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Stainless Steel—What is it? Why do we use it?

This introduction provides an overview of stainless steel alloys and their properties. The selection and use of stainless steels for medical instruments and implantable devices will be addressed in future articles.

History

The concept of stainless steel was first discovered in the 1820's, when it was found that iron ore containing chromium was more resistant to acids than iron ore without chromium. Increasing the chromium content was shown to increase the material's resistance to attack by the acids; i.e. it increased the corrosion resistance. It was the need to improve the corrosion resistance of cannon barrels that led to this discovery.

The industrial usefulness of stainless steel was established during the period from 1900-1916, when several patents were issued for alloys of iron, chromium and carbon. A 1916 U.S. Patent was issued for an alloy containing 9-16% chromium and carbon below 0.7%. This alloy is essentially the present day Type 420 stainless steel.

Today

Modern stainless steels are still iron-based alloys containing chromium and carbon. However, the alloys now contain numerous other elements to enhance the material's performance (See Figure 1.) These elements include: nickel, molybdenum, copper, titanium, columbium (niobium), silicon, manganese, sulfur and nitrogen. Today, there over 400 unique combinations of these elements that are being produced as stainless steels.

Corrosion resistance is generally improved by increasing the amount of chromium, nickel, molybdenum, copper and nitrogen. Titanium and columbium prevent the formation of chromium carbides, thus reducing the likelihood of inter-granular corrosion in stainless steel that has been exposed to elevated temperatures.

Additions of carbon, molybdenum, columbium, titanium and nitrogen increase the *strength* of stainless steels. In general, copper and nickel do not directly affect the strength, but they reduce the work hardening rate of stainless steel, thereby increasing the material's ability to be severely cold-formed.

Figure 1. Effects of Alloying Elements (increasing amounts)

Element	Range(%)	Corrosion Resistance	Strength/ Hardness	Toughness	Fabrication
Cr - Chromium	10.5 to 30	Improve			
C – Carbon	<1.6	May reduce	Increase	Reduce	Reduce forming
Ni – Nickel	<40.0	Improve	Reduce work hardening	Increase	Improve forming
Mo - Molybdenum	<8.0	Improve	Pit/Crevice	Increase	Increase
Cu - Copper	<4.0	Improve	Reduce work hardening	Increase	
Mn – Manganese	<26.0	May reduce			
Cb – Columbium	<1.0	Improve	Increase		
Ti -Titanium	<2.3	Improve	Increase		
N – Nitrogen	<1.2	Improve	Increase	Increase	Stiffer
S – Sulfur & Se – Selenium	<1.0	Reduce	Reduce		Improve Machinability

Hardness is increased with the addition of carbon, nitrogen, and potentially with copper, titanium and columbium. *Toughness* and *ductility* can be enhanced by increasing nickel, molybdenum and nitrogen. Carbon, on the other hand, generally reduces toughness and ductility. Elements such as sulfur and selenium improve the *machinability* of stainless steels. However, additions of these elements can be detrimental to corrosion resistance and toughness.

Classifications

All stainless steels are iron-based alloys that contain at least 10.5% chromium, and varying amounts of carbon. Typically, they are segregated into five groups, or classifications, based upon the metallurgical structure of the alloys. While the mechanical and physical properties within a classification are similar in nature, the level or intensity in unique alloys within the classification vary.

Ferritic Stainless Steels

These steels contain 11% to 30% Cr and < 0.1% carbon. Molybdenum may be added for improved pitting corrosion resistance. Additions of titanium and/or columbium (niobium) may be made to prevent carbide precipitation when exposed to elevated temperatures, and also to control grain size during welding. (See Figure 2.)

