: ASM Metals Handbook

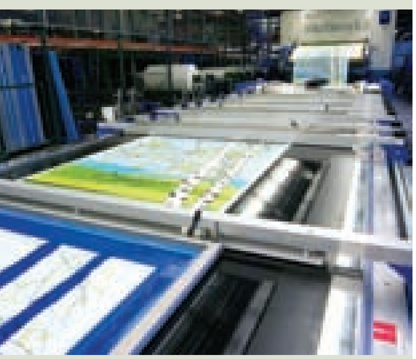


Photo countesy of: Nickel Institute

There is relatively little difference in density or specific heat between the families. However, the differences in thermal conductivity and expansion are significant and of practical importance (see Table 2). The lower thermal conductivity of the austenitic grades may be advantageous in reducing the speed with which fire spreads through a building. Lower thermal conductivity might be a disadvantage where high heat transfer is desirable, which is why stainless steel pans often have a copper or aluminum base. However, effects at the surface may have a far greater impact on overall heat transfer than conduction through the wall, see the heat exchanger example in the table. If higher mechanical strength can allow thinner-walled components to be used, this may more than offset the lower thermal conductivity.

Table 2
Effect of Metal Conductivity on “U” Values
Heating Water with Saturated Steam

	Film Coefficients				Thermal Conductivity of Metal		“U” Value	
	h_0		h_1					
Material	W/m²•K	Btu/hr/ft²/°F	W/m²•K	Btu/hr/ft²/°F	W/m•K	Btu/hr/ft²/°F/in	W/m²•K	Btu/hr/ft²/°F
Copper	1704	300	5678	1000	387	2680	1300	229
Aluminum	1704	300	5678	1000	226	1570	1295	228
Carbon Steel	1704	300	5678	1000	66	460	1266	223
Stainless Steel	1704	300	5678	1000	15	105	1124	198

where h_0 = outside fluid film heat-transfer coefficient
h_1 = inside fluid film heat-transfer coefficient
Stainless steel is 300 Series Type

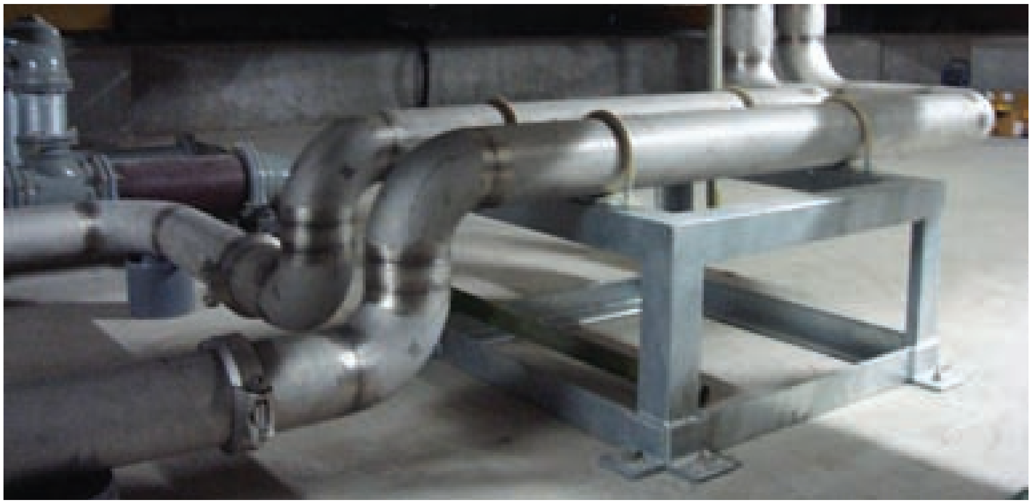
$$\text{“U”} = \frac{1}{\frac{1}{h_o} + \frac{\text{thickness of metal wall}}{\text{thermal conductivity}} + \frac{1}{h_1}}$$

Reference: NI publication 9014

The thermal expansion coefficients of austenitic stainless steels are 60-70% higher than those of the other grades. However, this can be allowed for at the design stage in cases where thermal cycling is expected – for example, with roofing, cryogenic equipment, and equipment intended to operate at high temperatures. Distortion during welding is a particular problem and is discussed more fully in the section on fabrication. The general approach is to minimize the heat input.

It is worth noting that the thermal expansion coefficient of austenitic stainless steel is still less than that of other common metals such as aluminum and copper.

Some austenitic grades can develop small amounts for ferromagnetism as a result of martensite formed by cold work, see Table 3. Increasing nickel content reduces the effect, so that whilst the effect can be quite pronounced in Type 301, though 310 remains non-magnetic after extensive cold work.



In Japan, stainless steels are used extensively for building water service.

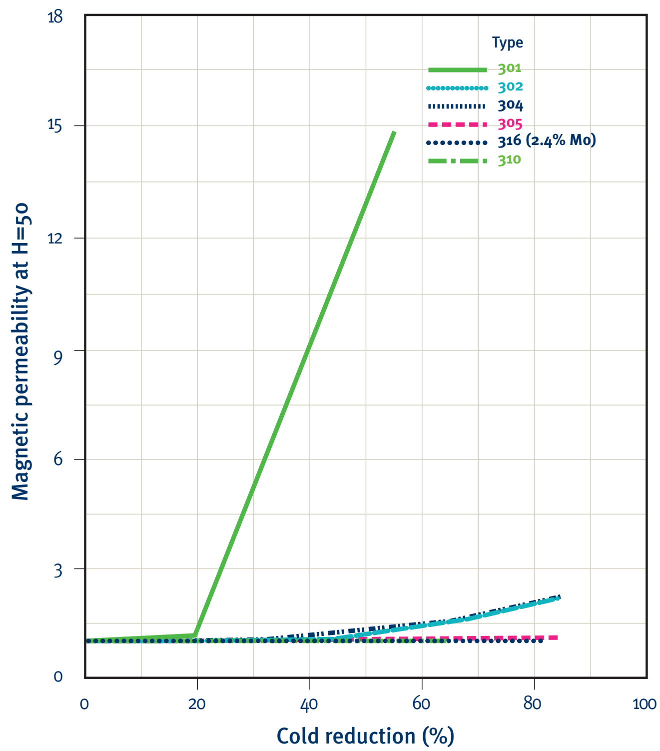
Photo courtesy of: Japanese Stainless Steel Association

"Austenitic grades are generally non-ferromagnetic at room temperature… used in magnetic resonance imaging body scanners."

The austenitic grades are generally non-ferromagnetic at room temperature, unlike other grades. This property enables the grades to be used in cases where ferromagnetic materials must be avoided, such as near the powerful magnets used in magnetic resonance imaging body scanners or concrete reinforcing bar at docks where naval ships are demagnetized. Some austenitic grades can develop small amounts for ferromagnetism as a result of martensite formed by cold work, see Figure 1. Increasing nickel content reduces the effect, so that whilst the effect can be quite pronounced in Type 301, Type 310 remains non-magnetic after extensive cold work.

"Lack of ferro-magnetism in austenitic grades make it easy to separate them... for recycling."

Figure 1:
Effect of cold work on the magnetic permeability of Chromium-nickel stainless steels



Austenitic stainless steels are one of the world's most recycled materials

Photo courtesy of: Tim Pelling for the Nickel Institute

The lack of ferromagnetism in the austenitic grades makes it easy to separate them from other stainless steel grades and from carbon steel when scrap is being sorted for recycling.

Room-temperature mechanical properties

Figure 2:
Stress-strain cuves for 4 different types of stainless steel

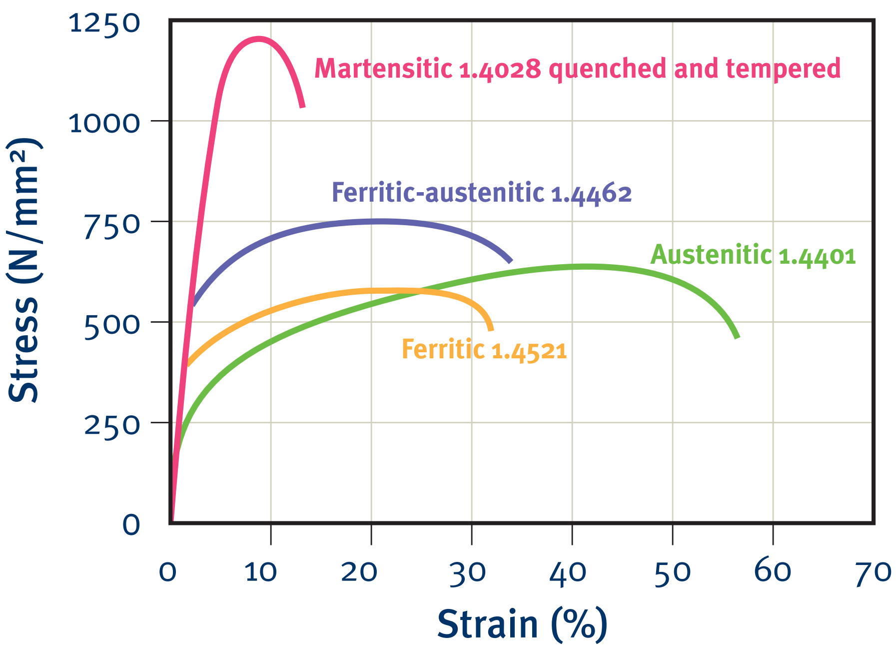


Figure 2 compares tensile properties showing that there are significant differences in how the different grades behave. All stainless steels have a room-temperature elastic modulus of around 200 GPa, similar to other steels. However, that is where the similarity of room-temperature mechanical properties ends. As Figure 2 shows, the austenitic stainless steels have a high work-hardening rate and high ductility in the annealed condition. These are attributable to their face-centred cubic crystal structure. Thus, while the yield strength* may be similar to that of the ferritic grades, the tensile strength and ductility are much greater. There are two consequences of this: the first is that the austenitic grades can be cold-worked to have high proof and tensile strengths with, at the same time, good ductility and toughness; the second is that a lot of energy is required to deform them so that they can absorb energy as part of a vehicle design to mitigate the effects of a crash. That toughness is retained even at high deformation rates (again, an important factor in crashworthiness).

*Stainless steels do not show a well-defined yield point so the yield stress usually refers to the 0.2% proof stress.

Photo courtesy of:
Cleanup Corporation

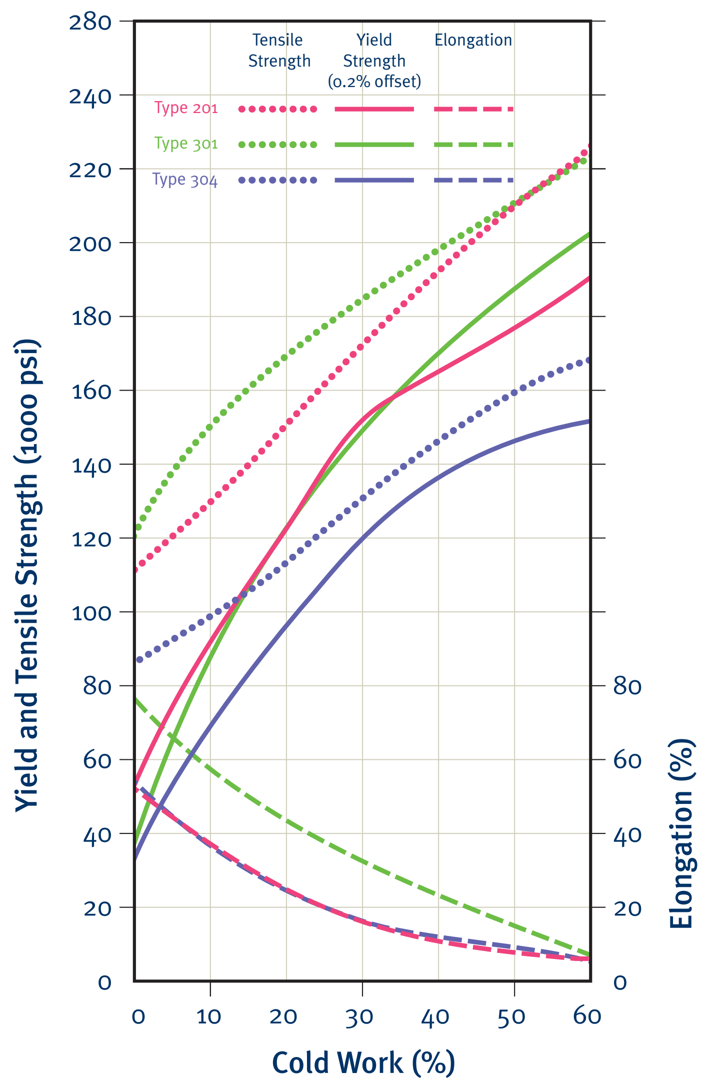
The austenitic grades cannot be strengthened by heat treatment. They can, however, be strengthened by cold working to very high levels.

