Atlas Steels Technical Handbook of Stainless Steels

Forward

This Technical Handbook of Stainless Steels has been produced as an aid to all Atlas Steels personnel, their customers and the engineering community generally. It is intended as a source of ongoing reference data.

Details of specific products are given in the Atlas Steels "Product Reference Manual", the series of "Grade Data Sheets" and "Tech Notes" as listed below. Copies can be viewed or downloaded from the Atlas Steels intranet or website.

Atlas Steels Grade Data Sheets

Austenitic Stainless Steels

253MA (UNS S30815)
301, 301L, 301LN
302HQ
303, 303Se
304, 304L, 304H
310, 310S, 310H
316, 316L, 316H
321, 321H
904L

Ferritic Stainless Steels

3CR12
3CR12Ti
409
430, 430F
439
444

Duplex Stainless Steels

2101
2304
2205
2507
2507Cu

Martensitic Stainless Steels

410
416
420
431

Precipitation Hardening Stainless Steels

Stainless Steel 630 (17-4PH)

Atlas Steels Tech Notes

No. 1	Qualitative Sorting Tests for Stainless Steels.
No. 2	Pitting & Crevice Corrosion of Stainless Steels.
No. 3	Stainless Steels – Properties & Equivalent Grades.
No. 4	Machining of Stainless Steels.
No. 5	Cleaning, Care & Maintenance of Stainless Steels.
No. 6	Life Cycle Costing.
No. 7	Galvanic Corrosion.
No. 8	"L", "H" and Standard Grades of Stainless Steels.
No. 9	Stainless Steel Tube for the Food Industry.
No. 10	Restrictions of Hazardous Substances (RoHS).
No. 11	Magnetic Response of Stainless Steels.
No. 12	Pipe Dimensions.
No. 13	"3CR12" & "3CR12Ti" The 12% Chromium Ferritic Stainless Steels.
No. 14	Aluminium Alloys 5052 and 5251 - Quite Similar but Completely Different.

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The Family of Materials

Materials can be divided into metals and non-metals; the history of civilisation has largely been categorised by the ability to work metals – hence "bronze age" and "iron age" - but until quite recently most large-scale construction was still in non-metals, mostly stone or masonry and wood.

Today a vast number of materials compete for their share of the market, with more new materials being added every year. Some particularly exciting developments are now occurring in the fields of ceramics, plastics and glasses and composites of these materials. The day of the ceramic car engine is probably not all that far off - already there are some high temperature components made from the new generation of tougher ceramics, and the modern motor vehicle also offers many examples of the use of engineering plastics. Recent developments in metals have re-asserted their competitive position in auto engineering, in particular the use of aluminium and magnesium alloys. A major revolution under way at present is the replacement of much copper telecommunications cabling with glass optical fibre. For metals to compete they must be able to demonstrate superior properties to their competitors.

Type	Typical Grade	Alloy Content	Typical Uses
plain carbon steels	1020	0.2% C	bridges, building frames & machinery shafts
low alloy steels	4140	0.4% C, 1.0% Cr, 0.2% Mo	highly stressed shafts & forged machine components
stainless & high alloy steels	304	0.05% C, 18% Cr, 9% Ni	corrosion resistant tanks, bolts & springs
tool steels	H13	0.4% C, 1.05% Si, 5.2% Cr, 1.3% Mo, 1.0% V	tools for casting and hot forging

Figure 1 Typical grades in each steel group

In a similar fashion each of the metals has to compete for its market share, based on demonstrated superiority of properties or economics. It is therefore worth identifying the various metals available and indicating just what their most important features are. A basic differentiation is to divide metals into "ferrous" and "non-ferrous", i.e. those iron-based and all the others.

Amongst the non-ferrous metals the most important for engineering applications are the families of aluminium alloys (with very low densities, high electrical and thermal conductivity, good formability and good corrosion resistance these find applications in aircraft, high tension electricity conductors, yacht masts etc.) and of copper alloys (with very high electrical and thermal conductivities and ready formability these find their principal applications in electrical wiring). Other important non-ferrous alloys (an alloy is simply a mixture of two or more metals) are the brasses and bronzes.

The family of ferrous metals incorporates a vast number of alloys. Those alloys containing a very high proportion of carbon (over about 2%) are called cast irons. Virtually all the remainder are termed steels and these can be found in either cast form (produced by pouring molten metal into a mould of the shape of the finished part) or wrought form (cast as ingots or continuous cast billets or slabs, but then hot rolled or forged to produce bars, plates or complex shapes such as rail sections and beams). They can also be formed to finished shape by sintering powdered metal at high temperature. Steels are categorised by their major alloying elements (carbon, manganese, chromium, nickel and molybdenum) and by the presence or absence of minor elements (silicon, sulphur, phosphorus, nitrogen and titanium), as shown in the table in Figure 1.

"Micro" additions of alloys are also present in some grades.

Atlas Steels distributes product from all four categories (plain carbon, low alloy, stainless and tool steels).

Steel Grade Designations

Designation systems for metals vary widely. In the past every producer had their own name for each grade they produced - some examples were "Duraflex" (BHP's name for 1045) and "Sixix" (Atlas Steels Canada's name for M2 high speed steel).

Thankfully this practice is now reducing, with benefits to all users. In some instances, there is justification for the use of a specific trade name, for instance where a manufacturer has made a grade significantly different from other similar products. This is particularly appropriate in new product areas such as duplex stainless steels, where national standards lag behind commercial alloy development, and where grades are still evolving. Some producers, however, cling to the use of trade names for quite standard grades in the hope of generating sales based on perceived rather than actual product superiority.

Apart from trade designations a variety of naming systems exist, supported by one or another standards body. In Australia metals designations tend to follow those of the USA - principally the American Iron and Steel Institute (AISI) and American Society for Testing and Materials (ASTM). These bodies many years ago developed three-digit designations for stainless steels, four-digit designations for carbon and low alloy steels and one letter plus one or two digits designations for tool steels. All three systems have proven inadequate for coping with an on-going series of new alloy developments, so a new Unified Numbering System (UNS) has been implemented by ASTM and the Society of Automotive Engineers (SAE). The UNS designations have been allocated to all metals in commercial production, throughout the world; a single letter indicates the alloy family (N = nickel base alloys, S = stainless steels, etc.) and five digits denote the grade. This system is now incorporated in all ASTM standards, and some standards from other countries such as Australia.

Japanese grade designations are based on the AISI/ASTM designations as far as stainless steels are concerned, with some modifications and exceptions. They follow their own system for other steels.

Until recent years British Standards had a designation system for steel grades based upon the AISI/ASTM system, but with extra digits to specify slight variants of grades, e.g. 316S31 was a particular variant of Grade 316 stainless steel.

Other European national standards were quite different, and differed among themselves. The most commonly encountered system was the German Werkstoff (Workshop) Number giving all steels a single digit plus four-digit designation, e.g. "1.4301" for Grade 304. A second identifier associated with each grade is the DIN designation, e.g. "X 5 CrNi 18 9" for Grade 304.

In addition to these national specifications there are International Standards (ISO) which tend to follow various European systems, and a newly developing set of "Euronorm" (EN) European specifications from the European Union. These Euronorms have now largely replaced national specifications from Britain, Germany, France and other member nations. For stainless steels the most common grade designation system in Australia and New Zealand is that of the American ASTM. There is however increased awareness of the Euronorm system.

An interesting development in 2006 was the minor revision of composition limits for grade 304 flat rolled product in ASTM A240 with the specific aim of harmonizing it with the European equivalent grade 1.4301. There is a long way to go, but perhaps this is the beginning of a truly uniform world-wide agreement on specifications.

Numerous cross references between grades are published; a very comprehensive publication is the German "Stahlschlüssel" (Key to Steel). This is particularly good for German specifications but does cover all significant steel specifying countries, including Australia, and lists trade names in addition to national specifications. Several web sites also give specification comparisons.

A summary of these grade equivalents (or near alternatives) is shown in Appendix 2.

Stainless Steels – Introduction to the Grades and Families

The group of alloys which today make up the family of stainless steels had their beginning in the years 1900 to 1915. Over this period research work was published by metallurgists in France and Germany on ferritic, martensitic and austenitic stainless steels. Commercialisation began in the years 1910 to 1915, with the Americans Dansitzen and Becket's work on ferritic steels and Maurer and Strauss developing austenitic grades in Germany. The often-related development of martensitic steels was in 1913 in Sheffield, England; Harry Brearley was trying a number of alloys as possible gun barrel steels, and noticed that samples cut from one of these trial Heats did not rust and were in fact difficult to etch. When he investigated this curious material - it contained about 13% chromium - it led to the development of the stainless cutlery steels for which Sheffield became famous.

Although the consumption of stainless steels is growing very rapidly around the world (average of 5.8% per annum in the Western world over the period 1950 to 2001) average per capita consumption in Australia is very low by comparison with other developed, and many developing countries. In 1999 Australians each consumed about 5kg, compared with about 8kg per head in France, 13kg in Japan, 16kg in Germany, 26kg in Singapore and 38kg in Taiwan. On average each Chinese consumed about 1.3kg, but this figure is rapidly rising.

The Families of Stainless Steels

Stainless steels are iron based alloys containing a minimum of about 10.5% chromium; this forms a protective self-healing oxide film, which is the reason why this group of steels have their characteristic "stainlessness" or corrosion resistance. The ability of the oxide layer to heal itself means that the steel is corrosion resistant, no matter how much of the surface is removed; this is not the case when carbon or low alloy steels are protected from corrosion by metallic coatings such as zinc or cadmium or by organic coatings such as paint.

Although all stainless steels depend on the presence of chromium, other alloying elements are often added to enhance their properties. The categorisation of stainless steels is unusual amongst metals in that it is based upon the nature of their metallurgical structure - the terms used denote the arrangement of the atoms which make up the grains of the steel, and which can be observed when a polished section through a piece of the material is viewed at high magnification through a microscope. Depending upon the exact chemical composition of the steel the microstructure may be made up of the stable phases austenite or ferrite, a "duplex" mix of these two, the phase martensite created when some steels are rapidly quenched from a high temperature, or a structure hardened by precipitated micro-constituents.

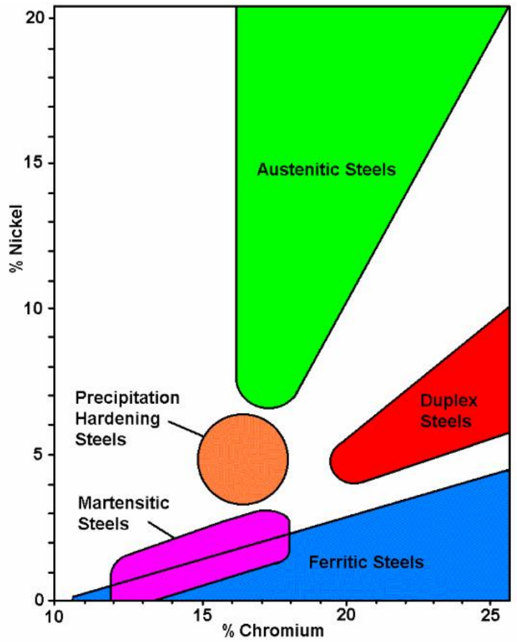

Figure 2 Families of stainless steels

The relationship between the different families is as shown in Figure 2.

A broad-brush comparison of the properties of the different families is given in Figure 5.

Austenitic Stainless Steels
This group contain at least 16%chromiumand 6% nickel (the basic grade 304 is sometimes referred to as 18/8) and range through to the high alloy or "super austenitics" such as 904L and 6% molybdenum grades.

Additional elements can be added such as molybdenum, titanium or copper, to modify or improve their properties, making them suitable for many critical applications involving high temperature as well as corrosion resistance. This group of steels is also suitable for cryogenic applications because the effect of the nickel content in making the steel austenitic avoids the problems of brittleness at low temperatures, which is a characteristic of other types of steel.

The relationship between the various austenitic grades is shown in Figures 3.

Ferritic Stainless Steels
These are plain chromium (10½ to 29%) grades such as Grades 430 and 409. Their moderate corrosion resistance and poor fabrication properties are improved in the higher alloyed and stabilised grades such as 439 and 444 and in the proprietary grade 3CR12.

The relationship between the various ferritic grades is shown in Figure 4.

Martensitic Stainless Steels
Martensitic stainless steels are also based on the addition of chromium as the major alloying element but with a higher carbon and generally lower chromium content (e.g. 12% in Grades 410 and 416) than the ferritic types; Grade 431 has a chromium content of about 16%, but the microstructure is still martensite despite this high chromium level because this grade also contains 2% nickel.

The relationship between the various martensitic grades is shown in Figure 4.

Duplex Stainless Steels
Duplex stainless steels such as 2205 and 2507 (these designations indicate compositions of 22% chromium, 5% nickel and 25% chromium, 7% nickel but both grades contain further minor alloying additions) have microstructures comprising a mixture of austenite and ferrite. Duplex ferritic - austenitic steels combine some of the features of each class: they are resistant to stress corrosion cracking, albeit not quite as resistant as the ferritic steels; their toughness is superior to that of the ferritic steels but inferior to that of the austenitic steels, and their strength is greater than that of the (annealed) austenitic steels, by a factor of about two. In addition, the duplex steels have general corrosion resistances equal to or better than 304 and 316, and in general their pitting corrosion resistances are superior to 316. They suffer reduced toughness below about -50°C and after exposure above 300°C, so are only used between these temperatures.

The relationship between the various duplex grades is shown in Figures 3.

Precipitation Hardening Stainless Steels
These are chromium and nickel containing steels which can develop very high tensile strengths. The most common grade in this group is "17-4 PH"; also known as Grade 630, with the composition of 17% chromium, 4% nickel, 4% copper and 0.3% niobium. The great advantage of these steels is that they can be supplied in the "solution treated" condition; in this condition the steel is just machinable. Following machining, forming etc. the steel can be hardened by a single, fairly low temperature "ageing" heat treatment which causes no distortion of the component.

Characteristics of Stainless Steels
The characteristics of the broad group of stainless steels can be viewed as compared to the more familiar plain carbon "mild" steels. As a generalisation the stainless steels have:

- Higher work hardening rate
- Higher ductility
- Higher strength and hardness
- Higher hot strength
- Higher corrosion resistance
- Higher cryogenic toughness
- Lower magnetic response (austenitic only)

These properties apply particularly to the austenitic family and to varying degrees to other grades and families.

These properties have implications for the likely fields of application for stainless steels, but also influence the choice of fabrication methods and equipment.

Standard Classifications
There are many different varieties of stainless steel and the American Iron and Steel Institute (AISI) in the past designated some as standard compositions, resulting in the commonly used three-digit numbering system. This role has now been taken over by the SAE and ASTM, who allocate 1-letter + 5-digit UNS numbers to new grades. The full range of these standard stainless steels are contained in the Iron and Steel Society (ISS) "Steel Products Manual for Stainless Steels", and in the SAE/ASTM handbook of Unified Numbering System. Certain other grades do not have standard numbers, but are instead covered by other national or international specifications, or by specifications for specialised products such as standards for welding wire.

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The following diagrams show most of the grades of stainless steels distributed by Atlas Steels and some other important grades, identified by their grade numbers or common designations, illustrating some of the important properties of the various families of grades.

Austenitic and Duplex Stainless Steels

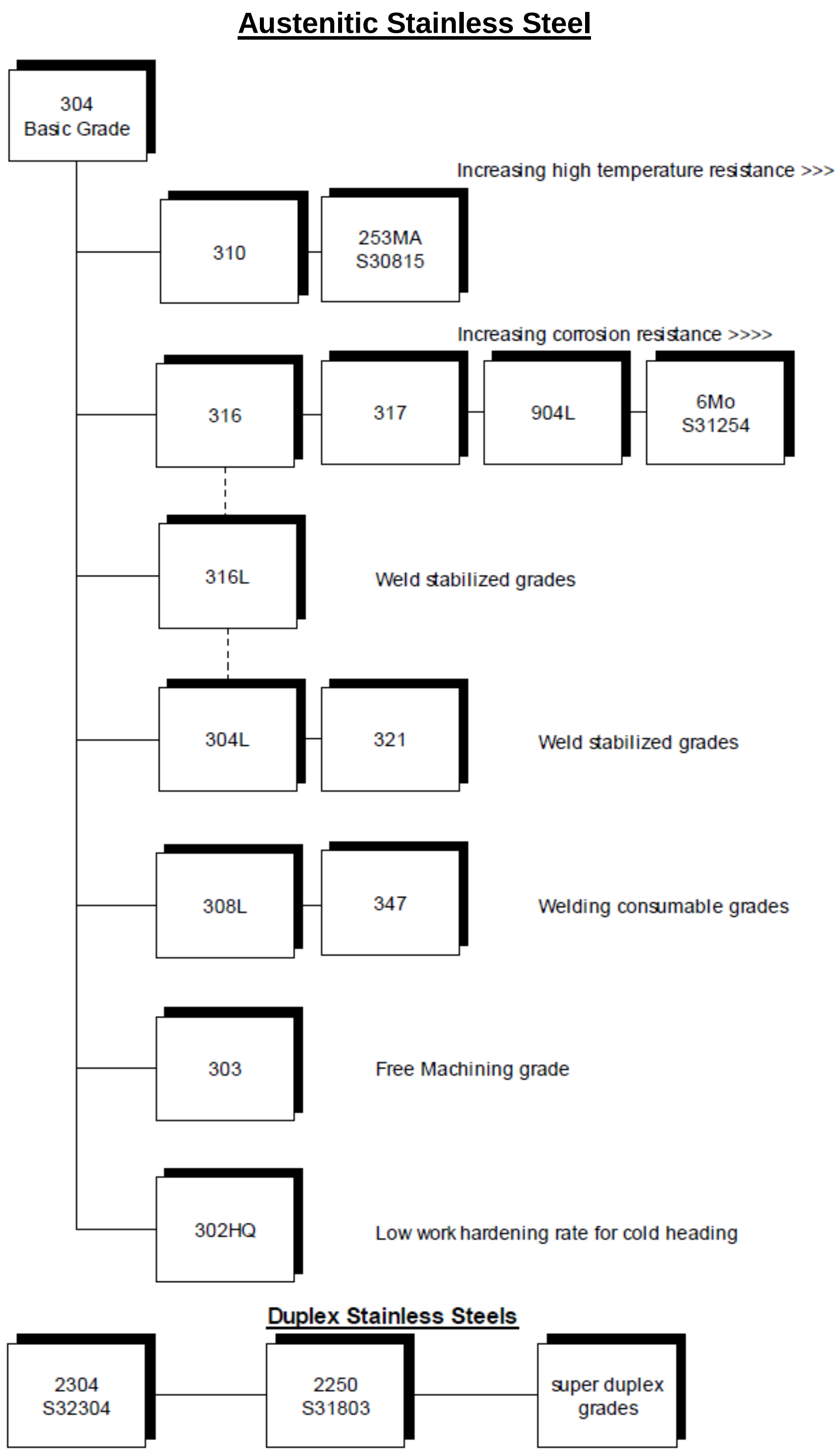

Figure 3 The families of Austenitic and Duplex Stainless Steels

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Ferritic and Martensitic Stainless Steels

