Stainless Steel

Revised by
R. A. Lula, Consultant

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From *An Introduction to Stainless Steel*
by J. Gordon Parr and Albert Hanson

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Preface to the Revised Edition

An Introduction to Stainless Steel, written by J. Gordon Parr and Albert Hanson and published by the American Society for Metals, was a welcome contribution to the metallurgical literature in 1966. It was written at a time when stainless steels began to play an important role in all emerging technologies and to be used on a large scale in such everyday applications as appliances and automobiles. *An Introduction to Stainless Steel* has since been used by producers, fabricators, and users of stainless steels.

The metallurgy of stainless steels is a dynamic, fertile technical field fueled by continuous demands for new alloys with better properties and by the resourcefulness of the alloys system, which provides numerous possibilities for innovations. As a result, since the publication of the first edition, the metallurgy of stainless steels has been enriched not only by the development of a host of new alloys, but also by physical metallurgy studies that shed light on previously unexplicated phenomena.

The object of this revised edition is to provide the technical community with the latest developments and information essential to stainless steel metallurgy.

Natrona Heights, PA
May, 1985

R. A. LULA

Preface to the First Edition

"Stainless steel" is a generic term covering a large group of alloys. Commonly known for their corrosion resistance, these steels also exhibit a large range of other useful properties, the divergence of which can only be understood after the constitution and treatment are examined in an orderly fashion.

Such examination is the purpose of this book. The stainless steels are categorized, the reasons why each category has special properties are studied, and the properties themselves are enumerated. Methods of fabrication and heat treatment are considered on the same basis. Naturally, the mechanism and the achievement of corrosion resistance are also considered.

Because this is an introductory book, no pretense of including all information on stainless steels is made. Nevertheless, adequate data are presented to make this book a convenient basic reference once the reader has become acquainted with this group of steels.

It is our hope that this book will be understood by anyone engaged in the use or study of metals. So that the body of the book will not fail through a reader's lack of familiarity with metallurgical principles, a short introduction to the general subject is offered in Chapter 3. And so that the meaning of the more common terms used in specifying mechanical properties may be appreciated, an explanatory appendix is included.

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From Metals Handbook, Eighth Edition, Vol. 1, Figs. 4.6–4.9, 4.12, 4.13, 5.1, 6.2, 6.5, and Tables 5.1, 5.2 and 6.4. From Metals Handbook, Eighth Edition, Vol. 2, Figs. 4.5, 4.11 and Table 4.5. From *Metal Progress*, Figs. 6.6, 6.7, and Tables 6.1, 6.6 and 6.7. From Stainless Steel, by Carl Zapffe, Fig. 4.14.

February, 1966
Windsor, Ontario, Canada

J. GORDON PARR
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The Usefulness of Stainless Steels

Stainless steels do not rust in the atmosphere as most other steels do. The term "stainless" implies a resistance to staining, rusting, and pitting in the air, moist and polluted as it is, and generally defines a chromium content in excess of 11% but less than 30%. And the fact that the stuff is "steel" means that the base is iron.

Stainless steels have room-temperature yield strengths that range from 205 MPa (30 ksi) to more than 1725 MPa (250 ksi). Operating temperatures around 750 C (1400 F) are common, and in some applications temperatures as high as 1090 C (2000 F) are reached. At the other extreme of temperature some stainless steels maintain their toughness down to temperatures approaching absolute zero.

With specific restrictions in certain types, the stainless steels can be shaped and fabricated in conventional ways. They can be produced and used in the as-cast condition; shapes can be produced by powder-metallurgy techniques; cast ingots can be rolled or forged (and this accounts for the greatest tonnage by far). The rolled product can be drawn, bent, extruded, or spun. Stainless steel can be further shaped by machining, and it can be joined by soldering, brazing, and welding. It can be used as an integral *cladding* on plain carbon or low-alloy steels.