Enhanced proof strength levels from 350 to 1,300 MPa and tensile strength levels from 700 to 1,500 MPa are listed in EN 10088-2:2005. ASTM A666 lists the strength properties for various tempers for the 200 and 300 series stainless steels. For any particular temper (strength) (e.g., ¼ hard), the properties vary slightly with the grade.

Manganese is particularly effective in enhancing the cold work strengthening effect in, for example, Type 201. See Figure 3, which also shows that, for similar austenitic grades, the lower the nickel content, the more pronounced is the effect of cold work.

"Austenitic grades can be strengthened by cold working to very high levels."

Figure 3:
Effect of cold working on the mechanical properties of Type 201, 301 and 304.
Allegheny Ludlum Steel Corp.



However, other alloying elements also have a strengthening effect so that the more highly alloyed grades have significantly higher tensile properties, as shown in Table 3.

Table 3
Minimum Mechanical Properties in Basic ASTM Specifications for High Performance Austenitic Stainless Steels

Name	UNS Number	ASTM Specification	Yield Strength (minimum)		Tensile Strength (minimum)		Elongation (minimum)
			MPa	ksi	MPa	ksi	%
201	S20100	A240	260	38	515	75	40
201LN	S20153	A240	310	45	655	95	45
304	S30400	A240	205	30	515	75	40
304L	S30403	A240	170	25	485	70	40
321	S32100	A240	205	30	515	75	40
Type 316L	S31603	A240	170	25	485	70	40
316Ti	S31635	A240	205	30	515	75	40
Type 317L	S31703	A240	205	30	515	75	40
Alloy 20	N08020	A240	240	35	550	80	30
317LMN	S31726	A240	240	35	550	80	40
904L	N08904	A240	220	31	490	71	35
Alloy 28	N08028	B709	214	31	500	73	40
6% Mo	S31254	A240	310	45	655	95	35
4565S	S34565	A240	415	60	795	115	35
7% Mo	S32654	A240	430	62	750	109	40

The duplex grades have inherently higher strength at room temperature than the basic austenitic grades. This is due to their duplex structure, as shown in Table 4 below.

Table 4
Minimum mechanical properties in basic ASTM sheet and plate specifications for duplex stainless steels

Name	UNS Number	Yield Strength (minimum)		Tensile Strength (minimum)		Elongation (maximum)
		MPa	ksi	MPa	ksi	%
2304	S32304	400	58	600	87	25
2205	S32205	450	65	655	95	25
2101	S32101	450	65	650	94	30
2507	S32750	550	80	795	116	15

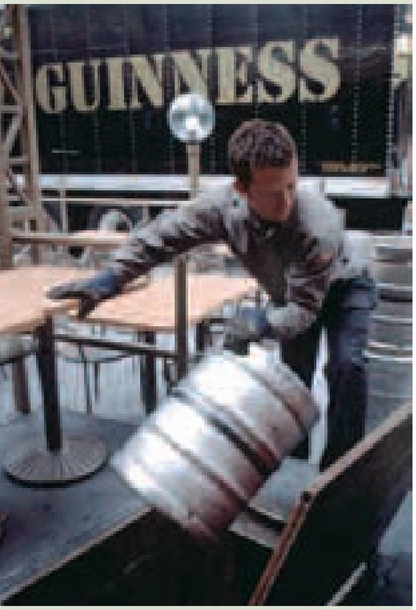
This is a result of the inherent high strength of the ferrite phase coupled with the high work-hardening rate of the austenite phase. Recent trends in the development of duplex grades have been toward both leaner and more highly alloyed grades.

Even higher strengths can be obtained in the precipitation-hardening grades. Tensile strengths up to 1,793 MPa can be achieved, exceeding the strength of martensitic grades. This strength is achieved with good ductility and corrosion resistance and requires heat treatment at only modest temperatures of up to 620 °C.

Photo courtesy of: iStock photos

Nickel (and other elements) in solid solution increase the proof stress of ferritic grades. However, because of the lower work-hardening rate of the ferritic structure, the tensile strengths are less that in similar austenitic grades.

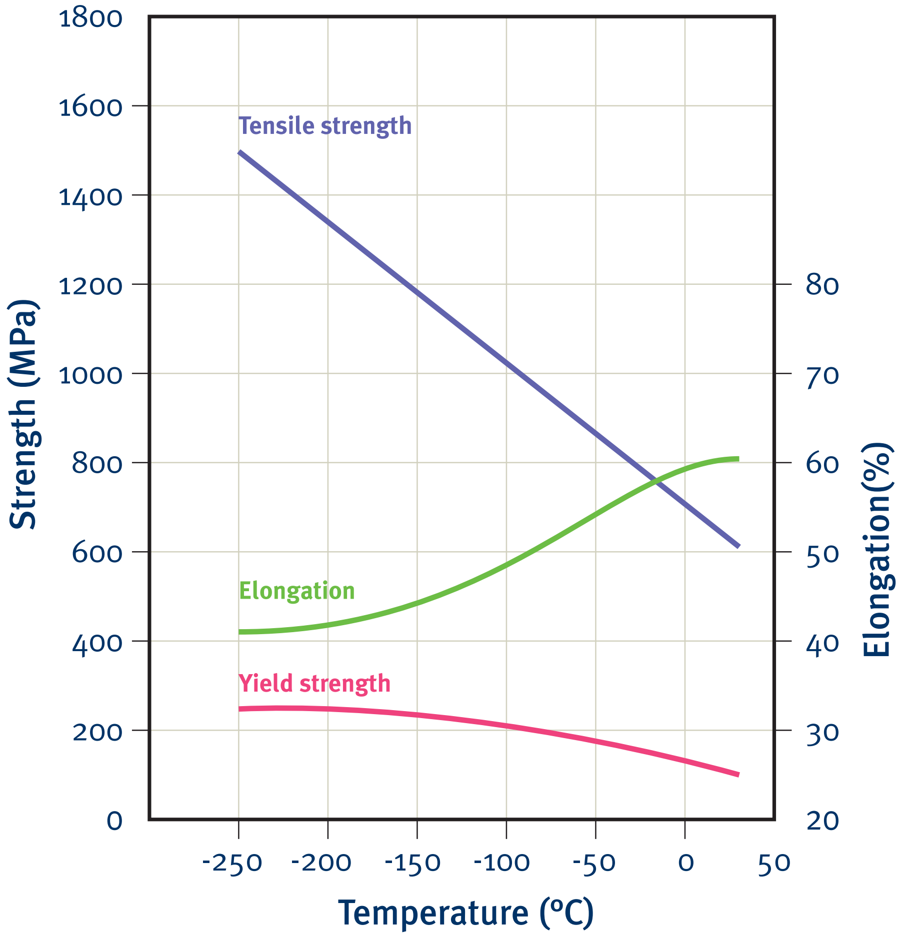
Low-temperature mechanical properties Proof and tensile strengths of the austenitic grades also increase at low temperatures, as shown in Figure 4.



Beer Kegs in 304

Photo courtesy of: Tim Pelling for Nickel Institute

Figure 4:
Low temperature strength of Type 304 stainless steel

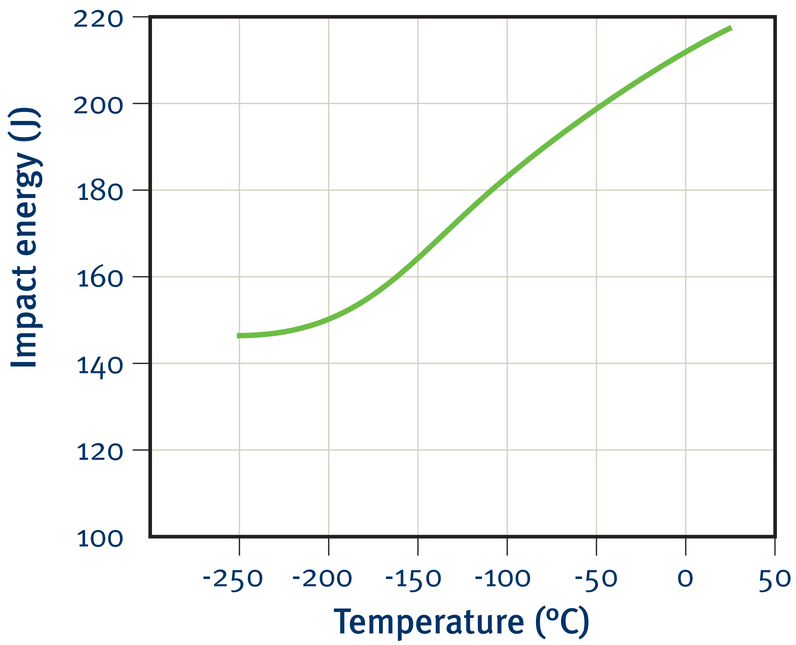


“Duplex grades have inherently higher strength.”

Figures 4 and 5 also show that (in contrast to some other families of stainless steel) both ductility and toughness of the austenitic grades are maintained to low temperatures. This is also true of cold-worked material. Therefore, the austenitic grades are suitable for service even at liquid helium temperatures.

The useful toughness of the duplex grades does extend to around minus 100 °C, which is below that of the ferritic grades.

Figure 5:
Low temperature impact properties of Type 304L stainless steel



“Austenitic grades retain ductility to cryogenic temperatures.”

Higher levels of nitrogen in the austenitic grades do stabilize the austenitic structure at low temperatures and so maintain the low magnetic permeability of those grades in the annealed condition, as shown in Table 5.

Table 5
Magnetic Permeability of Annealed Stainless Steel as Function of Temperature

Magnetic permeability of annealed steel:	**μ max at 20°C(1)**	**μ max at –196°C**	**μ max at –269°C**
Type 304	1.005–1.03	2.02–2.03	–
Type 304L	1.08–1.3	1.2–1.6	1.1–1.5
Type 316	1.02–1.05	–	–
Type 316L	1.02–1.1	1.03–1.09	1.03–1.0
Type 321	1.03–2.0	–	2.75
Type 347	1.005–1.03	–	1.40
Type (316N)	1.0	1.0–1•01	1.03–1.06

Reference: NI publication 4368

Photo courtesy of: Babcock & Wilcox

"*Fire and explosion resistance are advantageous.*"

Application Case History: *Runner blade replacements increase capacity by 400 Megawatts*

Since 1992, Ontario Power Generation (OPG) (formerly Ontario Hydro) in central Canada has been increasing the power output from its hydroelectric turbines, or units, by replacing runner blades with better-designed, lighter, higher-strength blades cast from stainless steel J91540 containing 4% Ni.

This alloy has good corrosion resistance, and cavitation resistance comparable to S30400.

The alloy's weldability is important for any in situ cavitation repairs. Its high strength is important, as increasing the efficiency of a blade also increases the differential pressure between its pressure side (above) and suction side (below).

The new blades increased each unit's capacity to between 64 and 65.4 MW from 56 MW.

Photo: Ontario Power Generation

High-temperature mechanical properties Two particularly important factors to consider here are hot strength and thermal stability, which will be discussed in detail in Chapter 5.

Structural Properties Both austenitic and duplex stainless steels are used structurally in many applications where corrosion resistance or fire and explosion resistance are advantageous. The Steel Construction Institute (www.steel-sci.org) has produced a reference publication titled *A Design Manual For Structural Stainless Steel.* It is also available from the EuroInox website (www.euro-inox.org). Another reference is the ANSI/ASCE-8-90 *Specification for the Design of Cold-Formed Stainless Steel Structural Members.*

Cast stainless steels This document focuses on wrought stainless steels. Most wrought austenitic and duplex stainless steels have a cast equivalent grade which will have a different designation. Cast grades generally have slightly modified compositions to improve fluidity and to prevent hot cracking, which can have some impact on their corrosion resistance in certain media. Residual element content may also vary considerably. Grain size may vary from wrought products resulting in slightly different mechanical properties. See NI publication 11022 for more details.

'Cloud Gate' by Anish Kapoor

Photo courtesy of: Outokumpu and James Steinkamp, Steinkamp Photography

Chapter 2
Corrosion Resistance

Chapter 2

Corrosion Resistance

“Stainless steels are most often specified because of their increased corrosion resistance.”

The corrosion of materials is a complicated process. The corrosivity of an acid may vary considerably based on temperature, the percentage of acid, the degree of aeration, the presence of impurities (which can have inhibiting or accelerating effects), flow rate, and so on. In addition, equipment design, welding and fabrication, heat treatment, surface condition, and cleaning chemicals all have roles to play in determining how long a piece of equipment will last.