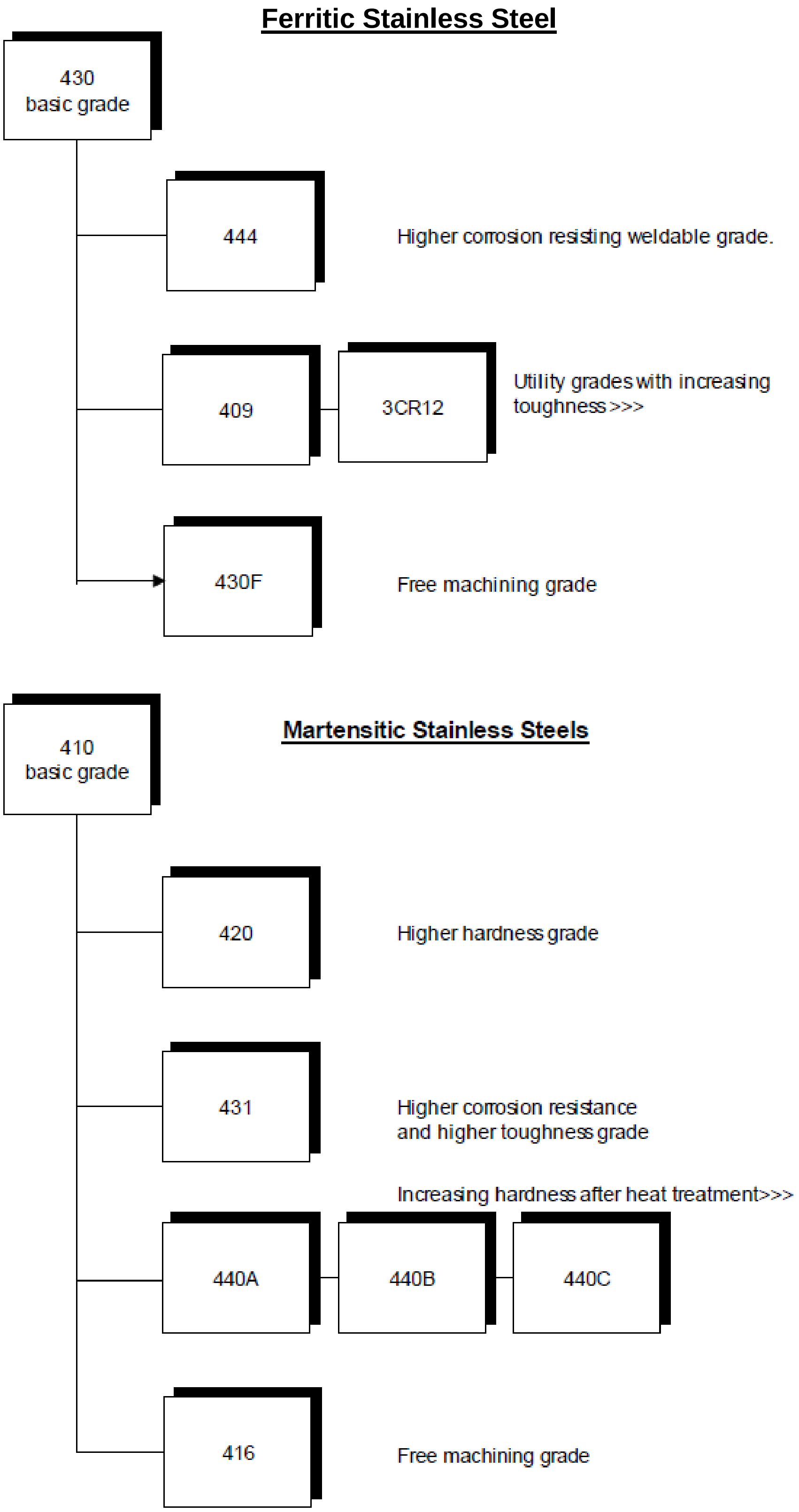

Figure 4 The families of Ferritic and Martensitic Stainless Steels

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Comparative Properties of the Stainless Steel Alloy Families

Alloy Group	Magnetic Response (note 1)	Work Hardening Rate	Corrosion Resistance (note 2)	Hardenable	Ductility	High Temperature Resistance	Low Temperature Resistance (note 3)	Weldability
Austenitic	Generally, No	Very High	High	By Cold Work	Very High	Very High	Very High	Very High
Duplex	Yes	Medium	Very High	No	Medium	Low	Medium	High
Ferritic	Yes	Medium	Medium	No	Medium	High	Low	Low to High
Martensitic	Yes	Medium	Medium	Quench & Temper	Low	Low	Low	Low
Precipitation Hardening	Yes	Medium	Medium	Age Hardening	Medium	Low	Low	High

Notes:

1. Attraction of the steel to a magnet. Note some austenitic grades can be attracted to a magnet if cold worked, cast or welded.
2. Varies significantly between grades within each group. e.g. free machining grades have lower corrosion resistances, those grades higher in chromium, molybdenum and nitrogen have higher resistances. Corrosion resistance is not primary related to the alloy group (structure) but more by the composition.
3. Measured by toughness or ductility at sub-zero temperatures. Austenitic grades retain ductility to cryogenic temperatures.

Figure 5 Comparative properties

Corrosion Resistance

Although the main reasons why stainless steels are used is corrosion resistance, they do in fact suffer from certain types of corrosion in some environments and care must be taken to select a grade which will be suitable for the application. Corrosion can cause a variety of problems, depending on the applications:

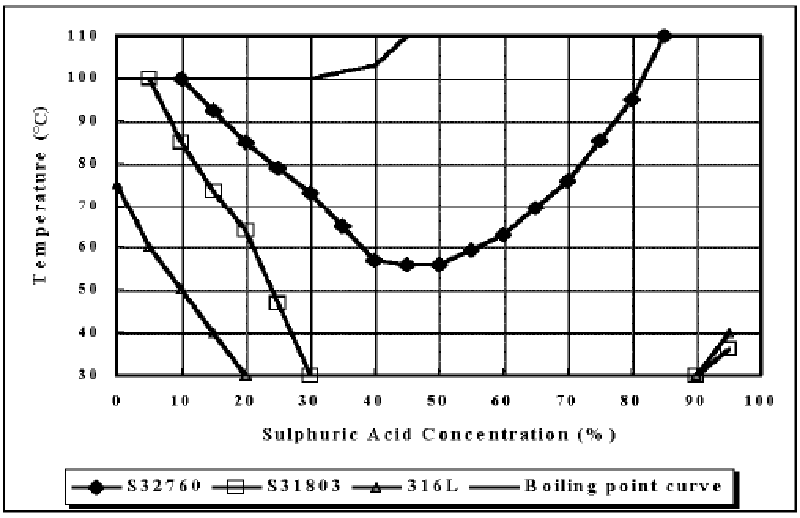
- Perforation such as of tanks and pipes, which allows leakage of fluids or gases,
- Loss of strength where the cross section of structural members is reduced by corrosion, leading to a loss of strength of the structure and subsequent failure,
- Degradation of appearance, where corrosion products or pitting can detract from a decorative surface finish,
- Finally, corrosion can produce scale or rust which can contaminate the material being handled; this particularly applies in the case of food processing equipment.

Corrosion of stainless steels can be categorised as:

- General Corrosion
- Pitting Corrosion
- Crevice Corrosion
- Stress Corrosion Cracking
- Sulphide Stress Corrosion Cracking
- Intergranular Corrosion
- Galvanic Corrosion
- Contact Corrosion

General Corrosion

Corrosion whereby there is a general uniform removal of material, by dissolution, e.g. when stainless steel is used in chemical plant for containing strong acids. Design in this instance is based on published data to predict the life of the component.



Published data list the removal of metal over a year - a typical example is shown in Figure 6.

Tables of resistance to various chemicals are published by various organisations.

Figure 6 ISO-corrosion curves for various stainless steels in sulphuric acid

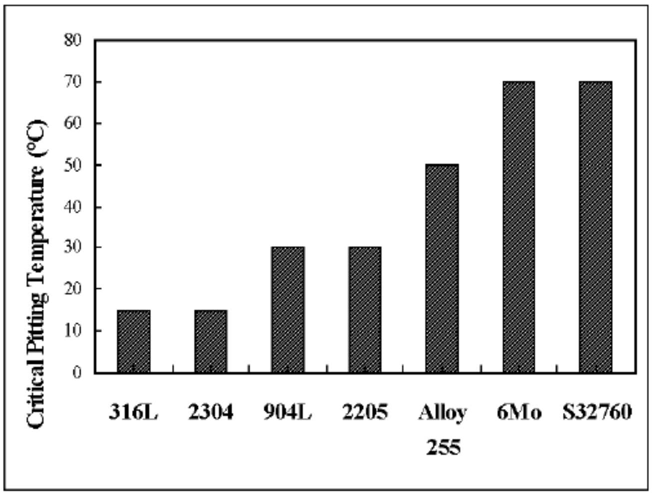
Pitting Corrosion

Under certain conditions, particularly involving high concentrations of chlorides (such as sodium chloride in sea water), moderately high temperatures and exacerbated by low pH (i.e. acidic conditions), very localised corrosion can occur leading to perforation of pipes and fittings etc. This is not related to published corrosion data as it is an extremely localised and severe corrosion which can penetrate right through the cross section of the component. Grades high in chromium, and particularly molybdenum and nitrogen, are more resistant to pitting corrosion.

The Pitting Resistance Equivalent number (PRE) has been found to give a good indication of the pitting resistance of stainless steels. The PRE can be calculated as:

$$PRE = \%Cr + 3.3 \times \%Mo + 16 \times \%N$$

One reason why pitting corrosion is so serious is that once a pit is initiated there is a strong tendency for it to continue to grow, even although most of the surrounding steel is still untouched.



The tendency for a particular steel to be attacked by pitting corrosion can be evaluated in the laboratory. A number of standard tests have been devised, the most common of which is that given in ASTM G48.

A graph can be drawn giving the temperature at which pitting corrosion is likely to occur, as shown in Figure 7.

Figure 7 Critical pitting temperatures for different alloys, rated by ASTM G48A test

The graph is based on a standard ferric chloride laboratory test, but does predict outcomes in many service conditions.

A very common corrosive environment in which stainless steels are used is marine, generally up to a few hundred metres from quiet (e.g.: bay) water, or up to a few kilometres from a shore with breaking waves. Corrosion in this environment is sometimes called "tea staining" … a term used by ASSDA (Australian Stainless Steel Development Association) to describe light surface rusting, usually visible as a fairly wide-spread brown-red discolouration. A very full description of the causes and prevention of tea staining is given in the ASSDA Technical Bulletin on the topic, available at the ASSDA website at www.assda.asn.au.

For many years 316 has been regarded as the "marine grade" of stainless steel. It must be recognised however, that in the more aggressive marine environments 316 will not fully resist pitting corrosion or tea staining. It has been found that finer surface finishes – generally with an Ra value of no coarser than 0.5µm will assist in restricting tea staining. It is also important that the surface is free of any contaminants.

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Crevice Corrosion

The corrosion resistance of a stainless steel is dependent on the presence of a protective oxide layer on its surface, but it is possible under certain conditions for this oxide layer to break down, for example in reducing acids, or in some types of combustion where the atmosphere is reducing. Areas where the oxide layer can break down can also sometimes be the result of the way components are designed, for example under gaskets, in sharp re-entrant corners or associated with incomplete weld penetration or overlapping surfaces. These can all form crevices which can promote corrosion.

To function as a corrosion site, a crevice must be of sufficient width to permit entry of the corrodent, but sufficiently narrow to ensure that the corrodent remains stagnant. Accordingly, crevice corrosion usually occurs in gaps a few micrometres wide, and is not found in grooves or slots in which circulation of the corrodent is possible. This problem can often be overcome by paying attention to the design of the component, in particular to avoiding formation of crevices or at least keeping them as open as possible.

Crevice corrosion is a very similar mechanism to pitting corrosion; alloys resistant to one are generally resistant to both. Crevice corrosion can be viewed as a more severe form of pitting corrosion as it will occur at significantly lower temperatures than does pitting. Further details of pitting and crevice corrosion are given in Atlas Tech Note No. 2.

Stress Corrosion Cracking (SCC)

Under the combined effects of stress and certain corrosive environments stainless steels can be subject to this very rapid and severe form of corrosion. The stresses must be tensile and can result from loads applied in service, or stresses set up by the type of assembly e.g. interference fits of pins in holes, or from residual stresses resulting from the method of fabrication such as cold working. The most damaging environment is a solution of chlorides in water such as sea water, particularly at elevated temperatures. As a consequence, many stainless steels are limited in their application for holding hot waters (above about 50°C) containing even trace amounts of chlorides (more than a few parts per million). This form of corrosion is only applicable to the austenitic group of steels and is related to the nickel content. Grade 316 is not significantly more resistant to SCC than is 304. The duplex stainless steels are much more resistant to SCC than are the austenitic grades, with grade 2205 being virtually immune at temperatures up to about 150°C, and the super duplex grades are more resistant again. The ferritic grades do not generally suffer from this problem at all.

In some instances, it has been found possible to improve resistance to SCC by applying a compressive stress to the component at risk; this can be done by shot peening the surface for instance. Another alternative is to ensure the product is free of tensile stresses by annealing as a final operation. These solutions to the problem have been successful in some cases, but need to be very carefully evaluated, as it may be very difficult to guarantee the absence of residual or applied tensile stresses.

From a practical standpoint, Grade 304 may be adequate under certain conditions. For instance, Grade 304 is being used in water containing 100 - 300 parts per million (ppm) chlorides at moderate temperatures. Trying to establish limits can be risky because wet/dry conditions can concentrate chlorides and increase the probability of stress corrosion cracking. The chloride content of seawater is about 2% (20,000 ppm). Seawater above 50oC is encountered in applications such as heat exchangers for coastal power stations.

Recently there has been a small number of instances of chloride stress corrosion failures at lower temperatures than previously thought possible. These have occurred in the warm, moist atmosphere above indoor chlorinated swimming pools where stainless steel (generally Grade 316) fixtures are often used to suspend items such as ventilation ducting. Temperatures as low as 30 to 40°C have been involved. There have also been failures due to stress corrosion at higher temperatures with chloride levels as low as 10 ppm. This very serious problem is not yet fully understood.

Sulphide Stress Corrosion Cracking (SSC)

Of greatest importance to many users in the oil and gas industry is the material's resistance to sulphide stress corrosion cracking. The mechanism of SSC has not been defined unambiguously but involves the conjoint action of chloride and hydrogen sulphide, requires the presence of a tensile stress and has a non-linear relationship with temperature.

The three main factors are:

a) **Stress level**
A threshold stress can sometimes be identified for each material – environment combination. Some published data show a continuous fall of threshold stress with increasing H2S levels. To guard against SSC NACE specification MR0175 for sulphide environments limits the common austenitic grades to 22HRC maximum hardness.

b) **Environment**
The principal agents being chloride, hydrogen sulphide and pH. There is synergism between these effects, with an apparently inhibiting effect of sulphide at high H2S levels.

c) **Temperature**
With increasing temperature, the contribution of chloride increases but the effect of hydrogen decreases due to its increased mobility in the ferrite matrix. The net result is a maximum susceptibility in the region 60-100°C.

A number of secondary factors have also been identified, including amount of ferrite, surface condition, presence of cold work and heat tint at welds.

Intergranular Corrosion

Intergranular corrosion is a form of relatively rapid and localised corrosion associated with a defective microstructure known as carbide precipitation. When austenitic steels have been exposed for a period of time in the range of approximately 425 to 850°C, or when the steel has been heated to higher temperatures and allowed to cool through that temperature range at a relatively slow rate (such as occurs after welding or air cooling after annealing), the chromium and carbon in the steel combine to form chromium carbide particles along the grain boundaries throughout the steel. Formation of these carbide particles in the grain boundaries depletes the surrounding metal of chromium and reduces its corrosion resistance, allowing the steel to corrode preferentially along the grain boundaries. Steel in this condition is said to be "sensitised".

It should be noted that carbide precipitation depends upon carbon content, temperature and time at temperature, as shown in Figure 8. The most critical temperature range is around 700°C, at which 0.06% carbon steels will precipitate carbides in about 2 minutes, whereas 0.02% carbon steels are effectively immune from this problem.

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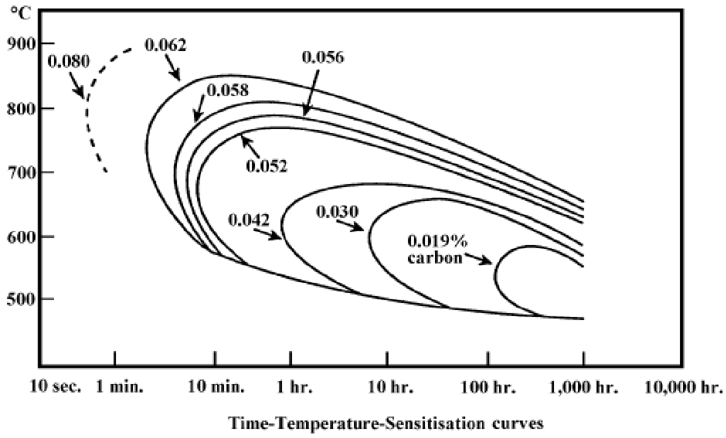
It is possible to reclaim steel which suffers from carbide precipitation by heating it above 1000°C, followed by water quenching to retain the carbon and chromium in solution and so prevent the formation of carbides. Most structures which are welded or heated cannot be given this heat treatment and therefore special grades of steel have been designed to avoid this problem. These are the stabilised grades 321 (stabilised with titanium) and 347 (stabilised with niobium). Titanium and niobium each have much higher affinities for carbon than chromium and therefore titanium carbides, niobium carbides and tantalum carbides form instead of chromium carbides, leaving the chromium in solution and ensuring full corrosion resistance.

Figure 8 Susceptibility to intergranular corrosion of grade 304 with various carbon contents (ref AWRA Tech Note 16)



Another method used to overcome intergranular corrosion is to use the extra low carbon grades such as Grades 316L and 304L; these have extremely low carbon levels (generally less than 0.03%) and are therefore considerably more resistant to the precipitation of carbide.