These ferro-magnetic alloys may not be hardened or strengthened by heat treatment. While their hardness and strength may be increased by cold working, they are generally used in the annealed condition. They provide varying levels of corrosion resistance, from basic resistance to atmospheric corrosion, through excellent resistance to corrosion due to halides, such as chlorides. The absence of nickel ensures good resistance to halogen stress corrosion cracking. Typical ferritic stainless steels include: Types 405, 409-Cb, Chrome-Core® alloys, and AL 29-4® Alloy. These steels find application in fasteners, automotive, ornamental applications, kitchen utensils and solenoid valves. [*Chrome-Core® is a Registered Trademark of Carpenter Technology Corporation. AL 29-4® is a Registered Trademark of Allegheny Technologies.*]

Martensitic Stainless Steels

These steels contain at least 10.5 % chromium, and varying amounts of carbon. Varying amounts of nickel, molybdenum and vanadium are added to improve the material's corrosion resistance and response to heat treating. The carbon content ranges from <0.1% to >1.6%, and these steels develop hardness as high as HRC 63. These alloys exhibit the best edge retention, wear and galling resistance characteristics (due to the formation of carbides during heat treating) of any other stainless steel at same hardness. Thus, they are the preferred stainless steels for cutting and shaping devices. (See Figure 2.)

These steels are ferro-magnetic like the ferritic steels, but they are hardenable by thermal treatment. The heat treatment consists of hardening (1850°F-1950°F), quenching rapidly (to <60°F), and then tempering (350°F-600°F). Because of the high hardening temperature, physical distortion of the part can be a problem. This problem is generally addressed by performing the final machining or grinding operations after the part is fully heat treated.

Martensitic stainless steels are considered to have the lowest level of corrosion resistance of all the stainless steels. These alloys find use in surgical instruments (drills, rasps, reamers, scalpels, saw blades, etc.) bearings, cutting devices, valve and pump components and in wear and galling resistant applications. Typical martensitic stainless steels include: Type 410, 420, 440C, TrimRite®, and Chromflex®. [*TrimRite® is a Registered Trademark of Carpenter Technology Corporation. Chromflex® is a Registered Trademark of Sandvik AB.*]

Austenitic Stainless Steels

The "18-8" austenitic stainless steels are considered by many people to be *"The Stainless Steel."* The 18 Cr – 8 Ni alloys were the first alloys in this classification. Today, there are well over 100 such alloys.

Austenitic stainless steels are low carbon alloys of chromium and nickel. Significant amounts of molybdenum and copper may be added to improve corrosion resistance. Increasing the amount of nickel and copper improves the material's ability to be severely cold-deformed. Nitrogen may be added to increase the strength and corrosion resistance of these alloys. The following section on nitrogen-strengthened austenitic stainless steels will address the addition of nitrogen in greater depth.

Columbium (niobium) and titanium are added to prevent the formation of chromium carbides during exposure to temperatures in the range of 850^{o}F to 1600^{o}F, such as would occur during welding. The formation of chromium carbides causes a depletion of chromium in the area adjacent to the carbide, resulting in reduced corrosion resistance because the chromium is not available to combat the corrosion. (See Figure 2.)

While austenitic stainless steels are considered *non-magnetic*, there are occasions when some of them can be *magnetic*. The leaner, lower alloy content types of austenitic stainless steels can exhibit ferro-magnetic properties if they are severely cold-worked. This cold-working can result from intentional cold reduction or forming operations, or from extensive machining. Cold-working is the only way that the hardness of these alloys may be increased. They can not be hardened by heat treating.

Their superior toughness and ductility make this group of stainless steels the easiest to fabricate. They are also considered to have the best weldability of all of the stainless steels. Generally, austenitic stainless steels exhibit better corrosion resistance than other groups of stainless. The notable exception is their poor resistance to stress corrosion cracking in environments that contain halides, such as chlorides. The chloride stress corrosion cracking resistance is significantly reduced in stainless steels containing nickel in the range of 6% to 30%. The most severe reduction occurs in alloys with 8% to 12% nickel. The most commonly used austenitic stainless steels contain between 7% and 12% nickel.

Austenitic stainless steels find use in environments from potable water to aggressive chemicals. The molybdenum-bearing grades find extensive use in chloride-containing environments, such as the human body, to combat pitting and crevice corrosion. Typical applications where these alloys might find use include: tableware, fasteners, pumps, valves, fittings, surgical implants and

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instruments (bone plates, needles, clamps, mallets, forceps, etc.), and food and chemical processing equipment. Types 302, 303, 304/L, and 316/L are the most frequently used austenitic stainless steels. The more corrosion resistant alloys in this classification include: Type 317, Alloy 20Cb-3®, and AL6XN. [*20Cb-3 is a Registered Trademark of Carpenter Technology Corporation. AL6XN® is a Registered Trademark of Allegheny Technologies.*]

Nitrogen-Strengthened Austenitic Stainless Steels
These steels were developed because of the need for higher strength austenitic stainless steels. The addition of nitrogen increases the material's strength as well as its corrosion resistance. Chromium, nickel, manganese, molybdenum and nitrogen are the most common elements in these alloys. The manganese is added to the alloy to allow the increased amounts of nitrogen to be 'held' in solution. Typically, the nickel content is lower than in other stainless steels with similar corrosion resistance. (See Figure 2.)