Stainless steels are most often specified over carbon or low alloy steels because of their increased corrosion resistance. However, as with many generalizations, there are exceptions to the rule. For example there are cases where some stainless steels may fail sooner than carbon steels. Similarly, while 316L is, in most cases, more corrosion-resistant than 304L, there are circumstances when the latter is more resistant than the former – for example, in highly oxidizing acids such as nitric or chromic acid.

The role of nickel in corrosion resistance of stainless steels is often quite subtle. Not only does it have an effect purely as a bulk alloying element, it affects the passive oxide layer and the micro-structure (for example, by reducing the formation of detrimental phases). Selecting the proper alloy means finding one that will last the required length of time without contaminating the product contained.

General corrosion Table 6 shows data extracted from Schwind, et al[1]. Among other alloys, 304, 201 and 430 were tested according to an MTI procedure, where for a given acid concentration, the maximum temperature is given where the corrosion rate is less than 0.13 mm/a (5 mils/yr). The higher the number, the higher the corrosion resistance of the alloy.

Nuclear Power Plant

Photo courtesy of: Duke Energy

Table 6
Maximum temperature for a corrosion rate of less than 0.13 mm/yr in Different Solutions for Types 304, 201 and 430 Stainless Steels

Test solution	Critical temperature (°C)		
	304	201	430
96% sulphuric acid	50	20	40
85% phosphoric acid	80	70	<20
10% nitric acid	>b.p.	>b.p.	>b.p.
65% nitric acid	100	80	70
80% acetic acid	100	100	<20
50% sodium hydroxide	90	65	90

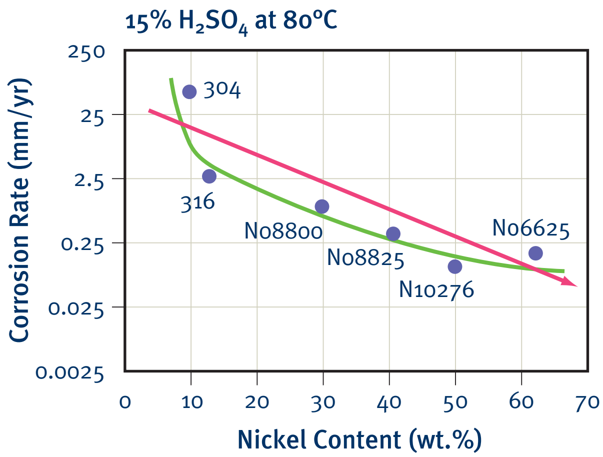
b.p.= boiling point

There was one environment in which all three alloys performed similarly, yet in all the environments reported, 304 either had equivalent or higher corrosion resistance. There were environments where 201 was much better than 430, as well as environments where 430 was better than 201. When dealing with general corrosion, it is therefore important to focus not on the role of any one element but on the combination of elements.

[1]Schwind, M. et al., Stainless Steel World, March 2008, p66ff

Increasing the nickel content of an alloy in a reducing solution such as sulphuric acid is one way to improve corrosion resistance. Normally one does not use an alloy when it has a high corrosion rate, but those conditions may occur during "upset" or abnormal operating conditions. Figure 6 shows the effect of increasing nickel content in reducing the corrosion rate in a 15% sulphuric acid solution at 80° C. As mentioned earlier, the corrosion resistance of any stainless grade results from the combination of the alloying elements and not from any one alloying element alone.

Figure 6:
Effect of nickel content on the corrosion rate of various alloys in 15% sulphuric acid at 80°C.
(from Sedriks[2])

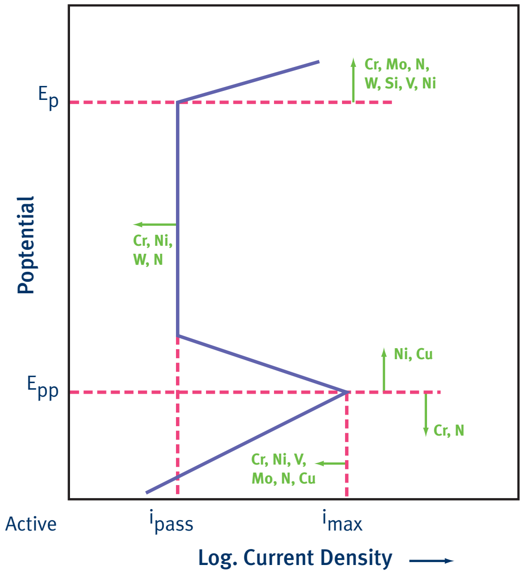


Another way of looking at corrosion resistance is from the perspective of electrochemical behaviour. This can be illustrated by the schematic of the effect alloying elements in stainless steels on the anodic polarization curve, Figure 7.

Desalination plants typically use austenitic and duplex stainless steels

Photo courtesy of: Tim Pelling for Nickel Institute

Figure 7:
Schematic of the effect of different alloying elements on the anodic polarization curve of stainless steel.
(from Sedriks[2])

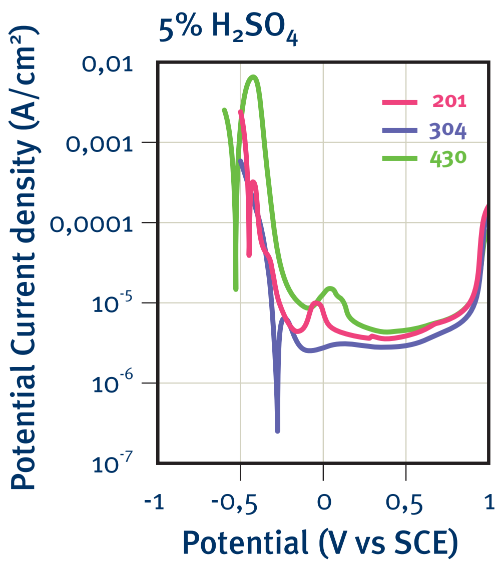


Nickel reduces the current density of Epp (the primary passivation potential) and pushes that potential in a more noble direction. It also reduces the passivation current density, resulting in a lower corrosion rate in the passive condition, and increases the potential (Ep) at which the material goes into the trans-passive range.

[2] Sdriks, A.J. (Corrosion of Stainless Steels, 2nd edition, Wiley-InterScience 1996.)

Figure 8 shows how this works in practice by a comparison of 304, 201 and 430 for 5% sulphuric acid solution.

Figure 8:
Comparison of the polarization curves for 304, 201 and 430 in 5% sulphuric acid.
(from Schwind[1])

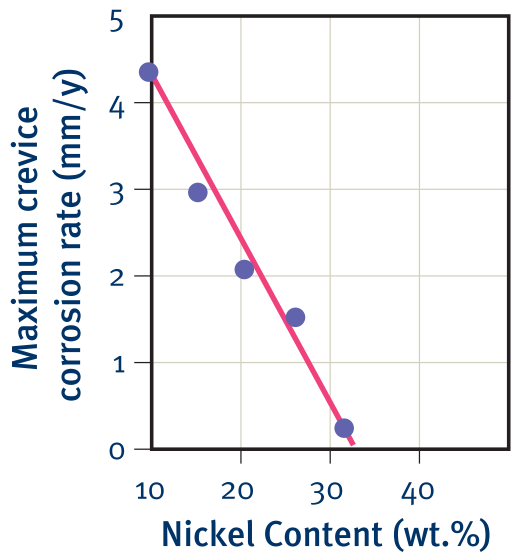


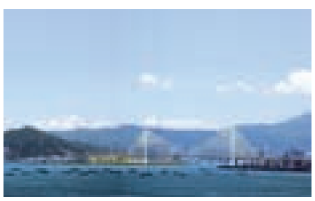
This comparison shows that nickel has positive effects on reducing corrosion rates both when active corrosion is occurring and when a stainless steel is in the passive state. Normally an alloy is chosen that will have an acceptable corrosion rate in the passive state. However, small changes in process conditions, such as a temporary increase in temperature, may cause an alloy to "go active." It is important, then, to have an alloy that does not have an unreasonably high active corrosion rate and will re-passivate quickly when process conditions return to normal.

Chloride pitting resistance The relative resistance of an alloy to initiation of pitting corrosion is given by the Pitting Resistance Equivalent Number (PREN). The most commonly used formula is PREN = %Cr + 3.3(%Mo) + 16(%N), though there are many different formulae that have tried to correlate the behaviour observed in tests to the alloying composition. Some, for example, include a positive figure for tungsten, while others have a negative factor for manganese. Sedriks attributes a small but positive effect of nickel. The bulk alloying content is important, but it only describes one factor in determining the practical pitting resistance of an alloy. The presence of intermetallic phases (sigma, chi, etc.), owing to poor heat treatment and the presence of inclusions (especially manganese sulphides), are a major factor in reducing pitting resistance. In the case of high chromium and molybdenum alloyed stainless steels, intermetallic phases may form during normal welding, with the ferritic stainless steels being most sensitive (see chapter 5 on joining). The most significant contribution of nickel to pitting resistance is that it changes the structure of the material, allowing ease of production of the stainless material of the appropriate thickness along with ease of welding and fabrication without forming detrimental intermetallic phases, especially of the higher alloyed grades.

Crevice Corrosion Nickel is known to decrease the active corrosion rate in crevice corrosion, as shown in Figure 9. This is analogous to the decrease in corrosion resistance with increasing nickel content shown in Figure 6. In both cases, the metal is corroding in an active state.

Figure 9:
Effect of nickel content on the propagation rate of crevice corrosion on a 17%, Cr-2.5% Mo stainless steel.
(from Sedriks[1])





Application Case History: *Zero Maintenance*

Its deck will soar 75 metres above the entrance to Hong Kong's Kwai Chung container port, and its two pole towers will rise 290 metres into the sky. When it is completed, in 2009, the 1,600-metre-long Stonecutters Bridge will be a key component in China's global trade activity.

To satisfy the rigorous structural and surface finish requirements, Arup Materials Consulting in London, England, chose S32205 duplex hot-rolled plate (containing 4.5 to 6.5% nickel) to form the top 120 metres of the towers. About 2,000 tonnes of S32205, mostly 20 mm thick, will be used.

Arup also specified S30400 stainless steel reinforcing bar (containing 8.0 to 10.5% nickel) in the concrete piers and main tower splash zones. This required 2,882 tonnes of rebar in diameters up to 50 mm.

In seeking material for the skin, designers decided that although carbon steel had the necessary structural strength of 450 MPa, it did not offer the required zero maintenance. "The strength that was required could not be met by an austenitic stainless steel, which has a design strength of about 300 MPa," explains Graham Gedge, Arup's specialist in project materials. "It had to be thicker and thus heavier and more expensive: with S32205, we knew we could achieve a strength of 450 MPa with hot rolled plate."

There was another reason for discounting standard austenitic stainless steel: long-term performance in this polluted marine environment would have required a carefully controlled surface preparation. The durability assessment of the environment in which these materials are expected to perform is C5M, the worst atmospheric exposure possible under the ISO environmental classification.

S32205 is ideal for the finish the designers specified. "S32205 is less susceptible to pitting and staining than other candidate alloys, and allows us more flexibility in choice of final surface finishes," Gedge explains. "The control of final surface roughness becomes less critical, even if it will trap some dirt and salt."

The combination of duplex towers and stainless steel reinforcing bar should result in a bridge that will endure.

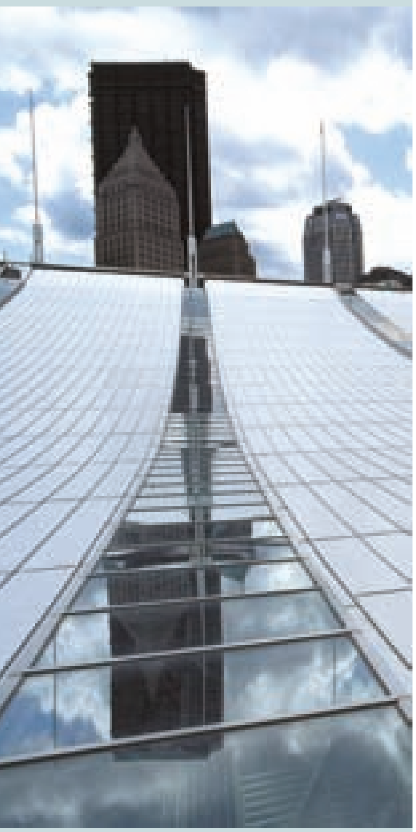
Photo: Arup Materials Consulting, Arup Hong Kong [bridge].