Many environments do not cause intergranular corrosion in sensitised austenitic stainless steels, for example, glacial acetic acid at room temperature, alkaline salt solution such as sodium carbonate, potable water and most inland bodies of fresh water. For such environments, it would not be necessary to be concerned about sensitisation. There is also generally no problem in light gauge steel since it usually cools very quickly following welding or other exposure to high temperatures. For this reason, thin gauge sheet is often only available in standard carbon content, but heavy plate is often only available in low carbon "L" grades. More information on L, H and standard grades is given in Atlas Tech Note No. 8.

It is also the case that the presence of grain boundary carbides is not harmful to the high temperature strength of stainless steels. Grades which are specifically intended for these applications often intentionally have high carbon contents as this increases their high temperature strength and creep resistance. These are the "H" variants such as grades 304H, 316H, 321H and 347H, and 310. All of these have carbon contents deliberately in the range in which precipitation will occur.

Sensitised steels have also been found to suffer from intergranular stress corrosion cracking (IGSCC). This problem is rare, but can affect un-stabilised ferritic and austenitic grades if they are treated or held in appropriate temperature ranges.

Galvanic Corrosion

Because corrosion is an electrochemical process involving the flow of electric current, corrosion can be generated by a galvanic effect which arises from the contact of dissimilar metals in an electrolyte (an electrolyte is an electrically conductive liquid). In fact, three conditions are required for galvanic corrosion to proceed ... the two metals must be widely separated on the galvanic

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series (see Figure 9), they must be in electrical contact, and their surfaces must be bridged by an electrically conducting fluid. Removal of any of these three conditions will prevent galvanic corrosion.

The obvious means of prevention is therefore to avoid mixed metal fabrications or only use those close together in the galvanic series; copper alloys and stainless steels can generally be mixed without problem for instance. Frequently this is not practical, but prevention can also be by removing the electrical contact - this can be achieved using plastic or rubber washers or sleeves, or by ensuring the absence of the electrolyte such as by improvement to draining or using protective hoods. This effect is also dependent upon the relative areas of the dissimilar metals. If the area of the less noble material (the anodic material, further towards the right in Figure 9) is large compared to that of the more noble (cathodic) the corrosive effect is greatly reduced, and may in fact become negligible. Conversely a large area of noble metal in contact with a small area of less noble will accelerate the galvanic corrosion rate. For example, it is common practice to fasten aluminium sheets with stainless steel screws, but aluminium screws in a large area of stainless steel are likely to rapidly corrode.

The most common instance of galvanic corrosion is probably the use of zinc plated carbon steel fasteners in stainless steel sheet. Further details of galvanic corrosion are given in Atlas Tech Note No. 7.

Contact Corrosion

These combines elements of pitting, crevice and galvanic corrosion, and occurs where small particles of foreign matter, in particular carbon steel, are left on a stainless steel surface. The attack starts as a galvanic cell - the particle of foreign matter is anodic and hence likely to be quickly corroded away, but in severe cases a pit may also form in the stainless steel, and pitting corrosion can continue from this point. The most prevalent cause is debris from nearby grinding of carbon steel, or use of tools contaminated with carbon steel. For this reason, some fabricators have dedicated stainless steel workshops where contact with carbon steel is totally avoided.

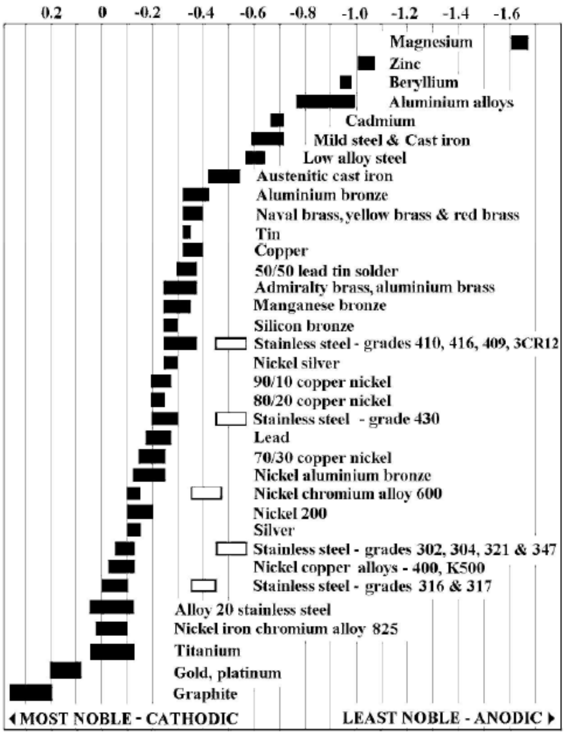

Figure 9 Galvanic series for metals in flowing sea water. More negative values for stainless steels are for active conditions, such as in crevices

All workshops and warehouses handling or storing stainless steels must also be aware of this potential problem, and take precautions to prevent it. Protective plastic, wood or carpet strips can be used to prevent contact between stainless steel products and carbon steel storage racks. Other handling equipment to be protected includes fork lift tines and crane lifting fixtures. Clean fabric slings have often been found to be a useful alternative.

If stainless steel does become contaminated by carbon steel debris this can be removed by passivation with dilute nitric acid or pickling with a mix of hydrofluoric and nitric acids. See the later section on pickling and passivation for further details.

Contamination by carbon steel (also referred to as “free iron”) can be detected by:

- A “ferroxyl” test is very sensitive, but requires a freshly made up test solution. Refer to ASTM A380.
- Copper sulphate will plate out copper on free iron. Again, details in ASTM A380.
- The simplest test is to wet the surface intermittently for about 24 hours; any contamination will be revealed as rust spots.

High Temperature Resistance

The second most common reason stainless steels are used is for their high temperature properties; stainless steels can be found in applications where high temperature oxidation resistance is necessary, and in other applications where high temperature strength is required. The high chromium content which is so beneficial to the wet corrosion resistance of stainless steels is also highly beneficial to their high temperature strength and resistance to scaling at elevated temperatures, as shown in the graph of Figure 10.

Scaling Resistance

Resistance to oxidation, or scaling, is dependent on the chromium content in the same way as the corrosion resistance is, as shown in the graph of Figure 10. Most austenitic steels, with chromium contents of at least 18%, can be used at temperatures up to 870°C and Grades 309, 310 and S30815 (253MA) even higher. Most martensitic and ferritic steels have lower resistance to oxidation and hence lower useful operating temperatures. An exception to this is the ferritic grade 446 - this has approximately 24% chromium, and can be used to resist scaling at temperatures up to 1100°C.

The table in Figure 11 shows the approximate maximum service temperatures at which the various grades of stainless steels can be used to resist oxidation in dry air. Note that these temperatures depend very much on the actual environmental conditions, and in some instances substantially lower temperatures will result in destructive scaling.

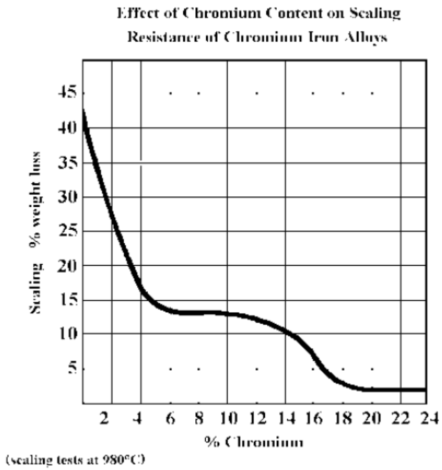

Figure 10 Effect of chromium content on scaling resistance

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Figure 11 Maximum service temperatures in dry air, based on scaling resistance (ref: ASM Metals Handbook)

Grade	Intermittent (°C)	Continuous (°C)
304	870	925
309	980	1095
310	1035	1150
316	870	925
321	870	925
410	815	705
416	760	675
420	735	620
430	870	815
S30815	1150	1150

Creep Strength

The high temperature strength of materials is generally expressed in terms of their "creep strength" - the ability of the material to resist distortion over a long-term exposure to a high temperature. In this regard the austenitic stainless steels are particularly good. Design codes such as Australian Standard AS1210 "Pressure Vessels" and AS4041 "Pressure Piping" (and corresponding codes from ASME and other bodies) also stipulate allowable working stresses of each grade at a range of temperatures. The low carbon versions of the standard austenitic grades (Grades 304L and 316L) have reduced strength at high temperature so are not generally used for structural applications at elevated temperatures. "H" versions of each grade (e.g. 304H) have higher carbon contents for these applications, which results in significantly higher creep strengths. "H" grades are specified for some elevated temperature applications. A more complete description of the application of L, H and standard austenitic grades is given in Atlas Tech Note No. 8.

The scaling resistances of the ferritic stainless steels are generally as suggested by the graph of Figure 10. So, 11% chromium grades (409 or 3CR12) have moderate sealing resistances, 17% grades (430) have good sealing resistance and 25% Cr grades (446) have excellent sealing resistance. The ferritic structure however, does not have the high creep strength of the austenitic grades, so the use of ferritics at very high temperatures is often limited to low stress application. Addition of niobium to ferritic grades does improve the creep strength substantially, and some niobium-stabilised grades find application in high temperature auto exhaust components for instance.

Although the duplex stainless steels have good oxidation resistance due to their high chromium contents, they suffer from embrittlement if exposed to temperatures above about 350°C, so they are restricted to applications below this.

Both martensitic and precipitation hardening families of stainless steels have high strengths achieved by thermal treatments; exposure of these grades at temperatures exceeding their heat treatment temperatures will result in permanent softening, so again these grades are seldom used at elevated temperatures.

Structural Stability

The problem of grain boundary carbide precipitation was discussed under intergranular corrosion. This same phenomenon occurs when some stainless steels are exposed in service to temperatures of 425 to 815°C, resulting in a reduction of corrosion resistance which may be significant. If this problem is to be avoided the use of stabilised grades such as Grade 321 or low carbon "L" grades should be considered. It must be understood that a high carbon content, as in the "H" grades, such as 304H, is beneficial to elevated temperature strength. Such steels do not have good aqueous corrosion resistance, but this is often not a problem. Refer to Atlas Tech Note No. 8 for further details.

A further problem that some stainless steels have in high temperature applications is the formation of sigma phase. The formation of sigma phase in austenitic steels is dependent on both time and temperature and is different for each type of steel. In general Grade 304 stainless steel is practically immune to sigma phase formation, but not so those grades with higher chromium contents (Grade 310) with molybdenum (Grades 316 and 317) or with higher silicon contents (Grade 314). These grades are all prone to sigma phase formation if exposed for long periods to a temperature of about 590 to 870°C. Sigma phase embrittlement refers to the formation of a precipitate in the steel microstructure over a long period of time within this particular temperature range. The effect of the formation of this phase is to make the steel extremely brittle and failure can occur because of brittle fracture. Once the steel has become embrittled with sigma it is possible to reclaim it by heating the steel to a temperature above the sigma formation temperature range, however this is not always practical. Because sigma phase embrittlement is a serious problem with the high silicon grade 314, this is now unpopular and largely replaced by high nickel alloys or by stainless steels resistant to sigma phase embrittlement, particularly S30815 (253MA). Grade 310 is also fairly susceptible to sigma phase formation in the temperature range 590 to 870°C, so this "heat resistant" grade may not be suitable for exposure at this comparatively low temperature range and Grade 321 is often a better choice.

Environmental Factors

Other factors which can be important in the use of steels for high temperature applications are carburisation and sulphidation resistance. Sulphur bearing gases under reducing conditions greatly accelerate the attack on stainless alloys with high nickel contents. In some instances, Grade 310 has given reasonable service, in others grade S30815, with a lower nickel content is better, but in others a totally nickel-free alloy is superior. If sulphur bearing gases are present under reducing conditions, it is suggested that pilot test specimens be first run under similar conditions to determine the best alloy.

Thermal Expansion

A further property that can be relevant in high temperature applications is the thermal expansion of the particular material. The coefficient of thermal expansion is expressed in units of proportional change of length for each degree increase in temperature, usually x10-6/°C, μm/m/°C, or x10-6cm/cm/°C, all of which are identical units. The increase in length (or diameter, thickness, etc) can be readily calculated by multiplying the original dimension by the temperature change by the coefficient of thermal expansion. For example, if a three-metre-long Grade 304 bar (coefficient of expansion 17.2 μm/m/°C) is heated from 20°C to 200°C, the length increases by:

$$3.00 \times 180 \times 17.2 = 9288 \ \mu m = 9.3 \ mm$$

The coefficient of thermal expansion of the austenitic stainless steels is higher than for most other grades of steel, as shown in the following table.

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Figure 12 Coefficient of thermal expansion - average values over the range 0-100°C

	Coefficient of Thermal Expansion (x10-6/°C)
Carbon Steels	10
Austenitic Steels	17
Duplex Steels	14
Ferritic Steels	11
Martensitic Steels	11
* or micrometres/metre/°C	

This expansion coefficient not only varies between steel grades, it also increases slightly with temperature. Grade 304 has a coefficient of 17.2 x 10-6/°C, over the temperature range 0 to 100°C, but increases above this temperature; details of these values are given in the table of physical properties in Appendix 3 of this Handbook, and in the individual Atlas Grade Data Sheets.

The effect of thermal expansion is most noticeable where components are restrained, as the expansion results in buckling and bending. A problem can also arise if two dissimilar metals are fabricated together and then heated; dissimilar coefficients will again result in buckling or bending.

In general, the quite high thermal expansion rates of the austenitic stainless steels mean that fabrications in these alloys may have more dimensional problems than similar fabrications in carbon or low alloy steels, in ferritic, martensitic or duplex stainless steels.

The non-austenitic stainless steels also have somewhat higher thermal conductivities than the austenitic grades, which may be an advantage in certain applications. Thermal conductivities of stainless steels are again listed in the table of physical properties in Appendix 3 of this Handbook, and in the individual Atlas Grade Data Sheets.

Localised stresses from expansion during heating and cooling can contribute to stress corrosion cracking in an environment which would not normally attack the metal. These applications require design to minimise the adverse effects of temperature differentials such as the use of expansion joints to permit movement without distortion and the avoidance of notches and abrupt changes of section.

Cryogenic Properties

The austenitic stainless steels possess a unique combination of properties which makes them useful at cryogenic (very low) temperatures, such as are encountered in plants handling liquefied gases. These steels at cryogenic temperatures have tensile strengths substantially higher than at ambient temperatures while their toughness is only slightly degraded. Typical impact strengths are as shown in Figure 13.

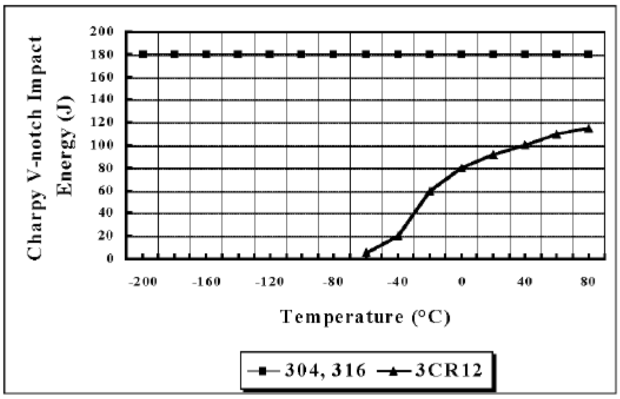

Figure 13 Typical impact energies of stainless steels down to cryogenic temperatures.

Note: There is substantial variation in cryogenic impact properties, depending on test methods and steel condition.

Considerable austenitic stainless steel has therefore been used for handling liquefied natural gas at a temperature of -161°C, and in plants for production of liquefied gases. Liquid oxygen has a boiling temperature of -183°C and that of liquid nitrogen is -196°C.

The ferritic, martensitic and precipitation hardening steels are not recommended for use at sub-zero temperatures as they exhibit a significant drop in toughness, even at only moderately low temperatures, in some cases not much below room temperature.

The duplex stainless steels have a better low temperature ductility than the ferritic and martensitic grades; they are generally quite useable down to at least -50°C but have reduced ductility below this temperature. This therefore usually places a lower temperature limit on their usefulness. The "ductile to brittle transition" from which these grades suffer is also a common feature of carbon and low alloy steels, some of which have Ductile to Brittle Transition Temperatures (DBTT) close to 0°C.

These limitations are incorporated into design codes, such as for instance the “material design minimum temperature (MDMT)” quoted in the Australian pressure vessel code AS1210.

The ductile to brittle transformation is not a permanent change; a steel that is brittle at low temperatures returns to its ductile condition when it is brought back to higher temperatures.

Magnetic Properties

Magnetic Permeability is the ability of a material to carry magnetism, indicated by the degree to which it is attracted to a magnet. All stainless steels, except for the austenitic group, are strongly attracted to a magnet. All austenitic grades have very low magnetic permeabilities and hence show almost no response to a magnet when in the annealed condition; the situation is, however, far less clear when these steels have been cold worked by wire drawing, rolling or even centreless grinding, shot blasting or heavy polishing. After substantial cold working Grade 304 may exhibit quite strong response to a magnet, whereas Grades 310 and 316 will in most instances still be almost totally non-responsive, as shown in Figure 14.

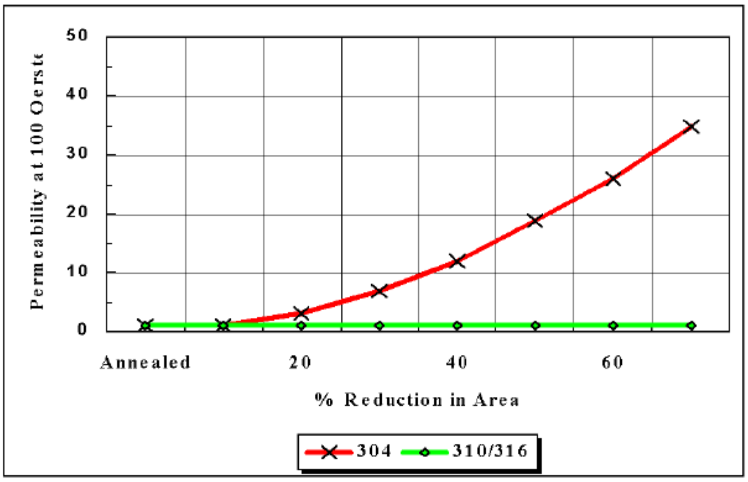

Figure 14 Magnetic response of austenitic stainless steels after cold work.