The generic term "stainless steel" covers scores of standard compositions as well as variations bearing company trade names and special alloys made for particular applications. Stainless steels vary in their composition from a fairly simple alloy of, essentially, iron with 11% chromium, to complex alloys that include 30% chromium, substantial quantities of nickel, and half a dozen other effective elements. At the high-chromium, high-nickel end of the range they merge into other groups of heat-resisting alloys, and one has to be arbitrary about a cutoff point. If the alloy content is so high that the iron content is about half, however, the alloy falls outside the stainless family. Even with these imposed restrictions on composition, the range is great, and naturally, the properties that affect fabrication and use vary enormously. It is obviously not enough to specify simply a "stainless steel."

Classification

The various specifying bodies categorize stainless steels according to chemical composition and other properties. For example, the American Iron and Steel Institute (AISI) lists more than 40 approved wrought stainless steel compositions; the American Society for Testing and Materials (ASTM) calls for specifications that may conform to AISI compositions but additionally require certain mechanical properties and dimensional tolerances; the Alloy Casting Institute (ACI) specifies compositions for cast stainless steels within the categories of corrosion- and heat-resisting alloys; the Society of Automotive Engineers (SAE) has adopted AISI and ACI compositional specifications. Military specification MIL-HDBK-5 lists design values. In addition, manufacturers' specifications are used for special purposes or for proprietary alloys. Federal and military specifications and manufacturers' specifications are laid down for special purposes and sometimes acquire a general acceptance.

However, all the stainless steels, whatever specifications they conform to, can be conveniently classified into six major classes that represent three distinct types of alloy constitution, or structure. These classes are ferritic, martensitic, austenitic, manganese-substituted austenitic, duplex austenitic-ferritic, and precipitation-hardening. Each class is briefly described here, but will be treated in detail in Chapter 4.

Ferritic Stainless Steels

This class is so named because the crystal structure of the steel is the same as that of iron at room temperature. The alloys in the class are magnetic at room temperature and up to their Curie temperature (about 750 C; 1400 F). Common alloys in the ferritic class contain between 11 and 29% chromium, no nickel, and very little carbon in the wrought condition. The 11% ferritic chromium steels, which provide fair corrosion resistance and good fabrication at low cost, have gained wide acceptance in automotive exhaust systems, containers, and other functional applications. The intermediatechromium alloys, with 16-17% chromium, are used primarily as automotive trim and cooking utensils, always in light gages, their use somewhat restricted by welding problems. The high-chromium steels, with 18 to 29% chromium content, have been used increasingly in applications requiring a high resistance to oxidation and, especially, to corrosion. These alloys contain either aluminum or molybdenum and have a very low carbon content.

Martensitic Stainless Steels

Just as iron-carbon alloys are heat treatable, so alloys with a properly adjusted composition of iron, chromium, and carbon (and other elements) can be quenched for maximum hardness and subsequently tempered to improve ductility. We recall that the *hardenability* of alloy steels is greater than that of plain carbon steels; that is, as the alloy content increases, so will a greater thickness be hardened under given quenching conditions. The martensitic stainless steels, which necessarily contain more than 11% chromium, have such a great hardenability that substantial thicknesses will harden during air cooling, and nothing more drastic than oil quenching is ever required. The hardness of the as-quenched martensitic stainless steel depends on its carbon content. However, as we shall see, the development of mechanical properties through quenching and tempering is inevitably associated with increased susceptibility to corrosion.

Austenitic Stainless Steels

The high-temperature form of iron (between 910 and 1400 C, or 1670 and 2550 F) is known as austenite. (Strictly speaking the term austenite also implies carbon in solid solution.) The structure is nonmagnetic and can be retained at room temperature by appropriate alloying. The most common austenite retainer is nickel. Hence, the traditional and familiar austenitic stainless steels have a composition that contains sufficient chromium to offer corrosion resistance, together with nickel to ensure austenite at room temperature and below. The basic austenitic composition is the familiar 18% chromium, 8% nickel alloy. Both chromium and nickel contents can be increased to improve corrosion resistance, and additional elements (most commonly molybdenum) can be added to further enhance corrosion resistance.