Alessi Kettle
Photo courtesy of: Alessi

Stress Corrosion Cracking There are many different types of stress corrosion cracking (SCC). Austenitic stainless steels have very good stress corrosion cracking reistance in hydrogen sulphide environments, such as are found in the natural gas sector. Austenitic stainless steels and more recently duplex stainless steels have shown excellent long term performance and guidelines for their use can be found in standards such as NACE MR0175/ISO 15156.

Chloride stress corrosion cracking has been studied for years, and many people are familiar with the "Copson Curve," derived from testing in aggressive boiling magnesium chloride. It has shown that the ferritic stainless steels without a nickel addition are superior to the standard stainless steels with 6-12% nickel. Alloys with more than 45% nickel were found to be virtually immune to cracking in magnesium chloride. In practice, most other chloride solutions are far less aggressive than the magnesium chloride, and while grades such as 304 and 316L are generally avoided, the stainless alloys with 6% molybdenum have sufficient resistance in most cases, as do the duplex stainless steels.

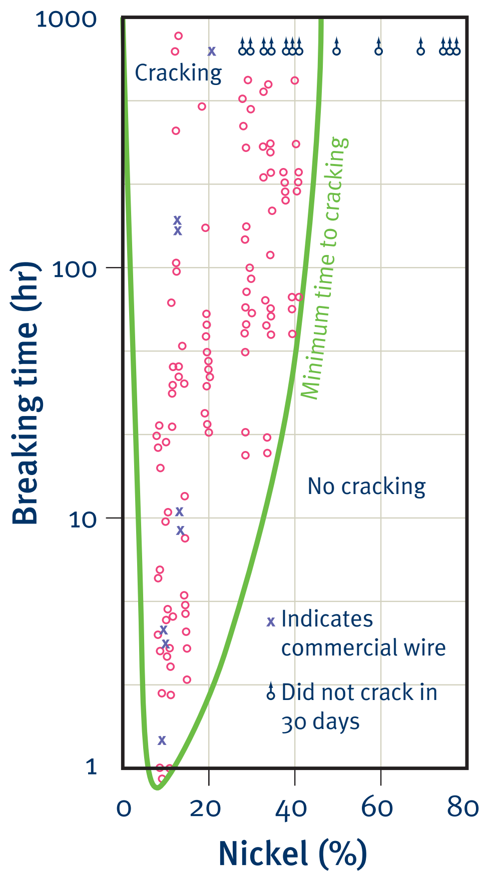
"Nickel contributes to corrosion resistance."



Innovative use of stainless steel for solar reflectance and energy savings

Photo courtesy of: Rafael Vinoly Architects PD [Pittsburgh convention centre]

Figure 10: Copson Curve – Effect of nickel on the susceptibility of stainless steels to chloride stress corrosion cracking in boiling magnesium chloride.



Offshore platforms rely on nickel-containing stainless steels for processing equipment and piping, as well as to prevent seawater corrosion.

Photo courtesy of: KM Europa Metal

“Austenitic stainless steels are very useful in hydrogen sulphide environments.”

Application Case History: *Soy Sauce Fermentation Vessels*

The same qualities that lend soy sauce its cachet create such severe conditions during fermentation that the stainless steel tanks common to other food-processing industries are not up to the job of brewing the popular sauce. Instead, Japan has tended to use fibreglass and resin-lined steel, both of which resist corrosion.

The acids produced during fermentation lower the pH to about 4.7 in an already corrosive stew containing about 17% sodium chloride. Problem is, the mix of organic acids and sodium chloride in the sauce is so corrosive and the fermentation process so long (about six months) that the cost of maintaining the tanks can be prohibitively expensive.

A recent study shows that molybdenum-bearing super austenitic stainless steel S32053 resists the corrosion that affects other stainless steels immersed in conventional brewing tanks.

“The super austenitic stainless steel is less susceptible to corrosion, whereas S31603 suffers crevice corrosion and stress corrosion cracking, and duplex stainless steel S32506 is susceptible to crevice corrosion,” writes Yutaka Kobayashi of Nippon Yakin Kogyo, one of the largest stainless steel producers in Japan.

Based on the experimental results, Yamasa Corporation, which has been making soy sauce since 1645, built 100 fermentation tanks in S32053 with capacities of up to 390,000 litres for its Japanese operations. The tanks have been in commercial use since October 2002 without any corrosion.

If the S32053 tanks withstand the test of time in Yamasa’s plant, their marketability will be significant. The opportunities to use super austenitic stainless steel for new fermentation tanks seem great.

Photo: Tom Skudra for Nickel Institute / Nippon Yakin Kogyo Co. Ltd.

Photo courtesy of: Veer

"No maintenance for 120 years."

Application Case History: *Concrete Reinforcing Bar*

Think of the time and money to be saved if a bridge spanning a saltwater estuary were to require no maintenance for, say, 120 years. No need to break into the concrete piers to replace rusted rebar, no traffic tie-ups while road crews undertake repairs.

Dublin-based Arup Consulting Engineers not only envisioned such a trouble-free bridge; they designed and built it using stainless steel rebar. The twin spans of the Broadmeadow Bridge in eastern Ireland, part of a motorway that links Dublin and Belfast, opened to traffic in June 2003.

"We had an aggressive environment – salt water, wetting and drying – where future access for maintenance is very, very difficult," says Troy Burton, Arup's associate director and the principal design engineer for the bridge. "We wanted to guarantee a 120-year design life... and we needed to convince our client that we had a durable solution that would cost little money in the future to maintain."

The solution was to use stainless S31600 rebar to reinforce all 16 piers that carry the 313-metre bridges across the estuary.

Using stainless rebar was a first for Arup. "It pretty well ticked all the boxes in terms of a permanent, durable solution," Burton says.

In all, 169 tonnes of stainless were used.

Burton says using stainless rebar added less than three per cent to the approximate 12-million-Euro cost of building the bridge – a negligible expense, given the savings in maintenance and repairs over its lifetime. It is difficult to reach the Broadmeadow Bridge's piers without damaging the ecologically sensitive mudflats, making it essential that the structure not require maintenance.

The Broadmeadow Bridge inspired Ireland's National Road Authority to mandate the use of stainless steel to attach parapets to all new bridges.

Photo: Arup Consulting Engineers

Chapter 3
High Temperature

Chapter 3

High Temperature

“Structural stability is a major reason for their widespread use at high temperatures.”

At elevated, as well as at lower, temperatures, a material is selected on the basis of its properties, and usually there are compromises. At elevated temperatures, properties of interest to the designer include mechanical ones, such as yield and tensile strength, creep strength or creep rupture, ductility, thermal fatigue, and thermal shock resistance. Physical properties of possible interest include thermal expansion, thermal conductivity, and electrical conductivity. Properties that show environmental resistance include oxidation, carburization, sulphidation and nitriding. Fabrication properties include weldability and formability. Other properties such as wear, galling and reflectivity may also need to be considered.

These properties are of interest at all the temperatures to which the material is subjected, and it is especially important to look at potential changes to properties during service life. The structural stability of austenitic stainless steels is a major reason for their widespread use at high temperatures.

In general, austenitic stainless steels remain strong at elevated temperatures, at least compared with other materials. Figure 11 compares the short-time high-temperature yield and tensile strengths of some austenitic and ferritic stainless steels at various temperatures. At temperatures below about 540° C (1,000° F), the differences are not that large. Above that temperature, the strength levels drop off rapidly on the ferritic grades. Some special ferritic stainless steels can be alloyed for increased high-temperature strength.

Application Case History: *Vacuum Chambers*

Housed at the University of Saskatchewan, Canada, the synchrotron, as it is called, produces electrons that give off light millions of times brighter than the Earth’s sun. Researchers use the light for various design and manufacturing projects.

Stainless steel, of which S30400, S30403 and S31603 are the most common types, is used extensively in the vacuum chambers.

Achieving a vacuum requires the removal of as many molecules as possible. Impurities not only slow the electron beam; they diffract the electrons, much like fog scatters the beam from a car’s headlights. Some synchrotrons have been made of copper or aluminum, but stainless steel is more routine from a fabrication point of view, says Mark de Jong, CLS’s director of operations.

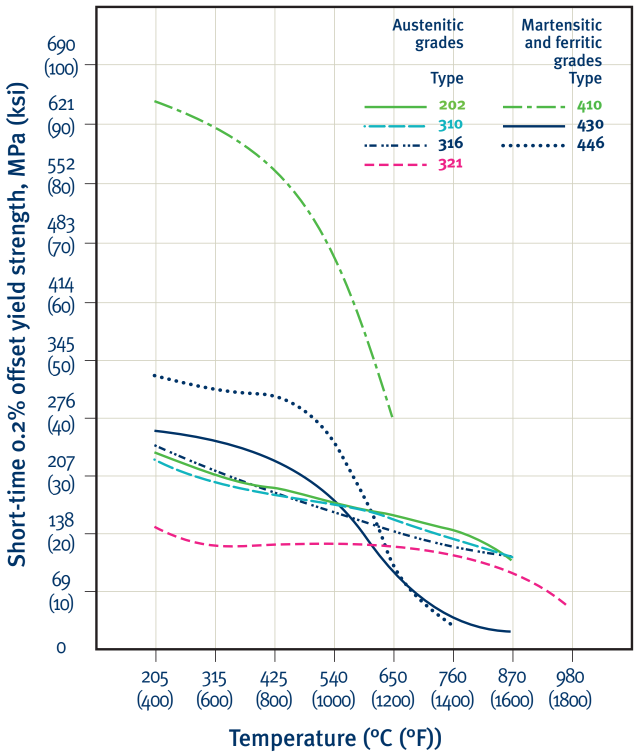
The vacuum chamber components must be cooked in huge bake ovens for as long as 40 hours at temperatures as high as 250ºC. This removes gases absorbed during manufacture. Aluminum begins to lose its strength at 150ºC, but stainless steel does not – a critical attribute considering that the components are baked under vacuum. “Stainless doesn’t lose strength at the typical pressures of our bake-out,” confirms Mark de Jong.

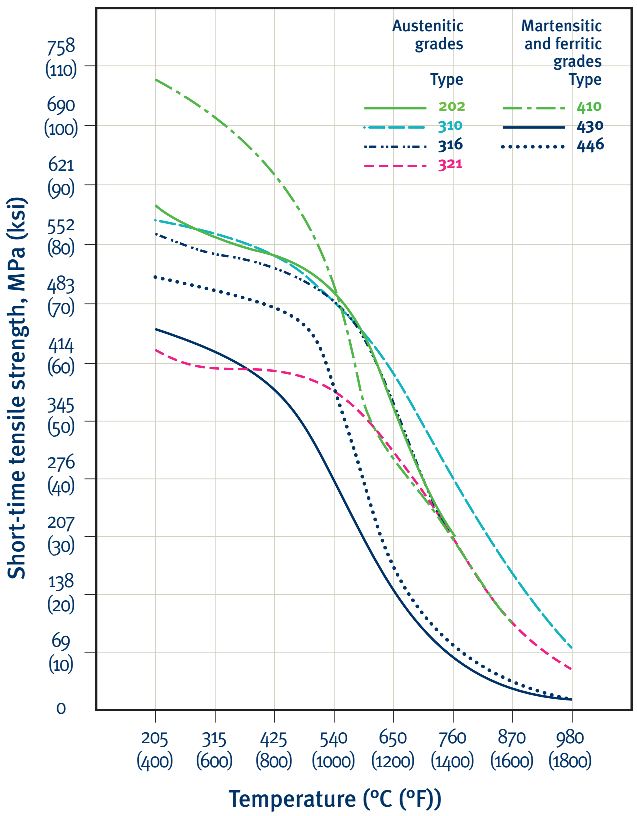
Ontario, Canada-based Johnsen Ultravac uses S30400 in some of the vacuum chambers it manufacturers. The cost of S30400 is low, compared with other metals. It is also easy to machine and weld, and sufficiently hard that it can cut into the copper gaskets. The synchrotron’s many fittings, flanges, ion pumps and valves are always stainless steel, so mating them to like-metals simplifies the engineering.

A half-kilometre of 203.2 mm stainless pipe, and another half-kilometre of 76.2 mm stainless pipe carry de-ionized water, which cools the electromagnets and X-ray-absorbing copper blocks in the stainless steel pump cylinders. S31600 and S31603 were chosen because the de-ionized water would corrode carbon steel.