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The change in magnetic response is due to atomic lattice straining and formation of martensite. In general, the higher the nickel to chromium ratio the more stable is the austenitic structure and the less magnetic response that will be induced by cold work. Magnetic response can in some cases be used as a method for sorting grades of stainless steel, but considerable caution needs to be exercised.

Any austenitic (300 series) stainless steel which has developed magnetic response due to cold work can be returned to a non-magnetic condition by stress relieving. In general, this can be readily achieved by briefly heating to approximately 700 – 800°C (this can be conveniently carried out by careful use of an oxy-acetylene torch). Note, however, comments elsewhere in this publication about sensitisation (carbide precipitation) unless the steel is a stabilised grade. Full solution treatment at 1000 – 1150°C will remove all magnetic response without danger of reduced corrosion resistance due to carbides.

Many cold drawn and/or polished bars have a noticeable amount of magnetism because of the previous cold work. This is particularly the case with grades 304 and 303, and much less so for the higher nickel grades such as 310 and 316, as shown in the graph of Figure 14. Even within the chemical limitations of a single standard analysis range there can be a pronounced variation in the rate of inducement of magnetic response from cold work.

Austenitic stainless steel castings and welds (which could be viewed very small costings) are usually deliberately designed to have a minor proportion of ferrite. Approximately 5-12% of ferrite assists in preventing hot cracking. This microstructure responds slightly to a magnet, and in fact ferrite meters based on measuring this response can be used to quantify the proportion of ferrite.

If magnetic permeability is a factor of design or is incorporated into a specification, this should be clearly indicated when purchasing the stainless steel from a supplier.

Magnetically Soft Stainless Steels

In some applications there is a requirement for a steel to be "magnetically soft". This is often required for solenoid shafts, where it is necessary for the plunger to respond efficiently to the magnetic field from the surrounding coil when the current is switched on, but when the current is switched off the magnetic field induced in the steel must quickly collapse, allowing the plunger to return to its original position. Steels which behave in this way are said to be magnetically soft. For corrosion resisting applications there are ferritic stainless steels which are magnetically soft, usually variants of a grade "18/2" (18%chromium and 2% molybdenum) but with very tightly controlled additions of silicon and often with sulphur added to make them free machining. Special mill processing guarantees the magnetic properties of the steels.

Mechanical Properties

The mechanical properties of stainless steels are almost always requirements of the product specifications used to purchase the products distributed by Atlas Steels.

For flat rolled products the properties usually specified are tensile strength, yield stress (almost always measured as 0.2% proof stress), elongation and sometimes Brinell or Rockwell hardness. Much less frequently there are requirements for impact resistance, either Charpy or Izod. Bar, tube, pipe, fittings etc. also usually require at least tensile strength and yield stress. Hardness is commonly measured for annealed tube. These properties give a guarantee that the material in question has been correctly produced, and are also used by engineers to calculate the working loads or pressures that the product can safely carry in service.

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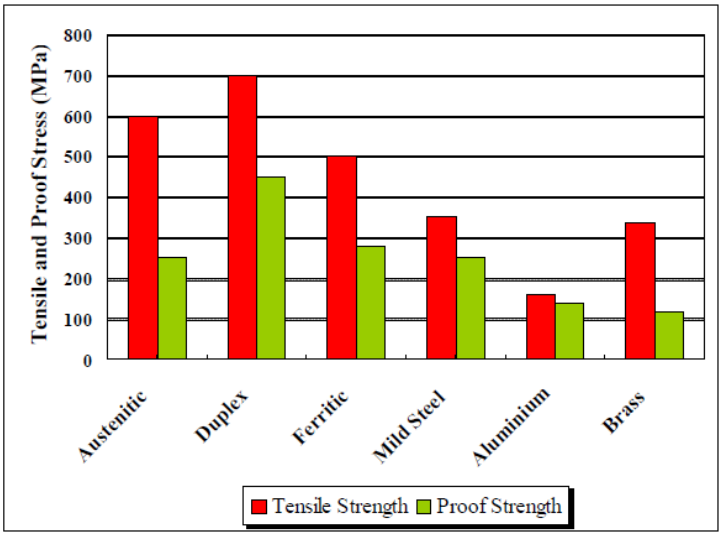

Figure 15 Typical tensile properties of annealed materials

Typical mechanical properties of annealed materials are as in the graph of Figure 15. Note that the high cold work hardening rate of the austenitic grades in particular results in actual properties of some commercial products being significantly higher than these values. The yield stress (usually measured as the 0.2% proof stress) is particularly increased by even quite minor amounts of cold work. More details of the work hardening of stainless steels are given in the section of this handbook on fabrication.

An unusual feature of annealed austenitic stainless steels is that the yield strength is a very low proportion of the tensile strength, typically only 40-45%. The comparable figure for a mild steel is about 65-70%. As indicated above a small amount of cold work greatly increases the yield (much more so than the tensile strength), so the yield also increases to a higher proportion of tensile. Only a few % of cold work will increase the yield by 200 or 300MPa, and in severely cold worked material like spring temper wire or strip, the yield is usually about 80-95% of the tensile strength.

As engineering design calculations are frequently made on yield criteria the low yield strength of austenitic stainless steels may well mean that their design load cannot be higher than that of mild steel, despite the tensile strength being substantially higher. Design stresses for various grades and temperatures are given in Australian Standards AS1210 "Pressure Vessels" and AS4041 “Pressure Piping”.

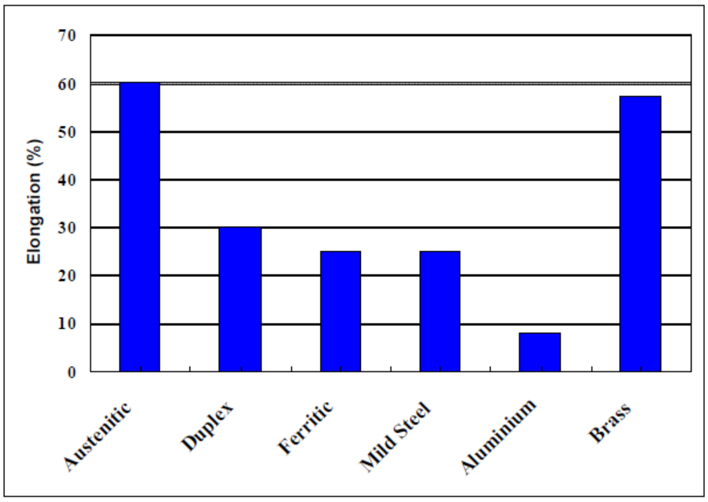

Figure 16 Typical elongations of annealed materials

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The other mechanical property of note is the ductility, usually measured by % elongation during a tensile test. This shows the amount of deformation a piece of metal will withstand before it fractures. Austenitic stainless steels have exceptionally high elongations, usually about 60 - 70% for annealed products, as shown in Figure 16. It is the combination of high work hardening rate and high elongation that permits the severe fabrication operations which are routinely carried out, such as deep drawing of kitchen sinks and laundry troughs.

Hardness (usually measured by Brinell, Rockwell or Vickers machines) is another value for the strength of a material. Hardness is usually defined as resistance to penetration, so these test machines measure the depth to which a very hard indenter is forced into a material under the action of a known force. Each machine has a different shaped indenter and a different force application system, so conversion between hardness scales may not be very accurate. Standard tables have been produced, and a summary of these for stainless steels, is given in Appendix 4 of this handbook. These conversions are only approximate, and should not be used to determine conformance to standards. Conversions for carbon and low alloy steels are more reliable than those for austenitic stainless steels.

It is also sometimes convenient to do a hardness test and then convert the result to tensile strength. Although the conversions for carbon and low alloy steels are fairly reliable, those for austenitic stainless steels are much less so. No standard conversion tables for hardness to tensile strength is published for austenitic alloys, and any conversions should be regarded with suspicion.

Mechanical Properties of Wire

The mechanical properties of the majority of the stainless steel wire and bar products stocked by Atlas Steels are generally sufficiently described by the tensile strength. Each of the wire products require mechanical properties which are carefully chosen to enable the product to be fabricated into the finished component and to withstand the loads which will be applied during service. Spring wire has the highest tensile strength; it must be suitable for coiling into tension or compression springs without breaking during forming. However, such high tensile strengths would be completely unsuitable for forming or weaving applications because the wire would break on forming.

Weaving wires are supplied in a variety of tensile strengths carefully chosen so that the finished woven screen will have adequate strength to withstand the service loads, and yet soft enough to be crimped and to be formed into the screen satisfactorily.

Mechanical properties of “Cold Heading” wire for fasteners are another example where a careful balance in mechanical properties is required. In this type of product, the wire must be ductile enough to form a quite complex head, but the wire must be hard enough so that the threads will not
deform when the screw or bolt is assembled into the component. Good examples are roofing bolts, wood screws and self-tapping screws; to achieve the mechanical properties required for such components requires careful consideration of the composition of the steel so that the work hardening rate will be sufficiently high to form hard threads on thread rolling and yet not so high as to prevent the head from being formed.

Mechanical Properties of Bar

For bar products a compromise must also be made; a large proportion of bar will be machined, so it is important that the hardness be not too high, but better load carrying capacity is achieved if the strength is high, and for drawn bar a good bright finish is achieved only by a reduction which significantly increases strength levels.

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In practice round, austenitic stainless steel bar from about 5mm up to about 26mm in diameter is most commonly manufactured by cold drawing to its final size, typically on a "Schumag" or similar machine. The resulting finish is called Bright Drawn or "BD". The approximately 10% reduction in area of this draw gives a significant increase in tensile strength and much more so in proof stress. By contrast, bars with diameters of about 26mm and over are most commonly manufactured by taking hot rolled annealed bar and simply cutting off the rough and uneven outer surface to achieve final size. Such a finish is called Smooth Turned or "ST". Final straightening does slightly increase the strength (and more so the surface hardness) but these large sized bars have properties quite close to annealed.

Typical mechanical properties for these products are shown in Figure 17.

Finish	Size approx. (mm)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
Drawn	5 - 26	700	600	35
Turned	>26	600	300	55

Figure 17 Typical mechanical properties of 304/316 round bars

There are other implications of these two manufacturing routes:

1. Large diameter ST bars will have better machine abilities than the same grade in smaller BD sizes, because a lower hardness, lower strength steel is easier to cut.

2. Large diameter ST bars will be free of surface laps or seams because the hot rolled surface has been cut off in turning. The smaller BD bars may have minor surface imperfections because no metal has been removed; the original hot rolled surface has merely been burnished smooth by drawing, thus covering minor blemishes.

3. All drawn wire and bar has a higher surface hardness because that is where most of the cold work is concentrated. This makes little difference in the small diameter wires and bars, but for bar approaching 25mm in diameter the surface will be significantly higher hardness than its centre. Even ST bar has a higher surface hardness because of cold working imparted by final machining and bar straightening.

Fabrication

Forming Operations

One of the major advantages of the stainless steels, and the austenitic grades in particular, is their ability to be fabricated by all the standard fabrication techniques, in some cases even more severely than the more well-known carbon steels. The common austenitic grades can be folded, bent, cold and hot forged, deep drawn, spun and roll formed. Because of the materials' high strength and very high work hardening rate these operations require more force than for carbon steels, so a heavier machine may be needed, and more allowance may need to be made for spring-back.

Austenitic stainless steels also have very high ductility, so are in fact capable of being very heavily cold formed, despite their high strengths and high work hardening rates, into items such as deep drawn kitchen sinks and laundry troughs. Few other metals can achieve this degree of deformation without splitting.

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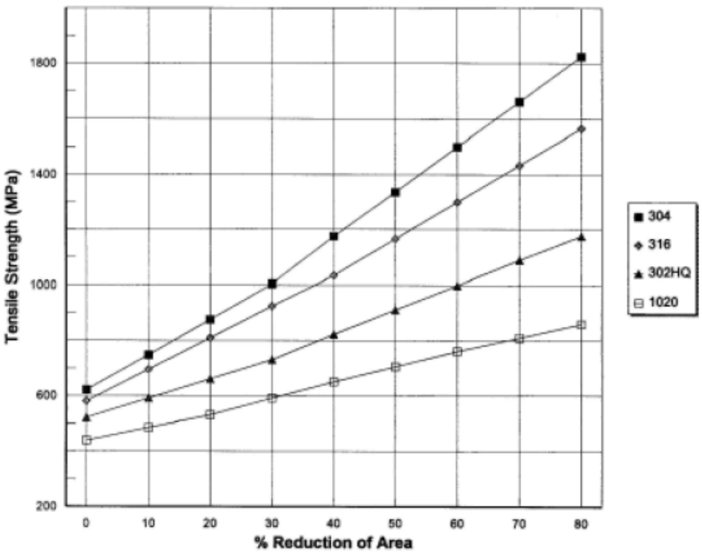
All metals work harden when cold worked, and the extent of work hardening depends upon the grade selected. Austenitic stainless steels work harden very rapidly, but the ferritic grades work harden only a little higher than that of the plain carbon steels. The rapid cold working characteristics of austenitic stainless alloys makes them particularly useful where the combination of high strength and corrosion resistance are required, such as for manufacture of springs for corrosive environments. The relationship between the amount of cold work (expressed as "% reduction of area") and the resulting mechanical properties is shown in the chart in Figure 18.

Figure 18 Effect of Cold work on tensile strength of stainless steels. Values are typical for cold drawn wire.



It is important to realise that work hardening is the only way in which austenitic stainless steels can be hardened. By contrast the martensitic stainless steels (e.g. 410, 416, 420 and 431) can be hardened by a quench-and-temper thermal treatment in the same way as carbon and low alloy steels. Ferritic stainless steels (such as Grades 430, 439 and 444) are similar to austenitic grades in that they can only be hardened by cold working, but their work hardening rates are low, and a substantial lift in strength cannot be achieved.

In cold working such as cold drawing, tensile properties over 2000 MPa may be obtained with Grades 301, 302 and 304. However, these very high tensile properties are limited to thin sections and to fine wire sizes.

As the size increases, the amount of cold work necessary to produce the higher tensile properties cannot be practically applied. This is because the surface of larger sections rapidly work hardens to the extent that further work is not practical, while the centre of the section is still comparatively soft. To illustrate this point, Grade 304 6mm round, cold drawn with 15 per cent reduction in area will show an ultimate strength of about 800 MPa. A 60mm round, drawn with the same reduction will have about the same tensile in full section. However, if sections are machined from the centre of each bar, the 60mm round will show much lower tensile properties, whereas the 6mm round will test about the same as in full section. Also, the 6mm round can be cold worked to much higher tensile properties, whereas the 60mm round must be annealed for further cold work, because of excessive skin hardness.

In general, the austenitic grades showing the greatest work hardening rate will also have the highest magnetic permeability for a given amount of cold work.

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Ferritic and martensitic alloys work harden at rates similar to low carbon steel and are magnetic in all conditions at room temperatures. Wire sizes may be cold worked to tensile properties as high as approximately 1000 MPa. However, bar sizes are seldom cold worked higher than 850 MPa. Although the ferritic grades (e.g. 430, 409 and 3CR12) cannot be heat treated, the martensitic grades (e.g. 410, 416 and 431) are usually heat treated by hardening and tempering to develop mechanical properties and maximum corrosion resistance. Cold working, therefore, is more of a sizing operation than a method of producing mechanical properties with these grades.

The rate of work hardening, while relatively consistent for a single analysis, will show a marked decrease in the rate as the temperature increases. This difference is noticeable at temperatures as temperatures as low as 80°. At slightly increased temperature there is also a reduction in strength and increase in ductility. Advantage is taken of this in some deep drawing applications as well as in "warm" heading of some difficult fasteners.

Another feature of cold forming of stainless steels is that more severe deformation is possible at slower forming speeds - this is quite different from carbon steels which have formabilities virtually the same no matter what the forming rate. So, the advice given to those attempting difficult cold heading (or other high speed forming operations) is to slow down; stainless steel is almost always headed slower than is carbon steel.

Machining

Austenitic stainless steels are generally regarded as being difficult to machine, and this has led to the development of the free-machining Grade 303. There are also free-machining versions of the standard ferritic (Grade 430) and martensitic (Grade 410) grades - Grades 430F and 416 respectively - these grades have improved machinability because of the inclusions of Manganese Sulphide (formed from the sulphur added to the steel) which act as chip breakers.

The free-machining grades have significantly lower corrosion resistances than their non-free machining equivalents because of the presence of these non-metallic inclusions; these grades are particularly prone to pitting corrosion attack and must not be used in aggressive environments such as for marine exposure. The free-machining grades containing high sulphur levels also have reduced ductility, so cannot be bent around a tight radius nor cold forged. Because of the sulphur additions these grades are very difficult to weld, so again would not be chosen for welded fabrication.

Ugima **Improved Machinability Grades**

Recently a number of manufacturers have offered "Improved Machinability" versions of the standard austenitic Grades 304 and 316. These steels are produced by proprietary steel melting techniques which provide enough of a chip-breaking effect to significantly improve the machinability, but they remain within the standard grade composition specifications and still retain mechanical properties, weldability, formability and corrosion resistance of their standard grade equivalents. These materials are marketed under trade names such as "Ugima". For "Ugima" the improvement in achievable machining speed is about 20% over the equivalent standard grades; in addition, it is commonly experienced that greatly enhanced tool life is obtained, which considerably reduces the cost of machining. In many instances this is of even greater benefit than is the potential improvement in cutting speed.

A "Ugima 303" is available as a "super-machinable" grade; like other 303 stainless steels weldability, formability and corrosion resistance are compromised in order to achieve maximum machinability. Relative machinabilities of various stainless steels, expressed as comparison of

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achievable cutting speeds, are shown in the graph of Figure 19. More information on machining of stainless steels is in Atlas Tech Note No. 4.