Manganese-Substituted Austenitic Stainless Steels

The austenitic structure can be encouraged by elements other than nickel, and the substitution of manganese and nitrogen produces a class that we believe is sufficiently different in its properties to be separated from the chromium-nickel austenitic class just described. The most important difference lies in the higher strength of the manganese-substituted alloys.

Duplex Austenitic-Ferritic Stainless Steels

The structure of these steels is a hybrid of the structures of ferrite and austenite; and the mechanical properties likewise combine qualities of each component steel type. The duplex steels combine desirable corrosion and mechanical properties, and their use is as a result increasing in both wrought and cast form.

Precipitation-Hardening Stainless Steels

Just as the familiar aluminum age-hardening alloys can be heat treated to improve their strength through a process that is associated with the formation of a precipitate, so stainless steels can be designed so that their composition is amenable to precipitation hardening. This class cuts across two of the other classes, to give us martensitic and austenitic precipitation-hardening stainless steels. In this class we find stainless steels with the greatest useful strength as well as the highest useful operating temperature.

Properties

Properties are substantially influenced by chemical composition and microstructure. Hence specifications include chemical composition, or, more correctly, an analysis of the most important elements (traces of unreported elements also may be present) as well as a heat treatment that provides the optimum structure.

Mechanical properties—strength, ductility, hardness, creep resistance, fatigue—of various wrought and cast stainless steels are discussed at length in Chapters 4 and 5. To give some idea of the ball park in which the stainless game is played, some favorable extremes of data are presented in Table 1.1.

We assume that the reader knows how physical properties—density, thermal conductivity, electrical resistivity, and so on—are defined, to the extent that will be required by this book.

Although the corrosion-resistant properties of stainless steel are dealt with in some detail in Chapters 7 and 8, it is necessary to introduce the subject here because many applications depend so much on corrosion resistance. A stable, protective layer forms very rapidly on the surface of stainless steel when it is in most oxidizing environments, and it is produced almost immediately in air at normal temperatures. It has been established that the protective layer is actually a very thin chromium oxide film. If corrosive media attack the oxide, or if they establish conditions that prevent its renewal when it is abraded, then the steel will succumb to corrosion.

Table 1.1. Best performance properties of some stainless steels

Steel	Condition	Approximate composition, %	Property(a)
17-7 PH (precipitation-hardening)	Wrought, aged	17 Cr, 7 Ni, 0.05 C, 1 Mn, 1 Al	Yield strength of 1790 MPa (260 ksi) at room temperature
301 (austenitic)	Wrought, annealed	18 Cr, 8 Ni, 0.1 C	Izod value of 135 J (100 ft·lb) at −185 C (−300 F)
316 (austenitic)	Wrought	18 Cr, 8 Ni, 0.05 C, 2 Mo	Extremely slight rust stain on 15% of sample surface and average pit depth of 1 mil after 15-yr exposure in marine atmosphere (Kure Beach, N.C.)
HK (austenitic)	Cast	26 Cr, 20 Ni, 0.4 C	Rupture strength of 35 MPa (5000 psi) at 870 C (1600 F) after 1000 h
HI (austenitic)	Cast	28 Cr, 15 Ni, 0.3 C	Less than 1.3-mm (50-mil)-thickness loss per year in oxidizing or reducing flue gas at 1090 C (2000 F)

(a) This is simply the property to which we wish to draw attention.

Under these circumstances, corrosion can be mitigated to some extent by the influence of other alloying elements that, in any case, play their part in specific environments. But in the broad case, and considering the simple model of stainless steel protected by a chromic oxide film, we would anticipate attack by reducing mineral acids (hydrochloric, hydrofluoric) and by reducing organic acids. Depending on oxygen content, concentration, temperature, and other factors, sulfuric acid is or is not corrosive. Nitric acid, a highly oxidizing liquid, maintains the protective oxide layer. In the organic acids associated with most food products (citric, malic, tartaric), stainless steel resists corrosion; hence its wide application in the foodstuffs and dairy industries.

The outstanding performance of the stainless steels is in atmospheric environments. In dry or wet rural atmospheres any stainless is—to put it crassly—stainless. In polluted atmospheres the performance varies very considerably from one grade of stainless to another.