Photos: Canadian Light Source Inc., Johnsen Ultravac, University of Saskatchewan

Figure 11:
Yield and tensile strength of stainless steels at elevated temperatures.
(from NI publ. 9004)



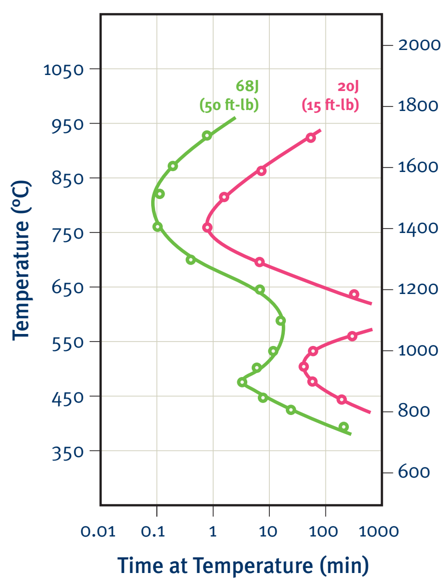


> "Austenite is immune to 475°C embrittlement."

Photo courtesy of: Eero Hyrkäs

Ferritic stainless steels with 13% or more chromium will embrittle in the temperature range of 400-550° C (750-1020° F) in shorter time periods and to as low as 270° C with longer times in the higher-alloyed (chromium/molybdenum) grades. The temperature of the shortest time to embrittlement, called the "nose of the curve," is around 475° C (885° F), and this phenomenon is thus called "475° C embrittlement" (or "885°F" embrittlement"). The embrittlement phenomenon which is shown in Figure 12 as the lower "nose," also affects the ferrite phase in duplex stainless steels, which is one reason most duplex alloys have a maximum temperature for long-time exposure of about 270° C (520° F) or slightly lower. Although austenite is immune to this embrittlement, the ferrite in austenitic stainless welds and castings will embrittle, though usually there is a small enough amount that it does not have a significant detrimental effect on properties except at cryogenic temperatures. Ferritic stainless steels with less than 13% chromium, such as 409 or 410S, may be immune to this embrittlement or else the embrittlement may occur only with long time exposure, depending on actual chromium content. Nonetheless, their low chromium content and low strength limit their usefulness to about 650° C (1,200° F). The low alloyed ferritic stainless steels do find widespread application in automotive exhaustive systems.

Figure 12: Embrittlement curve for ferritic alloy S44800 showing embrittlement both from 475°C exposure and intermetallic phaseformation.
(from Allegheny Ludlum)

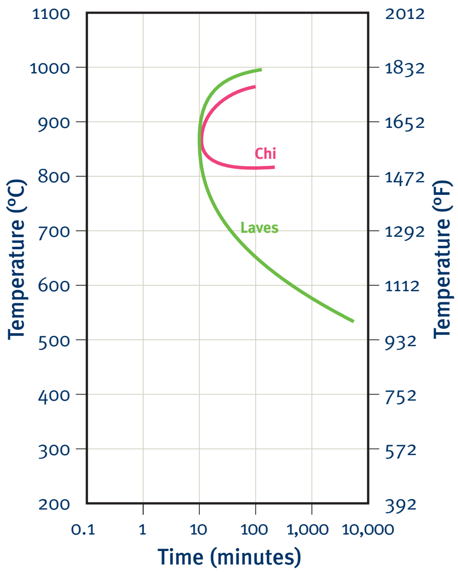


Another microstructural change that needs to be taken into account is the formation of deleterious hard and brittle intermetallic phases such as sigma. For the sake of simplicity, we will call all these intermetallic phases "sigma" phases. They can occur in both austenitic and ferritic stainless steels, including duplex alloys. The upper "nose" of Figure 12 is this embrittlement in a high-alloyed ferritic stainless steel. Figure 13 shows the intermetallic formation for a 5% molybdenum stainless steel. The temperature range for formation varies depending on the composition of the alloy but is generally in the range of 565-980° C (1,050-1,800° F). However, some of the lower chromium ferritic grades can form sigma as low as 480° C (900° F), albeit with very long times. The nose of the curve is generally in the upper end of the temperature range.

In addition to temperature, the time required to form sigma phase varies considerably depending on composition and processing (the amount of cold work, for example). Chromium, silicon, molybdenum, niobium, aluminum and titanium promote sigma phase, whereas nickel, carbon and nitrogen retard its formation. With a sufficiently high level of nickel, sigma phase formation can be completely suppressed. If a material is to be used in the sigma phase formation range, it is important to evaluate how much embrittlement is likely to occur over the service life of the component and how much effect this will have on the component's performance. The embrittlement is normally not a problem when the material is at operating temperature (except when thermal fatigue is involved) but can become a serious one at ambient temperatures.

Grain size can be an important factor when using materials for high-temperature service. In austenitic stainless steel, a fine grain size is generally not desirable as it is associated with inferior

Figure 13:
Isothermal precipitation kinetics of intermediate phases in a 0.05C-17Cr-13Ni-5Mo alloy containing 0.145% nitrogen annealed at 1150°C (2102°F)



creep strength. A medium-to-fine grain size gives the best combination of properties, although in certain cases where high creep and rupture strength is important, a coarse grain size in an austenitic alloy may be preferred. The downside of a coarse grain size is twofold: inferior thermal fatigue and thermal shock properties. In purely ferritic stainless steels, grain growth can happen rapidly above 1,100° C (2,010° F). This can occur during welding and may result in a coarse and low-ductility heat-affected zone (HAZ). Coarsening of the grains occurs much more quickly in ferritic stainless steels than in austenitic alloys.

Carbon in austenitic stainless steels is generally beneficial for high-temperature service, giving increased creep strength throughout the temperature range. If carbides form, they may result in some corrosion problems when corrosives are present (normally at lower temperatures, during shutdown conditions). In most design codes for elevated temperature pressure vessels, there are austenitic grades with minimum carbon contents as well as a maximum that have higher design strengths than for the low carbon grades or where there is no minimum carbon content. For example, 304H has a minimum carbon content of 0.04%.

When using any material at high temperatures, the thermal expansion must be taken into account in the design of the equipment; otherwise, failure will result. The thermal expansion coefficient of the ferritic stainless steels is lower than that of austenitic grades but must always be allowed for in the design. The higher nickel stainless grades, such as 310 and 330, have a lower thermal expansion rate than the standard 304 and stabilized variations. The nickel alloys (Alloy 600, for example) have even lower rates of expansion.

Many factors affect the thermal conductivity of a component in practice. The austenitic stainless steels have a lower thermal conductivity than either ferritic stainless steels or carbon steel, which is to say they have lower heat transfer through the metal. Surface oxide layers also act as barriers to heat transfer.

Oxidation resistance of an alloy is important and relatively easy to measure, though problems can arise in real-life applications. Ideally an oxide layer would form on the stainless steel and the growth rate would slow, in time, at very low levels. The oxide would also have the same expansion coefficient as the stainless steel. In reality, when the oxide layer thickens above a certain level and the temperature fluctuates, the oxide layer partially spalls off and new oxide growth begins. Maximum temperatures for continuous and intermittent conditions are usually quoted.

Chromium content is important for the formation of a protective oxide layer at increasingly elevated temperatures and is sometimes aided by smaller additions of silicon, aluminum and cerium. The oxide layer is never perfect, and with both thermal expansion/contraction and mechanical stresses, many cracks and other defects will form. Thicker oxide films may spall off, with a new oxide film forming underneath, resulting in a loss of metal thickness. The generally

Waste-to-energy plant

Photo courtesy of: Technical University of Denmark

“…thermal expansion… must always be allowed for…”

higher thermal expansion rate of austenitic stainless steels, compared with ferritic alloys, causes austenitic grades to have a higher rating in continuous service than in intermittent service in standardized tests. The opposite is true in the case of ferritic stainless grades. This is illustrated in Table 7 which gives the approximate scaling temperature and suggested maximum service temperature in air in continuous and intermittent service for some stainless alloys. There are a number of special stainless steels with optimized oxidation properties available. Manganese has a detrimental effect on oxidation resistance, and therefore the 200 series has only limited use at high temperatures.

Rolled Alloys

Application Case History: *Flue Gas Desulphurization*

Flue gas desulphurization (FGD) systems are essential for reducing air pollution from fossil-fuel burning power plants. Corrosion conditions can be very severe. The materials used range from high nickel alloys in the most corrosive areas to nickel-containing stainless steels in the less corrosive areas. This spray piping is in UNS N08367, a 24% Ni, 6% Mo stainless steel, chosen for its corrosion resistance and ease of fabrication in these section sizes.

"Preventing metal dusting requires the use of special nickel alloys."

Table 7
Oxidation Resistance of Some Standard Steel Grades

Grade	Approx. Scaling T		Maximum Service Temperature in Air			
			Continuous		Intermittent	
	C	F	C	F	C	F
403	700	1,300	700	1,300	820	1,500
430	825	1,500	820	1,500	870	1,600
446	1,100	2,000	1,100	2,000	1,175	2,150
304	900	1,650	925	1,700	870	1,600
309	1,065	1,950	1,000	1,850	1,000	1,850
310	1,150	2,100	1,150	2,100	1,040	1,900

The resistance of a stainless steel to carburization is a function of the nature of the protective oxide scale and the nickel content. Reducing environments at high temperature that contain either carbon monoxide or a hydrocarbon can cause carbon to diffuse into the metal, making the surface layer hard and brittle. The solubility of carbon in a stainless steel decreases as the nickel content increases. As a result, the alloys used in carburizing environments are either stainless steels with high nickel content or nickel alloys.

Silicon is beneficial in enhancing the protective oxide layer, so often the selected alloy will have an elevated silicon content. Alloy 330 with 19% chromium, 35% nickel and 1.25% silicon is commonly used. Nickel-free stainless steels have poor carburization resistance. Preventing metal dusting, also called "catastrophic carburization," a special form of carburization, requires the use of special nickel alloys. Sulphur in hot gases, on the other hand, may be detrimental to the high-nickel alloys, especially if the environment is reducing in nature. Generally, one will choose a lower-nickel austenitic stainless steel, or, in severe cases, a high-chromium ferritic grade. In such a situation, a compromise in properties has to be made, no matter which grade is selected.

Chapter 4
Forming

Chapter 4

Forming

“Austenitic stainless steels can be formed by a wide variety of processes.”

Hot Forming The hot forming characteristics of the 200 and 300 series of austenitic stainless steels are considered excellent in terms of operations such as hot rolling, forging and extrusion. The temperature range for these operations typically starts somewhat below the annealing temperature. Table 8 shows typical hot forming temperatures for some common austenitic stainless steel grades and a few duplex grades, along with their solution annealing temperatures. These are general ranges; often more restrictive practices are necessary for specific operations and grades.

It is important to have a uniform temperature for the piece, as hotter areas will deform more easily than cooler ones. Most often, hot formed components will receive a full solution anneal to ensure maximum corrosion resistance. Special care must be taken in hot forming the high alloy austenitic grades such as the 6% Mo stainless steels. They are subject to hot cracking during forging and will need an adequate soak during subsequent annealing to remove intermetallic phases that will have formed during hot forming. The duplex grades, while they have higher strength at lower temperatures, are generally quite weak at the hot forming and annealing temperatures, and care must be taken to ensure dimensional stability during these operations. Specific data should be consulted for each grade, and tests should be made after hot operations to ensure that the material has the expected corrosion properties.

Photo courtesy of: Alessi

Table 8
Suggested Hot-Forming Temperature Ranges and Solution Annealing Temperatures for Some Selected Duplex, 200 and 300 Series Stainless Steels

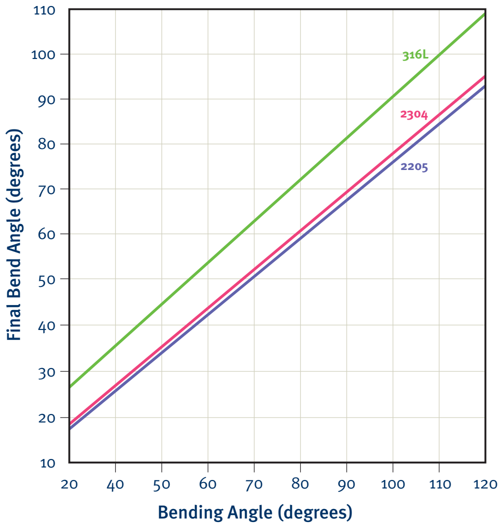
Grades	Hot Forming Temperature Range		Solution Annealing Temperature	
	°C	°F	°C	°F
Standard grades, Types 304, 305,316, 321 etc.	1,200-925	2,200-1,700	1,040 min.	1,900 min.
High-temperature grades Types 309, 310	1,175-980	2,150-1,800	1,050 min.	1,925 min.
6% Mo grades	1,200-980	2,200-1,800	1,150 min.	2,100 min.
201, 202, 204	1,200-925	2200-1,700	1,000-1,120	1,850-2,050
S32205	1,230-950	2,250-1,750	1,040 min.	1,900 min.
S32750	1,230-1025	2,250-1,875	1,050-1125	1,925-2,050

Warm Forming It is not unusual to warm an austenitic stainless steel piece to facilitate forming. Unlike the ferritic or duplex grades, austenitic stainless steels are not at risk for the 475°C embrittlement mentioned in Chapter 3. The low carbon and stabilized austenitic stainless steels can withstand short periods of time at temperatures of up to 600° C (1,100° F) without any significant detrimental effects to their corrosion resistance. For duplex stainless steels, avoid warm forming above 300° C (575° F).