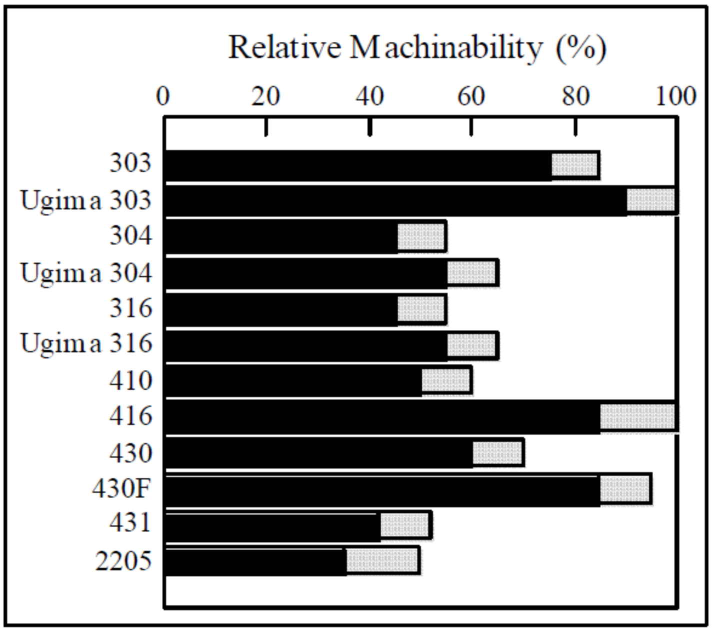

Figure 19 Relative machinabilities of stainless steels

Rules for Machining Stainless Steels

1. Some general rules apply to most machining of austenitic stainless steels:
2. The machine tool must be sturdy, have sufficient power and be free from vibration.
3. The cutting edge must be kept sharp always by re-sharpening or replacement. Dull tools cause glazing and work hardening of the surface. Sharpening must be carried out as soon as the quality of the cut deteriorates. Sharpening should be by machine grinding using suitable fixtures, as free- and sharpening does not give consistent and long-lasting edges. Grinding wheels must be dressed and not contaminated.
4. Light cuts should be taken, but the depth of the cut should be substantial enough to prevent the tool from riding the surface of the work - a condition which promotes work hardening.
5. All clearances should be sufficient to prevent the tool from rubbing on the work.
6. Tools should be as large as possible to help to dissipate the heat.
7. Chip breakers or chip curlers prevent the chips from being directed into the work.
8. Constant feeds are most important to prevent the tool from riding on the work.
9. Proper coolants and lubricants are essential. The low thermal conductivity of austenitic stainless alloys causes a large percentage of the generated heat to be concentrated at the cutting edges of the tools. Fluids must be used in sufficient quantities and directed to flood both the tool and the work.

Welding

The weldabilities of the various grades of stainless steels vary considerably. Nearly all can be welded, and the austenitic grades are some of the most readily welded of all metals. In general, the stainless steels have weldabilities which depend upon the family to which they belong. Recommendations for welding the common grades are given in Figure 20, and in the individual Atlas Steels Grade Data Sheets available on the Atlas Steels website. Australian Standard AS 1554.6 covers structural welding of stainless steels, and gives a number of pre-qualified conditions for welding. Pre-qualified welding consumables for welding of same-metal and mixed-metal welding are also given in AS 1554.6. This excellent standard (available from Standards Australia) also enables specification of welding procedures appropriate to each particular application. It is also highly relevant to non-structural welding.

Austenitic Stainless Steels

The austenitic grades are all very readily welded (except for the free-machining grade 303 noted elsewhere). All the usual electric welding processes can be used - Manual Metal Arc (MMAW or "stick"), Gas Tungsten Arc (GTAW or TIG), Gas Metal Arc (GMAW or MIG), Flux Cored (FCAW), Submerged Arc (SAW) and laser. A full range of welding consumables is readily available and standard equipment can be used.

The use of low carbon content grades (304L and 316L) or stabilised grades (321 or 347) needs to be considered for heavy section product which is to be welded. This overcomes the problem of "sensitisation" discussed in the previous section on intergranular corrosion. As the sensitisation problem is time/temperature dependent, so thin materials, which are welded quickly, are not usually a problem. It should be noted that if a fabrication has become sensitised during welding the effect can be reversed and the material restored to full corrosion resistance by a full solution heat treatment.

The free-machining grade 303 is not recommended for welded applications as it is subject to hot cracking; the Ugima improved machinability grades, Ugima 304 and Ugima 316, offer a much better combination of reasonable machinability with excellent weldability.

Duplex Stainless Steels

Duplex stainless steels also have good weldability, albeit not quite as good as that of the austenitics. Again, all the usual processes can be used, and a range of consumables is available. For the most common duplex grade 2205 the standard consumable is a 2209 - the higher nickel content ensures the correct 50/50 ferrite/austenite structure in the weld deposit, thus maintaining strength, ductility and corrosion resistance. One of the advantages of duplex stainless steels over austenitic is their comparatively low coefficient of thermal expansion. This is only a little higher than that of carbon steels, as shown in the table in the section of this handbook on high temperature properties of stainless steels.

Ferritic Stainless Steels

The ferritic grades are weldable but not as readily as the austenitic grades. The three major problems encountered are sensitisation, excessive grain growth and lack of ductility, particularly at low temperatures. Sensitisation can be avoided by use of stabilised grades. Filler metal can be of a similar composition or more commonly an austenitic grade (e.g. Grades 308L, 309, 316L or 310) which is helpful in improving weld toughness. The excessive grain growth problem is difficult to overcome, so most grades are only welded in thin gauges, usually up to 2 or 3mm. Heat input must be kept low for the same reason. Stabilised ferritic grades include 409 and 430Ti and the more modern 439 and 444.

These possess considerably better weldability compared to the un-stabilised alternatives such as 430. Such grades can be welded, even in structural or pressure vessel applications, but only in thin gauges.

3CR12 and 3CR12Ti are proprietary ferritic grades which have a very low carbon content and the remaining composition, and the mill processing route balanced to enable welding. The CR12 types are the only ferritic grades weldable in heavy section plate. As for other ferritic grades it is normal to use austenitic stainless steel fillers.

Martensitic Stainless Steels

Martensitic stainless steels can if necessary be welded (again with the high sulphur free machining grade 416 being not recommended) but caution needs to be exercised as they will produce a very hard and brittle zone adjacent to the weld. Cracking in this zone can occur unless much care is taken with pre-heating and with post weld heat treatment. These steels are often welded with austenitic filler rods to increase the ductility of the deposit.

Welding Dissimilar Metals

Welding together of different metals, such as of Grade 316 to Grade 444 or a stainless steel to a mild steel, can be carried out, although some extra precautions need to be taken. It is usually recommended that over-alloyed austenitic welding rods, such as Grade 309, be used to minimise dilution effects on the stainless steel component. The composition of the weld deposit resulting from dissimilar grade welding is shown in the Schaeffler diagram or its successors by De Long and more recently the WRC. Australian Standard AS 1554.6 contains a table giving the pre-qualified consumables for each combination of dissimilar metal welds.

Further Information on Welding

Specific recommendations are given in Figure 19. Further details on welding of stainless steels are given in the booklet "Guidelines for the Welded Fabrication of Nickel-containing Stainless Steels for Corrosion Resistant Services" (Nickel Institute Reference Book, No. 11 007) available from the Nickel Institute. Specific details on applications can be provided by the welding electrode, gas and equipment manufacturers. Excellent information is also included in WTIA Tech Note No. 16 on "Welding Stainless Steels ". This is available from the Welding Technology Institute of Australia.

Soft Soldering

All grades of stainless steel can be soldered with lead-tin soft solder. Leaded solders should not be used when the product being soldered is used for food processing, serving or transport. Soldered joints are relatively weak compared to the strength of the steel, so this method should not be used where the mechanical strength is dependent upon the soldered joint. Strength can be added if the edges are first lock-seamed, spot welded or riveted. In general welding is preferable to soldering.

Recommended procedure for soldering:

1. The steel surfaces must be clean and free of oxidation.

2. A rough surface improves adherence of the solder, so roughening with grinding wheel, file or coarse abrasive paper is recommended.

3. Use a phosphoric acid based flux. Hydrochloric acid based fluxes require neutralising after soldering as any remnant traces will be highly corrosive to the steel. Hydrochloric acid based fluxes are not recommended for soldering of stainless steels.

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4. Flux should be applied with a brush, to only the area being soldered.

5. A large, hot iron is recommended. Use the same temperature as for carbon steel, but a longer time will be required because of stainless steel's low thermal conductivity.

6. Any type of solder can be used, but at least 50% tin is recommended. Solder with 60-70% tin and 30-40% lead has a better colour match and greater strength.

Brazing ("Silver Soldering")

When welding is impractical and a stronger joint than soft soldering is required, brazing may be employed. This method is particularly useful for joining copper, bronze, nickel and other nonferrous metals to stainless steel. The corrosion resistance of the joint will be somewhat lower than that of the stainless steel, but in normal atmospheric and mildly corrosive conditions brazed joints are satisfactory. Because most brazing operations involve temperatures at which carbide precipitation (sensitisation) can occur in the austenitic grades, low carbon or stabilised grades (304L, 316L or 321) should be used. Ferritic grades such as 430 can be quenched from the brazing temperatures, but hardenable martensitic grades (410, 420, 431) should not be heated above 760°C when brazing. The free machining grades 303, 416 and 430F should generally not be used as a dark scum forms on the surface when fluxing and heating, which adversely affects the appearance of the steel.

Recommended procedure for brazing:

1. Use silver brazing alloys with melting points from 590-870°C. Select the alloy for best colour match.

2. Remove dirt and oxides from the steel surfaces and apply flux immediately.

3. A slightly reducing flame should be played across the joint to heat uniformly.

4. For high production work use induction heating or controlled atmosphere furnaces (argon, helium, vacuum or dissociated ammonia with dew point of about -50°C).

5. After brazing remove all remaining flux with high pressure steam or hot water.

6. When brazing grade 430 use a silver solder with 3% nickel. This alloy also helps to minimise crevice corrosion when used with austenitic grades.

Grade	Pre-heat	Post Weld Heat Treatment	Filler
304	(a)	Cool rapidly from 1010-1090°C only if welding over about 3 – 5mm thickness.	308L
304L	(a)	Not required.	308L
309	(a)	Usually unnecessary as this grade is generally used at high temperatures (b).	309
310	(a)	As for 309.	310
316	(a)	Cool rapidly from 1060-1150°C only if welding over about 3 – 5mm thickness.	316L
316L	(a)	Not required.	316L
321	(a)	Not required.	347
253MA	(a)	Not required.	S30815 (h)
410	(c)	Air cool from 650-760°C.	410 (d)
430	(c)	Air cool from 650-760°C.	430 (d)
444	(a)	Not required.	316L
3CR12	(g)	Not required.	309 (e)
2205	(f)	Not generally required.	2209

This table gives broad over-view recommendations. Further details are available from welding consumable suppliers. For critical application, welding procedures should be qualified in accordance with AS1554.6 or other applicable standards.

Notes:

a) Unnecessary when the steel is above 15°C.

b) Where corrosion is a factor, 309S and 310S (0.08% Carbon maximum) are used, with a post weld heat treatment of cooling rapidly from 1120-1180°C.

c) Pre-heat at 200-320°C; light gauge sheet is frequently welded without pre-heat.

d) May be welded with 308L, 309 or 310 electrodes without pre-heat if the steel is above 15°C.

e) May be welded with 309, 309L, 309Mo, 309MoL, 316L or 308L, depending on the application.

f) If temperature is below 10°C, then a 50°C pre-heat is recommended.

g) In case of critical structural welding of 3CR12 destined for corrosive environments, please refer to an Atlas Steels Service Centre.

h) 309 Consumables can be used if a reduced creep strength and oxidation resistance can be tolerated.

Figure 20 Recommendations for welding of stainless steels.

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Heat Treatment

Stainless steels are often heat treated; the nature of this treatment depends on the type of stainless steel and the reason for the treatment. These treatments, which include annealing, hardening and stress relieving, restore desirable properties such as corrosion resistance and ductility to metal altered by prior fabrication operations or produce hard structures able to withstand high stresses or abrasion in service. Heat treatment is often performed in controlled atmospheres to prevent surface scaling, or less commonly to prevent carburisation or decarburisation.

Annealing

Austenitic Stainless Steels

The austenitic stainless steels cannot be hardened by thermal treatments (but they do harden rapidly by cold work). Annealing (often referred to as “solution treatment”) not only recrystallises the work hardened grains but also takes chromium carbides (precipitated at grain boundaries in sensitised steels) back into solution in the austenite. The treatment also homogenises dendritic weld metal structures, and relieves all remnant stresses from cold working. Annealing temperatures usually are above 1040°C, although some types may be annealed at closely controlled temperatures as low as 1010°C when fine grain size is important. Time at temperature is often kept short to hold surface scaling to a minimum or to control grain growth, which can lead to "orange peel" in forming.

Annealing of austenitic stainless steel is occasionally called quench annealing because the metal must be cooled rapidly, usually by water quenching, to prevent sensitisation (except for stabilised and low carbon grades).

Before annealing or other heat-treating operations are performed on stainless steels, the surface must be cleaned to remove oil, grease and other carbonaceous residues. Such residues lead to carburisation during heat treating, which degrades corrosion resistance.

Duplex Stainless Steels

The duplex grades are generally solution treated in a very similar way to the austenitic and at very similar temperatures. Duplex grades are more susceptible than are austenitic to precipitation of sigma phase in the temperature range 600 – 950°C; a full solution treatment followed by rapid cooling will correct this.

Martensitic and Ferritic Stainless Steels

All martensitic and most ferritic stainless steels can be subcritical annealed (process annealed) by heating into the upper part of the ferrite temperature range, or full annealed by heating above the critical temperature into the austenite range, followed by slow cooling. Usual temperatures are 760 to 830°C for sub-critical annealing, but this is different for each grade.

When material has been previously heated above the critical temperature, such as in hot working, at least some martensite is present even in ferritic stainless steels such as grade 430. Relatively slow cooling at about 25°C/hour from full annealing temperature, or holding for one hour or more at subcritical annealing temperature, is required to produce the desired soft structure of ferrite and spheroidised carbides. However, parts that have undergone only cold working after full annealing can be sub-critically annealed satisfactorily in less than 30 minutes.

The ferritic types that retain predominantly single-phase structures throughout the working temperature range (grades 409, 442, 446 and 26Cr-1Mo) require only short recrystallisation annealing in the range 760 to 955°C.

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Atmosphere Control
Stainless steels are usually annealed in controlled atmospheres to prevent or at least reduce scaling. Treatment can be in a salt bath, or in a vacuum annealing furnace. Steel mills anneal most stainless steel in open (oxidising) furnaces, so a subsequent pickle is usual to remove the resultant high temperature oxide. Another option is "bright annealing" in a highly reducing atmosphere. Products such as flat rolled coil, tube and wire are regularly bright annealed by their producers, usually in an atmosphere of nitrogen and hydrogen. The result is a surface requiring no subsequent scale removal; the product is as bright after as before annealing. These products are often referred to as "BA".

Stabilising Annealing
A stabilising anneal is sometimes performed after conventional annealing for grades 321 and 347. Most of the carbon content is combined with titanium in grade 321 or with niobium in grade 347 when these are annealed in the usual manner. A further anneal at 870 to 900°C for 2 to 4 hours followed by rapid cooling precipitates all possible carbon as a titanium or niobium carbide and prevents subsequent precipitation of chromium carbide. This special protective treatment is sometimes useful when service conditions are rigorously corrosive, especially when service also involves temperatures from about 400 to 870°C, and some specifications enable this treatment to be specified for the product – in some ASTM specifications it is an optional “Supplementary Requirement”.

Hardening

Martensitic Stainless Steels

Martensitic stainless steels are hardened by austenitising, quenching and tempering much like low alloy steels. Austenitising temperatures normally are 980 to 1010°C, well above the critical temperature. As-quenched hardness increases with austenitising temperature to about 980°C and then decreases due to retention of austenite. For some grades the optimum austenitising temperature may depend on the subsequent tempering temperature.

Preheating before austenitising is recommended to prevent cracking in high-carbon types and in intricate sections of low-carbon types. Preheating at 790°C, and then heating to the austenitising temperature is the most common practice.

Martensitic stainless steels have high hardenability because of their high alloy content. Air cooling from the austenitising temperature is usually adequate to produce full hardness, but oil quenching is sometimes used, particularly for larger sections. Parts should be tempered as soon as they have cooled to room temperature, particularly if oil quenching has been used, to avoid delayed cracking. Parts sometimes are refrigerated to approximately -75°C before tempering to transform retained austenite, particularly where dimensional stability is important, such as in gauge blocks made of grade 440C. Tempering at temperatures above 510°C should be followed by relatively rapid cooling to below 400°C to avoid "475°C" embrittlement.

Precipitation Hardening Steels
Precipitation hardening stainless steels are usually supplied in the “solution treated” condition, often referred to as “Condition A”. The intention is that any fabrication will be done while the steel is in this condition, and then the final hardening heat treatment carried out.

Some precipitation- hardening stainless steels require more complicated heat treatments than standard martensitic types. For instance, a semi-austenitic precipitation-hardening type may require annealing, trigger annealing (to condition austenite for transformation on cooling to room temperature), sub-zero cooling (to complete the transformation of austenite) and aging (to fully harden the alloy). On the other hand, martensitic precipitation-hardening types (such as 17-4PH or Grade 630) often require nothing more than a simple aging treatment.

Heat treatment procedures are summarised in the individual Atlas Steels Grade Data Sheets.

Stress Relieving

Stress relieving of austenitic stainless steels at temperatures below 400°C is an acceptable practice but results in only modest stress relief. Stress relieving at 425 to 925°C significantly reduces residual stresses that otherwise might lead to stress corrosion cracking or dimensional instability in service. One hour at 870°C typically relieves about 85% of the residual stresses. However, stress relieving in this temperature range can also precipitate grain boundary carbides, resulting in sensitisation that severely impairs corrosion resistance in many media. To avoid these effects, it is strongly recommended that a stabilised stainless steel (grade 321) or a low-carbon type (304L or 316L) be used, particularly when lengthy stress relieving is required. See also the section of this Handbook dealing with intergranular corrosion.

Full solution treatment (annealing), generally by heating to about 1080°C followed by rapid cooling, removes all residual stresses in austenitic grades, but is not a practical treatment for most large or complex fabrications.

When austenitic stainless steels have been cold worked to develop high strength, low temperature stress relieving will increase the proportional limit and yield strength (particularly compressive yield strength). This is a common practice for austenitic stainless steel spring wire. A two-hour treatment at 345 to 400°C is normally used; temperatures up to 425°C may be used if resistance to intergranular corrosion is not required for the application. Higher temperatures will reduce strength and sensitise the metal, and generally are not used for stress relieving cold worked products.

Stainless steel weldments can be heated to temperatures below the usual annealing temperature to decrease high residual stresses when full annealing after welding is impossible. Most often, stress relieving is performed on weldments that are too large or intricate for full annealing or on dissimilar metal weldments consisting of austenitic stainless steel welded to low alloy steel.

Stress relieving of martensitic or ferritic stainless steel weldments will simultaneously temper weld and heat affected zones, and for most types will restore corrosion resistance to some degree. However, annealing temperatures are relatively low for these grades, and normal subcritical annealing is the heat treatment usually selected if the weldment is to be heat treated at all.

Surface Hardening

Only limited surface hardening treatments are applicable to the stainless steels. In most instances hardening of carbon and low alloy steels is due to the martensitic transformation, in which the achievable hardness is related to the carbon content - as most martensitic stainless steels have carbon contents ranging from fairly low to extremely low, this hardening mechanism is of little use.