Selection

The justification for selecting stainless steel is corrosion and oxidation resistance. Stainless steels possess, however, other outstanding properties that in combination with corrosion resistance contribute to their selection. These are the ability to develop very high strength through heat treatment

Table 1.2. Production of stainless and heat-resisting steels in the United States(a)

Year	Ingot production, thousands of tonnes (tons): Chromium steels	Ingot production, thousands of tonnes (tons): Chromium-nickel steels	Total mill shipments, thousands of tonnes (tons)
1976	424 (467)	1029 (1134)	924 (1019)
1977	488 (538)	1145 (1262)	1014 (1118)
1978	496 (547)	1192 (1314)	1080 (1191)
1979	494 (544)	1340 (1477)	1235 (1361)
1980	351 (387)	1098 (1210)	1022 (1127)
1981	368 (406)	1129 (1245)	1055 (1163)

(a) Data from American Iron and Steel Institute.

or cold working; weldability; formability; and in the case of austenitic steels, low magnetic permeability and outstanding cryogenic mechanical properties.

Stainless steels have been used in increasing amounts as shown in Tables 1.2 and 1.3. Table 1.2 gives production figures by type, and Table 1.3 by product form.

The choice of a material is not simply based on a single requirement, however, even though a specific condition (for example, corrosion service) may narrow the range of possibilities. For instance, in the choice of stainless steel for railroad cars, while corrosion resistance is one determining factor, strength is particularly significant. The higher price of stainless steel compared with plain carbon steel is moderated by the fact that the stainless has about twice the allowable design strength. This not only cuts the

Table 1.3. Mill shipments of stainless steel in 1981 in the United States(a)

Steel products	Net tonnes	(tons)
Semifinished	80,676	(88,929)
Shapes and plates	110,971	(122,323)
Bars	117,060	(129,034)
Pipe and tubing	35,478	(39,107)
Wire	23,359	(25,748)
Hot rolled sheets	26,535	(29,249)
Cold rolled sheets	458,141	(505,006)
Hot rolled strip	8,344	(9,198)
Cold rolled strip	194,870	(214,804)
Total net shipments	1,055,435	(1,163,398)

(a) Data from American Iron and Steel Institute.

amount of steel purchased, but, by reducing the dead weight of the vehicle, raises the load that can be hauled. The same sort of reasoning is even more critical in aircraft and space vehicles.

But weight saving alone may be accomplished by other materials, for examples, the high-strength low-alloy steels in rolling stock and titanium alloys in aircraft. Thus, the selection of a material involves a careful appraisal of all service requirements as well as a consideration of the ways in which the required parts can be made. It would be foolish to select a material on the basis of its predicted performance if the required shape could be produced only with such difficulty that cost skyrocketed.

The applicability of stainless steels may be limited by some specific factor, for example, an embrittlement problem or susceptibility to a particular corrosive environment. In general terms, the obvious limitations are:

1. In chloride environments susceptibility to pitting or stress-corrosion cracking requires careful appraisal. One cannot blindly assume that a stainless steel of some sort will do. In fact, it is possible that no stainless will serve.
2. The temperature of satisfactory operation depends on the load to be supported, the time of its application, and the atmosphere. However, to offer a round number for the sake of marking a limit, we suggest a maximum temperature of 870 C (1600 F). Common stainless steels can be used for short times above this temperature, or for extended periods if the load is only a few thousand pounds per square inch. But if the loads or the operating periods are great, then more exotic alloys are called for.

The type of compilation given previously in Table 1.1 ignores that prime engineering parameter, cost. And while it indicates upper performance limits, it does not suggest any guide to economy. For example, while 316 performs well in the Kure Beach atmosphere, the use of this comparatively high-priced stainless steel is not required for architectural purposes. And the very high yield strength of the 17% chromium, 7% nickel precipitation-hardening steel would not be called for in, let us say, rolling-stock construction. The data in Table 1.4 suggest, in a very broad way, the most economical class of stainless for various types of service. (Here we assume that general considerations of corrosion resistance, strength, and high-temperature properties call for the use of a stainless steel.) The choice may be completely changed, however, through considerations of fabrication or availability.