Cold Forming Austenitic stainless steels have outstanding ductility. A common acceptance criterion is that they can be cold-bent 180° with a radius of one-half the material thickness, without regard to rolling direction. However, when forming temper rolled austenitic stainless steel, rolling direction is important, and tight bends should be oriented to the transverse rolling direction. The minimum bending radius needs to be increased as initial temper (strength) of the material is increased. For example, ½ hard Type 304 sheet with minimum yield strength of 760 MPa (110 ksi) should be able to be bent 180° over a mandrel with a radius equal to the sheet thickness. In general, the duplex stainless steels are not as ductile as the austenitic grades but still have good ductility in the annealed condition. The duplex grades are not commonly used in the temper rolled condition, except as cold drawn wire.

Most of the duplex grades and any of the higher strength 200 or 300 series stainless steels can be harder to form, owing to their higher yield strengths. Equipment that may be near its limit with annealed 300 series stainless steels may have great difficulty with the higher strength materials of the same thickness. Because of the work hardening, springback is a concern with all austenitic and duplex stainless grades. Generally speaking, the higher the initial strength and the greater the degree of cold working, the greater the amount of springback. Figure 14 compares the springback characteristic for bending of annealed Type 316L and the duplex 2205 grade. In this case, the duplex requires more overbending than the austenitic grade. To achieve a 90° angle, the 316L must be bent to 100° whereas the higher strength duplex requires bending to 115°.

Figure 14:
Comparison of springback characteristics of annealed 31 6L to duplex grades S32304 and S32205



Roll forming is a highly efficient and practical way to produce long lengths of shapes such as angles or channels in all the austenitic and duplex grades.

Drawing and Stretching Both the austenitic and ferritic stainless steels are commonly formed by both drawing and stretching. The combination of high ductility and high work hardenability that is characteristic of austenitic stainless steels leads to outstanding formability of sheet.

Drawing or deep drawing entails forming a sheet without clamping of the blank. The metal flows in the plane of the sheet with minimal thinning. In general, an austenitic material with a lower work-hardening rate (e.g., Type 304) is preferred for pure drawing operations. Stretch forming is forming of the sheet through a die with hard clamping of the edge of the blank. All deformation is accomplished by stretching, with a corresponding thinning of the sheet. Here a high work-hardening rate typical of Type 301 may be advantageous because it enables larger punch depths. The technology of sheet forming is complex and, in most practical operations, the actual forming is a combination of these two types. Surface finish, forming sequence, and lubrication are critical to ensuring the smooth, high quality appearance associated with austenitic stainless steel. The forming of standard Type 304 and its variants would be considered extraordinary except that it has been common practice for many years. Even with the high ductility of austenitic stainless steel, in extreme forming applications, one or more intermediate annealing steps may be necessary to restore ductility and enable further forming.

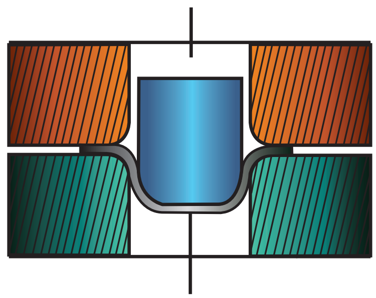
"The forming of standard Type 304 and its variants would be considered extraordinary except that it has been common practice for many years."

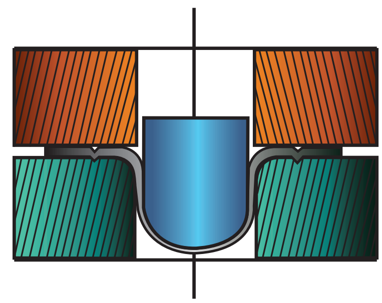
Drawing

- metal flows freely into die
- deformation of large circle into narrow cylinder must come
  from width rather than thickness
  (=high anisotrophy "r")

Stretching

- metal held by the blankholder
- considerable thickness reduction
- high elongation (A%) and
  hardening (n) required





Source: http://www.euroinox.org/fla_113_EN.html

Duplex stainless steels are not often significantly formed by drawing or stretching. Where this has been achieved successfully, the equipment and dies have been modified to take into account the lower ductility and higher strength.

Spin-forming Spin-forming (also known as lathe spinning) is a method of extensively forming sheet or plate to make rotationally symmetric parts. The method is well-suited to the forming of conical parts, something that is relatively difficulty to do by other methods. The deformation of the sheet may be large, and a low work-hardening rate grade such as Type 305 can be advantageous. Type 305 has a slightly higher nickel content and a slightly lower chromium content, both of which serve to reduce the work-hardening rate. The duplex stainless steel grades can also be spin-formed, though they require more powerful equipment and possibly more intermediate annealing steps.

Cold Heading For bar products, it is common to form heads for screws, bolts and other fasteners by axial stamping operations within a die. The material needs to have good ductility, and a small amount of work hardening is an advantage. Type 305 or an 18/8 type with copper (sometimes called Type 302HQ) are often used. There are 200 series stainless steels with low work-hardening properties that can also be easily cold headed. Cold heading has been done on some of the duplex stainless steels.

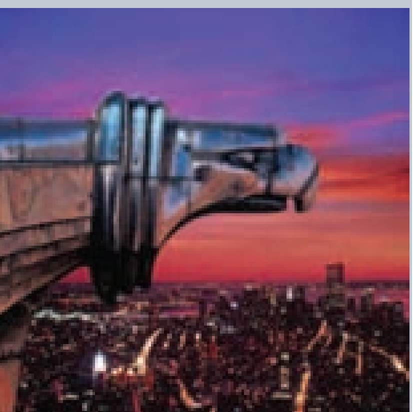


Photo courtesy of: Getty Images

Reactor Watches

Application Case History: *Watches*

"We pride ourselves on producing a high-quality watch that people can put on in the morning, do whatever activity they enjoy most, be it diving, surfing, snow skiing or snowboarding, then go out in the evening without ever having to take the watch off their wrist." says Jimmy Olmes, founder of California-based Reactor Watches.

"We chose S31603 for its wear and corrosion resistance, durability and ruggedness and because it's reasonably easy to machine. It's now the standard in the industry for sports performance watches." And like most stainless steels, its corrosion resistant quality means that it is appropriate for use by those who may be allergic to nickel.

Chapter 5
Joining

Chapter 5

Joining

Welding

Nickel and plays a major role in the weldability of all types and families of stainless steel. The austenitic grades have a forgiving nature, which means good and reproducible results can be obtained even under difficult circumstances. When welding any stainless grade, certain steps need to be taken to ensure good quality, including cleanliness and post-weld cleaning. Stainless steels are often used in demanding applications, such as those where corrosion resistance or high-temperature properties are needed, so it is necessary to ensure the weld metal is not the weakest link in the chain. Generally, the more highly alloyed a grade is, the more care and precaution need to be taken.

Photo courtesy of:
Rafael Vinoly Architects PC

Austenitic stainless steels One important property of austenitic stainless steels is that they are not hardenable by heat treatment, nor by the heat from welding. Because they are not susceptible to hydrogen embrittlement, austenitic stainless steels normally do not require any pre-heating or post-weld heating. Materials ranging in thickness from thin to heavy are quite easily welded. Cleanliness (freedom from oil, grease, water, scale, etc.) is very important.

Welding of austenitic stainless steels can be done by most commercial welding processes, with the exception of oxy-acetylene welding, which cannot be used on any stainless steel. The most common processes include SMAW (shielded metal arc), GMAW (gas metal arc), GTAW (gas tungsten arc), SAW (submerged arc), FCAW (flux-cored arc), spot or resistance, laser, and electron beam. Many, but not all austenitic stainless steels can be welded without filler metal and without any further heat treatment. Most of the super austenitic alloys require the use of filler metal to obtain proper corrosion resistance of the weld. Normally, the weld metal is able to meet the minimum yield and tensile strength requirements of the annealed base material. The ductility of the welds is generally lower than base metal, but they are still very ductile. Low carbon grades (L-grades) of filler metals are normally used for corrosion-resistant service. For high-temperature service, the higher carbon filler metals may give better high-temperature strength.

"The austenitic grades have a forgiving nature."

The compositions of many of the 300 series filler metals are adjusted so that they solidify with a certain amount of ferrite to prevent hot cracking during solidification. This allows for higher heat inputs and thus higher welding speeds. The presence of a certain amount of ferrite means that welds are slightly ferromagnetic. Those alloys that solidify fully or nearly fully austenitic must be welded with lower heat inputs. For certain applications, a low ferrite weld metal is desirable, and certain filler metals are produced for that purpose. For most 300 series stainless steels, a nominally matching filler metal is the most common filler metal used. Some exceptions to that rule are as follows:

1) When welding titanium-stabilized grades, niobium-stabilized filler metals are most often used, since titanium oxidizes in the arc. For example, 321 is welded with 347 filler metal.
2) The stainless steels with 6% or more molybdenum are welded with nickel alloy filler metals of the Ni-Cr-Mo type (for example, Alloy 625 or "C" type). There are some cases where grades with a molybdenum content as low as 3% are welded with a filler metal over-alloyed in molybdenum.

3) The 200 series are most often welded with 300 series filler metals of appropriate strength because of their better availability and, to some extent, better weldability. The high-nitrogen 200 series grades can lose some nitrogen during welding. For a few applications, a 200 series filler metal is the correct choice to achieve certain properties (though usually at a higher cost). The standard filler metals for the 304L and 316L grades are, by far, the most commonly available ones.

4) The free-machining austenitic stainless steels such as 303 contain high levels of sulphur and are generally considered unweldable. When it is absolutely necessary, small welds are made with 312 filler metal, even though there may be many small cracks that won't withstand much stress. Generally, it is best not to weld this grade.

The austenitic base metals generally have excellent cryogenic properties. For example, the ASME Boiler and Pressure Vessel Code does not require the low-temperature impact testing of wrought austenitic grades such as 304, 304L and 316L for service as low as minus 254° C (minus 450° F). However, castings and weld metal do need to be tested since they contain some ferrite, which does embrittle at low temperatures. Certain welding processes and/or certain filler metals may need to be used to meet the low-temperature impact requirements.

When welding dissimilar austenitic grades such as 304L and 316L, an austenitic filler metal is used. The grade selection depends on the required properties, most often corrosion resistance, of the weld metal. For welding of carbon steel or a ferritic, martensitic or precipitation-hardenable stainless steel to an austenitic stainless steel, again, an austenitic filler metal is mostly commonly used. Also, the required properties of the weld metal, such as strength and corrosion resistance, must be evaluated carefully before choosing the filler metal. Filler metals such as 309L, 309MoL and 312 are produced for such purposes, and all have compositions that result in a ferrite content higher than that of the standard grades, which makes them more forgiving to certain impurities and the difference in thermal expansion.

More information on welding of austenitic stainless steels can be found in Nickel Institute publication 11007, *Guidelines for the welded fabrication of nickel-containing stainless steels for corrosion resistant services.*

Photo courtesy of: Nickel Institute

Duplex Stainless Steels The base metal of most duplex stainless steels has a controlled composition and receives a controlled heat treatment to give a range of ferrite of 40-55%, with the balance being austenite. When making welds, the heating and cooling rates are less controlled, which gives a larger range of possible ferrite. It is important to avoid welding conditions where more than 65-70% ferrite results in either the weld metal or HAZ (heat-affected zone), as this may have very negative effects on corrosion resistance and perhaps mechanical properties.

For similar reasons, most specifications will also specify a minimum ferrite level of either 25% or 30%, though the consequences are not quite so severe. To avoid high ferrite, most duplex filler metals contain 2-3% more nickel than the base metal. In general, welding without filler metal must be avoided. In the case of one lean duplex stainless with about 1.5% nickel, the filler metal has about 6-7% more nickel to ensure suitable properties in the weld. Proper annealing of duplex welds can often reduce the ferrite content from unacceptably high levels; as a result, castings and welded pipe and fittings can be welded by filler metals without the elevated nickel content, or even without filler metal at all.

"Most duplex filler metals contain 2-3% more nickel than the base metal"

Welding of duplex is normally done without pre-heating or post-weld heat treatment. Welding of duplex stainless steels to austenitic grades is done using either a duplex filler metal or an austenitic one. The latter weld may be weaker than the duplex base metal but will be stronger than the austenitic base metal. Welding duplex to carbon steel is normally done with one of the higher ferrite-content austenitic filler metals (309L or 309MoL) or a duplex filler metal. Dissimilar welding to some higher-strength (hardness) carbon or low-alloy steels may require pre-heat and post-weld heat on the non-stainless metal, and this may have an effect on the duplex stainless steel. Metallurgical advice should be sought.