It is possible to surface harden austenitic stainless steels by nitriding. As in nitriding of other steels the hard layer is very hard and very thin; this makes the process of limited use as the underlying stainless steel core is relatively soft and unsupportive in heavily loaded applications. A further drawback is that the nitrided case has a significantly lower corrosion resistance than the original stainless steel.

A number of alternative, proprietary surface hardening processes for austenitic stainless steels have been developed but these have not yet become commercially available in Australia.

An interesting alternative is the PVD (Physical Vapour Deposition) process. This enables very thin but hard layers to be deposited on many materials, including stainless steels. The most commonly applied coating is Titanium Nitride "TiN", which in addition to being very hard is also an aesthetically pleasing gold colour. Because of its appearance this coating has been applied, generally on No8 mirror polished surface, to produce gold mirror finished architectural panels. Again, it must be noted that this hard and very thin surface layer rests on a core of relatively soft austenite, so engineering applications are limited.

Surface Finishing

To a very large extent stainless steels are used because of the corrosion resistance of their surfaces. This excellent corrosion resistance can only be achieved if proper cleaning and finishing operations are carried out after any fabrication process which has impaired the surface condition.

Passivation

This process is recommended where the surface has been contaminated by “free iron”. The presence of any iron, cast iron, mild steel, carbon steel or low alloy steel particles on the surface of stainless steel will promote pitting corrosion at the cells set up between the "free" iron and stainless steel. This potentially very serious (and certainly unsightly) problem most often occurs due to contamination by scraping with carbon steel tools or fixtures, or from grinding swarf. “Passivation” is a chemical process of removal of this contamination. Passivation also aids in the rapid development of the passive surface layer on the steel and removes manganese sulphide inclusions from the surface; all these actions result in increased resistance to pitting corrosion.

The removal of the iron can be readily carried out by the procedures in the table of Figure 21.

- Grades with at least 16% Chromium (except free machining grades such as 303):
  20-50% nitric acid, at room temperature to 40°C for 30-60 minutes.
- Grades with less than 16% Chromium (except free machining grades such as 416):
  20-50% nitric acid, at room temperature to 40°C for 60 minutes.
- Free machining grades such as 303, 416 and 430F:
  20-50% nitric acid + 2-6% sodium dichromate, at room temperature to 50°C for 25-40 minutes.

Notes:

1. If no dulling of the metal surface can be tolerated a trial treatment should first be carried out.
2. All passivation treatments must be followed by thorough rinsing.
3. Observe all precautions for handing acids – nitric acid is highly corrosive and dangerous to exposed skin.

Figure 21 Passivation procedures. Refer ASTM A380

Pickling

Pickling is an acid treatment to remove high temperature scale produced in welding, heat treatment or hot working. It also removes red rust from corrosion of the steel or from corrosion of contaminant iron or steel particles. Note that passivation is not sufficiently aggressive to remove this corrosion product after the free iron has begun to rust. High temperature dark scale is not only undesirable for aesthetic reasons - it also results in a reduced corrosion resistance of the underlying steel surface layer.

- All stainless steels (except free machining grades):
  8-11% sulphuric acid, at 65-80°C for 5-45 minutes.
  This treatment is useful to loosen heavy heat treatment scale prior to other treatments.
- Grades with at least 16% Chromium (except free machining grades):
  15-25% nitric acid + 1-8% hydrofluoric acid at 20-60°C for 5-30 minutes.
- Free machining grades and grades with less than 16% Chromium:
  10-15% nitric acid + 0.5-1.5% hydrofluoric acid at 20-60°C for 5-30 minutes.

Notes:

1. Trial treatments should be carried out first to confirm that dulling is acceptable.
2. Pickling should preferably be carried out on fully annealed stainless steels due to risk of grain boundary attack. This problem is especially relevant to steels sensitised in welding.
3. All pickling treatments must be followed by thorough rinsing.
4. Observe all precautions for handing acids – sulphuric, nitric and especially hydrofluoric acid are highly corrosive and dangerous to exposed skin.

Figure 22 Picking procedures. Refer ASTM A380

The type of scale and hence the methods to remove it will depend upon the steel grade and the heating conditions involved. The straight-chromium grades such as 410, 416, 430 444 scale more readily and unfortunately the resulting scale is also more tenacious.

All pickling operations result in metal removal, and the outcome is therefore to some degree a dulling of the visual brightness and perhaps also a significant reduction in dimensions.

The best solution to the scale problem is not to create it in the first place! Heat treatment in a vacuum or a good controlled atmosphere, such as bright annealing, eliminates the need for pickling, and generally results in a better final surface finish.

If pickling does need to be carried out the treatments given in Figure 22 can be used. An initial pickle in sulphuric acid is often beneficial for heat treated components as this softens the scale so that it can more readily be removed by subsequent pickling in hydrofluoric and nitric acids.

Pickling is often referred to as “Pickling and Passivating” because this treatment also achieves all the aims of a straight passivation.

A very convenient method for pickling is use of "Pickling Paste". This is a prepared mix of strong acids in a stiff paste which enables it to be applied to small areas and to vertical or even overhanging surfaces. It is especially useful for pickling to remove heat tint following welding. Again, precautions for handling acids must be followed and the residue flushed thoroughly to a suitable waste stream after completion. Most commercial pickling paste is formulated for the austenitic grades, so if it is used to clean lower alloyed grades such as 3CR12 the process must be closely monitored to ensure the paste is quickly removed and very thoroughly rinsed off afterwards.

Less aggressive pickling paste and pickling liquid is available, especially formulated for the low alloy stainless steels. These products are also advocated as being safer to use and less environmentally damaging.

Degreasing

Grease, oil, cutting fluids, drawing compounds and other lubricants must be removed from the surface of stainless steel components before heat treatment (to prevent carbon pick-up) or final passivating treatments (to enable full access by the treatment). Parts must also be degreased prior to further assembly by welding, again to prevent pick-up of carbon at high temperature.

Both liquid and vapour degreasers are used. Liquid cleaning is often by hot alkaline detergents; proprietary mixes may also contain various additives. The parts should be thoroughly rinsed afterwards.

Organic solvents can be applied by spraying, swabbing or vapour degreasing. These treatments should again be followed by thorough hot water rinsing.

As with cleaning operations on other metals, the rate of cleaning can be increased using brushing, jetting or stirring etc. during the operation.

Electropolishing

Electropolishing is an electrochemical process which brightens the steel surface by selective dissolution of the high points - it is the opposite of electroplating, and is carried out with broadly similar equipment. Apart from the obvious outcome of a visual brightening, electropolishing is a very effective way of improving pitting corrosion resistance.

The process can produce a very attractive corrosion resisting and hygienic finish, but trials should first be conducted to determine the optimum prior surface condition and polishing parameters. Electropolishing of some surfaces results in a frosted rather than smooth finish particularly if they are in the sensitised (i.e. grain boundary carbides) condition.

Grinding and Polishing

Stainless steels can be readily ground, polished and buffed, but certain characteristics of these materials require some modification of standard techniques for best results. Most notably, the high strength, tendency to "load up" abrasive media, and low thermal conductivity of stainless steels all lead to build-up of surface heat. This in turn can produce heat tinting (surface oxidation) or surface smearing, and in extreme cases even sensitisation of austenitic stainless steels or "burning" (rehardening) of heat treated martensitic grades. Techniques that help prevent build-up of surface heat include (a) use of lower speeds and feeds, and (b) careful selection of lubricants, and of proper grit size and type, to minimise loading of the abrasive.

Corrosion resistance of stainless steels may be adversely affected by polishing with coarse abrasives. Corrosion resistance is often adequate following polishing to a No.4 (approx. 180 – 240 grit) finish. Polishing with fine alumina or chromium oxide to obtain still higher finishes - such as buffed finishes No.7 and No.8 – removes fine pits and surface imperfections and generally improves corrosion resistance. Buffing can also be carried out by using a "Scotch-brite" buffing wheel.

There is evidence that surfaces with roughness values (Ra) coarser than 0.5µm have impaired resistance to corrosion. Information on “tea staining” corrosion of these coarse finishes is given in ASSDA Technical Bulletin No 2. (available at www.assda.asn.au).

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Iron contamination must be avoided or removed if polished stainless steel surfaces are to have good corrosion resistance. Abrasives and polishing compounds must be essentially iron-free (less than 0.01% for best results), and equipment used for processing stainless steels must not be used for other metals. If these conditions cannot be met, a cleaning/passivation treatment (after pre-cleaning to remove polishing compounds and lubricants) will be required to restore good corrosion resistance. Even if iron-free abrasives have been used, a final passivation or electropolish will improve corrosion resistance by removing manganese sulphide inclusions from the cut surface.

Mechanical Cleaning

Problems associated with chemical cleaning processes can be avoided by using mechanical cleaning. With all mechanical cleaning processes great care must be taken to prevent the stainless steel surface from becoming contaminated by iron, steel or iron oxide particles.

Sand blasting is often used - this must be with clean silica or garnet sand. Garnet is readily available with a “free of iron” guarantee, but this is less certain for silica. Shot, grit and cut wire blasting must be done with stainless steel media of a grade, equal in corrosion resistance to the metal being cleaned, and scale particles must be continually separated from the shot.

Wire brushing is useful to remove light heat tint, but again brushes must be of stainless steel, and these must never be used on materials other than stainless steels.

Barrel finishing and vibratory finishing both use abrasive media to mechanically polish small parts and are widely used on fasteners such as screws and bolts and on pipe fittings.

Mechanically cleaned parts are not quite as corrosion resistant as acid pickled material because mechanical cleaning leaves some scale residues and may not remove the chromium depleted layer of steel from beneath the scale. It can be used as a preparatory step to speed up subsequent acid pickling.

Blackening

Blackening to produce a non-reflective or low reflective black oxide surface can be accomplished by several methods. Immersion in sulphuric acid/potassium dichromate solutions at 80 to 99°C or immersion in a molten salt bath of sodium dichromate at 400°C are two methods. Black chromium plating is another.

Most treatments are performed by specialist firms, who should be consulted regarding a specific application. All these processes have suffered reduced Australian usage in recent years.

Surface Contamination in Fabrication

Stainless steels must have clean surfaces, free from contamination, to achieve their optimum corrosion resistance. During fabrication care must be taken to either protect the metal surface from contamination or to restore the surface after fabrication is complete.

Three common and undesirable contaminants that may be encountered during fabrication and shipping are carbon (mild) steel, salt (sodium chloride) and carbon.

Contamination by Carbon Steel

As well as carbon steel the same effect can come about by contact with any low alloy steel, tool steel or cast iron: any non-stainless ferrous material able to be deposited onto the stainless.

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The problem is visually very apparent as red rust spots on the stainless steel. The pattern of the rust often indicates the source of the contamination – rows of intermittent or continuous rust suggest a scrape while distributed spots suggest air-borne dust or particles.

The problem may not become apparent until the deposited carbon steel starts to rust; immediately following deposition, the only evidence is often a minor scratch or some small innocuous looking spot. The extent of the damage is often only revealed when the contaminated area becomes wet.

It is possible to test a stainless steel surface for contamination. ASTM A380 lists several options; the most sensitive is a "ferroxyl test" but a very practical, easy and relatively quick test is usually to intermittently wet the surface with potable water for about 24 – 48 hours. This will start the rusting of any contamination that is present.

Corrosion initiation from mild steel contamination may occur in two ways:

1. The protective oxide film on the stainless steel may be broken when the mild steel is brought into contact with the stainless steel. This contact creates a mild steel/stainless steel interface which is a corrosion cell.

2. The mild steel contamination may be at the outer surface of the oxide film on the stainless steel. Then, under moist conditions, the mild steel will corrode and cause both oxygen depletion and ionic concentration beneath the ferrous deposit.

Typical causes of contamination by carbon steel include:

- Using carbon steel hooks, chains, and wire ropes for lifting unprotected stainless steel materials (Suitably placed dunnage, or cover the lifting tackle to avoid damage).

- Lifting unprotected stainless steel with lifting gear contaminated from previously lifting unprotected carbon steel.

- Dragging stainless steel over mild steel, of hitting the stainless with carbon steel.

- Falling particles of mild steel welding and flame cutting dross from higher workings.

- Grinding dust thrown up by power tools used on mild steel.

- Contamination from tools that have previously been used on mild steel … commonly polishing tools, drills, files, and screwdrivers.

Contamination by Chlorides

When contamination by common salt (sodium chloride) occurs, the dissolved chloride ions enter the structure of the protective oxide film on the surface of the stainless steel. When moisture evaporates at the surface of the metal, the chloride ions concentrate and can break down the protective film.

Contamination by common salt can occur from:

- Sea spray and seawater.

- Environmental contamination, such as in butter and cheese plants where air blasting drives salt into the product.
- Sweaty hands.
- Salt applied to avert or melt road ice (not in Australia).
- Salts added to concrete to aid setting.
- Hydrochloric acid used to clean brickwork and chemically etch concrete floors.

Contamination by Carbon

Carbon contamination usually occurs when the metal is heated (e.g. during welding), under which conditions any organic materials may break down on the surface of the metal and contaminate both the solid surface and any molten metal; at elevated temperatures carbon can be absorbed by the stainless steel – this carburised region is then liable to become sensitised.

Contamination by carbon can occur from:

- Pencil, paint or marking pen markings.
- Combustion of oil films, paper, organic matter, backing strip materials, bonding agents or sooty gas flames in gas welding or heat treating.
- By welding to carbon steel.

Solid carbon (e.g. gasket material) can also act as a source of galvanic corrosion of the stainless, one of very few materials more noble than stainless.

Design Considerations in Fabrication of Stainless Steels

Whatever the intended function of a component it is essential that the design also consider the way in which it will be constructed. Some of these considerations such as allowing sufficient access for welders and for the tightening of bolts, are common to other metals, but in other respects the unique properties of stainless steels need to be considered.

Because of austenitic stainless steels' high expansion rate and low thermal conductivity, it is important to not unduly restrain components during welding, and to not constrain carbon steel and stainless steel which behave differently when heated.

The machinability of most stainless steels is somewhat lower than that of many other metals, so there is extra incentive to reduce the amount of machining required. One way in which this can be achieved is to use bright (i.e. cold finished) bar of a size such that no machining is required over the largest component size; this same result may be achieved by using bright finished hexagonal or other shaped bar.

If machining is to be carried out it is important that sufficient clean-up be allowed so that a reasonable cut is achieved; very light cuts can result in the tool skidding across a very heavily cold worked surface. Good machining practice for stainless steels, and the austenitic (300 series) grades in particular, is to use heavier feeds and lower speeds than for carbon steels.

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Grade Selection for Fabrication

Refer also to the section on Guidelines for Stainless Steel Grade Selection.

If extensive machining is to be carried out the use of free machining grades 303 or 416 should be considered, but consideration must also be given to the relatively low corrosion resistance, weldability and formability of these grades.

Improved Machinability grades such as the "Ugima" range (e.g. Ugima 303, 304 and 316) are available - these offer better machinability than standard stainless steels but still retain the excellent corrosion resistance, weldability and formability of their standard grade equivalents.

Stainless steel grades can also be selected for ease of cold forming; Grade 302HQ (UNS S30430) is a low work hardening rate grade available in wire form specifically for the cold forming of fasteners such as bolts and screws. By contrast grades 301 and 304 have a very high work hardening rate and can be supplied in a heavily cold worked condition suitable for the manufacture of springs; these require no hardening treatment after forming.

Components to be welded must be fabricated from a grade selected on that basis; to avoid problems associated with "sensitisation" - caused by holding in the temperature range of about 450 to 850°C - it may be necessary to use a low carbon "L" grade or a stabilised grade such as Grade 321. In the case of all welding it is essential that welding consumables are selected to match the grade being welded. See also the sections of this Handbook on intergranular corrosion, welding, and on grade selection.

Design to Avoid Corrosion

When designing for stainless steel fabrication it is necessary to be aware of the factors which can cause premature corrosion failures. The principal problems are:

- General corrosion - a widespread wall thinning caused typically by exposure to strong reducing acids particularly at high concentration or temperature.
- Pitting corrosion - related to chlorides, even in low concentrations and particularly at slightly elevated temperatures.
- Crevice corrosion - also related to chlorides but made worse by small crevices in which liquid is trapped.
- Intergranular corrosion due to prolonged heating in either welding or in application in conjunction with incorrect grade selection.
- Stress corrosion cracking due to applied tensile stress, again in conjunction with chlorides and raised temperature.
- Galvanic corrosion due to proximity of metals widely spaced in the electrochemical series.
- Contact corrosion due to contamination of the stainless steel by a material such as mild steel particles.

More detailed descriptions of each of these corrosion mechanisms are given in the section of this Handbook on Corrosion Resistance.

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Often measures to prevent several of these problems are similar. Design of stainless steel components must be made to prevent build-up of stagnant water, to encourage circulation of liquids, to discourage evaporation-concentration and to keep stresses and temperatures as low as possible.

Good design alone is not sufficient to prevent problems; fabricators must also be aware of these problems and may need to modify their practices accordingly. It is strongly recommended that specialist stainless steel fabricators be used.

Specific Design Points - To Retain Corrosion Resistance

1. **Invert Structural Members**
   Avoid entrapment of moisture within members and within attachments, as shown in Figure 23. Stagnant liquid remnants are likely to concentrate and to lead to pitting corrosion.

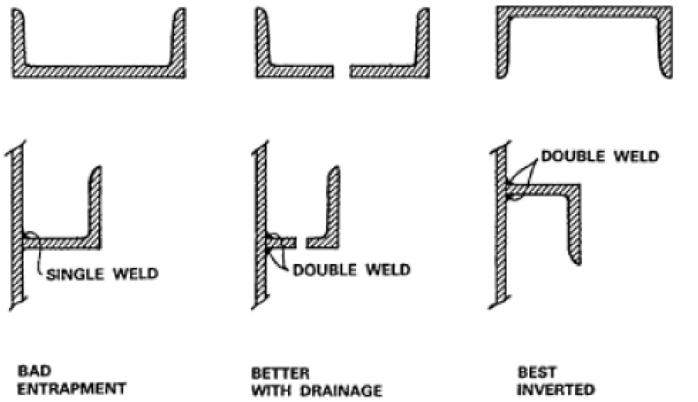

Figure 23

2. **Ensure Tanks & Pipes Drain Fully When Idle**
   Tanks and pipelines left with small residual fluid quantities also encourage pitting corrosion, as shown in Figure 24. The problem is made worse if the fluid is spread to a thin film.