Several of these alloys also contain increased silicon content to improve their resistance to galling. Examples include: 20Cb-3, and AL6XN. All of these alloys are non-magnetic in the annealed condition. Many of them are non-magnetic in all conditions, even after large amounts of cold deformation. This makes them ideal candidates for applications requiring good corrosion resistance and very low magnetic permeability, such as for drill collars used in the directional drilling of oil and gas wells.

In recent years, several nitrogen-strengthened austenitic stainless steels with very low nickel content have been developed for use in 'body contact' applications such as jewelry and implantable medical devices. Examples of nitrogen-strengthened austenitic stainless steels include: 18Cr-2Ni-12Mn Alloy, 22Cr-13Ni-5Mn Alloy, 734 Alloy, Nitronic® 60, GallTough®, and BioDur® 108. Pumps, valves, fittings, fasteners and medical devices (nails, bone plate, bone screws, etc.) are potential applications for these alloys. [*Nitronic® is a Registered Trademark of Armco, Inc. GallTough® and BioDur® are Registered Trademarks of Carpenter Technology Corporation.*]

Precipitation Hardening Steels
These steels might be considered *"The Best of Both Worlds."* They possess corrosion resistance similar to Type 304 austenitic stainless steels, with the strength of the martensitic stainless steels—in many cases with better toughness and ductility. These low carbon alloys contain 11% to 18% chromium and 3% to 12% nickel. Molybdenum may be present for improved corrosion resistance. Copper, titanium and/or columbium (niobium) are required for the precipitation (hardening) reaction. (See Figure 2.)

Precipitation hardening steels are normally strengthened by a single-step heat treatment in the temperature range of 900°F to 1150°F. This offers a significant advantage and potential cost saving compared to martensitic stainless steels, for which a two-step heat treatment is required. Precipitation hardening steels are ideal candidates when strength and toughness are required.

While their hardness may be similar to that of the martensitic stainless steels, they exhibit neither the edge retention nor wear and galling resistance characteristics. This is because of the strengthening mechanism. These alloys are strengthened through a precipitate, not through carbides as in the martensitic stainless steels. Edge retention, wear resistance and galling resistance all benefit from the presence of the hard carbides. Alloys in this classification include: PH13-8 Mo®, 15-5, Custom® 465, and the "old stand by" 17-4PH® (AISI 630). Medical instruments (clamps, reamers, forceps, etc.), fasteners, airframe components, shafts, pumps and valve trim are potential applications where precipitation-hardened stainless steels might be considered. [*PH13-8 Mo® is a Registered Trademark of Armco, Inc. Custom® is a Registered Trademark of Carpenter Technology Corporation. 17-4PH® is a Registered Trademark of Armco, Inc.*]

Editor: RSB Alloy Applications assists clients with the selection, application and fabrication of materials used in the design and manufacture of metallic devices. Their services include technological training on materials-related topics and technologies including materials development management, technical marketing of new or existing alloys, specification development and review, and the preparation and presentation of technical papers.

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Figure 2. Typical Stainless Steel Properties

Classification	Magnetic	Hardenable	Strength (Ksi) (YS/UTS)	Hardness	Corrosion Resistance	Fabricability	Weldability
Ferritic	Yes	No	50/85	HRB 86	Good	Moderate	Moderate
Martensitic	Yes	Heat Treatment	To 275/285	To HRC 63	Low	Low	Difficult
Austenitic	No	Cold Work	35/80 HRB 85	Good – Excellent	High	Excellent	
Nitrogen Strengthened	No	Cold Work	55/120 HRB 95	Good – Excellent	High	Moderate	
Precipitation Hardened	Yes/No	Cold Work & Heat Treatment	To 290/300	HRC 55	Good	Moderate	Good