Duplex stainless steels, and especially the higher-alloyed ones, which are used for severe environments, require extra steps to ensure a weldment that meets the expected corrosion and mechanical properties. More information on welding of duplex stainless steels can be found in IMOA's publication *Practical Guidelines for the Fabrication of Duplex Stainless Steels (NI publication 16000).*

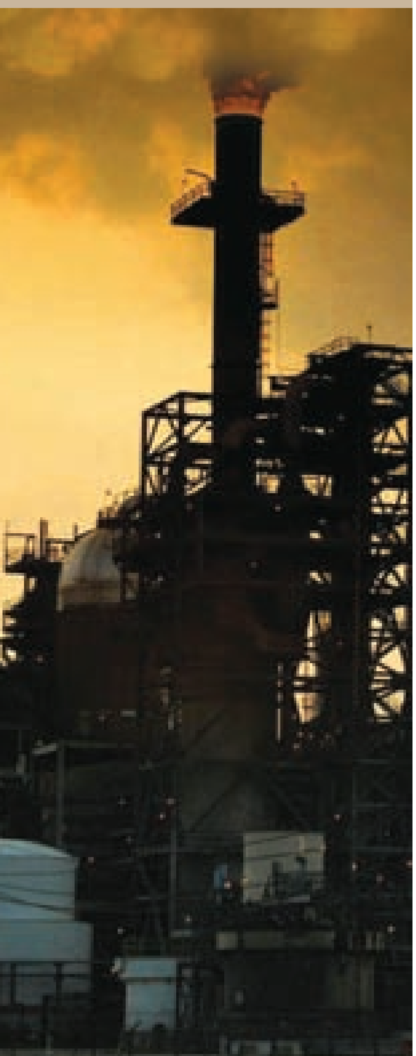


Photo courtesy of: Photos.com

Ferritic Stainless Steels For the 10.5-12% chromium ferritic stainless steels, which should be non-hardenable by heat treatment, welding is most often done either without filler metal or with a matching filler metal although often stabilized. Austenitic filler metals such as 308L are sometimes used when warranted by availability. Some of the weldable ferritic base metals (e.g., S41003) have an intentional nickel addition to control grain size both during manufacture of especially thicker sections and during welding. These are not true ferritic stainless steels and are better called "ferritic-martensitic alloys". They are usually welded with a 309L or occasionally other austenitic filler metal.

The 16-18% chromium ferritic grades that are molybdenum-free are most often welded with an austenitic filler metal, though matching filler metals may exist. These too are often stabilized.

The higher-alloyed ferritic stainless steels present special challenges in welding, discussion of which is outside the scope of this publication. In practice, austenitic filler metals are often used for welding these alloys. Always consult the alloy producer's data sheet for welding information. Since most of these alloys are not available in heavier wall thicknesses, there are often dissimilar metal welds – for example, a thin gauge ferritic tube to an austenitic tubesheet. These welds are always made using austenitic filler metals.

Martensitic and Precipitation-Hardenable (PH) Stainless Steels These materials also present special challenges when it comes to welding. If it is desirable that the weld metal be as strong (and hard) as the base metal, then a filler metal that responds to the same hardening treatment as the base metal should be used. This is most often not the case, and either austenitic stainless steel or nickel alloy filler metals are used. The resulting welds will be weaker than the base material, yet quite ductile. For martensitic grades, pre-heat and post-weld heat treatments are usually required, whereas for the PH grades, these may only be necessary in heavier thicknesses.

Post-weld Cleaning

Since all stainless steels rely on a protective oxide layer for corrosion resistance, it is important to perform an appropriate post-cleaning operation suitable to the end use. Details of such operations are described in NI publication 10004.

Other Joining Methods

Other joining methods used on stainless steels include brazing and soldering, as well as mechanical joining methods, all of which are mentioned below.

Brazing Austenitic stainless steels are regularly joined by brazing. Silver braze alloys are probably the most common braze metal, even though they are quite expensive. They are easy to use with a fairly low braze temperature and good corrosion resistance. Nickel braze filler metals, some with chromium, have greater corrosion resistance but require higher braze temperatures. For special applications, copper braze and gold braze filler metals are used. Before a braze metal is chosen, each application needs to be evaluated with regard to strength, corrosion resistance, the effect of braze temperature on the base metal, and the possibility of detrimental interaction of the braze metal with the base metal.

“Austenitic stainless steels are regularly joined by brazing.”

Soldering All stainless steels are fairly easily soldered, though titanium-stabilized grades can be problematic. Normally a lead-tin or a tin-silver solder is used. It is important that the protective oxide layer be removed by the flux. All solders have greatly inferior corrosion resistance and strength to the base metal.

Mechanical Joining Methods Joining methods such as bolting, screwing, riveting, clinching, lock seaming and gluing are all used with stainless steels. Generally, all these joints will have lower strength than welded joints. Corrosion may occur in the crevices that are formed. Potable water piping inside buildings is often cost effectively and securely joined by mchanical systems. Consideration should also be given to galvanic corrosion, where different metals, and even significantly different stainless alloys, are used. For example aluminum and galvanized carbon steel fasteners are less noble than stainless steel and may start to corrode quickly, particularly because of their small area in relation to the stainless steel.

Cross Reference for Filler Metals mentioned in this Chapter	
AWS (A5.4)	EN (1600)
308L	19 9 L
309L	23 12 L
309MoL	23 12 2 L
312	29 9
316L	19 12 2 L

Chapter 6
Sustainable Nickel

Chapter 6

Sustainable Nickel

Previous chapters have dealt with metallurgical aspects that relate to design and performance requirements. This chapter sets out some of the broader implications of those attributes, focusing on the sustainability aspects of those requirements.

Individuals and societies invest in products and systems to meet needs. In our complex age, the needs are many and increasing, and there are usually different ways in which they can be met. The cost of the resources needed, including the consequences of sourcing those resources, is testing the planet's ability to deliver. Materials that can reduce the intensity of material use become vital and here nickel contributes.

The efficient use of materials is essential. The luxury of taking care of needs in a crude, blunt fashion – throwing a lot of material and energy at a problem – is no longer sustainable. The employment of small amounts of nickel in stainless steels very often allows a decrease in material and energy needs, allowing lighter, hotter, more efficient, more elegant solutions to the needs of society. The presence or absence of nickel is, in many ways, a measure of eco-efficiency where it's the nickel that makes the positive difference.

"If something can deliver the same function with less material, it is an advance."

Only a few examples are offered here. They are representative, however, of thousands.

Building Lasting Infrastructure

Strength If something – a piece of infrastructure, a piece of equipment – can deliver the same function with less material, it is an advance. Because of their strength combined with corrosion resistance, nickel-containing, rebar can be of a lighter gauge and yet bear the same loads. Because the weight of steel in a structure is less, the amount of concrete needed for pillars can be proportionally reduced. In this example, the presence of a small amount of nickel allows a significant reduction in the amount of iron, cement and aggregate needed but delivers the same utility.

Enhanced corrosion resistance In climatic and geographic regions where salt or heavy industrialization is found, the addition of a small amount of nickel will allow very large reductions in the use of resources over the life cycle of structure or product. In many cases, it will increase the life of the product (and the uninterrupted availability of the function) by several multiples. It also can – depending on the product or function – totally remove the need for repeated maintenance and rehabilitation: no paint, no expensive repair of spalling concrete because of rusting rebar, no delay (with waste of fuel) and/or diversion (with increase in fuel use). In addition, the "cover" needed (the depth of the concrete and asphalt needed) to protect the rebar from corrosion attack is reduced. Less concrete and asphalt is needed. Less concrete and asphalt means less weight to be borne and the possibility of slimmer pillars and support beams resulting in less material used and less weight. The use of nickel-containing stainless steels enables this virtuous cycle.

"The material intensity of a bridge over its full cycle can be cut by 50%…"

Sustainability Indicative analyses show that the material intensity of a bridge or overpass over its full life cycle can be cut by 50% through the use of nickel-containing stainless steels. Elements going into this estimate take account of the energy associated with the production, use and final disposal of materials from paint to asphalt, and the higher percentage of material recovered and recycled at end-of-life because the nickel-containing stainless steels will have unimpaired quality and value. This is material (and financial resources and labour) that can be available for other societal needs even as the environmental impact of the structure is reduced.

Improving Energy Efficiency

Reflectivity Keeping heat in during the cold months of the year and keeping heat out of buildings during the hot months of the year is a challenge. Typically this has been managed through the use of energy: energy to heat, energy to cool, all with significant climate change implications. Intelligent design is a better way. The use of durable stainless steel roofing material with appropriate surface finishes and roof slopes allows a better heat balance. The result is less material intensity – the roof lasts the life of the building before being recycled at rates approaching 100% - and less energy intensity.

"The use of durable stainless steel roofing material allows a better heat balance."

Pittsburgh convention center

Photo courtesy of: Rafael Vinoly Architects PC

Enhanced corrosion resistance The obvious contributions for curtain walls and roofs has already been dealt with. There are, however, many more contributions that take small amounts of material, are hidden from sight, but which contribute significantly to efficiencies. One example are condensing gas boilers. They are the most energy-efficient boilers available, with efficiencies approaching 90 percent, a performance made possible because of nickel-containing stainless steel heat exchange surfaces. In this condensing heat exchange section, the combustion gases are cooled to a point where the water vapour condenses, thus releasing additional heat into the building.

Recycling at End-of-Life

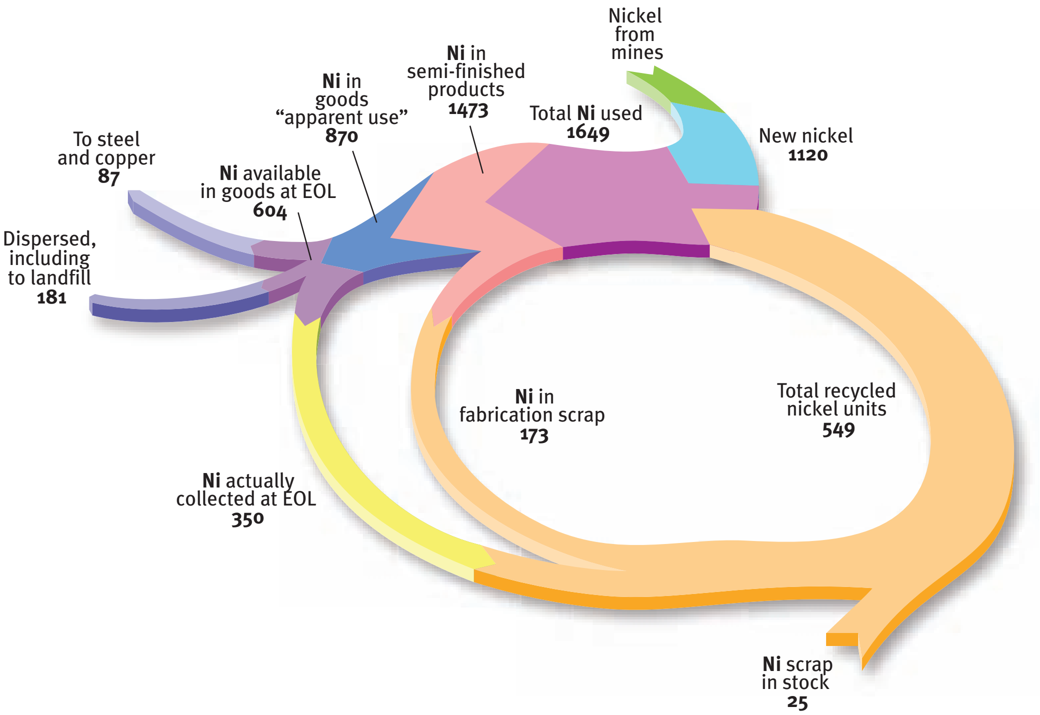
Almost any material can be recycled. The differences revolve around the amount of effort – including energy – needed to achieve the recycling and the quality of the recycled material. Metals in general perform very well in this regard and nickel-containing stainless steels are excellent for recycling. Nickel-containing scrap has significant economic value, sustains a large collection and scrap preparation industry, and allows the continuous and expanding production of "new" stainless steel with a global average of 60% recycled content without any loss of quality.

The 60% recycled content in the commodity grades of stainless steels is not a metallurgical limit. The constraint is the availability of supply. The expansion of demand for stainless steels, combined with the longevity of the products that contain stainless steel, means that there is a lag in scrap availability. There is no metallurgical reason why the recycled content of nickel stainless steels could not approach 100%.