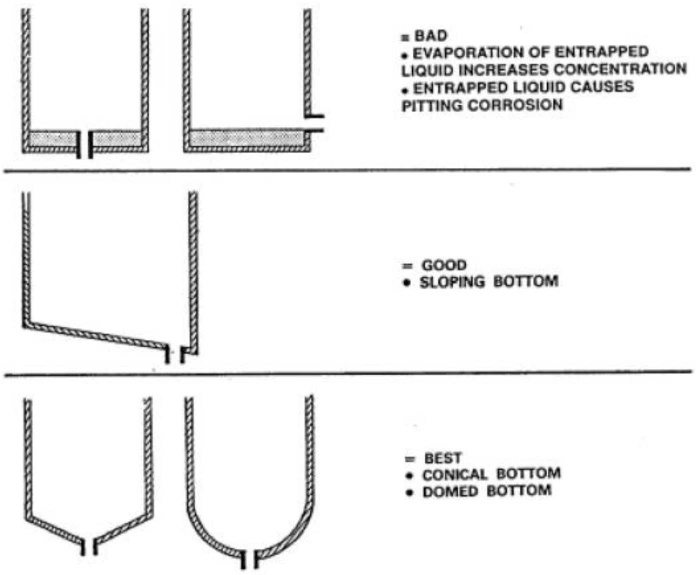

Figure 24

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3. **Raise Tanks Off the Floor**
Tank bottoms placed directly on concrete floors will create crevices; ideal sites for corrosion in the event of liquid spillage. Sealing the gap improves the position, but is subject to misapplication and deterioration. A drip skirt prevents liquid collecting beneath the tank, while raising the tank on legs removes the crevice entirely. These options are shown in Figure 25.

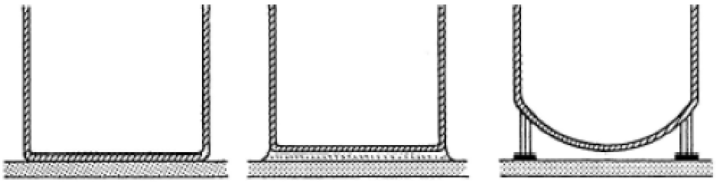

Figure 25

4. **Smooth, Rounded Corners Inside Tanks**
Efficient maintenance cleaning of tanks is often important to remove built-up debris or stains; this reduces the likelihood of crevice corrosion under sediments and may be important to retain hygienic conditions or prevent product contamination. All internal tank corners should if possible be well rounded and smooth. Welds should be in tank sides, not at corners. Welds should also be ground smooth (much easier if the weld is in the side, not corner) and full penetration or from both sides. All of these measures improve the fatigue resistance of the structure, as well as removing crevices.

5. **Insulation or Lagging of Pipelines and Vessels**
Thermal insulation of tanks and pipes should be free of chlorides. The insulation should be clad to totally prevent entry of water, as pitting corrosion or stress corrosion cracking can occur in the warm, moist environment. The outside of a hot tank or pipe can be a highly corrosive environment because of evaporation of liquid resulting in very high localised chloride contents. The outside may in fact be a more corrosive environment than the inside!

6. **Incomplete Filling Problems**
Vapour phases given off by some fluids can be quite corrosive; in these cases, if the tank cannot be filled completely the vapour space should be well ventilated to remove the vapour.

7. **Inlet Location**
When dosing or making up a tank a highly corrosive chemical may be added. In these instances, it is important that the inlet be located away from side walls and in a moving liquid stream, so that the addition is quickly diluted.

8. **Reduce Splashing Within Tanks**
A further problem may be caused by splashing during filling or mixing – splash drops on the inside tank walls will undergo evaporation and hence concentration of the corrosive species. Splashing should therefore be avoided, perhaps by ensuring that the inlet pipe terminates beneath the liquid level or by running mixing propellers slowly and fully submerged.

9. **Heater Location**
Corrosion of all types proceeds more rapidly at higher temperatures. It is therefore important that immersion heaters in vessels are placed so as not to locally heat any section

of the vessel wall, and processes should be run at the lowest constant temperature possible.

10. Avoid Settling in Pipes and Vessels

Crevice corrosion can occur beneath debris which settles out of stagnant or slow-moving liquid, and in some environments low liquid velocity also permits marine organisms to grow on the steel, with similar increase in crevice corrosion initiation. Designs should both maintain a reasonable flow rate (about 1 m/sec has been shown to substantially decrease the pitting rate in sea water) and result in total draining when the operation ceases. Dosing the fluid with a biocide may be a solution to the fouling problem, but chlorinated biocides such as hypochlorites can themselves be highly corrosive to stainless steels. Over-dosing must be avoided.

11. Pipe Welds

When joining pipe runs or using butt welding or socket weld fittings it is highly desirable to achieve full penetration welds. Incomplete weld penetration will result in a joint which appears good on the outside but has severe crevices at the root of the weld. Full penetration can be facilitated using consumable inserts or by GTAW with hand fed filler metal.

12. Structural Attachments

Crevices are readily created when supporting rings, attachment pads etc are welded to stainless steel vessels. Intermittent weld runs may give adequate mechanical strength, but only fully sealed welds give freedom from crevices.

13. Welding Mild Steel to Stainless Steel

Mixed-metal welding can be satisfactory, generally using an over-alloyed welding consumable such as Grade 309L, but caution must be exercised to prevent carbon migration into the part of the stainless steel exposed to the corrosive environment. Differential expansion rates can also lead to excessive stresses, particularly at tack welds. Stainless steel attachment pads between a stainless steel vessel and its mild steel support can assist in reducing these problems.

14. Weld Repair to Avoid Crevices

If a leaking tank is patched this should be done in a manner which avoids creating further crevices, on either inside or outside, as in Figure 26.

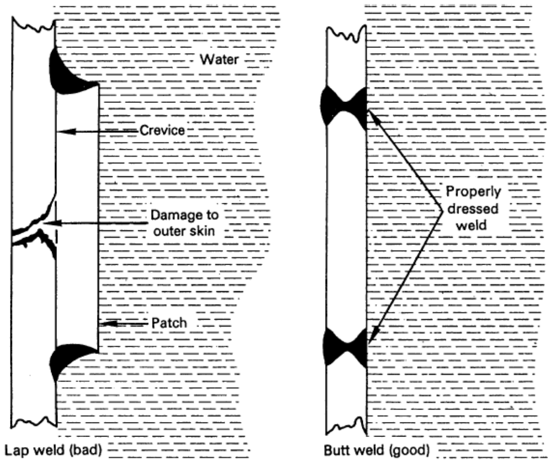

Figure 26

15. **Preparation for Welding**
Minimum amounts of energy should always be put into stainless steel welds. The material should be carefully prepared and shaped before welding commences. The welder should avoid chill casting the first metal laid down and shrinkage cracks in the final weld pools.

16. **De-scaling of Welds and Surface Cleaning**
To achieve maximum corrosion resistance all weld scale must be removed and the surface ground, polished and possibly buffed to the specified finish. Best resistance to corrosion is achieved when the steel surface is mirror smooth and totally free of scale or other contaminants. Pickling or passivating will assist in this process, and "pickling paste" is available to easily carry it out. See the section of this handbook on pickling and passivation.

17. **Avoid Sharp Machined Corners**
Machining should avoid sharp internal corners at sites such as changes of shaft diameter and the corners of keyways, as these may act as crevices both by their own geometry and by the tendency during service for material to build up in these sites (and perhaps be difficult to clean out). Radiusing of corners will also improve the fatigue resistance of any component subject to fluctuating stresses, as it does also for other materials.

18. **Avoid Sleeving of Shafts**
Fitting of sleeves to shafts creates possible crevice sites between the inner and outer components. A better solution from this point of view is to machine from a solid bar.

Guidelines for Stainless Steel Grade Selection

Fundamental Properties for Selection

When considering the choice of a stainless steel for a particular application, the first consideration needs to be based on which of the fundamental "competitive advantage" properties needs to be exploited, as tabulated in Figure 27. These basic properties for selection can be initially looked at from the point of view of the five basic alloy groups - austenitic, duplex, ferritic, martensitic and precipitation hardening and then the selection refined by considering individual grades.

Required Property	Alloy Groups and Grades Likely to be Selected
Corrosion Resistance	Selection depends upon environment. Corrosion resistance depends mainly on composition, not on alloy group. PRE gives a first guide to resistance. See text above.
Heat Resistance	Austenitic grades, particularly those high in chromium, often also with high silicon, nitrogen and rare earth elements (e.g. grade 310 and particularly 253MA). High chromium ferritic grades can be useful (e.g. 446). Ferritic grades with niobium have improved creep strength over other ferritic grades.
Cryogenic (low temperature) Resistance	Austenitic grades have excellent toughness at very low temperatures. All other grades have a transition from ductile to brittle behaviour at some temperature.
Magnetic Response	Austenitic grades have low magnetic permeability; higher nickel grades (e.g. 316 or 310) are guaranteed non-magnetic even if cold worked. All other grades always show magnetic response.
High Strengths	Martensitic and precipitation hardening grades. Duplex grades are higher strength than austenitics.

Figure 27 Competitive Advantage

Selection for Corrosion Resistance

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The selection of the most cost-effective grade for a particular corrosive environment can be a complex task. Often the most revealing guide to material selection is the simple consideration of what has been used before (here or in a similar environment), what was the service life and how and when did it corrode.

For resistance to environments such as strong acids, where uniform general corrosion is the controlling mechanism, there are published tables of recommended grades, and ISO-corrosion curves that indicate the rate at which the steel can be expected to corrode. These are usually constructed so that several grades can be compared, and the applicable one selected for the expected environment. Although this approach is useful, some care needs to be taken as there are often minor differences between apparently similar environments that can make a large difference to the corrosion rates in practice. Traces of chloride for instance can be harmful.
Local corrosion is very frequently the mechanism by which stainless steels are likely to corrode. The related mechanisms of pitting and crevice corrosion are very largely controlled by the presence of chlorides in the environment, exacerbated by elevated temperature. The resistance of a particular grade of stainless steel to pitting and crevice corrosion is indicated by its Pitting Resistance Equivalent number, or PRE, as shown in the table of Figure 28.

Grade	Alloy Group	PRE
3CR12	Ferritic	11
430	Ferritic	17
439	Ferritic	18
303	Austenitic	18*
304/L	Austenitic	18
316/L	Austenitic	24
444	Ferritic	25
2304	Duplex	26
2205	Duplex	34
904L	Austenitic	34
S31254	Austenitic	43
S32750	Duplex	43
S32520	Duplex	43
*See comment in the text regarding grade 303		

Figure 28

The PRE can be calculated from the composition as:

$$PRE = \%Cr + 3.3\ \%Mo + 16\ \%N$$

For grades containing tungsten the formula is sometimes written as:

$$PRE = \%Cr + 3.3\ (\%Mo + 0.5\ \%W) + 16\ \%N$$

Clearly grades high in the alloying elements chromium and especially molybdenum and nitrogen are more resistant. This is the reason for the use of grade 316 (2%Mo) as the standard for marine fittings, and explains the selection of duplex grade 2205 (S32205 or S31803) with 22%Cr, 3%Mo and a deliberate addition of 0.15%N for resistance to higher chlorides at higher temperatures. More severe chloride containing environments can be resisted by the "super austenitic" grades

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(e.g. N08904 and S31254) with up to 6%Mo and by the "super duplex" grades (e.g. S32750, S32550 and S32520) with very high chromium, molybdenum and nitrogen additions.
The use of these grades can extend the useful resistance in high chloride environments up to close to boiling point.

A particular problem for the common austenitic grades (e.g. 304 and 316) is stress corrosion cracking (SCC). Like pitting corrosion this occurs in chloride environments, but it is possible for SCC to take place with only traces of chlorides, so long as the temperature is over about 60°C, and so long as a tensile stress is present in the steel, which is very common. The ferritic grades are virtually immune from this form of attack, and the duplex grades are highly resistant. If SCC is likely to be a problem, it would be prudent to specify a grade from these branches of the stainless family tree.

Selection for Mechanical and Physical Properties
High strength martensitic (e.g. 431) and precipitation hardening (e.g. 630 / 17-4PH) grades are often the material of choice for shafts and valve spindles - here the high strength is as fundamental to the selection process as is the corrosion resistance. These grades have strengths up to twice that of grades 304 and 316.

More commonly, however, the grade is selected for required corrosion resistance (or resistance to high or low temperature or because of required magnetic response), and then the structure or component is designed around the mechanical and physical properties of the grade selected. These secondary aspects should be considered as early as possible in the selection process. The selection of a high strength duplex grade such as 2205 may not only solve the corrosion problem but also contribute to the cost effectiveness of the product because of its high strength. The selection of a ferritic grade such as 3CR12 may result in adequate corrosion resistance for a non-decorative application, and its low coefficient of thermal expansion could be desirable because of less distortion from temperature changes. The thermal expansion rates of the ferritic grades are similar to that of mild steel, and only 2/3 that of austenitic grades such as 304.

Selection for Fabrication
Again, it is usually the case that grades are selected for corrosion resistance and then consideration is given to how the product can be fabricated. Fabrication should be considered as early as possible in the grade selection process, as it greatly influences the economics of the product. The table in Figure 29 lists some common grades and compares their relative fabrication characteristics. These comparisons are on arbitrary 1 to 10 scales, with 10 indicating excellent fabrication by the particular method.

It is important to realise that there may be a trade-off between desirable properties. An example is grade 303. This has excellent machinability, but the high sulphur content which increases the cutting speed so dramatically also substantially reduces the grade's weldability, formability and corrosion resistance. With this grade the calculated PRE is wrong, as it does not factor in the negative effect of the sulphur. This grade must not be used in any marine or other chloride environments.

Grade	Form-ability	Machin-ability	Weld-ability
303	1	8*	1
304	8	5*	8
316	8	5*	8

Figure 29 Grade fabrication ratings

Selection Criteria

Before selecting a grade of stainless steel it is essential to consider the required properties such as corrosion resistance, but it is also important to consider the secondary properties such as the physical and mechanical properties and the ease of fabrication of any candidate grades.

The correct choice will be rewarded not just by long, trouble free life, but also by cost-effective fabrication and installation.

Appendix 1

Atlas Steels Technical Handbook of Stainless Steels

Grade Summary - Stainless & Heat Resisting Steels

Grade Design	UNS No.	Typical Composition (%)						Description and Applications
		C	Mn	Cr	Mo	Ni	Others	
Austenitic Stainless Steels								
301	S30100	0.10	1	17		7		Primarily for deep drawn components and high strength springs and roll- formed panelling.
302HQ	S30430	0.03	0.6	18		9	Cu 3.5	Wire for severe cold heading applications such as cross-recess screws.
303	S30300	0.06	1.8	18		9	S 0.3	Free machining grade for high speed repetition machining. Also available as "Ugima" 303 improved machinability bar for even higher machinability.
304	S30400	0.05	1.5	18.5		9		Standard austenitic grade – excellent fabrication characteristics with good corrosion resistance. Also available as "Ugima" 304 improved machinability bar.
304L	S30403	0.02	1.5	18.5		9		Low carbon version of 304 gives resistance to intergranular corrosion for heavy section welding and high temperature applications.
308L	S30803	0.02	1	19.5		10.5		Filler wire for welding 304 and similar grades.
309	S30900	0.05	1.5	23		13.5		Good corrosion resistance and good resistance to attack by hot sulphur compounds in oxidising gases. Filler for welding dissimilar metals.
310	S31000	0.08	1.5	25		20		Good resistance to oxidation and carburising atmospheres in temperatures 850-1100°C.
316	S31600	0.05	1	17	2	11		Higher resistance than 304 to many media, particularly those containing chlorides. Also available as "Ugima" 316 improved machinability bar.
316L	S31603	0.02	1	17	2	11		Low carbon version of 316 gives resistance to intergranular corrosion for heavy section welding and high temperature applications.
321	S32100	0.04	1	18		9	Ti 0.5	Titanium stabilised grade resists intergranular corrosion during exposure at 425-850°C. High strength in this temperature range.
347	S34700	0.04	1	18		9	Nb 0.7	Niobium stabilised grade resists intergranular corrosion as for 321, but more commonly used as a filler for welding 321.
904L	N08904	0.02	1	20	4.5	24	Cu 1.5	Super austenitic grade with very high corrosion resistance, particularly to sulphuric acid and warm chlorides.
253MA	S30815	0.08	0.6	21		11	N 0.16 Ce 0.06	Excellent scaling and creep resistance at temperatures up to 1150°C.

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Grade Design	UNS No.	Typical Composition (%)						Description and Applications
		C	Mn	Cr	Mo	Ni	Others	
Ferritic Stainless Steels								
3CR12	S41003	0.025	0.5	11.5		0.35		"Utility" stainless steel with useful resistance to wet abrasion, and good formability and weldability.
409	S40900	0.06	1	11			Ti 0.4	Resists atmospheric and automotive exhaust gas corrosion. Used extensively in auto exhaust systems.
430	S43000	0.03	0.4	16.5				Good combination of corrosion resistance and formability. Used for interior panelling and cold headed fasteners.
430F	S43020	0.07	1	16.5			S 0.025	Free machining version of 430. Not commonly available.
439	S43932	0.02	0.8	17.5			Ti/Nb 0.4	Weldable general-purpose chromium ferritic grade with corrosion resistance approaching that of 304.
444	S44400	0.02	0.8	18	2		Ti/Nb 0.4	Weldable chromium-molybdenum ferritic grade has excellent corrosion resistance to hot water containing minor amounts of chlorides.
Duplex Stainless Steels								
2304	S32304	0.02	0.8	23	0.3	3	N 0.15	High strength and with corrosion resistance matching that of 316.
2205	S32205 S31803	0.02	0.8	23	3	5	N 0.17	High strength and good resistance to pitting corrosion and stress corrosion cracking.
UR52N+ **2507Cu**	S32520 S32550	0.02	0.8	25	3.5	7	N 0.25 Cu 0.7	Super duplex grade exhibiting exceptional resistance to hot chlorides and strong acids, and with high strength.
2507	S32750	0.02	0.8	25	3	6	N 0.27	Super duplex grade exhibiting exceptional resistance to hot chlorides and strong acids, and with high strength.
Martensitic Stainless Steels								
410	S41000	0.01	0.5	12				Resists dry atmospheres, fresh water and other mild environments. Hardened and tempered to achieve best strength and corrosion resistance.
416	S41600	0.12	1.0	12				Free machining hardenable grade. Corrosion resistance not as good as for 410.
420	S42000	0.3	0.5	13				Higher carbon content than 410 gives higher hardness for cutlery, knife blades, dies and surgical instruments.
431	S43100	0.2	0.6	15		2		High strength, excellent toughness and corrosion resistance similar to that of 304. Used for pump shafts, bolts and valve components.
440c	S44004	1.0	0.5	17				Very high hardness grade excellent for corrosion resistant knives and cutting tools.
Precipitation Hardening Stainless Steels								
630 **(17-4ph)**	S17400	0.05	0.6	16		4	Cu 4 Nb 0.25	Precipitation hardening ("aging") treatment after machining gives high strength without distortion. Corrosion resistance similar to 304.