In some applications, the use of a stainless-clad material offers an economically attractive combination of a corrosion-resistant surface bonded onto a suitably strong, and reasonably cheap, backing. Clad plate, sheet,

Table 1.4. The most economical class of stainless for various types of service(a)

Type of service	Stainless class
Atmospheric corrosion	Austenitic and manganese-substituted austenitic
Interior trim	Ferritic
Freshwater corrosion	Ferritic
Marine environment	Austenitic and high-chromium ferritic
Low temperatures	Austenitic and manganese-substituted austenitic
High temperatures up to 650 C (1200 F)	Ferritic, martensitic, precipitation-hardening, austenitic
High temperatures above 650 C (1200 F)	Austenitic or precipitation-hardening
High strength at normal temperatures	Martensitic
High strength at elevated temperatures	Precipitation-hardening, martensitic
High strength at low temperatures	Austenitic or manganese-substituted austenitic

(a) It is assumed here that general considerations of corrosion resistance, strength, and high-temperature properties seem to indicate the use of a stainless steel.

and tubular products have been available for over 40 years. Any of a number of techniques produces a stainless steel layer integrally bonded to a plain carbon or low-alloy steel backing, and the thickness of the stainless cladding is usually between 10 and 20% of the total plate thickness. It is important to point out that an economic analysis of comparative prices of solid stainless or clad material must include the cost of fabricating the material into the structure. The difficulties that may arise, for example, in welding the composite material, can be overcome, but probably add to fabricating costs.

Selection Based on Life Cycle Cost

Modern engineering requires a life cycle cost analysis of equipment and plants before major capital investments are committed. This method requires identification and optimization of every relevant cost factor over the entire life cycle of an asset. Concerning the materials used in a new installation, their selection based on initial purchase price could be misleading; and a proper life cycle analysis would demonstrate that a lower-priced material would be rather costly in the long run.

Indeed the ultimate cost of a plant should include not only the purchase price, fabrication, and operation, but also maintenance, downtime, and early replacement costs.

With most stainless steel applications, the selection comes easily, as often only one material will perform adequately in the respective environment. The lower-chromium stainless steels, however, primarily the 12% chromium steels as exemplified by type 409 and its many proprietary modifications, form a category apart since they are used in functional applications in which they compete with lower-priced materials like galvanized steel and other coated materials. Life cycle cost analysis in these applications is highly recommended; such an analysis could point out that by using 409, a substantial cost reduction could be achieved over the entire life of an asset by maximizing the return on investment, and by reducing downtime, maintenance, and early replacements.

Applications Involving Resistance to Corrosion

Architecture

The austenitic stainless steels are being used in increasing amounts as architectural materials because of their durability and their nearly maintenance-free surface. The corrosion resistance of stainless steel is adequate for all kinds of outdoor applications. The various finishes available from the stainless steel producers enhance the esthetic appeal. Stainless steel can have a brushed finish, a highly polished finish, or a bright annealed finish but the most widely used is the 2B mill finish. The "dead soft" austenitic steel is used as a flushing and roofing material because it is easy to form as well as durable.

The Chrysler Building in New York City was one of the first to be built using stainless steel. Since its construction, numerous commercial industrial buildings have followed its lead. An outstanding use of stainless steel in a work of outdoor art is the "Gateway to the West" arch on the bank of the Mississippi River in St. Louis, Missouri.

Transportation Systems

The use of ferritic stainless steel in automotive trim was largely responsible for the increased production of types 430 and 434. Austenitic steels, including the manganese-substituted grades, are now being used to a greater extent, and the possibilities of using lighter-gage material with adequate strength and resistance to denting offer prospects for a greater number of stainless steel applications.

Type 409, a ferritic steel with about 11% chromium, is now used across the board in catalytic reactors for automobiles and is being adopted also for exhaust manifolds. This steel withstands corrosive conditions on the