Recycling does more than conserve physical resources although it does that very well. It also currently reduces energy demand by 33% and CO_2 production by 32% per tonne. As the ratio of scrap to virgin materials in stainless steel production increasingly favours scrap, the energy savings rise to a potential 67% for energy and 70% for CO_2. *(Yale[1])*

> *"Recycling currently reduces energy demand by 33% and CO_2 production by 32% per tonne."*

Nickel stocks and flows for the year 2000, in thousands of metric tonnes



Much of today's nickel stock is in use, bound in durable structures, engines, or piping that is still serving out its useful life in the product's life cycle.

Source: Yale University, 2008.

[1]Johnson, J. et al, The energy benefit of stainless steel recycling, Energy Policy. Vol. 36, Issue 1, Jan. 2008, p181ff.

Responsible Production and Use

The industry that produces the nickel and the value-chain that so directly supports the eco-efficient use of materials and energy is a global one. The primary nickel industry is present and active in every climatic and geographic area of the world and contributes to the economies of countries in every stage of economic development.

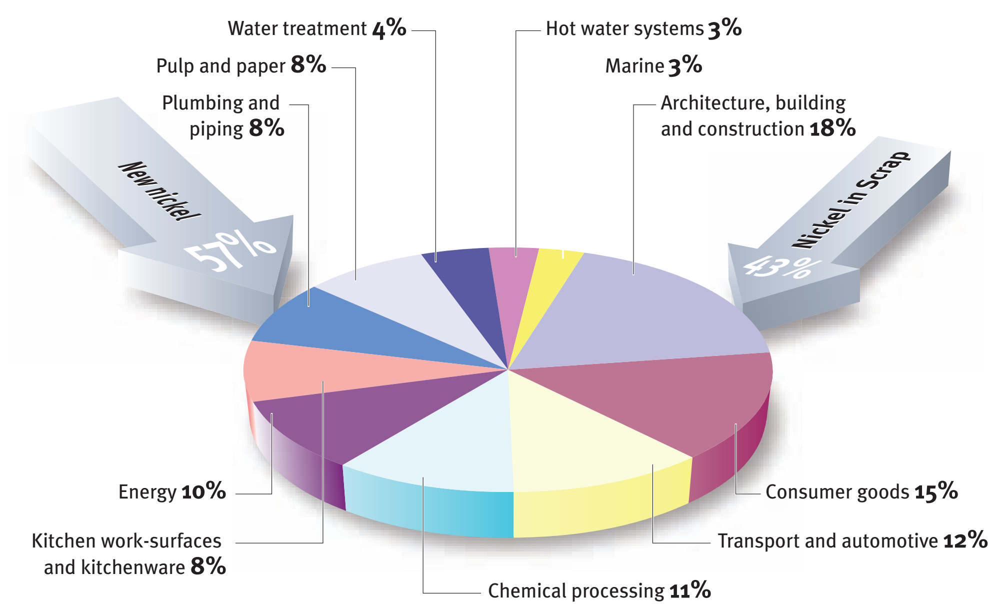
The management of the primary nickel industry is committed to responsible behavior in all its operations. By itself that may not stand out but the nickel industry goes further by actively engaging with the nickel value chain to transfer technology and techniques, maximize efficiencies, improve occupational health standards and performances, increase recycling and support basic science research on human and environmental health.

This commitment is codified in the Nickel Institute Sustainability Charter and acted upon through formal programs of product and material stewardship, and membership in the International Council on Mining and Metals (ICMM).

In summary, there are many reasons to use the nickel advantage for technical solutions to engineering and architectural challenges. At the same time, nickel's contributions to sustainability and climate change reduction are being maximized and nickel itself is being responsibly managed through its life cycle by the nickel value chain, starting with the primary nickel industry itself.

"There is no metallurgical reason why the recycled content of nickel stainless steels could not approach 100%."

End uses of nickel



Nickel is used in a wide range of applications. Architecture, consumer goods, transport and chemical processing use more than 50% of total nickel produced.

Source: Pariser, 2007.

Sources of Information on Nickel-Containing Stainless Steels

There are many sources of information on stainless steels including nickel-containing stainless steels available, which contain more detailed information than what is contained in this publication. Here are just a few:

Nickel Institute: Check the latest Publications Available catalogue or our website www.nickelinstitute.org which in addition to stainless steel also includes information about nickel alloys, copper-nickel alloys, nickel-containing irons and steel and nickel plating. In addition, *Nickel Magazine* contains many stories about nickel use, with a number of previous years issues archived on our website. Some of the more popular and relevant publications about stainless steel include:

Publ. No.	Title
14056	Stainless Steels: An Introduction to their Metallurgy and Corrosion Resistance
11021	High Performance Stainless Steels
11022	Castings - Stainless Steel and Nickel-base
2980	Engineering Properties of Austenitic Chromium-Nickel Stainless Steel at Elevated Temperatures
9004	High Temperature Characteristics of Stainless Steels
313	Austenitic Chromium-Nickel Stainless Steel at Subzero Temperatures
11023	Timeless Stainless Architecture
11024	Stainless Steels in Architecture, Building and Construction
10087	Stainless Steel for Potable Water Treatment Plants
10076	Stainless Steel in Municipal Waste Water Treatment Plants
12010	Stainless Steel in Swimming Pool Buildings
11003	Nickel Stainless Steels for Marine Environments, Natural Waters and Brines
11025	Stainless Steels and Specialty Alloys for Modern Pulp and Paper Mills
10057	Selection and Performance of Stainless Steels and other Nickel-bearing alloys in Sulphuric Acid
10075	Selection and Use of Stainless Steels and Nickel-bearing alloys in Nitric Acid
10063	Selection and Use of Stainless Steels and Nickel-bearing alloys in Organic Acids
10020	Alloys to Resist Chlorine, Hydrogen Chloride and Hydrochloric Acid
10015	Alloy Selection in Wet-Process Phosphoric Acid Plants
10074	Nickel-containing alloys in Hydrofluoric Acid, Hydrogen Fluoride, and Fluorine
10019	Alloy Selection for Caustic Soda Service
10071	Wrought and Cast Heat Resistant Stainless Steels and Nickel Alloys for the Refining and Petrochemical Industries
10073	Corrosion Resistant Alloys in the Oil and gas Industry
14054	Alloys for Marine Fasteners
11007	Guidelines for the Welded Fabrication of Nickel-containing Stainless Steels for Corrosion Resistant Applications
16000	Practical Guidelines for the Fabrication of Duplex Stainless Steels(Publ. by IMOA)
11026	Fabricating Stainless Steels for the Water Industry
10004	Fabrication and Post-fabrication Cleanup of Stainless Steels
10068	Specifying Stainless Steel Surface Treatment

ISSF (International Stainless Steel Forum) – www.worldstainless.org

Their website contains information on the production and use of stainless steels including Health and Environmental issues. Offers a Stainless Steel Specialist course. Has links with other websites.

Many countries and regions have their own organizations devoted to proper use of stainless steels. The major English language ones include:

EuroInox (European Stainless Steel Development Association) – www.euro-inox.org
Excellent publications in many European languages. Members are the various European national market development associations, including BSSA (British Stainless Steel Association) www.bssa.org.uk

SSINA (Specialty Steel Industry of North America) – www.ssina.com

ASSDA (Australian Stainless Steel Development Association) – www.assda.asn.org

NZSSA (New Zealand Stainless Steel Development Association) – www.hera.org/nz/nzssda/

ISSDA (Indian Stainless Steel Development Association) www.stainlessindia.org

SASSDA (South African Stainless Steel Development Association) – www.sassda.co.za

Other SSDA's include:

Brazil – www.nucleoinox.org.br
China – www.cssc.org.cn
Japan – www.jssa.gr.jp
Mexico – www.cendi.org.mx
Thailand – www.tssda.org

Other associations:

IMOA (International Molybdenum Association) – www.imoa.info/

ICDA (International Chromium Development Association) – www.icdachromium.com

Appendix

Composition of alloys mentioned in this publication.

Typical values in wt. % unless otherwise indicated.

UNS	AISI or common name	EN grade (approx.)	C (max.)	Cr	Ni	Mo	other
300 series Austenitic							
S30100	301	1.4310	0.15	17	7	-	-
S30200	302	1.4319	0.15	18	9	-	-
S30430	302HQ	1.4567	0.10	18	9	-	Cu
S30300	303	1.4305	0.15	18	9	-	S
S30400	304	1.4301	0.08	19	9	-	-
S30403	304L	1.4301	0.03	19	9	-	-
S30409	304H	1.4948	0.10 max. 0.04 min.	19	9	-	-
S30500	305	1.4303	0.12	18	12	-	-
S30900	309	1.4833	0.20	23	13	-	-
S31000	310	1.4841	0.25	25	20	-	-
S31600	316	1.4401	0.08	17	11	2.2	-
S31603	316L	1.4404	0.03	17	11	2.2	-
S31635	316Ti	1.4571	0.03	17	11	2.2	Ti
S31703	317L	1.4438	0.03	19	12	3.2	-
S31726	317LMN	1.4439	0.03	19	15	4.2	N
S32100	321	1.4541	0.08	18	10	-	Ti
S34700	347	1.4550	0.08	18	10	-	Nb
S31254	-	1.4547	0.02	20	18	6.2	N, Cu
S32053	-	-	0.03	23	25	5.5	N
S32654	-	1.4652	0.02	24	22	7.2	N, Cu, Mn
S34565	-	1.4565	0.03	24	17	4.5	N, Mn
N08020	Alloy 20	2.4660	0.06	20	34	2.5	Cu, Nb
N08028	Alloy 28	1.4877	0.03	27	32	3.5	Cu
N08330	330	1.4864	0.08	18	35	-	Si
N08904	904L	1.4539	0.02	20	25	4.5	Cu
200 series Austenitic							
S20100	201	1.4372	0.15	17	4.5	-	Mn
S20153	201LN	-	0.03	17	4.5	-	Mn, N
S20200	202	1.4373	0.15	18	5	-	Mn
Duplex							
S32101	2101	1.4162	0.03	21	1.5	-	Mn, N
S32304	2304	1.4362	0.03	23	4	0.2	N
S32205	2205	1.4462	0.03	22.5	5.5	3.2	N
S32506	–	–	0.03	25	6.5	3.3	N, W
S32750	2507	1.4410	0.03	25	7	4	N
400 series Ferritic							
S40900	409	1.4512	0.08	11	-	-	Ti
S43000	430	1.4016	0.12	17	-	-	–
S44600	446	1.4749	0.20	25	-	-	–
S44800	29-4-2	-	0.010	29	2.2	4	–
400 series Martensitic							
S41003	-	1.4003	0.03	11	0.5	-	–
S41000	410	1.4006	0.15	12	-	-	–
J91450	CA6NM	1.4317	0.06	13	4	0.7	–
Other Types							
S17400	630/17-4PH	1.4542	0.03	17	4	-	Cu, Nb

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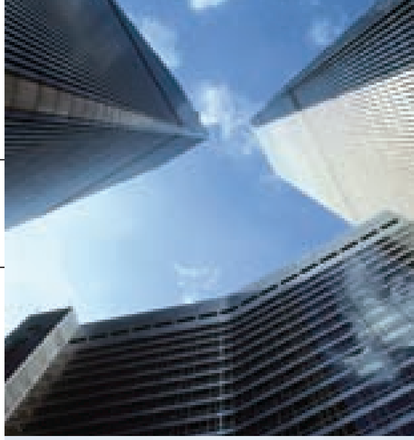



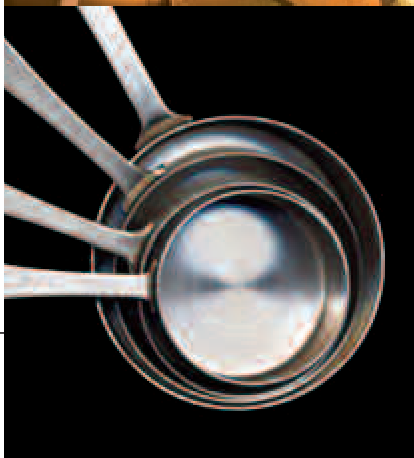

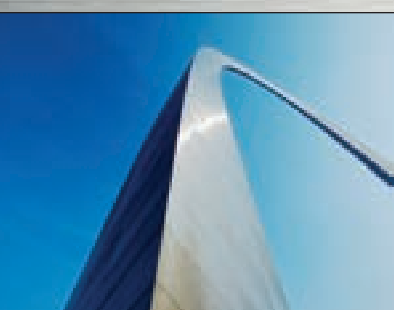

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