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Appendix 2

Comparison of Grade Specifications of Stainless Steels

Grade	UNS No	British BS	Euronorm No	Euronorm Name	Swedish SS	Japanese JIS
301	S30100	301S21	1.4310	X10CrNi18-8	2331	SUS 301
301LN	S30153	-	1.4318	X2CrNiN18-7	-	-
302	S30200	302S25	1.4319	-	-	SUS 302
303	S30300	303S31	1.4305	X8CrNiS18-9	2346	SUS 303
303Se	S30323	303S42	-	-	-	SUS 303Se
304	S30400	304S31	1.4301	X5CrNi18-10	2332	SUS 304
304L	S30403	304S11	1.4307	X2CrNi18-9	2352	SUS 304L
304H	S30409	-	1.4948	X6CrNi18-11	-	-
304N	S30451	-	-	-	2371	SUS 304N1
(302HQ)	S30430	394S17	1.4567	X3CrNiCu18-9-4	-	SUS XM7
305	S30500	305S19	1.4303	X4CrNi18-12	-	SUS 305
309S	S30908	309S24	1.4833	X12CrNi23-13	-	SUS 309S
310	S31000	310S24	1.4840	X15CrNi25-20	-	SUS 310
310S	S31008	310S16	1.4845	X8CrNi25-21	2361	SUS 310S
314	S31400	314S25	1.4841	X15CrNiSi25-21	-	-
316	S31600	316S31	1.4401	X5CrNiMo17-12-2	2347	SUS 316
316L	S31603	316S11	1.4404	X2CrNiMo17-12-2	2348	SUS 316L
316H	S31609	316S51	-	-	-	-
316LN	S31653	316S61	1.4406	X2CrNiMoN17-11-2	-	SUS 316LN
316Ti	S31635	320S31	1.4571	X6CrNiMoTi17-12-2	2350	SUS 316Ti
317L	S31703	317S12	1.4438	X2CrNiMo18-15-4	2367	SUS 317L
321	S32100	321S31	1.4541	X6CrNiTi18-10	2337	SUS 321
329	S32900	-	1.4460	X3CrNiMoN27-5-2	2324	SUS 329J1
347	S34700	347S31	1.4550	X6CrNiNb18-10	2338	SUS 347
403	S40300	403S17	1.4000	X6Cr13	2301	SUS 403
405	S40500	405S17	1.4002	X6CrAl13	-	SUS 405
409	S40900	409S19	1.4512	X2CrTi12	-	SUS 409
410	S41000	410S21	1.4006	X12Cr13	2302	SUS 410
416	S41600	416S21	1.4005	X12CrS13	2380	SUS 416
416Se	S41623	416S41	-	-	-	-
420	S42000	420S37	1.4021	X20Cr13	2303	SUS 420J1
420F	S42020	416S29	-	-	-	SUS 420F
430	S43000	430S17	1.4016	X6Cr17	2320	SUS 430
430F	S43020	-	1.4104	X14CrMoS17	2383	SUS 430F
431	S43100	431S29	1.4057	X17CrNi16-2	2321	SUS 431
434	S43400	434S17	1.4113	X6CrMo17-1	2325	SUS 434
440C	S44004	-	1.4125	X105CrMo17	-	SUS 440C
444	S44400	-	1.4521	X2CrMoTi18-2	2326	SUS 444
630	S17400	-	1.4542	X5CrNiCuNb16-4	-	SUS 630
631	S17700	460S52	1.4568	X7CrNiAl17-7	2388	SUS 631
904L	N08904	904S13	1.4539	X1NiCrMoCuN25-20-5	2562	-
(253MA)	S30815	-	1.4835	X9CrNiSiNCe21-11-2	2368	-
2205	S32205	318S13	1.4462	X2CrNiMoN22-5-3	2377	SUS 329J3L
2304	S32304	-	1.4362	X2CrNiN23-4	2327	-
2507	S32750	-	1.4410	X2CrNiMoN25-7-4	2328	-
(3CR12)	S41003	-	1.4003	X2CrNi12	-	-
(4565S)	S34565	-	1.4565	X2CrNiMnMoN24-17-6-4	-	-
(Zeron100)	S32760	-	1.4501	X2CrNiMoCuWN25-7-4	-	-
2507Cu	S32520	-	1.4507	X2CrNiMoCuN25-6-3	-	-

Designations in (parentheses) not recognised by ASTM; some are registered trademarks. The above comparisons are approximate only - in some instances they are very close, in others much less so. The list is intended as a comparison of functionally similar materials **not** as a schedule of contractual equivalents. If exact equivalents are needed original specifications must be consulted.

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Appendix 3

Typical Physical Properties – Annealed Condition

Grade	UNS No	Density kg/m³	Elastic Modulus (a) GPa	Mean Coefficient of Thermal Expansion (b)			Thermal Conductivity		Specific Heat	Electrical Resistivity
				0-100°C µm/m/°C	0-315°C µm/m/°C	0-538°C µm/m/°C	at 100°C W/m.K	at 500°C W/m.K	0-100°C J/kg.K	nΩ.m
201	S20100	7800	207	16.6	18.0	19.6	16.3	-	500	670
202	S20200	7800	-	17.5	18.4	19.2	16.3	-	500	690
301	S30100	7900	193	17.0	17.2	18.2	16.3	21.5	500	720
302	S30200	7900	193	17.2	17.8	18.4	16.3	21.5	500	720
302B	S30215	7900	193	16.2	18.0	19.4	-	-	500	720
303	S30300	7900	193	17.3	17.8	18.4	16.3	21.5	500	720
304	S30400	7900	193	17.2	17.8	18.4	16.3	21.5	500	720
304L	S30403	7900	193	17.0	17.2	18.2	16.3	21.5	500	720
302HQ	S30430	7900	193	17.2	17.8	18.8	16.3	21.5	500	720
304N	S30451	7900	196	17.2	17.8	18.4	16.3	21.5	500	720
305	S30500	7900	193	17.2	17.8	18.4	16.3	21.5	500	720
308	S30800	7900	193	17.2	17.8	18.4	15.2	21.6	500	720
309	S30900	7900	200	15.0	16.6	17.2	15.6	18.7	500	780
310	S31000	7900	200	15.9	16.2	17.0	14.2	18.7	500	720
314	S31400	7900	200	-	15.1	-	17.5	20.9	500	770
316	S31600	8000	193	15.9	16.2	17.5	16.3	21.5	500	740
316L	S31603	8000	193	15.9	16.2	17.5	16.3	21.5	500	740
316N	S31651	8000	196	15.9	16.2	17.5	14.4	-	500	740
317	S31700	8000	193	15.9	16.2	17.5	16.2	21.5	500	740
317L	S31703	8000	200	16.5	-	18.1	14.4	-	500	790
321	S32100	7900	193	16.6	17.2	18.6	16.1	22.2	500	720
329	S32900	7800	186	10.1	11.5	-	-	-	460	750
330	N08330	8000	196	14.4	16.0	16.7	-	-	460	1020
347	S34700	7900	193	16.6	17.2	18.6	16.1	22.2	500	720
384	S38400	7900	193	17.2	17.8	18.4	16.2	21.5	500	790
409	S40900	7700	208	11.0	11.7	12.4	25.8	27.5	460	600
410	S41000	7700	200	9.9	11.4	11.6	24.9	28.7	460	570
416	S41600	7700	200	9.9	11.0	11.6	24.9	28.7	460	570
420	S42000	7700	200	10.3	10.8	11.7	24.9	-	460	550
430	S43000	7700	200	10.4	11.0	11.4	23.9	26.0	460	600
430F	S43020	7700	200	10.4	11.0	11.4	26.1	26.3	460	600
431	S43100	7700	200	10.2	12.1	-	20.2	-	460	720
434	S43400	7700	200	10.4	11.0	11.4	-	26.3	460	600
436	S43600	7700	200	9.3	-	-	23.9	26.0	460	600
440C	S44004	7650	200	10.1	10.3	11.7	24.2	-	460	600
444	S44400	7750	200	11.0	10.6	11.4	26.8	-	420	620
446	S44600	7750	200	11.0	-	-	20.9	24.4	500	670
630	S17400	7750	196	10.8	11.6	-	18.4	22.7	460	800
631	S17700	7750	204	11.0	11.6	-	16.4	21.8	460	830
904L	N08904	8000	200	15.0	-	-	13.0	-	500	850
253MA	S30815	7800	200	17.0	17.2	18.2	15.5	-	500	850
2205	S32205	7800	200	13.7	14.7	-	19.0	-	450	850
2304	S32304	7800	200	13.0	-	-	16.0	-	470	850
2507	S32750	7800	200	13.0	14.0	-	14.2	-	460	850
3CR12	S41003	7740	200	10.8	11.3	12.5	30.5	40.0	480	570
4565S	S34565	8000	190	14.5	16.3	17.2	14.5	-	450	920
2507Cu	S32520	7800	205	13.5	14.0	14.5	17.0	-	450	850
Zeron100	S32760	7800	190	12.6	13.9	-	14.4	-	480	850

Note: (a) 1 GPa = 1000 MPa (b) µm/m/°C = x10-6/°C

Magnetic Permeability of all 300 series austenitic steels in the annealed condition is approximately 1.02.

Appendix 4

Hardness Conversions

Approximate conversions for Austenitic Stainless Steels and High Nickel Alloys

Brinell (HB)	Vickers (HV)	Rockwell C (HR C)	Rockwell B (HR B)
479	513	50	
450	482	48	
425	452	46	
403	427	44	
382	404	42	
363	382	40	
346	362	38	
330	344	36	
315	326	34	
301	309	32	106
286	285	28	104
271	266	26	102
256	248	23	100
240	234	20	98
226	220	17	96
213	209	14	94
202	198	12	92
192	188		90
183	179		88
174	171		86
167	164		84
160	157		82
153	151		80
147	144		78
142	140		76
137	137		74
132	133		72
128	129		70

Note:
Conversions between hardness scales are approximate only and should not be used to determine conformance with specifications. Data from ASTM A370 and ASTM E140. Actual values obtained for hardness will depend very much upon product type. Cold worked products may have significantly higher hardnesses close to the surface.

Conversions between hardness and tensile strength are not standardised for stainless steels, and no reliable conversions are possible.

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Appendix 5

Unit Conversions

To Convert	To	Multiply By
megapascal (MPa)	pound-force/in² (psi)	145.03
pound-force/in² (psi)	megapascal (MPa)	0.006895
megapascal (MPa)	ton-force/in² (tsi)	0.064749
ton-force/in² (tsi)	megapascal (MPa)	15.444
megapascal (MPa)	kilogram-force/mm² (kgf/mm²)	0.10197
kilogram-force/mm² (kgf/mm²)	megapascal (MPa)	9.8066
megapascal (MPa)	newton/mm² (N/mm²)	1.0000
pound (lb)	kilogram (kg)	0.4536
kilogram (kg)	pound (lb)	2.2046
newton (N)	kilogram (kg)	0.10197
kilogram (kg)	newton (N)	9.8066
ounce (oz)	gram (g)	28.35
gram (g)	ounce (oz)	0.035274
inch (in)	millimetre (mm)	25.40
millimetre (mm)	inch (in)	0.039370
foot (ft)	metre (m)	0.3048
metre (m)	foot (ft)	3.2808
gallon (gal)	litre (l or L)	4.546
litre (l or L)	gallon (gal)	0.2200

Formulae

Temperature	$°C = (°F - 32)x\frac{5}{9}$ $°F = (°Cx\frac{9}{5}) + 32$
Mass of plate or sheet	*Mass (kg) = T x W x L x Density* *Billing weight (kg) = T x W x L x Billing Factor* T is thickness in mm W is width in metres L is length in metres **Austenitic** / **Ferritic** **Density** 7.9 / 7.7 **Billing Factor** 8.177 / 8.000
Mass of round wire or bar	**Austenitic** *Mass (kg/m) = 0.006205 x d²* **Ferritic** *Mass (kg/m) = 0.006063 x d²*

More complete unit conversion factors are given in the table on the Atlas Steels Website. A spreadsheet for mass calculations of common products is also available on the Atlas Steels website.

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Appendix 6

Dimensional Tolerances for Bar

h and k Limit Deviation

Nominal Bar Size (mm)	Tolerance Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Up to 3	0.8	1.2	2	3	4	6	10	14	25	40	60	100	140	250	400	600
Over 3 to 6	1	1.5	2.5	4	5	8	12	18	30	48	75	120	180	300	480	750
Over 6 to 10	1	1.5	2.5	4	6	9	15	22	36	58	90	150	220	360	580	900
Over 10 to 18	1.2	2	3	5	8	11	18	27	43	70	110	180	270	430	700	1100
Over 18 to 30	1.5	2.5	4	6	9	13	21	33	52	84	130	210	330	520	840	1300
Over 30 to 50	1.5	2.5	4	7	11	16	25	39	62	100	160	250	390	620	1000	1600
Over 50 to 80	2	3	5	8	13	19	30	46	74	120	190	300	460	740	1200	1900
Over 80 to 120	2.5	4	6	10	15	22	35	54	87	140	220	350	540	870	1400	2200
Over 120 to 180	3.5	5	8	12	18	25	40	63	100	160	250	400	630	1000	1600	2500
Over 180 to 250	4.5	7	10	14	20	29	46	72	115	185	290	460	720	1150	1850	2900
Over 250 to 315	6	8	12	16	23	32	52	81	130	210	320	520	810	1300	2100	3200
Over 315 to 400	7	9	13	18	25	36	57	89	140	230	360	570	890	1400	2300	3600
Over 400 to 500	8	10	15	20	27	40	63	97	155	250	400	630	970	1550	2500	4000

Tolerance values given in μm (microns) = X0.001mm

h = all minus
k = all plus

Examples: 25.40mm diameter bar to h9 = +Nil, -0.052mm
160mm hot rolled bar to k14 = +1.000mm, -Nil

Note:

1. Tolerances are as given for shafts in ISO 286.2 and AS 1654.2. These references should be consulted for full details and for other tolerances.
2. Shaft k tolerances are according to the above table between k8 and k13 only.

Appendix 7

Further Information

Further information on the topics covered in this Technical Handbook can be found in the following references, among others:

1. Stahlschlüssel "Key to Steel". An extremely comprehensive cross reference of compositional specifications. Particularly good for European designations.

2. "Woldman's Engineering Alloys", ASM. Another comprehensive cross-reference of alloys, but with an American slant.

3. Iron and Steel Society (ISS) "Steel Products Manual - Stainless Steels" March 1999. Background data on products and on material specifications. This book was published in previous editions by the AISI - American Iron and Steel Institute.

4. ASTM (American Society for Testing and Materials) Standards. An Index volume lists all ASTM standards, and individual volumes cover flat product, tube/pipe and bars etc. Individual ASTM standards can be down-loaded from internet site www.astm.org.

5. UNS Numbering System book, published jointly by ASTM and SAE. Lists all commercially produced metals by UNS number.

6. AS (Australian Standards) cover some of the products handled by Atlas Steels, but in general, because we are sourcing on the world market, Australian Standards are less relevant than the major overseas standards. In stainless steel products ASTM standards are often universally recognised.

7. ASM "Specialty Handbook of Stainless Steels". A very good source of information on almost any topic related to stainless steels. This is compiled from the various ASM Metals Handbooks.

8. "Design Guidelines for the Selection and Use of Stainless Steel", American Iron and Steel Institute, Distributed by Nickel Institute (NiDI publication No. 9014).

9. "Australian Stainless Reference Manual" published by the Australian Stainless Steel Development Association (ASSDA). ASSDA has been established to assist all stakeholders in the Australian stainless steel industry, and membership is open to any company.

10. "Guidelines for the Welded Fabrication of Nickel-Containing Stainless Steels for Corrosion Resistant Services". Nickel Institute Reference Book, Series No. 11007.

11. “Specification for fabrication & installation of stainless steel plant & equipment in the food and beverage industry”. ASSDA. An industry specification for fabrication, with applicability beyond food processing plants.

12. Moore, P.J., Good Design in Stainless Steel, Metal Working Australia, Vol 8, No. 3, Aug/Sep 1993.

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13. ASM Handbook Vol 13, "Corrosion". An excellent resource on its topic, for all metals.
14. “Corrosion Handbook”, Outokumpu Stainless AB. An excellent reference on grade selection for many environments.
15. Lai, G.Y., "High Temperature Corrosion of Engineering Alloys", ASM, 1990. A good source for elevated temperature performance of all metals.
16. Sedriks, A.J. "Corrosion of Stainless Steels". Rigorous and in-depth discussion. 2nd edition 1996.
17. Dillon, C.P., “Corrosion Control in the Chemical Process Industries”. An excellent practical guide to selection of corrosion resistant materials.
18. “The Machining of Stainless Steels”, Stainless Steel Specialist Course, Module 9. ISSF.
19. WTIA Technical Note 16 "Welding Stainless Steels". Published by Welding Technology Institute of Australia.
20. Lacombe, P., Baroux, B., Beranger, G. (editors) – Stainless Steels, Les Editions de Physique, 1993.

Internet Sites of Interest

Organisation	Internet Address
Atlas Steels	www.atlassteels.com.au
Australian Stainless Steel Development Association – ASSDA	www.assda.asn.au
British Stainless Steel Association – BSSA	www.bssa.org.uk
New Zealand Stainless Steel Development Association – NZSSDA	www.hera.org.nz/nzssda/
Specialty Steel Industry of North America – SSINA	www.ssina.com
Southern Africa Stainless Steel Development Association – SASSDA	www.sassda.co.za
Nickel Institute	www.nickelinstitute.org
International Stainless Steel Forum – ISSF	www.worldstainless.org
European Stainless Steel Development Association – Euro Inox	www.euro-inox.org
American Society for Testing and Materials – ASTM	www.astm.org
Standards Australia – for standards writing	www.standards.com.au
SAI Global – to purchase Australian and many foreign standards	www.saiglobal.com
Standards New Zealand	www.standards.co.nz
Australasian Corrosion Association – ACA	www.corrosion.com.au/
Welding Technology Institute of Australia – WTIA	www.wtia.com.au
National Association of Testing Authorities – NATA	www.nata.asn.au